Innovations in CT-Guided Adaptive Radiation Therapy

Geoff Hugo, Ph.D.
Washington University Radiation Oncology
gdhugo@wustl.edu
@gdhugo

Disclosures

• Employee of Washington University
• Research Grants: NIH, Varian Medical Systems

Enabling Technologies for Adaptive RT

Onboard Imaging  Decision Making  Replanning
ART Accuracy and Clinical Efficiency

• High quality ART in the clinic requires accurate and efficient means to:
  – Assess change / decision making (when to adapt)
  – Transfer structures (targets and organs at risk contours)
  – Transfer dose (for accurate assessment of delivered dose)
  – Regenerate the treatment plan

• Deformable image registration is a key component of these basic elements of ART.

Topics

• Recent work on improved deformable image registration
• Do we need deformable image registration for adaptive RT?
• Image quality improvements in CT and cone beam CT
Conventional Deformation

Topology Preserving: Images can be stretched/squeezed to match without adding or removing image content.
Topology Preserving Deformation

- Articulation / Pose Change
- Breathing Motion

Challenges – Topological Change

Topological Change: Images can’t be stretched/squeezed to match without adding or removing image content
Challenges – Topological Change

Topology Change: Images can’t be stretched/squeezed to match without adding or removing image content

Topology Change - Examples

Atelectasis / large tissue change

- Atelectasis (partial collapse)
- Pleural effusion (fluid)
- Large volume changes in atelectasis (~150cc) during RT
- Associated with large tumor shifts (> 5mm in 83% of pts)
Atelectasis / large tissue change

- Dose recalculated on mid-treatment image
- Aligned to both bone and carina
- Compared to planned dose

Worst-case estimate

Dose changes can be significant
- Highlights need for ART/DIR

Thoracic Registration - Strategies

- Ignore regions with appearance change, identify ‘consistent anatomy’ between images
- Identify consistent anatomy that can be segmented (vessels, airways, lobes), register these regions
- Model other changes (tumor, atelectasis, pleural effusion, etc.)

Vessel Registration

- Filters applied to enhance tubular structures
- Produces a ‘vesselness measure’ image, [0, 1]
- ‘Vesselness measure image’ registered in parallel with original images
Vessel Registration

- Vessels segmented after enhancement
- No 'one to one' match (collapsed lung)
- Conventional registration methods may get stuck in 'local minima'.
- Need an algorithm that can handle global matching

Vessel Registration

- No one-to-one match
  - Collapsed lung
- ‘Varifolds’ used for fuzzy matching

Registering Atelectatic Lobes

Hypothesis:
- Atelectasis is mostly collapsed lung, so re-inflation should approximately preserve the mass of the affected lobe.
- mass-preserving cost function used in atelectatic and normal lung.
Registering Atelectatic Lobes

Hypothesis:
• Atelectasis is mostly collapsed lung, so re-inflation should approximately preserve the mass of the affected lobe.
• Mass-preserving cost function used in atelectatic and normal lung.

If mass is preserved, tissue should change intensity when expanded / contracted during registration.

Lung DIR Algorithm

Multi-resolution B-spline framework (elastic)
Mass-preserving metric within healthy lung
Intensity-based similarity metric within atelectasis
Co-registration of lobe label images
Co-registration of vesselness measure images

15 patients

Lung DIR Algorithm

Landmark registration error / mm

Unregistered
Intensity (CT) only
Intensity + Lobes
Intensity + Vessels
Intensity + Lobes + Vessels

15 patients
Results vs. Resolution Type

<table>
<thead>
<tr>
<th>Resolution Type</th>
<th>Mean Err</th>
<th>Max Err</th>
<th>DSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Change</td>
<td>2.50 (1.16)</td>
<td>16.18 (10.86)</td>
<td>0.91 (0.08)</td>
</tr>
<tr>
<td>Partial</td>
<td>2.80 (0.70)</td>
<td>25.77 (17.22)</td>
<td>0.90 (0.08)</td>
</tr>
<tr>
<td>Full</td>
<td>2.04 (0.13)</td>
<td>23.27 (9.60)</td>
<td>0.89 (0.04)</td>
</tr>
</tbody>
</table>

Registration in Cervical Ca RT

- Combined external beam RT and intracavitary BT => large uncertainty in cumulative dose

DIR challenges:
- Images with / without applicator => topology issues
- Large motion of anatomy in abdomen => complex / large deformations
- Mixed modality

Registration in Cervical Ca RT

- Combined external beam RT and intracavitary BT => large uncertainty in cumulative dose
- DIR challenges:
  - Images with / without applicator => topology issues
  - Large motion of anatomy in abdomen => complex / large deformations
  - Mixed modality
Registration in Cervical Ca RT

- Penn approach:
  - EBRT CT to BT CT, with/without EBRT boost
  - Pre-processing to equalize contrast and enhance organ boundaries (bladder, rectum, packing)
  - Contoured applicator
  - Commercial DIR then applied
  - Compared 'parameter adding' of D2cc to DIR-accumulated values between EBRT and BT for risk organs (bladder / rectum)
  - Rectum / bladder D2cc varied by 5% between DIR and parameter adding

- Rotterdam approach:
  - EBRT MR to BT MR
  - Automated feature extraction near contoured organs (bladder, cervix/uterus, rectum) used for feature-based DIR
    - 'Feature filter' similar to vesselness measure
    - Feature DIR registers points in a 'fuzzy matching' method where point correspondence is unknown
  - Organ, feature, and background transforms combined

- Landmark-based accuracy assessment (mean error):
  - Rigid:
    - 22.4 mm near organs
    - 4.3 mm away from organs
  - DIR:
    - 3.5 mm near organs
    - 3.4 mm away from organs
What about the target?

Tumor Regression

• How to accumulate dose to regressing tumor?
• Where is tissue lost (how to appropriately register)?
• Requires contrast / markers within tumor to study
Tumor Regression

Hugo et al., IJROBP 2011
Cumulative dose in adaptive RT

ART – Key Questions

- Image registration – role and need
- Do we need to know the delivered, cumulative dose?

Adapting the Plan

Original CT, Original Plan  Mid-ct CT, Original Plan
Adapting the Plan

Original CT, Original Plan

Mid-ct CT, Original Plan

Adapting the Plan

Original CT, Original Plan

Mid-ct CT, Adapted Plan

Adapting the Plan

Original CT, Original Plan

Mid-ct CT, Adapted Plan
Dose Accumulation

• Use the cumulative, delivered dose to
  – Assess coverage and normal tissue dose (decision support)
  – Avoid hot/cold spots in adaptation

• Is there a need for this?

Cumulative Dose

• Parameter adding vs. cumulative dose
• 18 patients, single adaptation

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD difference /%</th>
<th>Range difference /%</th>
<th>Number &gt; 5% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Lung Dose</td>
<td>5% ± 5%</td>
<td>1% - 16%</td>
<td>4 / 18</td>
</tr>
<tr>
<td>Mean Heart Dose</td>
<td>4% ± 3%</td>
<td>0% - 12%</td>
<td>6 / 18</td>
</tr>
</tbody>
</table>

Cumulative Dose

• Parameter adding vs. cumulative dose
• 18 patients, single adaptation

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD difference /%</th>
<th>Range difference /%</th>
<th>Number &gt; 5% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Lung Dose</td>
<td>5% ± 5%</td>
<td>1% - 16%</td>
<td>4 / 18</td>
</tr>
<tr>
<td>Mean Heart Dose</td>
<td>4% ± 3%</td>
<td>0% - 12%</td>
<td>6 / 18</td>
</tr>
</tbody>
</table>

• Similar results in cervical ca (other groups)
Cumulative Dose

- Requires clinical trial of ‘plan of day’ adaptive vs. cumulative dose adaptive to answer the question

CT image quality improvements

Free-breathing CBCT - challenges
Solution: Motion Compensation

4DCT (from simulation)

Image Registration

Motion Model

Projections / raw data

Image Reconstruction

Motion Compensated Reconstruction

Challenges:
- Breathing pattern changes
- Anatomy changes

Solution:
- Build model directly from cone beam data
Solution: Motion Compensation

Results: Clinical Dataset

Results: Clinical Dataset
WashU Halcyon 2.0

2.0 features
• Distal/proximal leaf shaping
• Dynamic beam flattening
• Kilovoltage cone beam CT imaging

Abdomen – Halcyon vs TrueBeam

Summary

• Image registration developed to manage large, geometric changes in the thorax.
• Next steps: Test whether cumulative dose is needed
• Image quality is improving for online adaptive radiation therapy
CORAL and Collaborators

Washington University in St. Louis:
- Jeff Bradley
- Bin Cai
- James Kavanaugh
- Hyun Kim
- Eric Laugeman
- Parag Parikh
- Mike Reisch
- Cliff Robinson

Virginia Commonwealth University:
- Elisabeth Weiss
- Nuzhat Jan
- Noah Kalman
- Nate Tamplin

This project supported by NIH/NCI research grant R01CA166119