Motion management and adaptive control for treating abdominal tumors

Baudouin DENIS de SENNEVILLE

July, 16th 2019

Mathematical Institute of Bordeaux, CNRS UMR5251/University of Bordeaux, France
Imaging Division, University Medical Center Utrecht, The Netherlands
b.desenneville@gmail.com
http://www.math.u-bordeaux.fr/~bdenisde
Workflow of a MR-HIFU intervention

- Positioning
- T<sub>1</sub>/T<sub>2</sub>-weighted planning images
- Tumor specific MRI (DWI, CE-T1w)
- Real-time motion compensation (gating or tracking)
- Real-time thermometry and thermal dose estimation
- Measurement of slow motion for dose realignment
- Observation of near field cool-down
- Perfusion imaging for NPV validation
- T<sub>2</sub>-weighted imaging for edema detection

1-3 hours

1-5 min

Preparation (anatomical imaging)

Therapy guidance during energy delivery

Therapy guidance between energy delivery

Validation of the therapeutic endpoint
MR-guided HIFU in abdominal organs

Overview of physiological motions

Challenges for efficient energy delivery

Image-based motion estimation

Control for intra-fraction

Control for inter-fraction
Physiological motion

Respiratory motion

![Graph showing displacement over time for kidney and liver.](image)
MR-guided HIFU in abdominal organs

Overview of physiological motions

Challenges for efficient energy delivery

Image-based motion estimation

Control for intra-fraction

Control for inter-fraction
Challenges for efficient energy delivery in the liver

Technical solutions

- Induced apneas [Gedroyc et al. 2006, Kopelman et al. 2006, [...]]


MR-guided HIFU in abdominal organs

Overview of physiological motions

Challenges for efficient energy delivery

Image-based motion estimation

Control for intra-fraction

Control for inter-fraction
**Image-based motion estimation**

- **General formulation**

\[
\hat{T} = \arg\min_T S(I_{ref}, T(I_{cur}))
\]

- **Elastic** organ deformation (voxelwise estimation)
  - Low **computation time**
  - Low number of **control parameters**

- **Inverse problem** solved throw a **variational** approach

\[
E(\vec{V}) = \int_\Omega D(\vec{V}) + \alpha R(\vec{V}) \, d\vec{r}
\]

- **Optical Flow algorithms**
  - [Horn & Schunck, 1981]
Image-based motion estimation

Optical flow algorithm

\[ E(\vec{V}) = \int_{\Omega} \left| \nabla I \cdot \vec{V} + I_t I \right| + \alpha \left| J(\vec{V}) - 1 \right|^2 \, d\vec{r} \]

- **Data fidelity term**:

  \[ I_t + \vec{V} \cdot \nabla I = 0 \]

  \[ D(\vec{V}) = \left| I_t + \vec{V} \cdot \nabla I \right| \]

- **Regularization term**:

  \[ \nabla \cdot \vec{V} = 0 \]

  \[ R(\vec{V}) = \left| J(\vec{V}) - 1 \right|^2 \]

- **Transport equation**
- [Horn & Schunck, 1981]
- [Zachiu et al. PMB 2016]

- **Incompressibility of the tissue**

  - Continuum mechanics:
    - Incompressible material subjected to an external force
    - [Zachiu et al. PMB 2018]
Image-based motion estimation

Variational approaches

\[ E(\vec{V}) = \int_{\Omega} D(\vec{V}) + \alpha R(\vec{V}) \, d\vec{r} \]

- **Data fidelity**
- **Regularization**

- Multi-resolution approach
- Iterative refinement approach
- Deep-learning approach
- Mono-/Multi-modal registrations

<table>
<thead>
<tr>
<th></th>
<th>Matlab CPU</th>
<th>C++ CPU</th>
<th>C++ 8 CPUs</th>
<th>CUDA GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-modal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>128×84</td>
<td>&gt; 10 s</td>
<td>300 ms</td>
<td>50 ms</td>
<td>&lt; 10 ms</td>
</tr>
<tr>
<td>Multi-modal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>256×256×64</td>
<td>&gt; 1 h</td>
<td>600 s</td>
<td>100 s</td>
<td>~ 20 s</td>
</tr>
</tbody>
</table>
MR-guided HIFU in abdominal organs

Overview of physiological motions

Challenges for efficient energy delivery

Image-based motion estimation

Control for intra-fraction

Control for inter-fraction
Fast 2D motion correction

1-3 hours

Preparation (anatomical imaging)

Therapy guidance during energy delivery

Therapy guidance between energy delivery

Validation of the therapeutic endpoint

Real-time motion compensation

1-5 min
Thermometry in the presence of physiological motion

**Before** hyperthermia

**During** hyperthermia

Breathing cycle

**Learning** temperature perturbation with motion
MR-guided HIFU in abdominal organs

Overview of physiological motions

Challenges for efficient energy delivery

Image-based motion estimation

Control for intra-fraction

Control for inter-fraction
« Slow » 3D Motion correction for abdominal HIFU

3D anchor images are periodically obtained and compared to a reference.

- Preparation (anatomical imaging)
- Therapy guidance during energy delivery
- Therapy guidance between energy delivery
- Validation of the therapeutic endpoint

1-3 hours
« Slow » 3D Motion correction for abdominal HIFU

Propagate the initial treatment plan down the flow of the motion (for the RT-community: “virtual couch shift”)

- Preparation (anatomical imaging)
- Therapy guidance during energy delivery
- Therapy guidance between energy delivery
- Validation of the therapeutic endpoint

1-3 hours
Experimental validation: In-Vivo Ablation of a Porcine Liver

Propagate the initial treatment plan down the flow of the motion (for the RT-community: “virtual couch shift”)

Project and accumulate the currently delivered thermal dose on the initial treatment plan “upstream” the flow of the motion (for the RT-community: “Continuous dose accumulation”)

Preparation (anatomical imaging)

Therapy guidance during energy delivery

Therapy guidance between energy delivery

Validation of the therapeutic endpoint

1-3 hours
Concluding remarks

- **Gating** strategies can be easily implemented in MR-guided HIFU
- MRI allows detailed intra- and inter-procedure motion tracking of the order of 1 mm
- A framework has been developed for 3D correction of (slow) peristaltic motion and 2D correction for respiratory motion
- MR motion tracking can be combined with **MR thermometry**
- MR **PRFS thermometry** can be adapted for moving organs
- Further technical progress is needed to reach ablation rates that allow widespread clinical applications