

Innovations in CT-Guided Adaptive Radiation Therapy

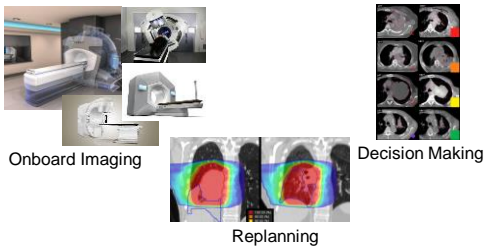
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Disclosures

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

Enabling Technologies for Adaptive RT



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

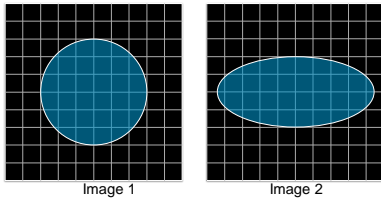
ART Accuracy and Clinical Efficiency

- 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.

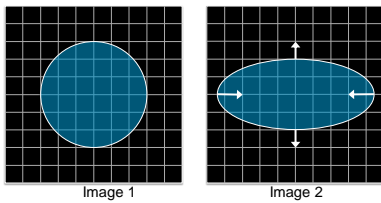
Topics

- 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

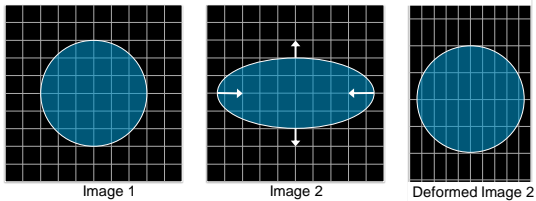
Conventional Deformation



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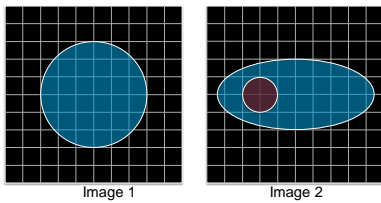


Topology Preserving: Images can be stretched/squeezed to match without adding or removing image content

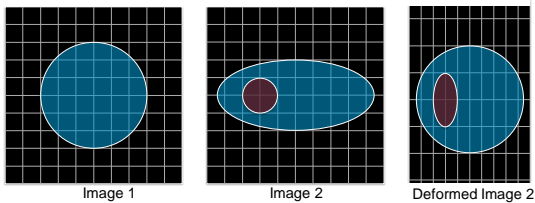
Topology Preserving Deformation

- Articulation / Pose Change
- Breathing Motion

Challenges – Topological Change

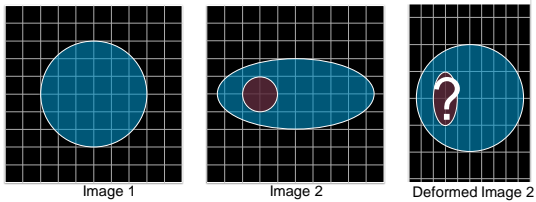


Challenges – Topological Change



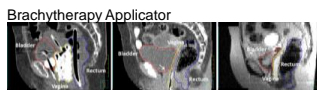
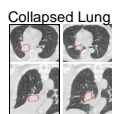
Topology Change: Images can't be stretched/squeezed to match without adding or removing image content

Challenges – Topological Change

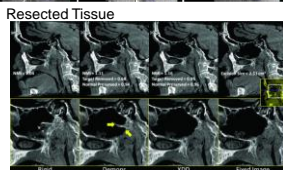
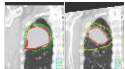


Topology Change: Images can't be stretched/squeezed to match without adding or removing image content

Topology Change - Examples



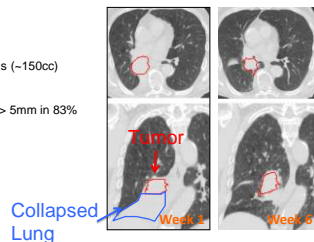
Tumor Growth / Response



S. Nithiananthan, Med Phys 39 2012

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)



Guy Med Phys 2016, Tennyson Adv RO 2016

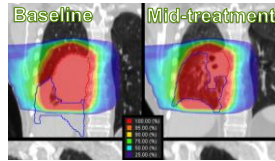
Atelectasis / large tissue change

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



Structure	Metric	Units	Bone aligned				Carina aligned			
			Mean	Stddev	Min	Max	Mean	Stddev	Min	Max
Spinal cord	D_{max}	Gy	0.67	2.99	-2.78	10.93	0.14	1.80	-2.94	4.29
Esophagus	D_{max}	Gy	0.99	2.69	-3.72	7.92	0.77	2.95	-4.56	7.07
Lungs	D_{max}	Gy	0.50	2.05	-2.89	5.69	0.06	1.71	-3.35	4.56

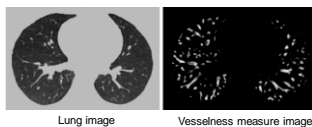
Guy Med Phys 2016, Tennyson Adv RO 2016

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



Cao et al., WBIR 2010

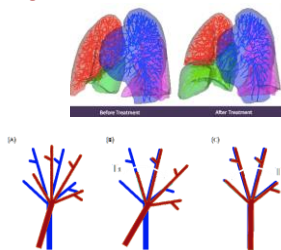
Vessel Registration

Vessels segmented after enhancement

No 'one to one' match (collapsed lung)

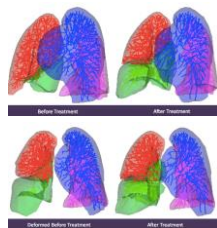
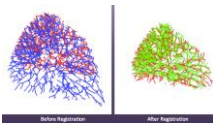
Conventional registration methods may get stuck in 'local minima'.

Need an algorithm that can handle global matching



Vessel Registration

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



Gorbunova, V., Durleman, S., Lo, P., Pennec, X., & De Bruijne, M. (2008). Curve-and surface-based registration of lung CT images via currents. In *Second International Workshop on Pulmonary Image Analysis*

Pan CVPR 2016

Registering Atelectatic Lobes

Hypothesis:

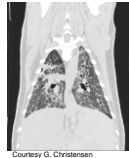
- Atelectasis is mostly collapsed lung, so re-inflation should approximately preserve the mass of the affected lobe.
- mass-preserving cost function used in atelectatic and normal lung.

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.

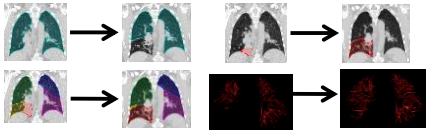


Courtesy G. Christensen

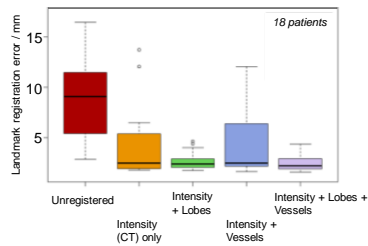
Lung DIR Algorithm

Multi-resolution B-spline framework (elastix)

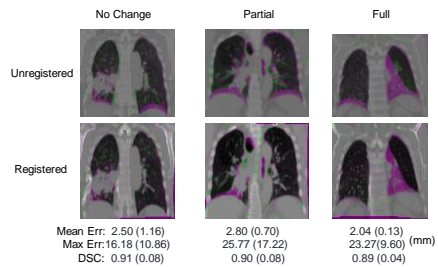
Mass-preserving metric within healthy lung
 \pm
 Intensity-based similarity metric within atelectasis
 \pm
 Co-registration of lobe label images
 \pm
 Co-registration of vesselness measure images



Lung DIR Algorithm



Results vs. Resolution Type

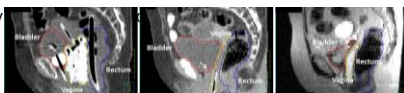


Registration in Cervical Ca RT

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

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



S. Oh AAPM 2016

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

B-K Teo, *Radioth Oncol* 115, 2015

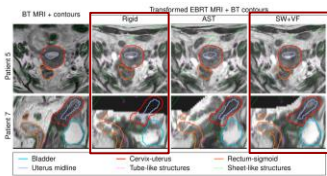
Registration in Cervical Ca RT

- 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

E. Vasquez Oronio, *Med Phys* 24, 2015

Registration in Cervical Ca RT

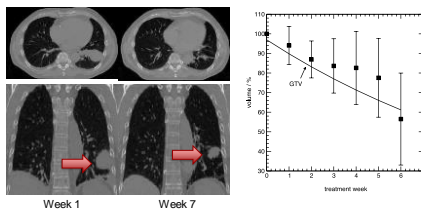
- Rotterdam approach:
- Landmark-based accuracy assessment (mean error):
 - Rigid:
 - 22.4 mm near organs
 - 4.3 mm away from organs
 - DIR:
 - 3.5 mm near organs
 - 3.4 mm away from organs



E. Vasquez Oronio, *Med Phys* 24, 2015

What about the target?

Tumor Regression



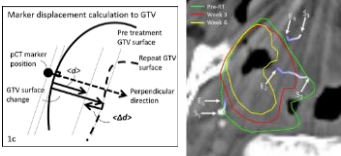
Glide-Hurst, IJROBP2010

Tumor Regression

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

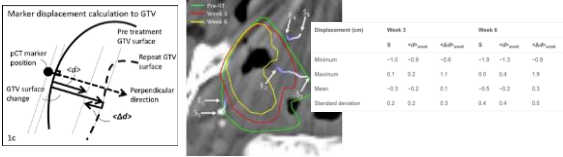
Tumor Regression

Analysis of GTV reduction during radiotherapy for oropharyngeal cancer:
Implications for adaptive radiotherapy
O Hamming-Vrieze, SR van Kranen... - Radiotherapy and ... 2017 - Elsevier

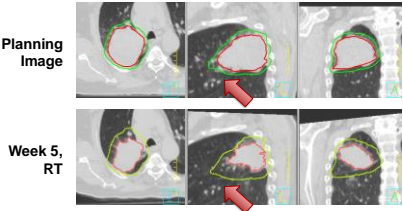


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Tumor Regression



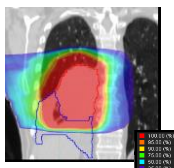
Hugo et al., UROBP 2011

Cumulative dose in adaptive RT

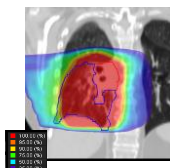
ART – Key Questions

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

Adapting the Plan

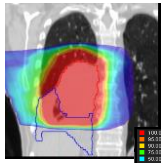


Original CT, Original Plan

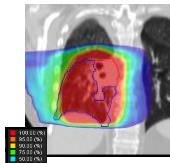


Mid-tx CT, Original Plan

Adapting the Plan

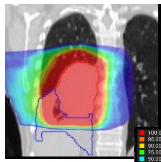


Original CT, Original Plan

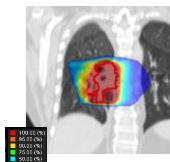


Mid-bx CT, Original Plan

Adapting the Plan

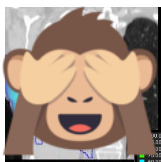


Original CT, Original Plan

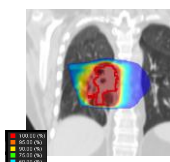


Mid-bx CT, Adapted Plan

Adapting the Plan

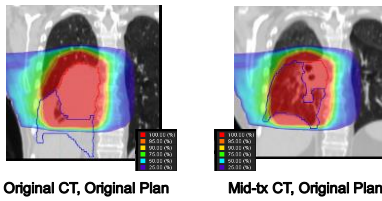


Original CT, Original Plan

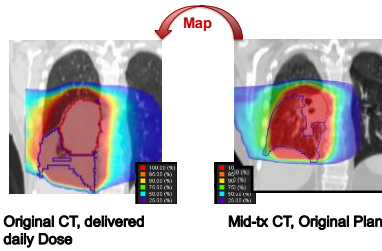


Mid-bx CT, Adapted Plan

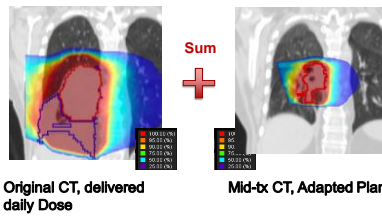
Cumulative Dose



Cumulative Dose



Cumulative Dose



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

	Mean +/- SD difference / %	Range, difference / %	Number > 5% difference
Mean Lung Dose	5% +/- 5%	1% - 16%	4 / 18
Mean Heart Dose	4% +/- 3%	0% - 12%	6 / 18

Cumulative Dose

- Parameter adding vs. cumulative dose
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- Similar results in cervical ca (other groups)

Cumulative Dose

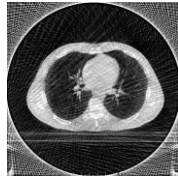
- Requires clinical trial of 'plan of day' adaptive vs. cumulative dose adaptive to answer the question

CT image quality improvements

Free-breathing CBCT - challenges

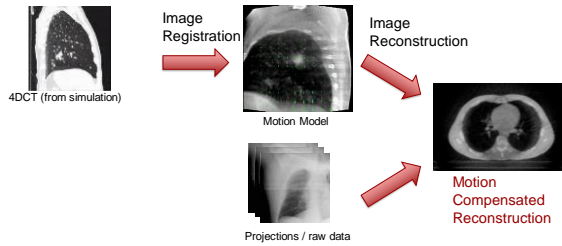


Motion Blurring

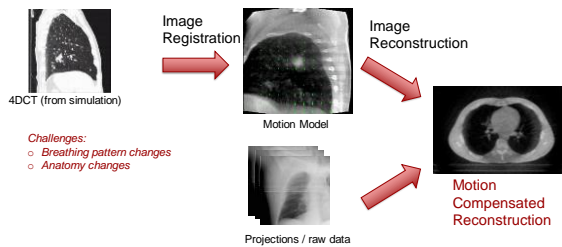


Streaking (View Aliasing)

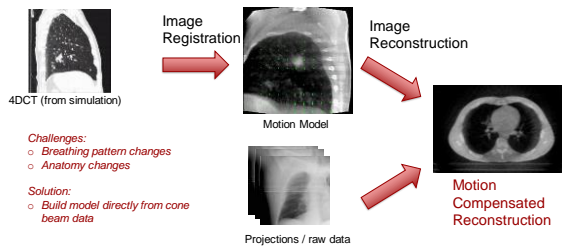
Solution: Motion Compensation



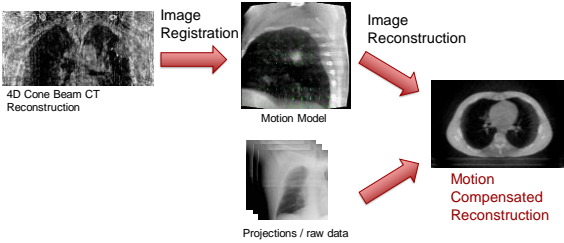
Solution: Motion Compensation



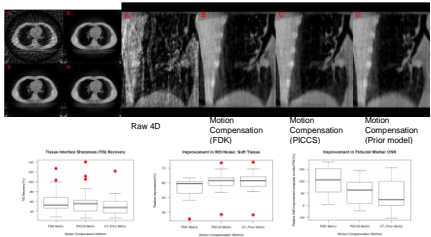
Solution: Motion Compensation



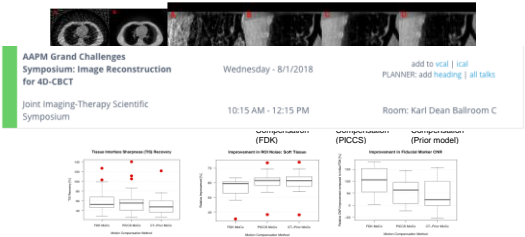
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Results: Clinical Dataset



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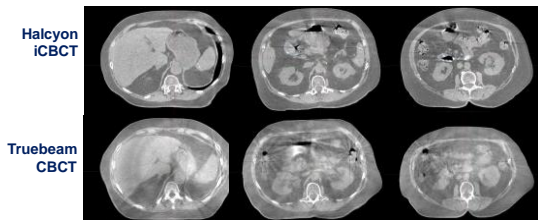
WashU Halcyon 2.0

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

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Nuzhat Jan
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Gary Christensen
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