Intrafraction Motion Management for Particle Therapy

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Learning Objectives

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

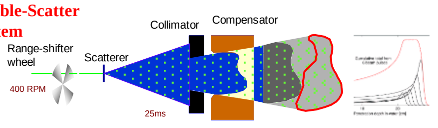
Disclosures

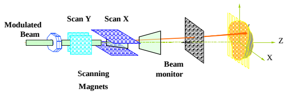
- Research grants: NIH; Varian
- Speaker Bureau Honorarium: Varian
- Consortium: Varian FlashForward™

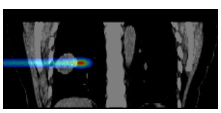
- Opinions expressed are solely my own

Proton Beam Delivery

Double-Scatter System





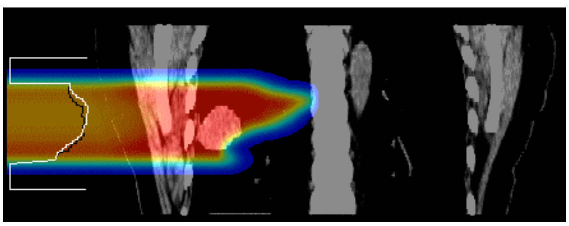


5ms/cm 1s per layer change

Pencil Beam Scanning System

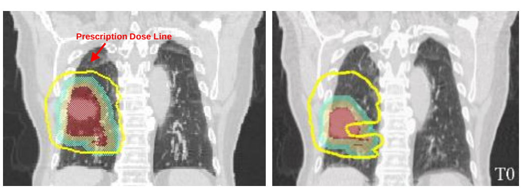
Charged Particle Specific Motion Issues

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



- Double-Scattered Proton Beam (not PBS)

Impact of Organ Motion on Proton Dose Distributions
4D Dose (4DD) is recommended!

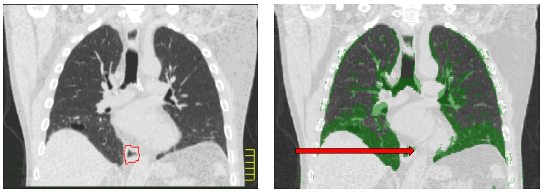


Treatment planned based on single phase

The same treatment plan calculated on 4D CT images

Kang et al. IJROBP, Vol 67, No.3, Page 906, 2007

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

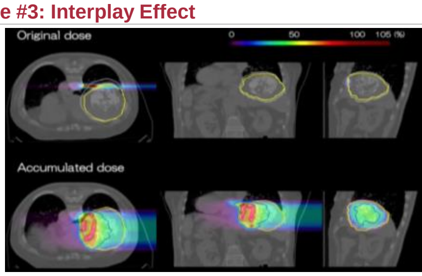


Red – Target Volume

Green– Tissue Swept in High Density

Small Tumor near GE Junction – Treat with Big Margin?

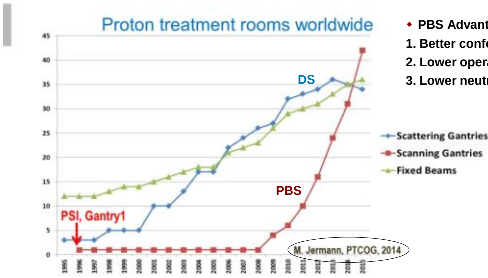
Issue #3: Interplay Effect



- 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

Shinichiro Mori

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

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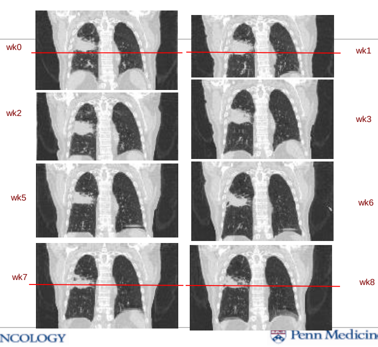
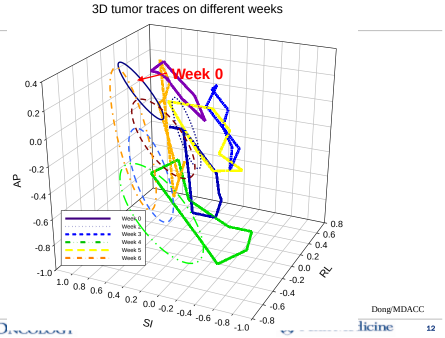
- Motion pattern changes over treatment course (the same as in photon therapy)
- Interfractional anatomic changes (the same as in photon therapy)



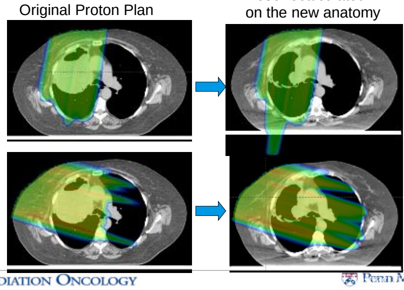
- Motion pattern changes over treatment course (the same as in photon therapy)
- Interfractional anatomic changes (the same as in photon therapy)



Adaptive RT is a strong indication for Particle Therapy

Original Proton Plan

Dose recalculated
on the new anatomy



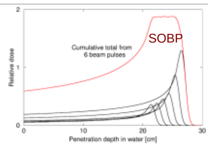
Current Motion Management Strategies

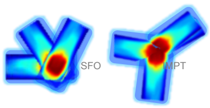
- **Treatment Planning**
  - Dose calculation on Avg. density CT data set
  - iGTV density override (optional); evaluate dose coverage in Insp & Exp phases
  - No. of fractions > 5
  - No. of beam angles > 2
  - Beam angle selection (avoid going through tissues with significant motion)
  - Use Single 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

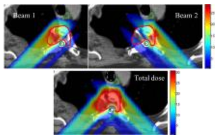
- **SFO: Single-Field Optimization**
  - SOBP based optimization
  - Each field contributes independently and works to cover entire target
  - Robustness depends on beam angle selection and anatomical changes in the direction of beam
- **MFO: Multi-Field Optimization**
  - Combined distribution of all 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





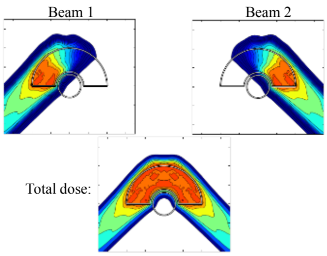
MFO



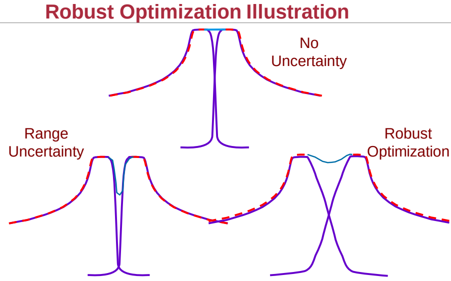
- dose gradients are especially sensitive to motion
- they imply the risk of hot and cold spots within the target in the presents of motion

Adopted from Antje-Christin Knopf

Advantage of Robust Optimization Smoothing of overlap area



Robust Optimization Illustration



R. Mohan

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

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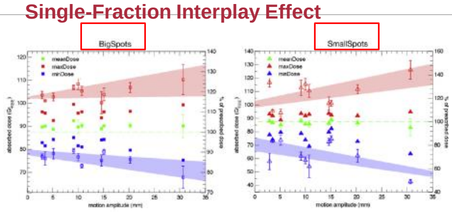
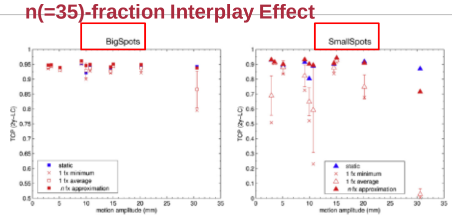
Single-Fraction Interplay Effect



- 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

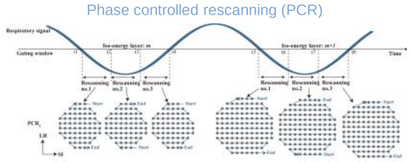
Grassberger et al. IJROBP (2013)

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

Phase controlled rescanning (PCR)

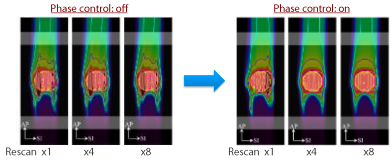


- If the motion timeline is known, dose rate manipulation can be used to optimize the time needed to scan one layer or the whole target volume.
- If PCR is not completed within a single gating window due to the particular irradiation specifications previously selected, the isoenergy layer is completed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

Shinichiro Mori - NIRS

Motion mitigation scanning

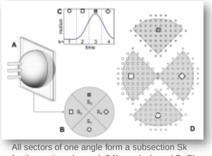
Phase controlled rescanning (PCR)



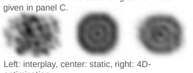
- Enabling phase control leads to dose degradation if no rescanning was done.
- Multiple-rescanning with phase control considerably improved dose conformity.
- Require fast scanning magnet to achieve PCR.

4D optimization and combined motion mitigation approaches

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



All sectors of one angle form a subsection Sk for the motion phases k 2 f1 . . . 4g (panel B, C). Each Sk is deformed according to the motion given in panel C.



Left: interplay, center: static, right: 4D-optimization

Graeff et al Radiother Oncol 109, 419-424 (2013)

- The concept is based on subdividing the target volume of interest into subsections.
- Beam spots were associated with specific motion phases whose sequences was 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.

Shinichiro Mori - NIRS

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 scheme
9. 3D plan – density: Max/mean/midV CT
10. 3D plan – geometry: CTV/gITV/rITV
11. Scanning path/direction

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

Beam delivery dynamics

15. Lateral position: Raster or spot
16. Dose rate: varied or constant
17. Energy switching time

18. Starting phase and combination for multi-fields

Motion mitigation approach

19. Rescan type and number
20. Combined with gating: GWs, surrogate
21. Combined with Tracking
22. 4D optimization

Ye Zhang @ PSI

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

Heng Li, Lei Dong, Christoph Bert, Joe Chang, Stella Flampouri, Kyung-Wook Jee, Liyong Lin, Michael Moyers, Shinichiro Mori, Joerg Rottmann, Erik Tryggestad, Sastry Vedam

Thank you!

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