Physics Uncertainty Issues for Prostate and Lung Cancers

Lei Dong, Ph.D.
Dept. of Radiation Physics
University of Texas M.D. Anderson Cancer Center, Houston, Texas

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Outline

- Review physics-related issues in proton therapy of prostate and lung cancers
- Discuss strategies and challenges for handling motion issue
Potential Factors Affecting Prostate Treatment

- Target Motion (Prostate and SVs)
  - Inter-fractional rigid movement
    - Bony registration
    - Soft tissue target registration
  - Inter-fractional deformation
  - Intra-fractional motion

- Variations in Nearby Structures
  - Rectum filling
  - Bladder filling
  - Femoral heads
Inter-fractional Variations

Planning contours mapped to 24 in-room CTs
Inter-fractional Variations

Simulation CT is a snapshot of patient’s anatomy!

Planning CT

Planning contours mapped to 24 in-room CTs
Inter-fractional Variations

Simulation CT is a snapshot of patient’s anatomy!

Planning contours mapped to 24 in-room CTs
Bi-lateral Proton

Robustness of IMPT for Multi-beam IMPT?

Femur Rotation
Day-to-day variation in femur position

Planning CT

Anatomy over 20 CT imaging sessions

P. Park/MDACC
Proton Distal Dose Variations Due to Femur Rotation

Original Plan

Daily CT

Melancon/MDACC
Can CBCT/CT-on-Rails based IGRT help?

Direct alignment of soft tissue target (the prostate)
- Not entirely
  - IGRT ensures the position of the prostate
  - It will not guarantee normal tissue outside the target
    - Relative motion of the target relative to bony structures: the compensator can be off if bone is not aligned
Immobilization is important for proton therapy!
Summary of Challenges in Prostate Proton Therapy

1. Uncertainties:
   - CT numbers and stopping powers ratios,
   - Inter-fractional changes of normal tissues in the beam path,
   - Intra-fractional organ motion,

2. Strategies
   - Optimization of beam angle selection
   - Better immobilization techniques
     - Leg position
     - Rectal balloon
Factors Affecting Proton Therapy of Lung Cancer

Free breathing treatment
Proton vs. IMRT
(motion effect to dose distribution)

Dong/MDACC
PTV Concept will not work

ICRU 62

Proton Therapy

(a)  (b)
Effect of aperture expansion

PLANNED

RC smear: 0 mm
AP margin: 0 mm
Setup error: 0 mm
Tumor motion: 0 mm

“DELIVERED”

RC smear: 0 mm
AP margin: 0 mm
Setup error: 10 mm
Tumor motion: 0 mm

Isodose levels
20
50
80
95
100

Courtesy of Martijn Engelsman (MGH)
Effect of aperture expansion

RC smear: 0 mm
AP margin: 5 mm
Setup error: 0 mm
Tumor motion: 0 mm

“DELIVERED”

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Aperture expansion alone is not a solution

Courtesy of Martijn Engelsman (MGH)
Effect of range compensator smearing to ensure target coverage

- The bolus thickness at point P, as calculated by the ‘simple’ technique, is replaced by the thinnest bolus thickness calculated anywhere within ±d of the point P.
Effect of range compensator smear

RC smear: 5 mm
AP margin: 0 mm
Setup error: 0 mm
Tumor motion: 0 mm

RC smear: 5 mm
AP margin: 0 mm
Setup error: 10 mm
Tumor motion: 0 mm

Isodose levels:
- 20
- 50
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- 100

Courtesy of Martijn Engelsman (MGH)
Effect of range compensator smearing

RC smear: 10 mm  
AP margin: 0 mm  
Setup error: 0 mm  
Tumor motion: 0 mm

RC smear: 10 mm  
AP margin: 0 mm  
Setup error: 10 mm  
Tumor motion: 0 mm

Planned "Delivered"

Isodose levels:
- 20
- 50
- 80
- 95
- 100

Smearing alone is not a solution

Courtesy of Martijn Engelsman (MGH)
Compensator Smearing and Aperture Expansion

RC smear: 0 mm
AP margin: 0 mm
Setup error: 0 mm
Tumor motion: 0 mm

RC smear: 7.5 mm
AP margin: 7.5 mm
Setup error: 0 mm
Tumor motion: 0 mm

Isodose levels:
- 20
- 50
- 80
- 95
- 100

Courtesy of Martijn Engelsman (MGH)
Compensator Smearing and Aperture Expansion

RC smear: 7.5 mm
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RC smear: 7.5 mm
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Courtesy of Martijn Engelsman (MGH)
How to evaluate a plan in the presence of anticipated motion?
CT Number uncertainties have a significant impact on proton dose distributions.

But commonly it’s not visible on proton plans.

0% uncertainty

-3.5%

+3.5%
Scatter plot of various human biological tissues listed in ICRU Report 44 and ICRP Report 23

Human biological tissues have different electron density ratios (HUs) and effective atomic numbers.

Proton Stopping-Power-Ratio depends on the effective atomic numbers (~ 3 - 4 % uncertainties)
Improving CT number Accuracy

- High Energy CT imaging to reduce metal artifacts
- Dual-energy CT imaging to characterize material compositions
  - Electron density
  - Effective atomic number
Challenges in planning moving target

- 4D dose calculation
  - Accumulating dose distributions voxel-by-voxel and phase-by-phase
    - Require deformable image registration and re-computing plans for each breathing phase using 4D CT
- 4D treatment plan optimization
  - Automatically adjust distal margin, aperture, compensator smearing parameters to satisfy target coverage and normal tissue sparing
- 4D treatment plan evaluation

None of these are currently available in a commercial product!
Proton Planning Guide for Non-Gated Treatment
- A practical approach by MDACC and MGH

- Target delineation
  - ITV delineated on a 4D CT set

- Dose calculation
  - Using the time-averaged CT based on the 4D CT set
  - Override iGTV with tissue density
    - A compromise to cover the moving target without altering TPS internal compensator design

- Planning
  - Evaluate DVHs using contours derived from Mid-ventilation CT

- Final Plan Summary
  - Copy the plan to Mid-ventilation CT without any density override
  - Report DVHs using lung volumes defined either for Mid-Ventilation or the Expiration phase
Special Situations

- **If gated treatment is not used**
  - Tumor near the diaphragm
    - The patient is not a good candidate for proton therapy if any beam cannot avoid a portion of the diaphragm before entering the treatment target.
    - **We don’t have a good solution!**

- **Stomach filling**
  - If we cannot avoid the beam direction through the stomach, the patient is not a good case for proton therapy.
Esophagus cancer near GE junction

Green: density changes

Red: GTV
More problems: Distal Edge Degradation Caused By Heterogeneities
“Texturized” Lung Equivalent Material
Monte Carlo vs. TPS Dose Calculations

Simulations with Validated Monte Carlo

- Texturized phantom: $3 \times 3 \times 3$ mm³ voxels
- Random 20% with unit density, rest air
- Average density = 0.2 gm/cc

Calculation Error!

<table>
<thead>
<tr>
<th>90-20% Falloff mm</th>
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<tbody>
<tr>
<td>Homogeneous Slab</td>
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<tr>
<td>Texturized voxels</td>
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Eclipse TPS
Monte Carlo
Summary of Physics Uncertainty Issues

- Proton beams are more sensitive to
  - Organ motion
  - Anatomy changes in the beam path
  - CT number accuracy
  - Treatment devices in the beam path (for example, the couch, immobilization devices)
- IGRT and motion management may help
- Proton plans are difficult to evaluate
- Many challenges remain due to practical reasons
  - Compromises may have to be made for routine practice
  - Use common sense!