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

Liyong Lin, PhD,
Assistant Professor
Department of Radiation Oncology
University of Pennsylvania

PENN RADIATION ONCOLOGY
Penn Medicine

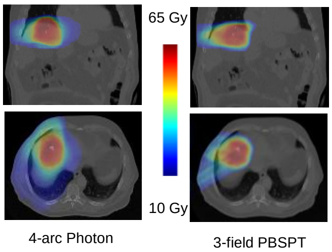
Acknowledgement

- 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

Skinner, Hong and Krishnan 2011 Frontier in Radiation Oncology

Motivation: Disadvantage of PBSPT

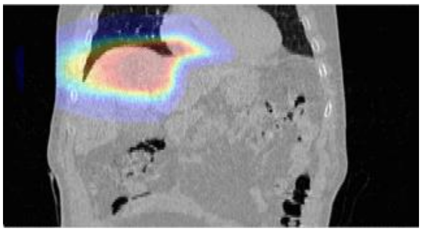
Organ motion and beam Interplay
are concerning in Pencil Beam Scanning Proton Therapy (PBSPT)…

Evaluation Tools Mitigation Methods

Overview

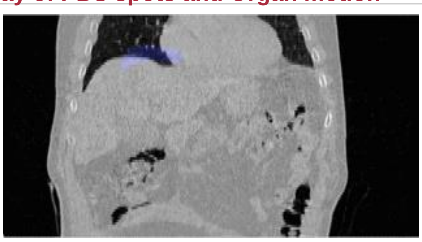
- **Motivation: Pencil Beam Scanning Proton Therapy (PBSPT) for Liver Tumors**
- **Evaluation tools for PBSPT of Liver Tumors**
- **Mitigation methods for patients with large motion**

Assuming all the spots are delivered on each phase



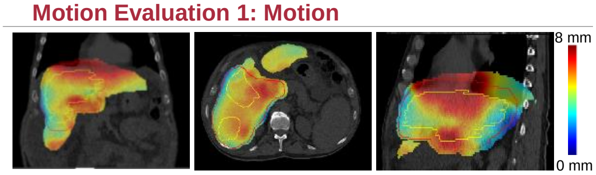
If dose were identical during delivery as in double scattered proton therapy…

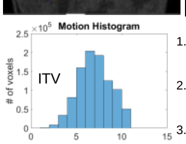
Interplay of PBS spots and Organ motion



Different spots of the PBS plan can fall into different phases

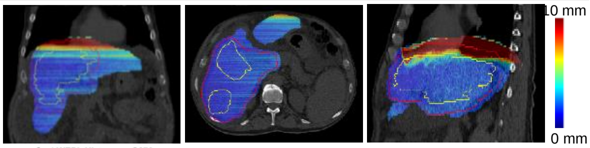
Motion Evaluation 1: Motion

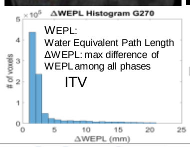




1. Deformable image registration to derive the motion amplitude among 4DCT phases
2. Visualization of motion amplitude more meaningful with CTV/ITV shown and potential mitigation strategies to PBSPT
3. Cutoff of cumulative motion histogram @ 90% voxels (motion amplitude) more related to dose degradation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

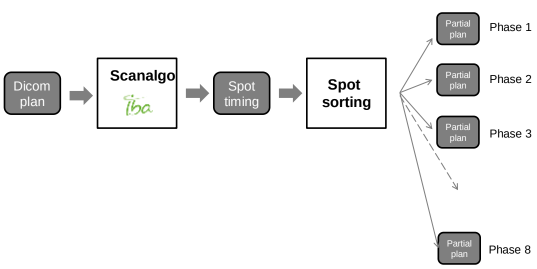
Motion Evaluation 2: ΔWEPL



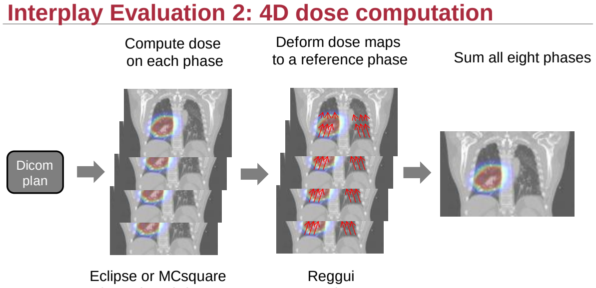


1. CT Visualization of WEPL > 10 mm helps (a) beam angle choice (b) potential mitigation strategies
2. ΔWEPL tend to have long tails
3. ΔWEPL Histogram is more flexible than one ΔWEPL value as clinical criteria (for example, motion index at cumulative ΔWEPL histogram (%) @ 10 mm)

Interplay Evaluation 1: Spot sorting



Interplay Evaluation 2: 4D dose computation



Overview

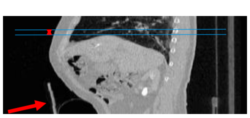
- **Motivation: Pencil Beam Scanning Proton Therapy (PBSPT) for Liver Tumors**
- **Evaluation tools for PBSPT of Liver Tumors**
- **Mitigation methods for patients with large motion**

Mitigation of Motion and Interplay

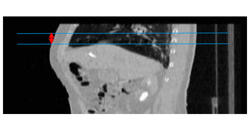
- **Patient Simulation**
  - Deep Inhale Breath Hold (DIBH)-very good if patients can hold long breath or finish deep inhale fast between breath holds
  - *Abdominal Compression (saves beam delivery time)*
  - Both methods have residual motion and inter fraction variation
- **Treatment Plan**
  - 4D 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

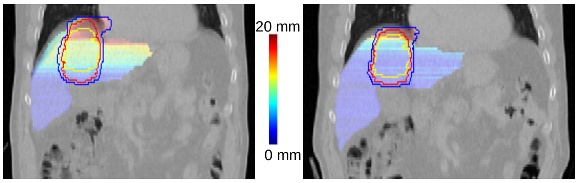
With abdominal compression



Without abdominal compression

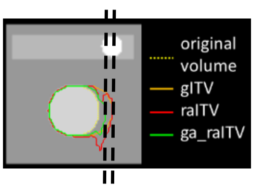


Margin Reduction and Beam Specific PTV (BSPTV)



- 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

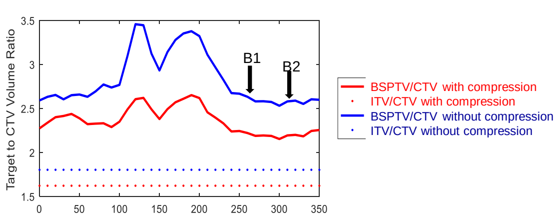


From Knopf PMB 58 (2013) 6079-94

- 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

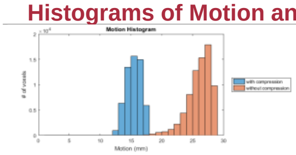
gITV=geometrical ITV raITV: range adapted ITV ga_raITV=gated raITV

Margin Reduction and Beam Angle Selection



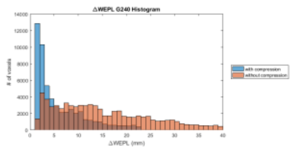
BSPTV overlap with OAR not shown here

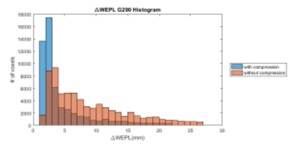
Histograms of Motion and ΔWEPL



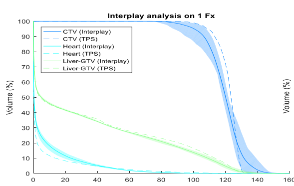
WEPL is calculated for each voxel in the ITV for each phase of the 4DCT.

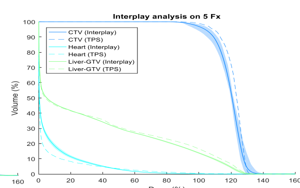
ΔWEPL is the difference between the maximum and minimum path lengths.





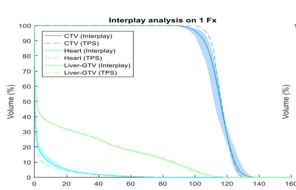
Can not treat without compression

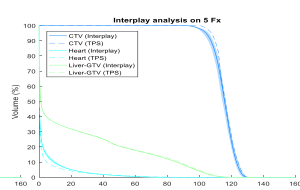




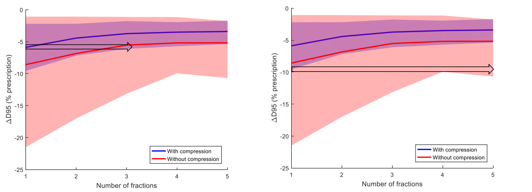
Multiple fractions alone can not adequately mitigate interplay ΔD95<5%. Volume Repainting per beam ~30 s would be time consuming…

Can potentially treat with compression





Smaller deviation with compression

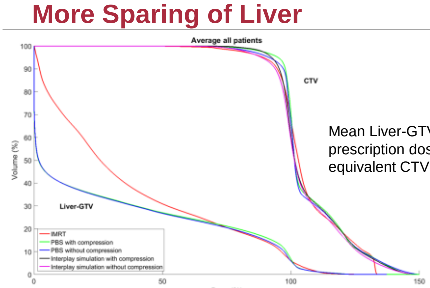


Compression belt's deviation @ 1st fx is equivalent to 3rd-5th fx without compression.

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



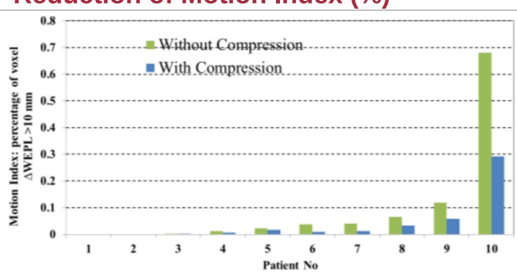
Mean Liver-GTV dose reduces by 9.5% prescription dose with statistically equivalent CTV coverage

Benefits of Abdominal compression

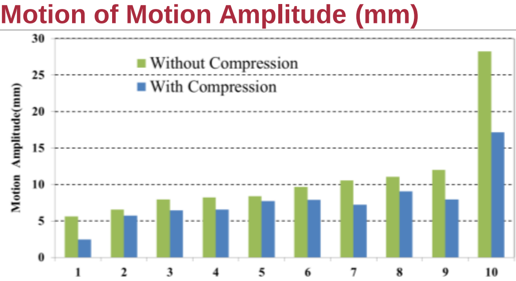
Ratios: without compression belt / with compression belt

Pat # Large/ Small	Avg Vector (mm)	Motion Amplitude95 (mm)	Avg ΔWEPL (mm)	ΔWEPL95 (mm)	ΔWEPL5mm (%)	ITV /CTV	BSPTV /CTV
1 L	7.0/5.0	11.6/7.9	3.8/3.2	11.7/7.4	10.8/10.5	1.12/1.10	1.31/1.26
2 L	10.4/6.1	12.2/10.4	4.0/3.9	8.0/6.7	32.8/26.0	1.11/1.09	1.23/1.21
3 L	8.1/5.4	12.6/8.6	3.6/2.6	8.1/4.8	11.8/4.3	1.13/1.10	1.27/1.22
4 S	**26.1/15.5**	**28.5/17.6**	**10.0/8.1**	**43.9/30.4**	**87.4/49.7**	**1.80/1.62**	**2.62/2.21**
5 L	7.1/5.9	10.3/8.4	4.8/3.5	20.7/11.3	18.7/11.3	1.37/1.35	1.51/1.48
6 S	6.6/5.5	8.2/6.6	2.6/2.1	5.7/4.4	11.6/0.9	1.63/1.55	2.64/2.50
7 S	7.5/7.0	8.6/8.0	2.3/2.2	3.3/3.1	3.2/0.0	1.61/1.59	2.27/2.22
8 L	7.0/5.9	10.5/9.3	3.0/2.5	8.5/5.3	10.7/5.9	1.08/1.06	1.19/1.16
9 L	5.3/4.5	7.0/6.1	2.9/2.4	6.5/5.3	8.0/5.7	1.09/1.08	1.25/1.23
10 S	4.3/2.0	5.8/2.5	1.9/1.5	3.0/2.3	0.3%/0.3%	1.19/1.08	1.58/1.43

Reduction of Motion Index (%)

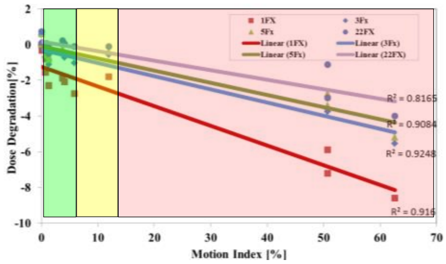


Motion of Motion Amplitude (mm)



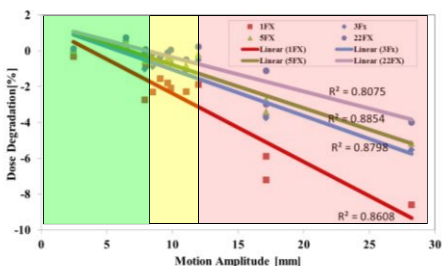
Motion Amplitude is set at 90% of voxels

Dose degradation vs. Motion index



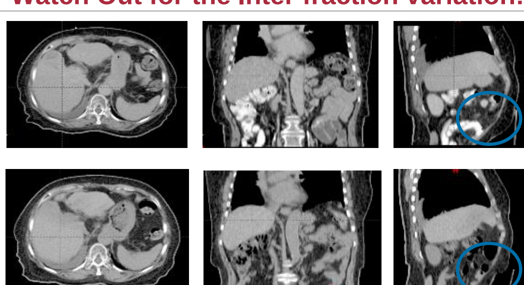
ΔD95

Dose degradation vs. Motion Amplitude



ΔD95

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!

Please visit Souris K SU-F-T52

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