Intrafraction Motion Management for Particle Therapy

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Learning Objectives

- Charged Particle Specific Motion Issues
- Current Methods
- New and Upcoming Methods

Disclosures

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Opinions expressed are solely my own

Proton Beam Delivery

Double-Scatter System

Pencil Beam Scanning System
Charged Particle Specific Motion Issues

Issue #1  PTV/ITV does not work (for particle therapy)

- Double-Scattered Proton Beam (not PBS)

Impact of Organ Motion on Proton Dose Distributions

Treatment planned based on single phase

The same treatment plan calculated on 4D CT images

Issue #2: Proton Range Depends on Tissue Movement Outside the Target

- Small Tumor near GE Junction – Treat with Big Margin?

- Mobile tumors pose a particular problem for scanned treatments due to interplay effects
- Hot and cold spots within the target; causing dose blurring as well

Issue #3: Interplay Effect

PBS – the future of proton therapy

- PBS Advantages
  1. Better conformal plans
  2. Lower operation efficiency
  3. Lower neutron doses
Other Inter-fractional Motion Issues in Particle Therapy

- Motion pattern changes over treatment course (the same as in photon therapy)
- Interfractional anatomic changes (the same as in photon therapy)
Adaptive RT is a strong indication for Particle Therapy

Current Motion Management Strategies

- **Treatment Planning**
  - Dose calculation on Avg. density CT data set
  - IGT density override (optional); evaluate dose coverage in Insp & Exp phases
  - No. of fractions > 5
  - No. of beam angles ≥ 2
  - Beam angle selection (avoid going through tissues with significant motion)
  - Use Single Field Optimization (SFO) as much as possible
  - Use Robustness optimization or analysis if available
  - Acquire evaluation CT to check anatomical changes routinely
  - Use large spots
- **Minimize motion**
  - Breath-hold treatment
  - Compression Belt
- **Delivery**
  - Repainting (layer-by-layer or volume)
  - Gating

Planning Technique: SFO vs. MFO

- **SFO: Single-Field Optimization**
  - SOBP based optimization
  - Each field contributes independently and works to cover entire target
  - Robustness depends on beam angle selection and anatomical changes in the direction of beam
- **MFO: Multi-Field Optimization**
  - Combined distribution of all fields used to cover target (similar to IMRT)
- **rMFO: Robustness Multi-Field Optimization**
  - Robustness evaluation built into the cost function in optimization
SFO vs. MFO

- Dose gradients are especially sensitive to motion.
- They imply the risk of hot and cold spots within the target in the presence of motion.

Adapted from Antje-Christin Knopf

Advantage of Robust Optimization

Smoothening of overlap area

Robust Optimization Illustration

No Uncertainty

Range Uncertainty

Robust Optimization

R. Mohan

Penn Radiation Oncology

Penn Medicine
The interplay effect is minimal for total dose delivery over the entire course of treatment.

**Single-Fraction Interplay Effect**
- BigSpots: 1SD: 8-17mm
- SmallSpots: 1SD: 2-4mm
- Monte Carlo: realistic spot delivery pattern

Grassberger et al. IJROBP (2013)

**n(=35)-fraction Interplay Effect**
- Static vs. n-fx approximation
  - Static: Blue Square
  - N fx: Red Triangle

Grassberger et al. IJROBP (2013)
Future Directions

- Understanding the Effect of Motion Uncertainties
  - 4D accumulated Dose (4DD) calculation to evaluate potential motion effects for each plan.

- Robustness Optimization to Minimize Motion Effect
  - Use 4D CT to calculate motion effects in addition to (1) setup error and (2) range uncertainties.

- Incorporate Machine Delivery Techniques
  - Phase-controlled Rescanning (synchronization of rescanning with patient’s breathing phases).
  - Delivery phase-gated sub-plans.
  - 4D dynamically accumulated dose (4DDD): considers the time-dependent delivery sequence or radiation fluence together with representative anatomic motion (determined using 4DCT).

Motion mitigation scanning

- If the motion timeline is known, dose rate manipulation can be used to optimize the time needed to scan one layer or the whole target volume.
- If PCR is not completed within a single gating window due to the particular irradiation specifications previously selected, the isoenergy layer is completed by extending the beam delivery to the next gating window.

Motion mitigation scanning

- Enabling phase control leads to dose degradation if no rescanning was done.
- Multiple rescanning with phase control considerably improved dose conformity.
- Require fast scanning magnet to achieve PCR.
**4D optimization and combined motion mitigation approaches**

**Synchronized delivery of pre-calculated fraction treatment plans based on specific motion phases.**

- The concept is based on subdividing the target volume of interest into subsections.
- Beam spots were associated with specific motion phases whose sequences were unknown prior to delivery.
- Complex motion mitigation approaches theoretically promise to be successful, they are limited by unpredictable variations of patient respiratory motion over the course of treatment.

**4D parameters**

1. Patient geometry
2. Field direction
3. Field arrangement
4. PBS beam data
5. Spot distance
6. Energy layer distance
7. Prescribed dose
8. Fractionation schema
9. 3D plan – density: Max/mean/midCT
10. 3D plan – geometry: CTV/gITV/rITV
11. Scanning path/direction

**Beam delivery dynamics**

11. Period
12. Amplitude
13. Irregularity
14. Deformation

**Motion mitigation approach**

15. Rescan type and number
16. Combined with gating: GWs, surrogate
17. Combined with Tracking
18. 4D optimization

**Summary**

- Motion management is an important factor for particle therapy
  - Affecting dose distribution
  - Influence by normal tissue motion in addition to tumor motion
  - Depending on dynamic beam delivery scheme
- Uncertainty management is an effective way to understand motion effects
- Incorporating machine delivery sequence with patient motion is a challenging but potentially more rewarding approach
  - AAPM TG 290 is coming

*Report of AAPM Task Group 290: Respiratory Motion Management for Particle Therapy*

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