Implementation of Pencil Beam Scanning (PBS) Proton Therapy Treatment for Liver Patients

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Acknowledgement

- 2-yr Grant from Varian Medical Systems
- Collaboration between Upenn and IBA-UCL
- Collaboration between UPenn and Qfix

Overview

- Motivation: Pencil Beam Scanning Proton Therapy (PBSPT) for Liver Tumors
- Evaluation tools for PBSPT of Liver Tumors
- Mitigation methods for patients with large motion
Motivation: Dosimetric Advantage by PBSPT

1. Reduction of Mean Liver Dose-related to Radiation Induced Liver Disease (RILD)
2. Total sparing of left Kidney and better sparing of right kidney
3. Better sparing of Stomach/Bowels/Duodenum
4. Better sparing of heart by lower mean dose
5. PBSPT spares proximal OAR better than Double Scattering Proton Therapy

Organ motion and beam Interplay are concerning in Pencil Beam Scanning Proton Therapy (PBSPT)...

Motivation: Disadvantage of PBSPT

Overview

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Assuming all the spots are delivered on each phase

If dose were identical during delivery as in double scattered proton therapy…

Interplay of PBS spots and Organ motion

Different spots of the PBS plan can fall into different phases

Motion Evaluation 1: Motion

1. Deformable image registration to derive the motion amplitude among 4DCT phases
2. Visualization of motion amplitude more meaningful with CTV/ITV shown and potential mitigation strategies to PBSPT
3. Cutoff of cumulative motion histogram @ 90% voxels (motion amplitude) more related to dose degradation than central mass motion
**Motion Evaluation 2: ΔWEPL**

1. CT Visualization of WEPL > 10 mm helps (a) beam angle choice (b) potential mitigation strategies
2. ΔWEPL tend to have long tails
3. ΔWEPL Histogram is more flexible than one ΔWEPL value as clinical criteria (for example, motion index at cumulative ΔWEPL histogram (%) @ 10 mm)

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**Interplay Evaluation 1: Spot sorting**

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**Interplay Evaluation 2: 4D dose computation**

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Mitigation of Motion and Interplay

- Patient Simulation
  - Deep Inhale Breath Hold (DIBH) very good if patients can hold long breath or finish deep inhale fast between breath holds
  - Abdominal Compression (saves beam delivery time)
  - Both methods have residual motion and inter fraction variation
- Treatment Plan
  - 4D robust optimization (not available in Eclipse but in several institutions)
  - Beam Specific PTV to ensure adequate treatment margin
- Plan Delivery
  - Gating - efficiency and reproducibility
  - Rescanning and Repainting – efficiency
  - Image guidance to ensure inter fraction reproducibility of DIBH and abdominal compression

Motion reduction with compression

With abdominal compression

Without abdominal compression
Margin Reduction and Beam Specific PTV (BSPTV)

- BSPTV from Park et al IJROBP 2012 did not allow 4DCT.
- Modified BSPTV from Lin et al JACMP 2015 allowed quadrature/linear summations of BSPTV (motion), BSPTV (range) and BSPTV (setup).
- Only BSPTV (motion) is shown here but quadrature summated BSPTV is used for treatment planning.

BSPTV (motion) similar to raITV

- BSPTV (motion) margin in the previous slide comes from lateral and beam directions assuming beam from top.
- Diaphragm motion is replaced with rib motion here.
- Gating limits tumor motion to smaller overlap below the moving rib.
- Gating not only reduces (a) lateral margin of gITV from original volume but also (b) proximal and distal margin in raITV to ga_raITV.

Margin Reduction and Beam Angle Selection

- BSPTV overlap with OAR not shown here.
Histograms of Motion and ΔWEPL

WEPL is calculated for each voxel in the ITV for each phase of the 4DCT. ΔWEPL is the difference between the maximum and minimum path length.

Can not treat without compression

Multiple fractions alone can not adequately mitigate interplay ΔDV<5%. Volume Repainting per beam ~30 s would be time consuming...

Can potentially treat with compression
Smaller deviation with compression

Compression belt’s deviation @ 1st fx is equivalent to 3rd-5th fx without compression.

Summary of Our Study of Ten Patients

- Reduction of Mean Liver-GTV dose in PBSPT than photon treatment
- Reduction of ITV and BSPTV volumes with compression
- Reduction of Motion Index (%) and Motion Amplitude (mm) with compression
- Correlate Motion Amplitude and Motion Index to degradation of D95
- Proposed Criteria for Motion Mitigation

More Sparing of Liver

Mean Liver-GTV dose reduces by 9.5% prescription dose with statistically equivalent CTV coverage
Benefits of Abdominal compression

<table>
<thead>
<tr>
<th>Part of Lungs</th>
<th>Avg Vector (mm)</th>
<th>Motion Amplitude with 90% of voxels (mm)</th>
<th>S.D. (mm)</th>
<th>Avg ΔWEPL (mm)</th>
<th>ΔWEPL (%</th>
<th>ITV (CTV)</th>
<th>BSVTV (CTV)</th>
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<tr>
<td>1 L</td>
<td>7.05,0</td>
<td>11.9,0</td>
<td>3.65,2</td>
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<td>12.2,0</td>
<td>4.03,9</td>
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<td>12.6,8</td>
<td>3.60,1</td>
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<tr>
<td>9 S</td>
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</tr>
</tbody>
</table>

Ratios: without compression belt / with compression belt

Reduction of Motion Index (%)

Motion of Motion Amplitude (mm)
Dose degradation vs. Motion index

![Graph showing dose degradation vs. motion index](image)

Dose degradation vs. Motion Amplitude

![Graph showing dose degradation vs. motion amplitude](image)

Watch Out for the Inter fraction variation!
Discussion

- Abdominal Compression always reduces intra fraction motion but caution for potential larger inter fraction motion
- For small motion, compression alone can be satisfactory; for large motion, combination with other methods are required
- Desire motion criteria for different anatomy and beam lines
- Desire better method than volume repainting to reduce delivery time as our beam lasts 30 to 180 seconds

Conclusion

- Visualize motion and ΔWEPL during CT simulation and treatment planning processes for better motion mitigation and beam angle selection
- Use BSPTV or 4D robust planning to ensure coverage of moving target
- Establish in-house criteria of motion index and motion amplitude

Thank you!

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Students, Fellows and Residents
- Kevin Souris, MS
- Adam Glick, MS
- Minglei Kang, PhD
- Sheng Huang, PhD
- Kristin Stuetzer, PhD

Collaborators
- Edgar Ben-Josef, MD
- Charles Simone II, MD
- Guillaume Jassen, PhD
- Haibo Lin, PhD
- James E McDonough, PhD
- Timothy D Solberg, PhD
- Edmond Sterpin, PhD
- John A Lee, PhD