Motion Mitigation in Spot Scanning Proton Therapy with An Automated Gating System and Voluntary Breath Holding

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Disclosures
No Conflicts of Interest

Outline

Introduction
• Motion Management
  o Spirometry System
• Gated Voluntary Breath Hold (SDX): Process Overview

Part 1: Commissioning & Implementation
• Preparation & Patient Training
  o Initial SIM
• Image Guidance and Treatment

Part 2: Dosimetric Comparisons
Breath Hold vs Non-Breath Hold
• Patient Data & Analysis
• Results:
  o Liver
  o Lung

Part 3: Breath Hold Plan Reproducibility
Breath Hold Plans
• Patient Data & QACT Evaluation
• Results:
  o Target Coverage
  o OAR Dose
Maryland Proton Treatment Center (MPTC)
University of Maryland

Varian ProBeam
5 room facility (4 gantries, 1 fixed beam)
- First treatment in February 2016
- 4 of 5 treatment rooms open and treating

- In all treatment gantries:
  - Pencil Beam Scanning (IMPT)
  - Volumetric imaging (cone beam CT)

 Siemens Definition Edge DECT
Dual Spiral Scan & TwinBeam

Siemens Aera MRI Scanner
1.5 T

SDX breath-hold system
Dyn'R
- First SDX patient: March 2018
- # of SDX patients = 45
- Liver, lung, esophagus, ...

Deep Thermal Therapy (DTT)
BSD-2000, Pyrexar
- First DTT patient: Oct 2018
- # of DTT patients = 20
- Pelvic and abdominal regions

Special Treatment

Introduction
- Motion Management
  - Spinnometry System
- Gated Voluntary Breath Hold (SDX): Process Overview

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  - OAR Dose
Motion Management

- External breathing metrics have been demonstrated useful in
  - Predicting the tumor motion
  - Reducing respiratory motion uncertainties
  - Sparing organs at risk

- Breath-hold (BH) technique
  - Mitigates motion of the target
  - Minimizes target margins
  - Improves normal-tissue sparing

The spirometry system monitors the patient’s breathing phase in real time.

Advantages:
- Clinical feasibility
- Reduces tumor motion
- Reduces treatment margins
- Audio-visual feedback improves reproducibility
- Gated treatment delivery
- Accurate surrogate for internal respiratory motion

Disadvantages:
- Signal drift
- Increase in the volumetric tidal flow compared to normal breathing (without spirometer)
- Uncomfortable for patients
- Gating module is not compatible for all treatment delivery systems
- Still is only a surrogate
SDX System

At MPTC we use SDX system (Dyn'R, France)
- Voluntarily breath-hold technique

SDX System
- Airflow tube
- Filter
- Mouthpiece
- Nose clip
- Video glasses (goggle)

SDX Calibration & Calibration Check

Calibration Syringe
A daily calibration/verification must be done on the SDX System
- Using a 3-Liter calibration syringe serving as a volumetric reference

- Check signal drift (problem of spirometry system)
**SDX Commissioning**

The SDX system with automatic gating module was commissioned at MPTC
- **Goal:** Check the effect of breathing interruption on delivered dose.
  - Point and 2D-planar dose measurements of 5 gated plans (3-4 fields per plan) with and without range shifter.

<table>
<thead>
<tr>
<th>Site</th>
<th>Beam Delivery Type</th>
<th># of Fields</th>
<th>Range Shifter (cm)</th>
<th>Point Dose %Diff</th>
<th>Gamma Index Passing Rate % [1%/1mm]</th>
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<tbody>
<tr>
<td>Esophagus</td>
<td>SFO</td>
<td>1</td>
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<td>0.20%</td>
<td>100</td>
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<td></td>
<td></td>
<td>2</td>
<td>0</td>
<td>0.20%</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0</td>
<td>0.20%</td>
<td>100</td>
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<tr>
<td>Lung</td>
<td>MFO</td>
<td>4</td>
<td>5 cm</td>
<td>0.00%</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>5 cm</td>
<td>0.20%</td>
<td>100</td>
</tr>
<tr>
<td>Abdomen</td>
<td>MFO</td>
<td>3</td>
<td>None / 5 cm</td>
<td>0.00%</td>
<td>100</td>
</tr>
</tbody>
</table>

- For each field: three measurements with 2, 3 and 5 breath-hold were done and evaluated against the one without breath-hold (reference).
  - Point dose (% difference)
  - 2D-planar dose gamma passing rate (1%/1mm)

**Results:**

Between non-breath-hold and breath-hold (reference) plans:
- The maximum percent difference of point dose measurements: 0.4%
- The lowest gamma passing rate: 97.2%
Gated Voluntary Breath Hold: Process Overview

SDX Treatment Process:

1st Day

- Preparation & Patient training
- CT imaging

Patient instruction:
- How to breathe and hold the breath through the spirometer

Set breath-hold level:
- Find the deepest inspiration breath-hold (DIBH)
- 70% to 80% of DIBH will be set as the breath-hold level

Preparation: Set breath-hold level and training

- Acquire 3-5 breath holds to establish the deep inspiration breath-hold level (DIBH)
- Reduce the selected level to 75-80%
  - More comfortable
  - More reproducible
  - 75% is the default value
  - It can be adjusted
- Patient breath-hold practice (reproducibility)

Initial CT simulation:
- SDX breath-hold system
- Normal 4D-CT (as a backup treatment)
Initial Simulation

- Imaging (CT):
  - SDX CT (manual)
    - Patient holds the breath at pre-established breath-hold level
    - The therapist starts CT scan acquisition
    - If patient goes out of breath-hold level, the therapist stops the imaging manually
  - Normal 4D-CT (backup plan)

Why Did We Need a Backup Plan?

- First ProBeam center using SDX system (March 2018)
- SDX v2.06
  - Connectivity & software issues of SDX system
- One SDX device in one of the treatment rooms
  - SDX problem
  - Treatment room problem
- Upgraded to v3.03 and then v3.11 (2019)
  - Much less connectivity & software issues
  - Bought the second SDX system

Gated Voluntary Breath Hold: Process Overview

SDX Treatment Process:

- Preparation & Patient training
- CT Imaging
- Treatment Planning
  - Two plans
    - SDX plan
    - Normal plan (4DCT, compression belt) as a backup plan

Treatment planning on both image sets:
- SDX plan
- Normal plan (4DCT, compression belt) as a backup plan

Physician plan evaluation
Gated Voluntary Breath Hold: Process Overview

SDX Treatment Process:

1st Day
- Preparation & Patient training
- CT Imaging

Treatment Planning
- Two plans
  - SDX plan
  - Normal plan
  - kV
  - Compression belt

Treatment day
- IGRT
  - kV
  - CBCT
  - Needs 30-35 sec breath hold
- Treatment

Image guidance:
- kV and CBCT images will be acquired at the pre-defined breath-hold level

Treatment:
- with the automatic gating module active and connected to the ProBeam system

For ProBeam system:
- IGRT (manual)
  - Stop the imaging manually
    - kV
    - CBCT (small FoV - full fan, ~30 secs)
- Treatment: (automatic)
  - Automatic Gating Module: immediately stops the beam
- Monitoring:
  - Weekly QA-CT: tumor response, anatomical changes

Implementation

Consultation for BH treatment
- SDX preparation and patient training
- ~30-45 minutes
- Physician & physicist evaluation of possibility of SDX treatment
- ~10 minutes
- Yes: BH and non-BH CT simulation
- ~10 minutes
- Non-BH treatment
- ~30 minutes
- Yes
- BH treatment
- ~45 minutes
- No: BH and non-BH treatment planning
- ~6 hours
- BH treatment planning
- ~8 hours
- Non-BH treatment planning
- ~8 hours
- Non-BH CT simulation
- ~10 minutes
- No
SDX Patients Summary

- First SDX patient: March 2018
- Total number of referred patients = 62 (until June 2019)
  - 14 patients excluded
  - 48 patients underwent SDX simulation
  - 45 patients: either treated or will be treated with SDX plan
  - For 2 patients, non-breath-hold plan was chosen over the breath-hold plan
    - Higher dose to the heart due to tumor location
  - 1 patient couldn’t tolerate breath-hold treatment and switched to non-breath-hold plan

<table>
<thead>
<tr>
<th>Status</th>
<th>Number of Patients</th>
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<tbody>
<tr>
<td>Treated</td>
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<tr>
<td>Under treatment</td>
<td>5</td>
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<table>
<thead>
<tr>
<th>Site</th>
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<tbody>
<tr>
<td>Liver</td>
<td>20</td>
</tr>
<tr>
<td>Mediastinum/Lung</td>
<td>14</td>
</tr>
<tr>
<td>Abdomen</td>
<td>5</td>
</tr>
<tr>
<td>Pancreas</td>
<td>3</td>
</tr>
<tr>
<td>Esophagus</td>
<td>3</td>
</tr>
</tbody>
</table>

Part 1: Summary & Recommendations

- What sites?
  - For any moving target due to respiratory motion
    - Patient should be able to hold breath > 25 seconds for current ProBeam system
- The smaller the target, the easier to implement this procedure
  - Preferably < 2 minutes delivery time per field (3-4 breath-holds)
- Ask patient to practice breath-hold before coming for initial CT and also treatment
- Make two treatment plans (SDX and normal) at the beginning
  - Synergy reliability and limitations
- Image guidance
  - kV & CBCT (small FoV, full field if patient can hold the breath for 30-35 seconds
- Weekly QA-CT
  - Tumor response, anatomical changes
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  • Results:
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    • Lung

Part 3: Breath-Hold Plan Reproducibility

Breath Hold Plans
• Patient Data & QACT Evaluation
  • Results:
    • Target Coverage
    • OAR Dose

Purpose:
We investigate the dosimetric comparison between breath-hold and non-breath-hold plans.

Before SDX upgrade and the second SDX system purchase

– One SDX device in one of the treatment rooms
  • SDX problem (connection and software issues)
  • Treatment room problem
  
  Therefore, for each patient we had a backup plan on 4DCT

Breath-hold (BH) technique
• Minimizes motion of the target
• Minimizes target margins
• Improves normal-tissue sparing

Site Number of Patients

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</tr>
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Twenty-seven patients treated with SDX system were used

The breath-hold level was set to 75% of DIBH

Clinically acceptable were created
• Breath-hold plan (breath-hold CT)
• Non-breath-hold plan (4D-CT)

The dose-volume histograms (DVH) of the two plans were compared for OAR sparing
• Mean dose: Liver, stomach, kidney, esophagus, heart
• Max dose: Small bowel, large bowel, heart, spinal cord
## Summary of 27 patients data

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<td>Volume (cc)</td>
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<td>201.0 ± 21.0</td>
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<tr>
<td></td>
<td>CTV1/ITV1</td>
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Breath-hold vs Non-Breath-hold Plans

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<th>Breath Hold</th>
<th>Non-Breath Hold</th>
<th>Ratio of Breath-hold Normalized to Non-Breath Hold (%)</th>
<th>p-value</th>
<th>Number of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (cc)</td>
<td>Total Target (CTV1/ITV1)</td>
<td>238.0 ± 251.0</td>
<td>344.9 ± 376.8</td>
<td>69.72% ± 23.80%</td>
<td>&lt;0.05</td>
<td>27</td>
</tr>
<tr>
<td>Mean Dose (cGy)</td>
<td>Liver</td>
<td>99.1 ± 121.1</td>
<td>145.2 ± 164.0</td>
<td>69.22% ± 22.12%</td>
<td>&lt;0.05</td>
<td>11</td>
</tr>
<tr>
<td>Max Dose (cGy)</td>
<td>Small Bowel</td>
<td>1504.2 ± 2018.7</td>
<td>1952.5 ± 1967.2</td>
<td>81.41% ± 44.25%</td>
<td>0.17</td>
<td>13</td>
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<tr>
<td></td>
<td>Large Bowel</td>
<td>779.0 ± 1315.7</td>
<td>1938.9 ± 1988.6</td>
<td>58.26% ± 39.96%</td>
<td>&lt;0.05</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Heart</td>
<td>3062.4 ± 1830.6</td>
<td>3277.7 ± 1843.4</td>
<td>93.99% ± 16.18%</td>
<td>0.06</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Spinal Cord</td>
<td>1155.5 ± 1353.0</td>
<td>1396.5 ± 1447.8</td>
<td>83.82% ± 51.41%</td>
<td>&lt;0.05</td>
<td>26</td>
</tr>
<tr>
<td>V20 (%)</td>
<td>Lung</td>
<td>6.74% ± 5.79%</td>
<td>10.74% ± 8.73%</td>
<td>76.79% ± 56.33%</td>
<td>&lt;0.05</td>
<td>20</td>
</tr>
</tbody>
</table>

Breath-hold vs Non-Breath-hold Plans

Average reduction of 30% in the irradiated volume with SDX

Breath-hold vs Non-Breath-hold Plans

Average max dose reduction with SDX:
- Small Bowel: 20%
- Large Bowel: 42%
- Heart: 5%
- Spinal cord: 18%

* p < 0.05
Breath-hold vs Non-Breath-hold Plans

Ratio of Breath-hold Normalized to Non-Breath-hold (%)

Average reduction with SDX:
- Lung V20: 25%
- Liver Mean dose: 30%

Breath-hold
Non-Breath-hold

* p < 0.05 10 patients 21 patients

Breath-hold vs Non-Breath-hold Plans

Ratio of Breath-hold Normalized to Non-Breath-hold (%)

Average mean dose reduction with SDX:
- Stomach: 28%
- Kidney: 32%
- Esophagus: 10%
- Heart: 25%

Breath-hold
Non-Breath-hold

* p < 0.05

Breath-hold vs Non-Breath-hold Plans

Ratio of Breath-hold Normalized to Non-Breath-hold (%)

- Liver group (11 patients)
- Mediastinum/lung group (10 patients)

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Liver group (11 patients)  
Ratio of Breath-hold Normalized to Non-Breath-hold (%)

Reduction:
- Target Volume ~25-40%
- Mean OAR Dose ~ 20%
- Max OAR Dose ~ 5-50%
- Lung V20 ~ 35%

Mediastinum/lung group (10 patients)  
Ratio of Breath-hold Normalized to Non-Breath-hold (%)

Reduction:
- Target Volume ~15-25%
- Mean OAR Dose ~ 5-50%
- Max OAR Dose ~ 5-25%
- Lung V20 ~ 35%

Part 2: Conclusions

- Breath-hold plans can significantly reduce the treated target volume to ~70-80%.
  - Liver group: 60-75%
  - Mediastinum/lung group: 75-85%

- For organs most affected by respiratory motion (lung and liver), BH technique consistently reduced dose by 20-35%

- For other OARs, BH plans resulted in lower
  - Mean dose by as much as 10-35%
  - Max dose by as much as 5-40%
Introduction

- Motion Management
  - Spirometry System
- Gated Voluntary Breath Hold (SDX): Process Overview

Part 1: Commissioning & Implementation

- Preparation & Patient Training
- Initial SIM
- Image Guidance and Treatment

Breath Hold vs Non-Breath Hold
- Patient Data & Analysis
- Results:
  - Liver
  - Lung

Part 2: Dosimetric Comparisons

Breath Hold vs Non-Breath Hold
- Patient Data & Analysis
- Results:
  - Liver
  - Target Coverage
  - OAR Dose

Part 3: Breath-Hold Plan Reproducibility

Breath-hold Plan Reproducibility

- Mitigates motion of the target
- Minimizes target margins
- Improves normal-tissue sparing

Do we need to monitor the reproducibility of the plan?

Can we use the same plan for the whole course of treatments?

Our recommendation for SDX plans:

Weekly QA-CT

Tumor response, anatomical changes

Assessing the reproducibility of SDX plans

QACT Patients Summary

We use 5mm robust evaluation for SDX plans:

- Reproducibility of the breath-hold plans was assessed by
  - Using QACT scans for each patient
  - Recalculating the initial treatment plan on the QACT scans.

<table>
<thead>
<tr>
<th>Site</th>
<th>Number of Patients</th>
<th>Number of QACTs</th>
</tr>
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<tbody>
<tr>
<td>Liver</td>
<td>10</td>
<td>62</td>
</tr>
<tr>
<td>Mediastinum/Lung</td>
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<td>Abdomen</td>
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<td>Esophagus</td>
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</tbody>
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Purpose:

We investigate the reproducibility of breath-hold plans using frequent quality assurance CT scans (QACTs).
QACT Evaluation

At MPTC, decision for replan or repeat of QACT based on:

- Target V95% decreased by more than 5% of the initial plan, or
- Dose to critical organs at risk (OARs) increased significantly (physician decision)

To evaluate the reproducibility of BH plan, we looked at:

- DVH variations of QACT plans with respect to the initial CT plan
- Errors reported as percent difference (for target) and absolute dose difference (for OARs) with respect to initial plan
- Error window (EW) required to cover the 95\(^{th}\) percentile variations

V95, D95, and Mean Dose

- Variation in target coverage (V95) was < 5%
- Mean dose \(\rightarrow\) EW ~ 1.8%
- V95\% \(\rightarrow\) EW ~ 3.7%

Two replans due to change in target coverage and OAR dose as a result of anatomical changes.
Target Coverage

Maximum and Minimum Dose

CTV1 Max dose → EW ~ 5.7%
CTV1 Min dose → EW ~ 18.1%

Larger variations observed in maximum and minimum doses

Introduction

Part 1: Commissioning & Implementation
Part 2: Dosimetric Comparison
Part 3: Reproducibility

OAR Dose

Mean Dose

Heart → EW ~ 1.0 Gy
Esophagus → EW ~ 1.4 Gy
Stomach → EW ~ 0.8 Gy
Kidney → EW ~ 0.3 Gy

Max Dose

Heart → EW ~ 5.1 Gy
Spinal Cord → EW ~ 4.8 Gy
Small Bowel → EW ~ 1.6 Gy
Large Bowel → EW ~ 2.5 Gy

Two replans due to significant change in heart dose as a result of anatomical changes
Lung and Liver

Variation comparable to other organs despite associated respiratory motion

- Lung V20: EW ~ 3.2%
- Liver Mean Dose: EW ~ 0.9 Gy

Part 3: Summary & Conclusions

- Out of 30 patient plans:
  - We had 4 replans due to tumor volume and/or anatomical changes
- Breath-hold technique can manage respiratory motion
  - Lung V20 and liver mean dose are comparable to other organs
- In the absence of anatomical changes, coverage and OAR doses were reproducible within clinically acceptable margins
- Using 5 mm robust evaluation gives fairly reproducible plan
- Small variations in the target coverage (V95%)
- Larger variations observed in maximum and minimum doses for the target and OARs