Ultrasound Guidance During Radiation Delivery: Confronting the Treatment Interference Challenge

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The team

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Disclosures

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  – NIH STTR grant to Sonitrack Systems
  – NSF
  – Philips Ultrasound
  – Interson
  – Stanford Bio-X IIP
Imaging during beam delivery

Add-on, real-time, volumetric, soft-tissue guidance during radiation beam delivery is largely unmet challenge.

Image guidance architecture

Telerobotic imaging

Remote Haptic Interface

Robot


Challenge: Tele-robotic imaging interfering with linac and beam!
Avoid beams through probe and robot

- **Avoid beams** through probe and robot
  - Can we assure resulting plan is clinically acceptable for a given patient?

Include probe and robot in plan

- **Include** probe and robot in plan
  - Can they be modelled sufficiently accurately?

Make probe and robot disappear

- **Make** probe and robot disappear
  - Has Dimitre gone mad?

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**CT simulation**

- **Guide** device placement to potential non-interfering imaging positions
- **Confirm** adequate image quality

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Augmented reality system for ultrasound guided radiation therapy
Renhui Gong, Ralf Bruder, Achim Schweikard, Jeff Schlosser, and Dimitre Hristov

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Probe placement map generation

Ralf Bruder, Filip Ernst and Achim Schweikard
Define target and map attenuation to target from surface

Probe placement map generation

CT simulation

Register probe and robot to CT during simulation by scanning optically tracked tool

Guide probe placement towards non-interfering positions during simulation: probe placement map

Probe placement map confirmation

Visualize probe in virtual space during actual imaging.
Probe placement map confirmation

Visualize live US images fused with CT and target.

Planning

- **Verify** non-interference of designed plan
- **Suggest** slight changes of robot placement if necessary
- **Design** plan trajectories to avoid robot

Incorporate robot model in planning

Custom xml descriptor defining joints and limits
Collision evaluation

Beam evaluation

Include probe and robot in plan

Beam eye-view to monitor entrance through probe/robot

Severe CT artifacts preclude CT-based modeling.
Megavoltage CT for electron density calibration

Electron density models of X6-1 and C5-2 ultrasound probes built with a Tomotherapy 3.5 MV CT scan.

Monte Carlo modeling of ultrasound probes for image guided radiotherapy
Magdalena Bazalova-Carter, Jeffrey Schlosser, Josephine Chen, and Dimitre Hristov
Submitted to Medical Physics

Experimental setup

Note detail differences between MC, film, and 2D array.

X6-1 Probe Horizontal Position
Table 2: Statistics of local dose difference comparison between MC simulations and 2D Array measurements for US probes in horizontal orientation.

<table>
<thead>
<tr>
<th></th>
<th>X6-1</th>
<th></th>
<th>X6-2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 MV</td>
<td>15 MV</td>
<td>6 MV</td>
<td>15 MV</td>
</tr>
<tr>
<td>Mean (%)</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Standard deviation (%)</td>
<td>1.3</td>
<td>1.4</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Max (%)</td>
<td>5.3</td>
<td>3.6</td>
<td>5.9</td>
<td>4.3</td>
</tr>
<tr>
<td>Volumes with &lt;3% local difference</td>
<td>95.7</td>
<td>90.6</td>
<td>97.4</td>
<td>90.1</td>
</tr>
</tbody>
</table>

Cable placement introduces dose discrepancies.

Cable placement introduces dose discrepancies.

Remotely-Actuated Ultrasound Scanning (RUSS)

Make probe and robot disappear (well ... partially)
# Frame rate and Field of View

For ~1 slice per elevational degree:

<table>
<thead>
<tr>
<th>Elevational Sweep Angle</th>
<th>Lateral Sweep Angle</th>
<th>Imaging Depth</th>
<th>Axial Slice Field of View</th>
<th># of Elevational Slices</th>
<th>Volumes Per Second</th>
<th>Planes Per Second</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>19°</td>
<td>15 cm</td>
<td>5.0 cm x 4.0 cm</td>
<td>15</td>
<td>3.3</td>
<td>48</td>
</tr>
<tr>
<td>23°</td>
<td>29°</td>
<td>10 cm</td>
<td>5.0 cm x 4.0 cm</td>
<td>22</td>
<td>2.2</td>
<td>48</td>
</tr>
<tr>
<td>45°</td>
<td>60°</td>
<td>5 cm</td>
<td>5.0 cm x 4.0 cm</td>
<td>44</td>
<td>1.1</td>
<td>48</td>
</tr>
<tr>
<td>15°</td>
<td>60°</td>
<td>15 cm</td>
<td>10.0 cm x 4.0 cm</td>
<td>15</td>
<td>1.1</td>
<td>16</td>
</tr>
<tr>
<td>23°</td>
<td>60°</td>
<td>10 cm</td>
<td>10.0 cm x 4.0 cm</td>
<td>22</td>
<td>1.1</td>
<td>24</td>
</tr>
<tr>
<td>45°</td>
<td>60°</td>
<td>5 cm</td>
<td>5.0 cm x 4.0 cm</td>
<td>44</td>
<td>1.1</td>
<td>48</td>
</tr>
</tbody>
</table>

# Spatial Resolution

- **Method:**
  - Lateral/elevational: point spread using -3dB peak drop-off
  - Axial: minimum resolvable spacing
Spatial Resolution: Results

<table>
<thead>
<tr>
<th>Depth [mm]</th>
<th>Resolution [mm]</th>
<th>Elevational Resolution [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>3.7</td>
</tr>
<tr>
<td>10</td>
<td>7.9</td>
<td>5.7</td>
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<tr>
<td>20</td>
<td>14.8</td>
<td>11.8</td>
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<tr>
<td>30</td>
<td>21.7</td>
<td>18.7</td>
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<tr>
<td>40</td>
<td>28.6</td>
<td>25.6</td>
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<tr>
<td>50</td>
<td>35.5</td>
<td>32.5</td>
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<tr>
<td>60</td>
<td>42.4</td>
<td>39.4</td>
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<td>70</td>
<td>49.3</td>
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<td>80</td>
<td>56.2</td>
<td>53.2</td>
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<tr>
<td>90</td>
<td>63.1</td>
<td>60.1</td>
</tr>
<tr>
<td>100</td>
<td>70.0</td>
<td>67.0</td>
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</tbody>
</table>

Tracking Resolution

<table>
<thead>
<tr>
<th>Method: US phantom placed on motion platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targets automatically tracked using normalized cross correlation</td>
</tr>
</tbody>
</table>

Tracking Resolution: Results

<table>
<thead>
<tr>
<th>Depth [mm]</th>
<th>Actual Target Displacement [mm]</th>
<th>Tracked Target Displacement [mm]</th>
<th>Target Displacement Error [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0</td>
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<tr>
<td>15</td>
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<td>0</td>
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<tr>
<td>85</td>
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<td>0</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Mean Target Tracking Error: 0.2 mm, 0.4 mm, 0.3 mm
Max Target Tracking Error: 0.4 mm, 1.7 mm, 0.9 mm
CT Compatibility

Radiotherapy Beam Compatibility

• Method 1: Compare planned and delivered dose through RUSS probe
• Method 2: Image-based tracking during beam delivery

Experimental Setup: Accuros Plan:

Radiotherapy Beam Compatibility: Results
# Radiotherapy Beam Compatibility: Results

All points met 2.0 mm / 3.0% dose deviation criteria

## RUSS summary

<table>
<thead>
<tr>
<th>Metric</th>
<th>Target: Intrafractional Liver Radiotherapy Guidance</th>
<th>Result with RUSS probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame rate and Field of View (FOV)</td>
<td>6.0 cm x 4.0 cm at 3.0-5.0 cm depth; 1 volume per second</td>
<td>@ 10 cm depth: 5.0 cm x 4.0 cm FOV, 2.2 Hz volume rate, 4.8 Hz plane rate</td>
</tr>
<tr>
<td>Tracking Resolution</td>
<td>2.0 mm in each direction</td>
<td>≤0.4 mm mean resolution</td>
</tr>
<tr>
<td>Imaging during radiation delivery</td>
<td>No statistically significant difference between tracking performance with beam on/off</td>
<td>p=0.52</td>
</tr>
<tr>
<td>Radiotherapy planning compatibility</td>
<td>±3.0% / 2.0 mm agreement between computed and measured dose distributions</td>
<td>All points agree within ±3.0% / 2.0 mm</td>
</tr>
</tbody>
</table>

- RUSS performance meets requirements for intrafractional radiotherapy motion management
- Low CT artifacts, beam compatibility, and low cost

## Conclusions

- **Addressing treatment interferences by tele-robotic US imaging requires simulation tools for avoidance or inclusion strategies**
- **Inclusion strategy feasible but possibly less practical than avoidance**
- **Dedicated “radiolucent” ultrasound probes may greatly facilitate RT ultrasound guidance but careful evaluation of performance trade-offs is necessary**