Introduction and Overview of DIR Methods and Challenges

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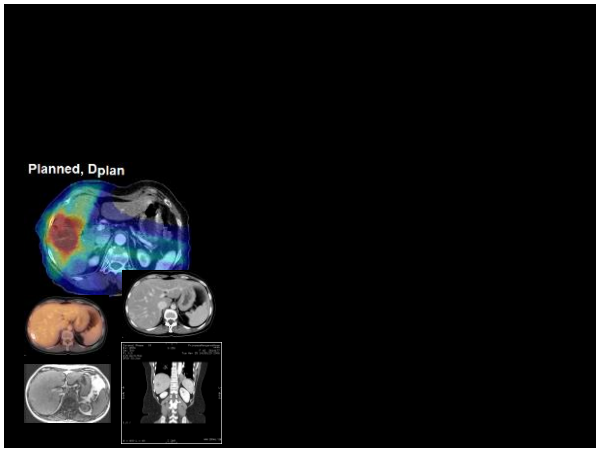
Disclosures

- Licensing agreement with RaySearch Laboratories

Objectives

- Clinical use of Deformable Image Registration (DIR)
- Overview of DIR methods
- Challenges in the clinical application of DIR
- Overall challenges in the field of DIR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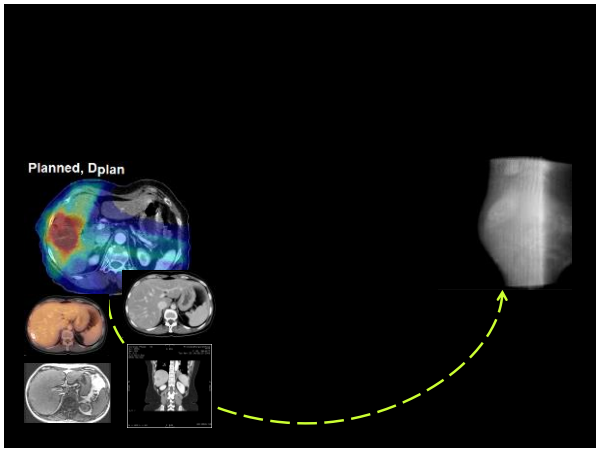
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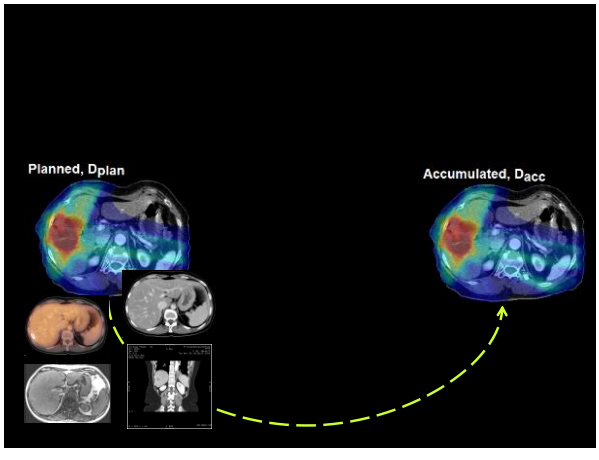
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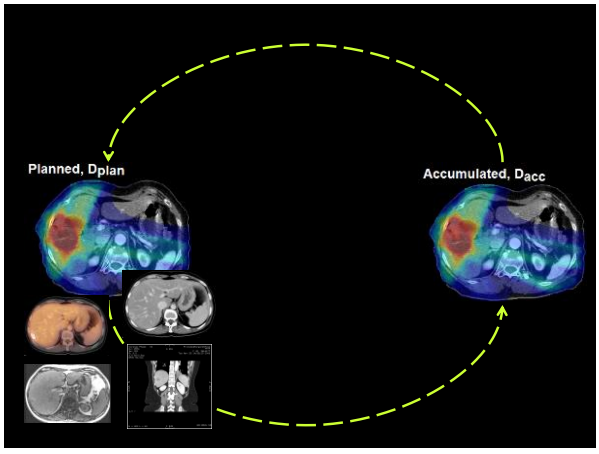


Role of Image Registration in RT

- Treatment (Re-)Planning
  - Motion (Re-)Assessment (e.g. 4D CT)
  - Multi-modality Images (e.g. MR-CT-PET)
  - Segmentation
- Treatment Delivery
  - Propagate Contours
  - Image guidance (e.g. CBCT-MVCT)
  - Motion (Re-)Assessment (e.g. 4D CBCT)
  - Deformable Dose Accumulation
- Treatment Assessment
  - Adaptive radiotherapy
  - Retreatment

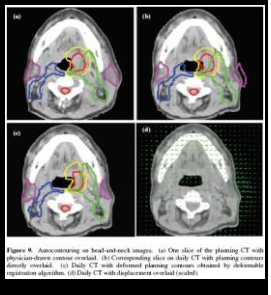
What Level of Accuracy do we Want and Need?

- Ideally ½ the voxel size
- Clinically acceptable ~ 2 mm (?)
- Even with the best algorithm, there will be cases where there are local uncertainties of > 2 mm
  - Predict these areas
  - Interpret them (quickly)
  - Account for them in the clinical process

Accuracy Determined by Dependent Activities

DIR for contour propagation

- Accuracy required: accurate enough to improve efficiency
- Results can be manually corrected

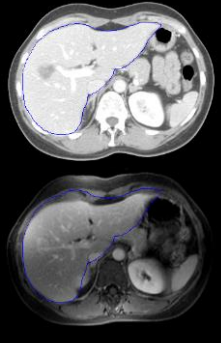


Wang, et al., PMB 2005

Accuracy Determined by Dependent Activities

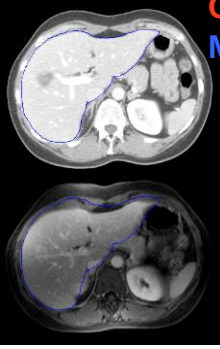
DIR for Multi-Modality Planning

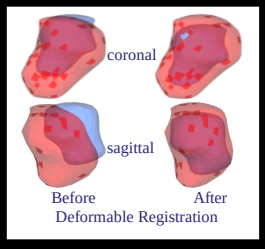
- Accuracy required: voxel level
- Uncertainties create a systematic error that propagates throughout the treatment



Accounting for Limitations in Registration at (Re-)Planning

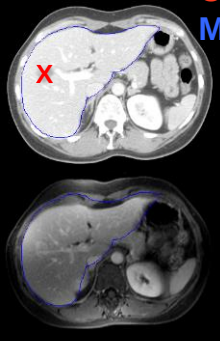
CT
MR



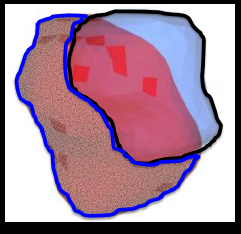


Accounting for Limitations in Rigid Registration

CT
MR

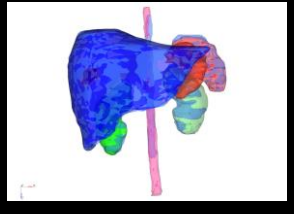


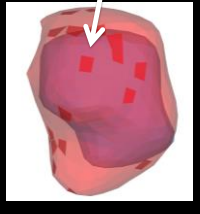
GTV (defined on MR, mapped to CT for Tx)



Region of CT-defined GTV that is missed

Accounting for Limitations in Deformable Registration



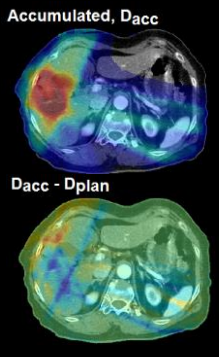


- Assess uncertainty around GTV
- Add margin around GTV definition to account for uncertainty when required

Accuracy Determined by Dependent Activities

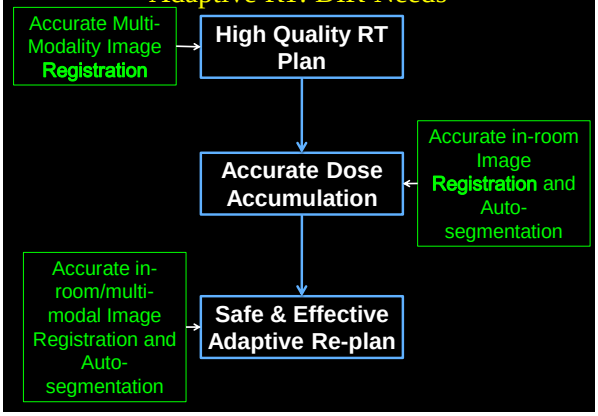
DIR for Dose Accumulation

- Accuracy required: Dose Grid Size or Dose Gradient
- Uncertainties create a systematic or random impact on dose, depending on number of fractions



M Velec, IJROBP, 2013

Adaptive RT: DIR Needs



Reliability of Registration Techniques

Deformable Registration

- Can it be reliable?
  - YES!
- Can it be unreliable?
  - YES!

Deformable Registration Algorithms How do they work?

- Match something
  - Intensity, gradients, boundaries, features
  - What happens when the intensity correspondence is not defined?
  - What happens with the features aren't visible?
- Constrain by a function
  - Geometric, physical, biomechanical
  - Can you rely on this model when the match above is missing?

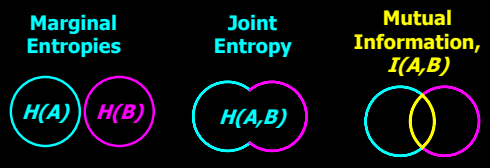
Issues become even more challenging in Adaptive RT
-- Dramatic changes in tumor/normal tissue volume
-- Non-diagnostic quality images

How is Registration Performed?

Metric	Regularization	Optimization
Your Eye	Translation	Brain-power
Least Squares (Points)	Translation + Rotation	Simplex
Chamfer Matching (surface matching)	Affine (Translation + Rotation + scaling + shearing)	Gradient descent
Contour matching		etc…
Mean Square Difference	Spline (B-spline, Thin plate spline)	
Correlation Coefficient	Physical (optical/fluid flow, elastic body)	
Mutual Information	Biomechanical	

Mutual Information

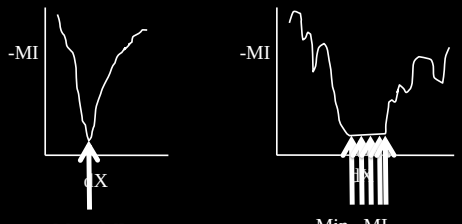
- Maximise the mutual information



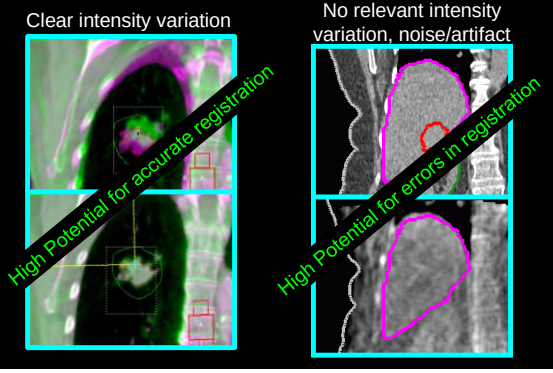
- Sensitivity of results: Vary the vector field and evaluate the change in similarity metric
  - Hub, et. al., IEEE TMI 2009

How Reliable is the Max MI?

- Actually, min -MI



Intensity Variation: Impact on CC/MSD



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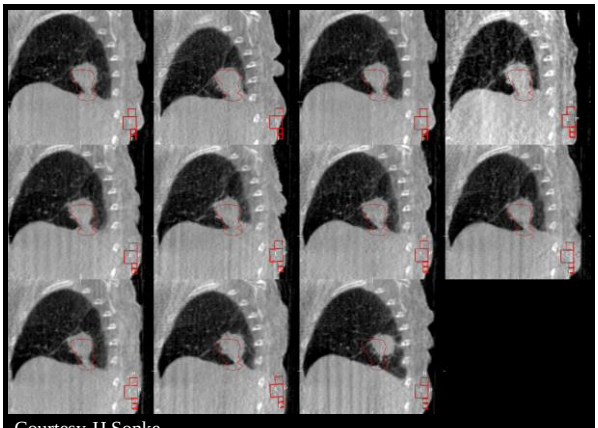
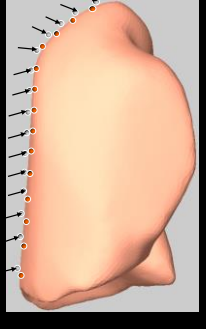


Courtesy JJ Sonke

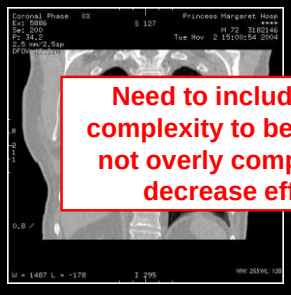
Appropriate Level of Transformation Complexity

Improves lung and rib accuracy to 2 mm
Al-Mayah, Med Phys, 2009

Contact Surface



Appropriate Level of Transformation Complexity



HyperElastic Bronchial Tree

Need to include relevant complexity to be reliable but not overly complex to only decrease efficiency

Leads to +++ time, no change in Accuracy
Al-Mayah, Med Phys, 2010

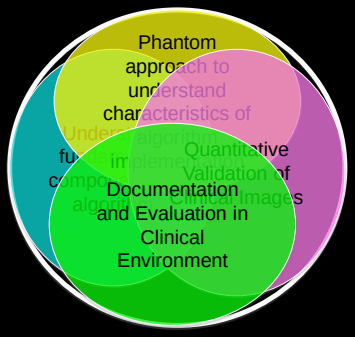
Challenge: Validation and QA

How do we Prove it is Reliable?

Commissioning is Important!

- LINAC
  - Know how it works
  - Accept and Commission
- Planning System
  - Know the dose calculation algorithm
  - Accept and Commission
- Deformable Registration Algorithm
  - **Find out how it works!**
  - **Accept and Commission the software**
  - **Perform an end-to-end test in your clinic**

Commissioning and QA
Understand the whole picture



Challenge: How do we Communicate the Uncertainty?

Uncertainty Assessment	Phrase	Description
0	Whole scan aligned	- Anatomy within 1 mm everywhere - Useful for structure definition everywhere - Ok for stereotactic localization
1	Locally aligned	- Anatomy local to the area of interest is un-distorted and aligned within 1mm - Useful for structure definition within the local region - Ok for localization provided target is in locally aligned region
2	Useable with risk of deformation	- Aligned locally, with mild anatomical variation - Acceptable registration required deformation which risks altering anatomy - Registered image shouldn't be used solely for target definition as target may be deformed - Increased reliance on additional information is highly recommended - Registered image information should be used in complimentary manner and no image should be used by itself
3	Useable for diagnosis only	- Registration not good enough to rely on geometric integrity - Possible use to identify general location of lesion (e.g. PET hot spot)
4	Alignment not acceptable	- Unable to align anatomy to acceptable levels - Patient position variation too great between scans (e.g. surgical resection of the anatomy of interest or dramatic weight change between scans)

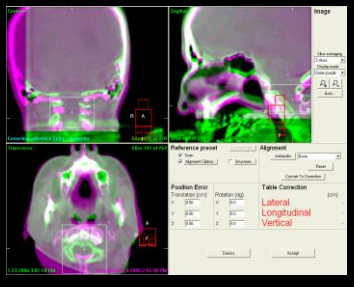
Challenge: Addressing so Many Complexities

Shrinking Breathing Filling

How do we make sure we are improving treatment and not introducing more error?

Visual Verification

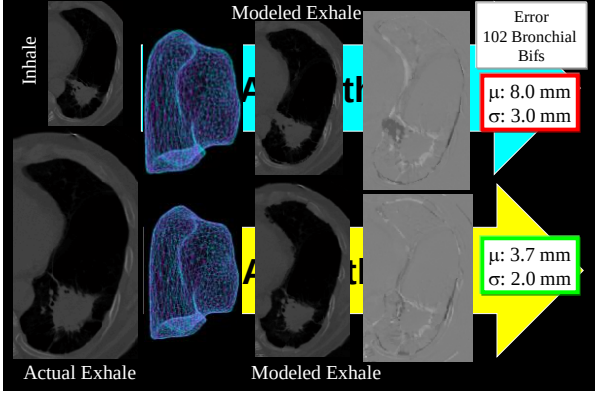
Excellent tool for established techniques
Not enough for Commissioning



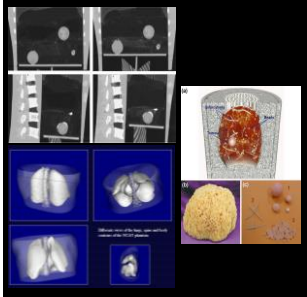
Validation Techniques

- Matching Boundaries
  - Does the deformable registration map the contours to the new image correctly?
- Volume Overlap
  - DICE, etc
- Intensity Correlation
  - Difference Fusions
  - CC, MI, etc
- Digital/Physical Phantoms
- Landmark Based
  - TRE, avg error, etc

Does Contour Matching Prove Reliability?



Digital or Physical Phantoms



- NCAT Phantom
- U of Mich lung phantom (Kashani, Balter)
- McGill lung phantom (Serban)

- Many great phantoms out there but also a lot of room for innovation – as described in the next 3 talks!

Example of Mathematical-Phantom Based Validation

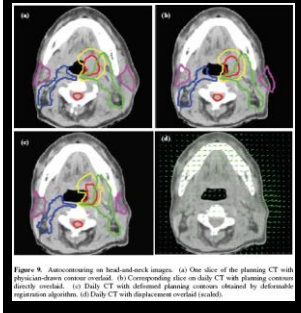


Figure 9. Autocontouring on head-and-neck images. (a) One slice of the planning CT with physician-drawn contour overlaid. (b) Corresponding slice on daily CT with planning contours directly overlaid. (c) Daily CT with deformed planning contours obtained by deformable registration algorithm. (d) Daily CT with displacement overlaid (scaled).

- Wang, et al, PMB 2005
- Difference in images (ext) and gradient of image (int) act as forces
- Addition of active force (gradient of moving image)
- Accuracy: 96% voxels < 2 mm for mathematical phantom

Objective assessment of deformable image registration in radiotherapy: A multi-institution study

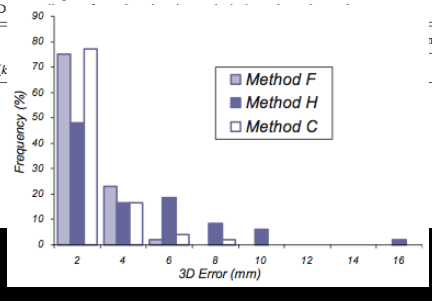
et. al. Med Phys 2008

Rojano Kashani[a)]
Department of Radiation Oncology, University of Michigan, 1500 E. Medical Center Drive, Ann Arbor, Michigan 48109-0010

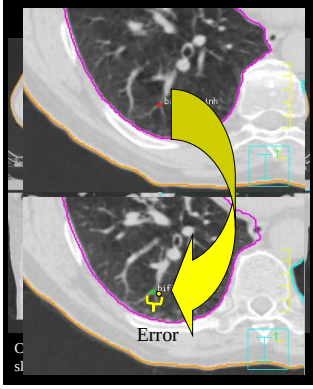
TABLE I. Summary of registration methods and references.

TABLE II. Maximum component errors in RL, AP, and SI directions, as well as the mean, standard deviation, and maximum 3D

Method (k					m)
					$d_k^{\max}$ [f]
A					10.1
B					5.1
C					8.1
D					6.4
E					10.3
F					5.5
G					6.0
H					15.4



Natural/Implanted Fiducials

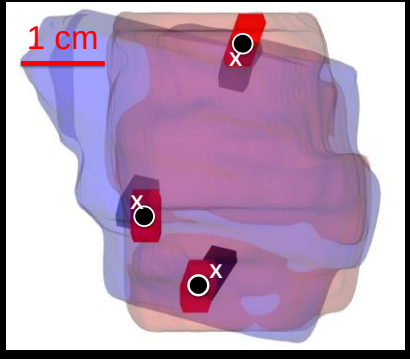


- Reproducibility of point identification is sub-voxel
  - Gross errors
  - Quantification of local accuracy within the target
  - Increasing the number increases the overall volume quantification
- Manual technique
- Can identify max errors

Accuracy of Points

RMS = 0.3 mm

Points Don't Tell the Whole Story



MIDRAS Results

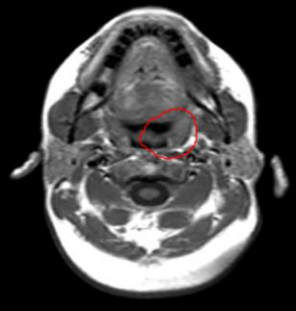
Brock, MIDRAS consortium, IJROBP 2010

- Liver 4D CT: Deform Exhale to Inhale
- Lung 4D CT: Deform Inhale to Exhale

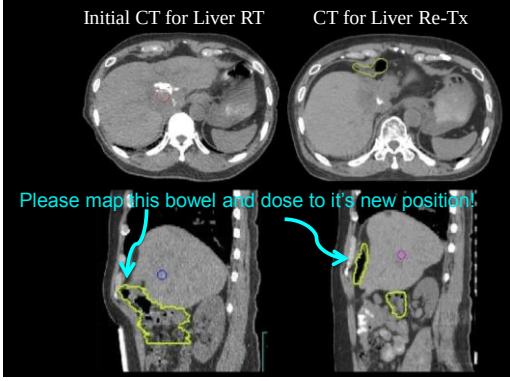
- Implementation matters
  - 3 Demons algorithms (Liver): μ = 2.3, 3.3, 4.8 mm
  - 3 Thin Plate Spline (Liver): μ = 2.1, 2.9, 7.8 mm
  - 4 B-Spline (Lung): μ = 1.6, 2.0, 2.5, 3.0 mm

Challenge: Pushing the Limits! Deformable Registration for Adaptive and Re-Treatment

Response Happens!

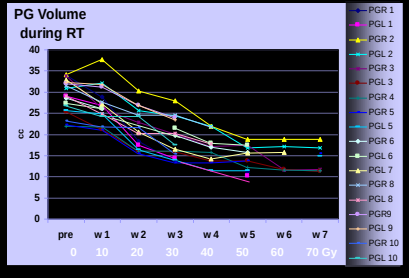


Deformable Registration for Re-Tx



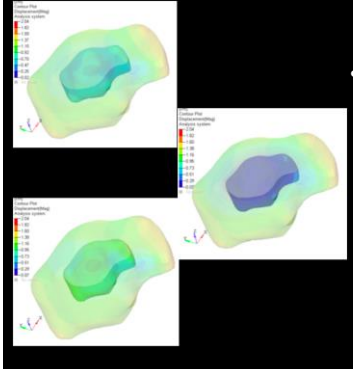
Prospective Monitoring of Changes in Parotid Gland (PG) Size vs Dose Accumulated

10 patients: weekly MRIs during RT



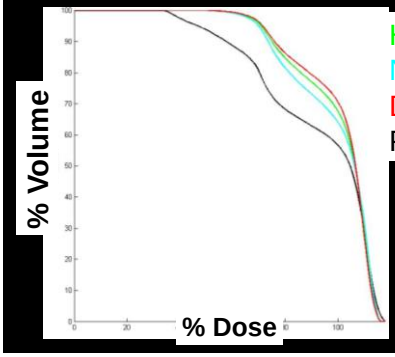
Average Reduction: 48 %

Challenge: Impact of Reliability



- Variation in volume reduction
  - Homogeneous
  - Dissolving rim
  - Necrotic Core

Modeling Volume Reduction Dosimetric Effect



Summary

- Many different deformable registration options, implementations
- Uncertainties must be incorporated
- Safe and effective re-planning requires accurate dose accumulation and quality RT plan – deformable registration is a critical component
- Issues that challenge deformable registration often become more extreme in the adaptive environment
- Relevant complexities for each anatomical site should be included in deformable registration to improve reliability
- Phantoms are essential for understanding challenges and potential pitfalls of deformable registration