Personalized Motion Management Strategies for Pencil Beam Scanning Proton Therapy

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Why Proton for radiation therapy?

- Depth in tissue
- Relative dose
- Protons
- Bragg Peak
- Protons Stop!

Some tumors move a lot...

- The interplay effect between tumor motion and beam scanning

Courtesy of P. Balter
Proton dose and motion

- Proton dose strongly depends on beam paths
- Organ motion creates changes in beam paths
- Interplay effect of spot scanning vs. respiratory motion → under- and Over-doses

Not all tumors move that much...

- 20 lung cancer patients (21 tumors)
- 2-mm gold marker under fluoroscopic imaging

Not all tumors move that much...

- 191 lung cancer patients (94 early stage, 97 locally advanced) NSCLC
- Locally advanced < early stage
- Superior/Inferior has the largest motion
### How to quantify the motion?

- **Along the beam direction:**
  - Motion in this direction has little dosimetric effect.
  - WET changes – selecting gantry angles with smallest ΔWET.

- **Perpendicular to the proton beam direction:**
  - In the axial plane – depending on gantry angle.
  - Superior/inferior direction – independent gantry angle.

### Tumor motion analysis

- Using ray tracing method to determine WET changes between T0 & T50 along the beam direction.
- Deformation vector between T0 & T50 - for motion analysis – 3 components:
  - Parallel to the proton beam.
  - Perpendicular to the proton beam in the axial plane.
  - Perpendicular to the proton beam – superior/inferior.

(Courtesy of P. Park)
Tumor motion analysis – Example
- Adenocarcinoma of the left lower lobe lung cancer

Gantry angles with smaller change of WET

Tumor motion analysis – Example
- Adenocarcinoma of the esophageal

Gantry angles with smaller change of WET

How to dosimetrically assess the motion interplay effect?
- Measurements
  - Simple dose distributions in simple phantoms

- Simulations:
  - 4D dose (4DD) – equally weighted average dose among the respiratory phases of 4DCT.
  - 4D dynamic dose (4DDD) – estimation of the delivered dose under the influence of the interplay effect.
  - 4DDD converges to 4DD as fraction increases – interplay effect will be averaged out.
  - \( \Delta \approx 1 \times 4DDD - 1 \times 4DD \) – Interplay Effect
Simulation results - Examples

- Magnitude of motion is NOT the only variable.
- Smaller volume has larger effect.

Li Y et al Med Phys 2014
Kardar et al. PRO, 2014

Motion analysis & dynamic dose

Adapted from Kardar et al. PRO, 2014

Scanning Direction

Tsunashima, PhD dissertation, 2012
Zenklusen et al, PMB 2010
Optimized Scanning Sequence

H Li et al, IJROBP, 2015

CTV size: 264cc
SpotSpace: 8mm
2Gy Single field plan
Geometry ITV
Motion Amp~20mm
period = 5.33(4.7 - 6.3)s

Volumetric rescanning (VS)
Layered rescanning (LS)
Spot scanning
Lateral settling time: 3ms
Energy switching time: 80ms

• Ye Zhang et al. 2015. Phys. Med. Biol. 60 8141

Rescanning

Isolayer rescanning

Reduce the max MU per spot

Kardar et al. PRV 2014
More on rescanning

- SFO with multiple fields – rescanning
- Fractionated treatment – rescanning
  - 11 patients selected from 112 stage III NSCLC patients
  - Excluding 3

Fractioned treatment is less effective for smaller spots

Grassberger et al. IJROBP 2013

4D Robust Optimization

- 4D robust optimization uses only 3 image sets:
  - Avg, T0 & T50:
  - 11 distal esophageal patients

- 4 out 11 patients were optimized with 4D robust optimization


3D dose vs 4D dose
4D dose vs 1FX 4D dynamic dose
**Breath hold**

- Simulation study
  - 15 patients with peripheral lung tumors previously treated with stereotactic radiation therapy
- Potential risk factors for reduced coverage are:
  - Small targets & Large baseline shifts

- External surrogate
  - Correlation with the target volume
- Internal surrogate
  - Fiducials
  - Tumor or diaphragm
- In-room volumetric imaging
  - CBCT
  - CT on-rail

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**Real-time-image Gated Spot Scanning Proton Therapy System**

Integration

Gating

Real-time Tumor-tracking Radiation Therapy

Spot scanning Proton Beam Therapy

Developed by Hokkaido University

Real-time-image Gated Proton Therapy (RGPT)

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**Phase Controlled Rescanning**

- Carbon therapy at NIRS
- Rescanning & gating combined

Integration

Volumetric RS

Layered RS

- White area = not yet rescanned
- Light gray area = 1x rescanned
- Gray area = 2x rescanned
- Black area = 3x rescanned

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Summary

- Respiratory motion remains a challenge for scanning beam proton therapy:
  - Practical strategies have been developed to selectively treat some patients.
  - The interplay effect is not as large as we use to think.
  - Rescanning will reduce the interplay effect.
  - Fractioned treatment provides effective rescanning.
  - 4D robust optimization would be a useful technique.
  - Breath hold, gating or combination would be further help for patients with larger motion.

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Thank you!
Options for Treating Moving Targets

- **Margin based approach:**
  - is needed but may not be sufficient.

- **Repainting (rescanning):**
  - divide dose delivery to multiple times to average the interplay effect.

- **Breath-hold and gating:**
  - irradiation in a pre-defined motion window (e.g., end exhale)

- **Tracking:**
  - compensate tumor motion by 3D adaptation of the proton beam

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**Example of performance check**

**Marker tracking and gated-irradiation**

Gold marker was moved in front of a chest phantom

MDACC's new facility will have RGPT

Courtesy of Umegaki

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**Not all tumors move that much...**

- Tumor motion was associated with diaphragm motion, the SI tumor location, size of the GTV, and disease T stage.
- 152 lung cancer patients stage III or IV NSCLC
- Tumors that moved > 0.5 cm:
  - Superior-inferior: 3%
  - Lateral: 2%
  - Anterior-posterior: 5%
- For 95% of the tumors, the magnitude of motion was:
  - Superior-inferior: < 1.3 cm
  - Lateral: < 0.4 cm
  - Anterior-posterior: < 0.6 cm
- Only 11% of tumors moving >1.0 cm.

H Liu et al. IJRRP 2007
Lung - IMPT

74 yr old male
Squamous, T2a N2 M0 IIIA

Chang et al. IJROBP (2016)