Treatment Planning Techniques in PBS

Mingyao Zhu, PhD
Emory University School of Medicine
Emory Proton Therapy Center
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Disclosure

• None
Outline

• Uncertainties in PBS
  – Range
  – Setup
  – RBE
  – Motion
  – Anatomy

• Mitigation techniques in treatment planning
  – bsPTV (margin)
  – Beam selection
  – Robust optimization
  – Adaptive RT
  – Re-painting
  – RBE/LET optimization
Introduction

• Uncertainties in PT:
  - Proton Range
  - Patient Setup
Range Uncertainty

• CT HU to stopping power ratio (SPR)
  – Both are dominated by electron density ratio
  – But elemental composition matters
  – Various among facilities
  – Typically 2.5-3.5% with additional 1-3mm

3.5 mm at a range of 10 cm
7 mm at a range of 20 cm

Depends on depth!

Paganetti, PMB 57(11), 2012
Range Uncertainty

- Tissue heterogeneities
  - Bragg peak degradation

Sawaguchi, et al., PMB, 53(17) 2008
Lomax 2008, PMB, 53
Solution—Margin

• PTV concept: accounts for setup and all geometric uncertainties to ensure dosimetric coverage of CTV

• PTV for proton planning needs to account for range uncertainties too.

• Beam specific PTV (bsPTV) expansion
Photon PTV margin

Setup up uncertainties in the direction parallel to beam’s central axis has minimal effect (inv. Sq.) and can’t be accounted for by margin.
Photon PTV margin

In the beam’s eye view, only “lateral” margin is needed to account for setup uncertainties in the direction perpendicular to beam’s central axis.
Using multiple beams requires margin in multiple directions
In the beam’s eye view, “lateral” margin is needed to account for setup uncertainties in the direction perpendicular to beam’s central axis
Along the beam’s central axis, distal and proximal margin are needed to account for Range Uncertainties!
Beam-specific proton PTV

- Deeper target $\rightarrow$ larger margin
- Distal margin $>$ proximal margin
- Beam angle dependent

Figure 1 Figures A and B illustrate distal and proximal PTV margins for an identical target located at different depth. Margins are also a function of beam direction (C). The concept of a PTV that is common for all beams does not fulfill the PTV requirement for proton planning (D). (Color version of figure is available online.)

Langen and Zhu, Semin. Rad. Onc. 2018
Patient Setup

• Lateral margin is used to account for motion perpendicular to the beam direction;

• However, lateral motion also affect proton dose deposition along the beam direction

Langen and Zhu, Semin. Rad. Onc. 2018
Beam specific PTV

• bsPTV: based on water-equivalent thickness (WET) ray-tracing accounting for
  – Range uncertainties calculated at distal and proximal surface;
  – Patient setup error;
  – Organ motion;

• bsPTV properties:
  – Beam angle dependent;
  – Affected by surrounding tissue density
  – Shape can be unintuitive
  – Can be used for planning and evaluation

3.5% range uncertainty

- Larger distance in lower density tissue;
- Larger margin with higher density tissue

3.5% range uncertainty + 3mm isocenter shift

- Lateral shift changes distal/proximal margin
- Ideal PTV shape may be very un-intuitive
Beam specific PTV for lung tumor

Beam specific PTV calculated for each beam angle based on CTV

- Range uncertainty alone
- Range + Setup uncertainty

Setup error ➔ much bigger margin
Introduction

• Uncertainties in PT:

- Proton Range
- Patient Setup
- Margin
- Beam selection
IMPT—Plan robustness

• BS-PTV does not guarantee robustness for inversely optimized IMPT plans;

• Plan robustness is a plan quality metric and needs to be evaluated;

• Ask: what happens to dose distribution if patient shifts and if range is incorrect?
Two basic planning techniques: SFO & MFO

SFO (Single field optimization)
Fields are optimized independently of each other
or: Right hand does not know what the left is doing
Two basic planning techniques: SFO & MFO

MFO (Multiple field optimization)
Fields are optimized in unison, they are a team
individual fields can have non-uniform dose

Total dose  L-lat dose  R-lat dose

Katja Langen
Split targets—by design MFO

3-field prostate+LN

Zhu, et al, ARO, in press
Split targets—by design MFO

5-field HN plan
SFO vs. MFO

• In general:
  – SFO is more robust than MFO;
  – MFO can spare normal tissue better for more complicated target shapes

• Use SFO if possible
  – For convex shaped target: SFO is usually good enough

• Use MFO only when needed
  – Concave shaped target, e.g. bi-lat HN
  – OAR surrounded by target,
  – If split the field-target
SFO with uncertainty
MFO with uncertainty

Dose gradient within target!
Robust Optimization

• Include robustness as an objective in optimization

Chen et al., PMB, 57 (2012), 591
Introduction

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- Robust optimization
Proton RBE

Protons are NOT high LET particles

Bushberg, Essentials of Medical imaging, 2nd Ed.
Proton RBE

@ 250 MeV: 3 MeV cm$^2$/g

3 MeV/cm = 0.3 keV/μm

@ 10 MeV: 5 keV/μm

@ 1 MeV: 20 keV/μm
RBE uncertainty—distal edge

ICRU Report 78: use of generic RBE value of 1.1 is recommended

1 physical proton Gy = 1.1 equivalent Gy or
1.1 cobalt-equivalent Gy

Units: CGy, GyE, Gy(E), Gy(RBE)

H4 cell
Survival fraction 0.1
Relative to mid-SOBP
RBE uncertainty—distal edge

- Use a generic RBE value adds uncertainty to the distal edge RBE dose;
- Biological dose is deeper/higher than physical distal edge dose;
- Real RBE value depends on multiple factors
  - Treatment technique
  - Dose
  - Cell/tissue type
  - End point
  - Radiosensitivity
  - Etc.

Choose generic RBE value of 1.1

Paganetti, PMB, 57 (2012) R99
RBE uncertainty management

• Use multiple beams
  – Spread uncertainty geometrically
  – Avoid stopping before critical OARs

• Robust optimize and evaluate beam dose

• Variable RBE in plan optimization
  – Not currently available
  – LET_d distribution

The current clinical practice of using a constant RBE for protons should generally be maintained but specific clinical scenarios warrant a change in current practice. (Report of AAPM TG-256, 2019)
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Motion during treatment

- If tumor and beam move independently, spot positions differ from planned positions;
- Similar to interplay between IMRT/VMAT and tumor motion
- Can leads to hot or cold spots in target
- Spot scanning is more sensitive to intra-fraction target motion since it is more dynamic

Groezinger, Thesis, TU Darmstadt
Motion during treatment

Grassberger et al, IJROBP (86) 2, 380, 2013
Motion during treatment

Open symbols: n=1
Solid symbols: n=4

Grassberger et al, IJROBP (86) 2, 380, 2013
Motion during treatment

• Motion during treatment is important for spot scanning

• Possible approaches:
  – Restrict motion
  – Beam gating
  – Re-scan or re-painting
  – Use big spot

• Be aware, but don’t be discouraged!
Introduction

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  - Anatomy variation
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  - Re-painting
Proton is sensitive to anatomy changes
Proton is sensitive to anatomy changes

Lower density proximal to target:
- Dose “over-shooting”
- Over-dosing to distal OAR
- Under-dosing to proximal Target
Proton dose is sensitive to anatomy changes
Proton dose is sensitive to anatomy changes

Higher density proximal to target:
- Dose “pulling-back”
- Under-dosing to distal Target
- Over-dosing to proximal OAR
Lung IMPT: anatomy changes dramatically

Original Proton Plan

Dose recalculated on the new anatomy

Bucci et al. ASTRO Abstract, 2007
Pelvic IMPT

Planning CT

Week 1 rescan CT

Zhu, ASTRO 2017
Head and neck IMPT

127% hot spot
Patient anatomy change

- Undesired dosimetric consequence

- Unpredictable dosimetric consequence

- Mitigation strategy:
  - Adaptive RT: frequent re-scan and re-plan
    - Resource intensive
    - Suboptimal treatment
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Anatomical robust optimization
Anatomical robust optimization

Robust optimization

- Setup: 5mm
- Range: 3.5%
- Isocenter offset
- SPR scaling
- Anatomy
- Multiple CT images
Types of multiple CT Robust Optimization

Planning CT + Adaptive CT + Synthetic CT
mCT RO for Lung IMPT

Planning CT + Adaptive CT

Lung IMPT: anatomy change dramatically

30% re-planning

Between PCT and ACT:
- Negligible variation of CTV volume
- Large difference of Range and SOBP

DVH comparison

mCT RO for lung IMPT

• Using 2 patient scans: PCT and ACT
  – Include both CTs in optimization

• On PCT:
  – Similar coverage
  – Slightly higher lung dose
  – Similar robustness
  – No statistically difference in heart or spinal cord dose

• On ACT:
  – Reduced cold spot—improve tumor control
  – Could potentially reduce re-planning frequency

mCT RO for lung IMPT is feasible!

mCT RO for head and neck IMPT

Planning CT + Adaptive CT

Yang, et al., Radiother Oncol. (2020)
mCT RO for head and neck IMPT

40% re-planning

Between PCT and ACTs:

- Negligible variation of CTV volume
- Large difference of Range and SOBP

Yang, et al., Radiother Oncol. (2020)
mCT RO for head and neck IMPT

Yang, et al., Radiother Oncol. (2020)
mCT RO for head and neck IMPT

• Using 2 patient scans: PCT and ACT1
  – Include both CTs in optimization

• For patients with large anatomical changes
  – mCT plan provide more robust target coverage
  – Slightly sacrificed dose conformity

mCT RO for HN IMPT can reduce the need of adaptive planning!

Yang, et al., Radiother Oncol. (2020)
mCT RO for sinonasal IMPT

Planning CT + Synthetic CTs

mCT RO for sinonasal IMPT

mCT RO for sinonasal IMPT

mCT RO for sinonasal IMPT

Total dose
Anatomical robust (3 synCT + pCT)
SFUD (5 mm margin)
Online adaptive

mCT RO for sinonasal cancer

• Better target coverage than SFUD (+ margin);
• Lower OAR dose than SFUD (+ margin);

• Online adaptation is the best, but implementation is not realistic;

• mCT RO plans are anatomically robust under conditions of large cavity filling variation, therefore can be an alternative to the online adaptation;

mCT RO for Pelvic IMPT

Planning CT + Synthetic CTs

Zhu, et al, ARO, in press
Bowel filling variation simulation

Native CT # and density

Purple: Override to Air

Pink: Override to Muscle
mCT RO for pelvic IMPT

- Patient position:
  5 mm

- Range Uncertainty:
  3.5%

- Image sets:
  3 CTs
mCT RO for Pelvic IMPT

- 15 patients with pelvic LN irradiation

- Similar target coverage and critical OAR doses
  - On pCT
  - On QACTs

- mCT RO further reduced hot-spot on normal tissue
  - On QACTs

Zhu, et al, ARO, in press
mCT RO Clinical implementation

• All prostate patients are planned with this method at MPTC;

• The frequency of re-scan reduced substantially:
  – From weekly scans to 2 scans throughout the treatment course;

• Haven’t observe concerning hot spots on the re-scan CTs so far;

• This method can be used for other disease sites
  – GYN
  – Bladder
  – Anal/rectal
  – Head and neck
  – etc...
Summary

- Uncertainties in PT:
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Questions?

Thank you!