Image Registration and Assessment for Adaptive Therapy

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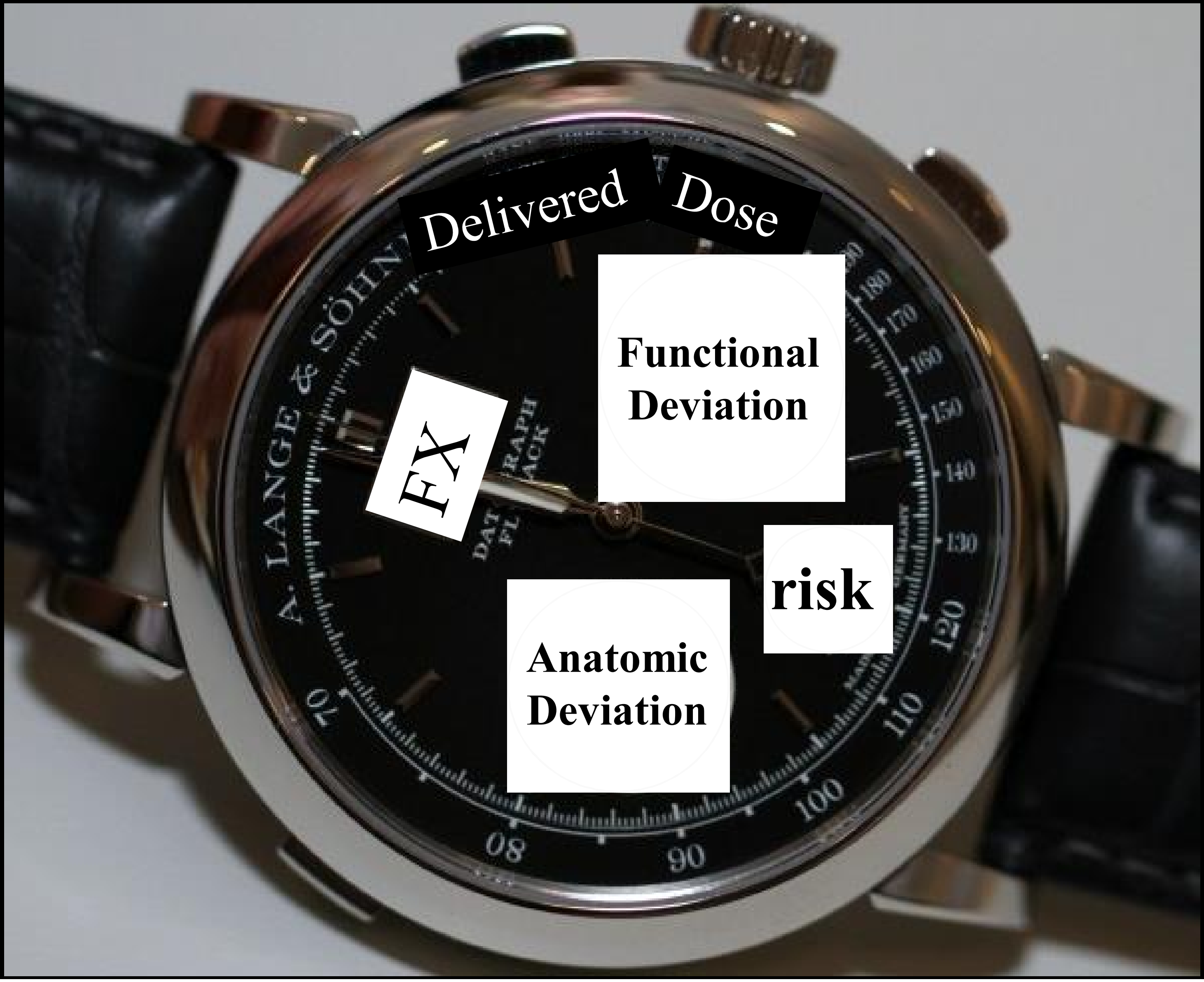
Disclosure

Å I have financial interest in deformable registration technology through a licensing agreement with RaySearch Laboratories

Beautiful, Streamlined System
Provides clear information

Hidden complexity:
Several gears working seamlessly together

Beautiful, Streamlined System Provides clear information



Hidden complexity: How do we get there?

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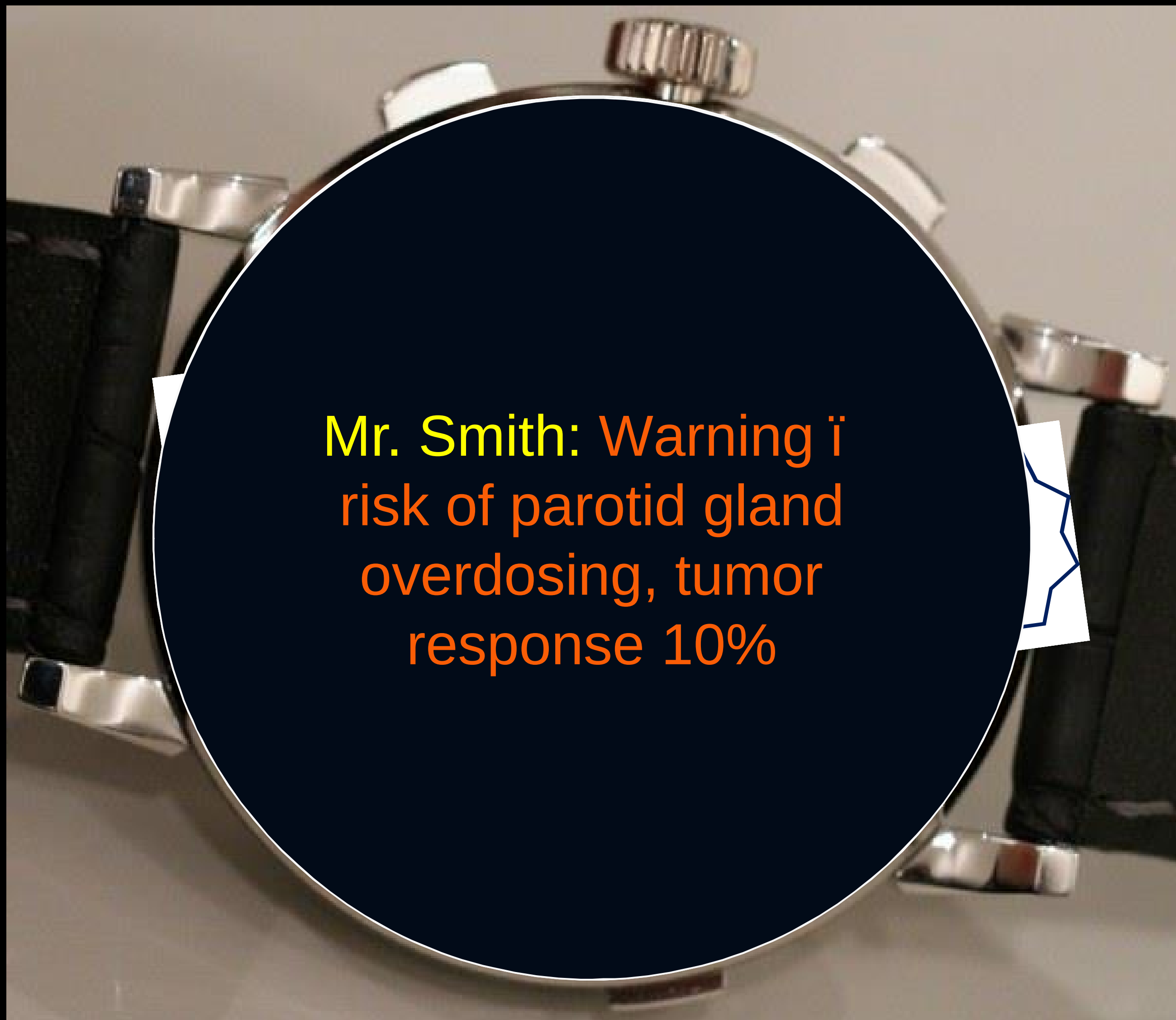
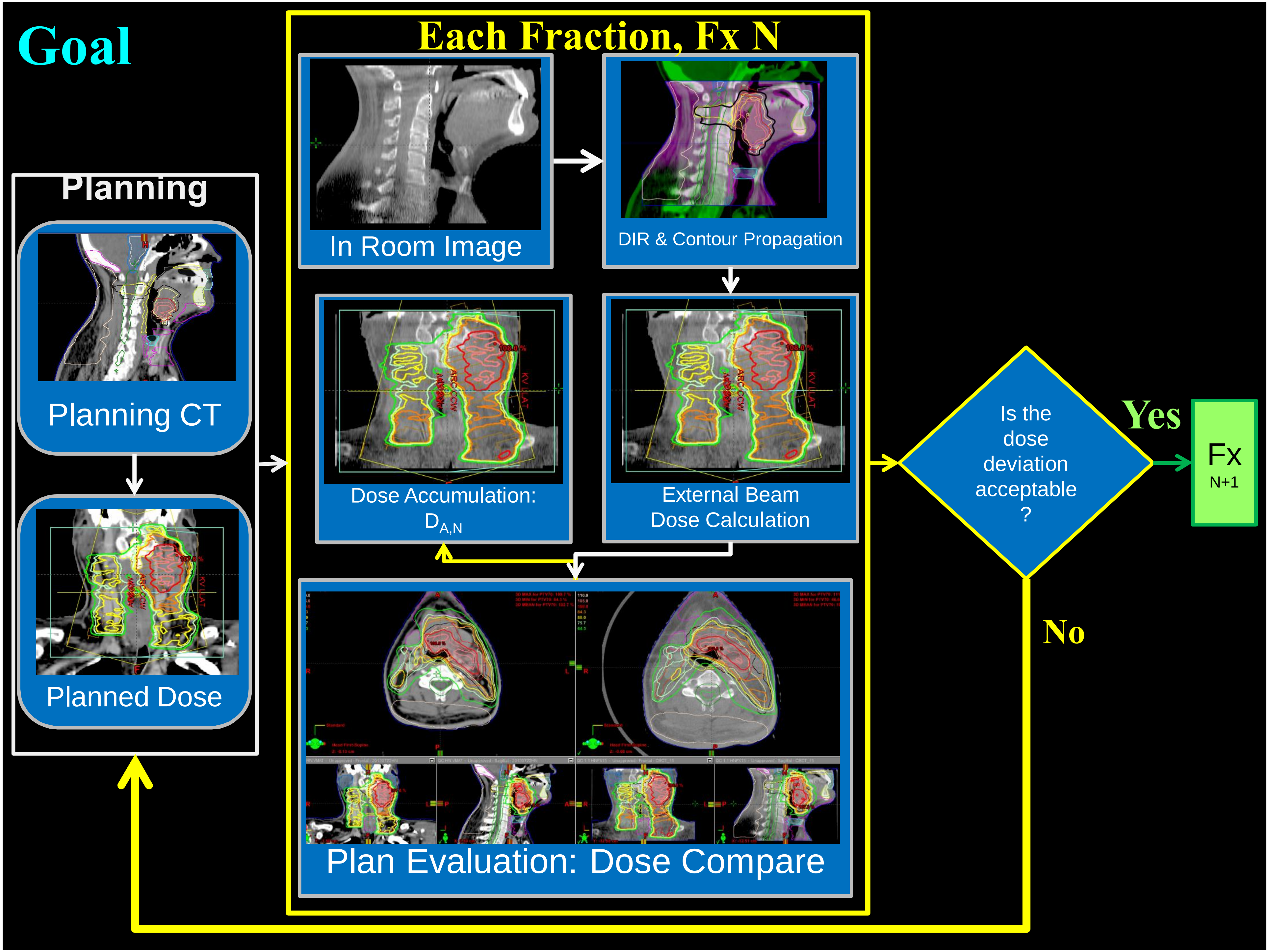


Why arenôt we there yet?

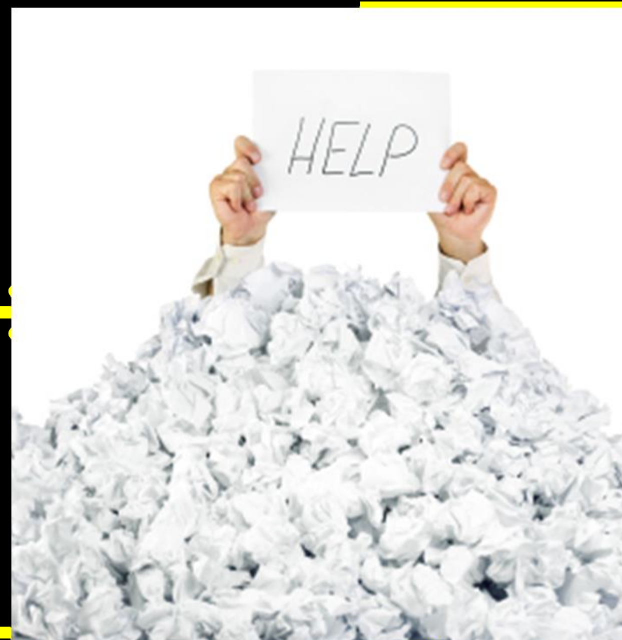
- Pub Med search for óadaptive radiotherapyô returns 1098 citations (dating back to late 1990s)
- At AAPM 2014 ~100 abstracts on óadaptiveô
- Many of the ógearsô existé
- However the lack of integration prohibits the widespread use of these tools on a large number of patients
- Many of the ógearsô are still missing
- Underlying infrastructure often cannot support the extensive amount of data generated by dose accumulation/adaptive protocols


Goal
Planning
Planning CT
Planned Dose
Each Fraction, Fx N
In Room Image
DIR & Contour Propagation
Dose Accumulation:
D A,N
External Beam
Dose Calculation
Plan Evaluation: Dose Compare
Is the
dose
deviation
acceptable
?
Yes
No
Fx
N+1

DATA!!!!

1 to N RT Structures

CT
4D CT
MR
PET
Re-Sim CT
Re-Sim
MR/PET



1 to N DVFs

1 to N Dose Distributions

Clinical Implementation

- Goal: to safely improve our ability to deliver the optimal treatment to each individual patient, efficiently, while contributing to the overall knowledge of the patient population
- Need to understand and incorporate uncertainties
- Must be a collaborative effort between vendors, physicists, and clinicians
- Vendors must provide the tools and information so that physicists can understand how to best implement the tools
- Physicists must provide feedback to the vendors on what is needed and how the tools are working

Tools Needed for Dose Accumulation & Adaptation

1. Images Obtained during Tx
2. Auto-Segmentation
3. Deformable Image Registration
4. Dose Re-calculation & Summation
5. Decision Making Tools
6. Plan Re-Optimization (including delivered dose)

Commissioning Image Registration

- LINAC
  - Know how it works

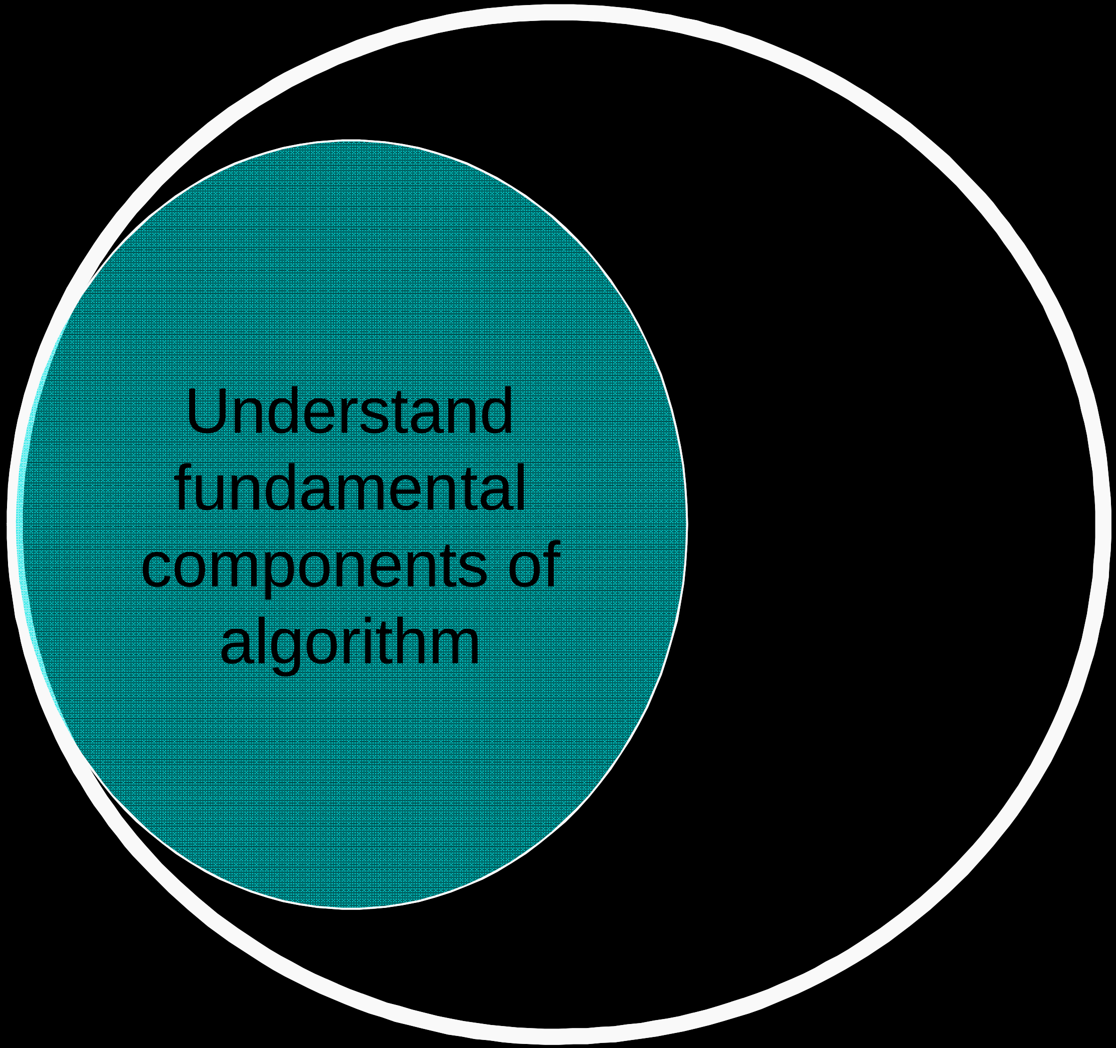
Why is this particularly challenging for deformable registration?

- **Algorithms typically don't rely on fundamental physics related to the human anatomy/physiology**

- 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



Learning the Basics

How?

Å AAPM Virtual Library

- ï 2014 AM: Image Registration I: Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201
- ï 2014 AM: Image Co-Registration II: TG132-Quality Assurance for Image Registration
- ï 2014 SCM: Image Registration for IGRT
- ï 2014 SCM: Image Registration for Treatment Planning
- ï 2013 AM: Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201
- ï 2013 AM: TG 132: Image Registration and Fusion
- ï 2012 AM: Deformable Registration in the Clinic: From Commissioning To Advanced Applications
- ï 2012 AM: Validation and QA of Deformable Image Registration Part II
- ï The list goes on!

Å Several books and review papers

Learning YOUR Clinic's Algorithm

How?

- At minimum, the vendor should disclose:
  - Similarity metric used
  - Regularization used
  - Transformation used
  - Optimization method
  - What knobs you can turn and what they do
- Read white papers
- Know that implementation matters

Why? Many Image Registration Techniques

Metric	Transformation	Optimization
Your Eye		Brain-power
Least Squares (Poin	otation	Simplex
Chamfer Matchin (surface matchi	ion g)	Gradient descent
Contour matching		etcé
Mean Square Di	in	
Correlation		
Mutual Information	anical	

Quick, Easy, local

Surface-based

Manual or auto-

Great for 4D CT

Good for same modality (x-ray), different contrast/noise (CECT, CT, CBCT)

Works for Multi-Modality

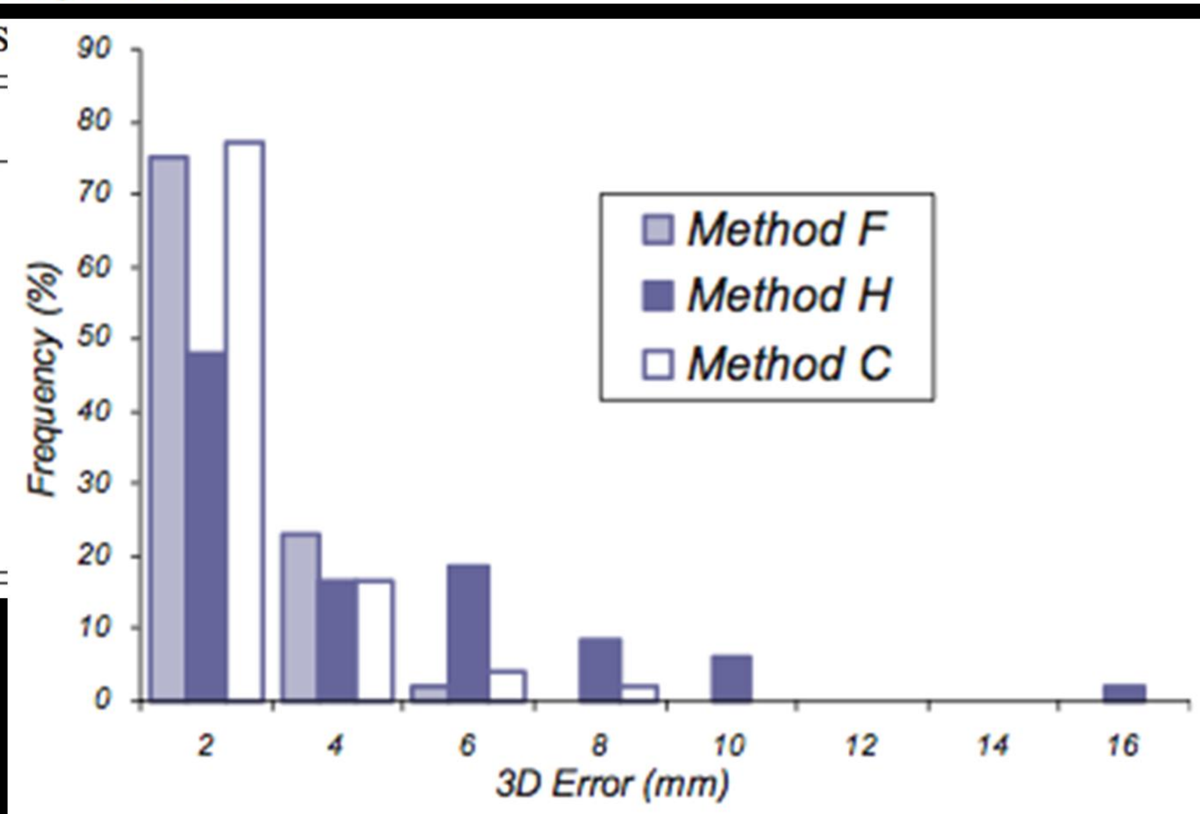
Why do we need to know the implementation?

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

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

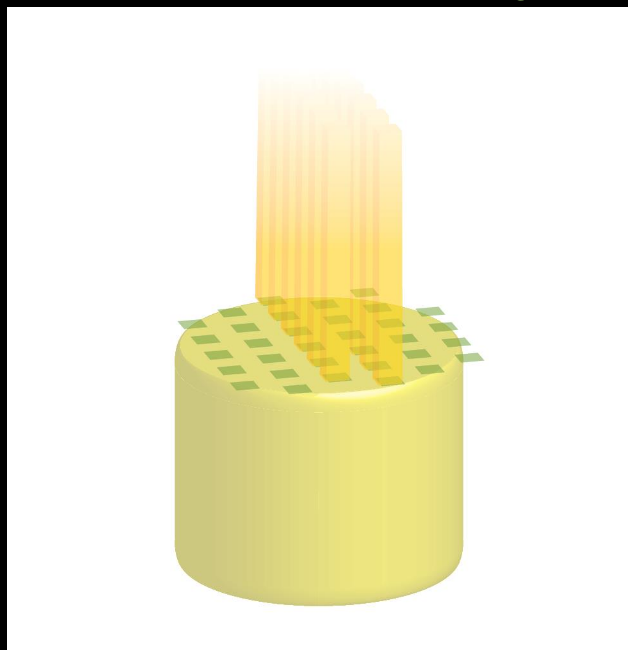
TABLE I. S

Method		
1		oam
2		masking
3		l the vertebrae
4		l the vertebrae
5		oam
6		masking
7		masking
8		masking

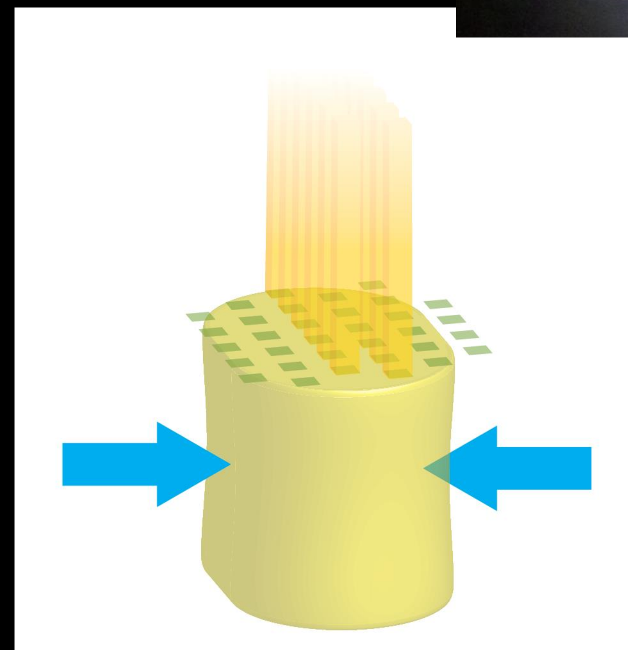


New method to validate Deformable Image Registration

Deformable 3D Presage dosimeters



Control
(No Deformation)



Deformed
(27% Lateral Compression)

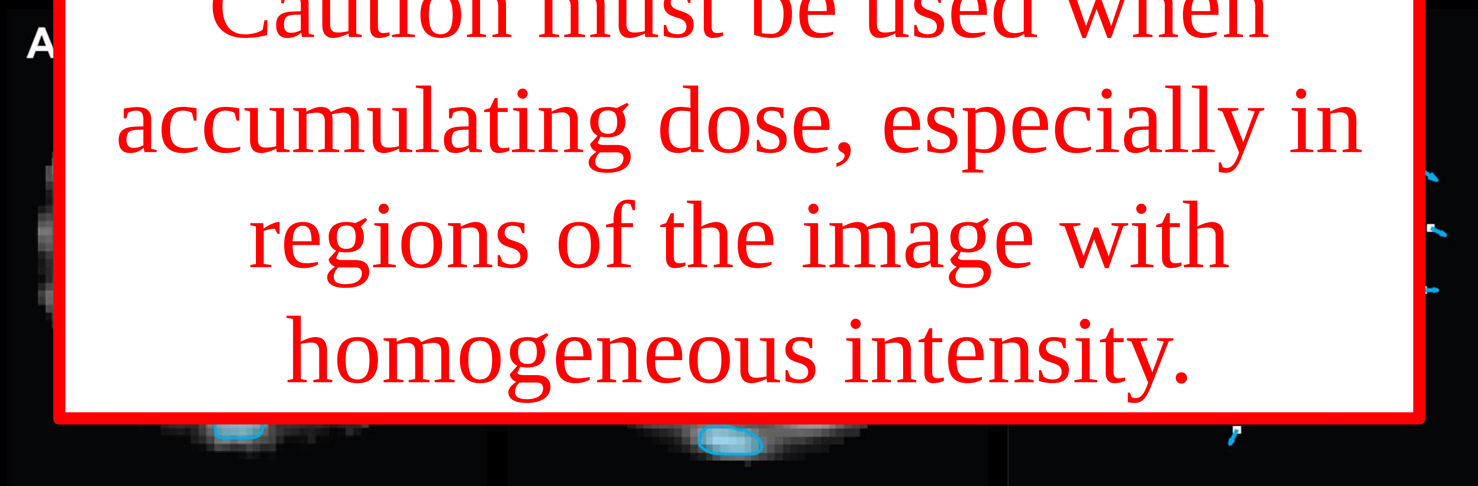
DUKE UNIVERSITY MEDICAL PHYSICS GRADUATE PROGRAM

Slides Courtesy of Mark Oldham and Shiva Das

Dosimeter & Deformable Registration-based Dose Accumulation: Dose Distributions

Field Shape Differences

DVF-based



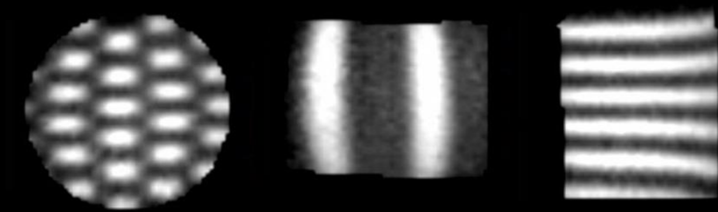
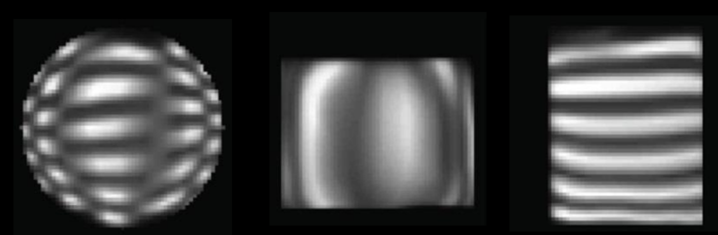
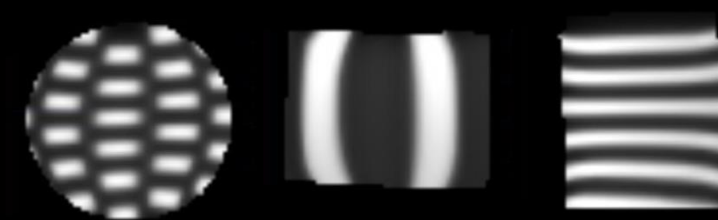
Caution must be used when accumulating dose, especially in regions of the image with homogeneous intensity.

Horizontal (Compression Axis) → 40% narrower to 175% wider

Vertical → 33% shorter to 50% taller

Slides Courtesy of Mark Oldham and Shiva Das

Different DIR Algorithms have Different Strengths and Weaknesses

Distribution	Coronal / Axial / Sagittal	3D $\gamma_{3\%/3mm}$
Measured, Optical CT		**96%[1] (control)**
DIR-predicted, Intensity-based DIR		**60%[1]**
DIR-predicted, Biomechanical Surface projection		**91%[2]**

1. Juang. IJROBP 2013;87(2): 414-421

2. M Velec ASTRO 2014

1. The subtleties in the implementation of image registration are:

0% 1. Not important

0% 2. Only important for someone who wishes to write their own algorithm

0% 3. Less important than the ability to do purple-green color blending

0% 4. Only important if it is a stand-alone image registration system

0% 5. Important to know and for commissioning as they impact the accuracy of the algorithm

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1. The subtleties in the implementation of image registration are:

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4. only important if it is a stand-alone image registration system
5. **important to know and for commissioning as they impact the accuracy of the algorithm**

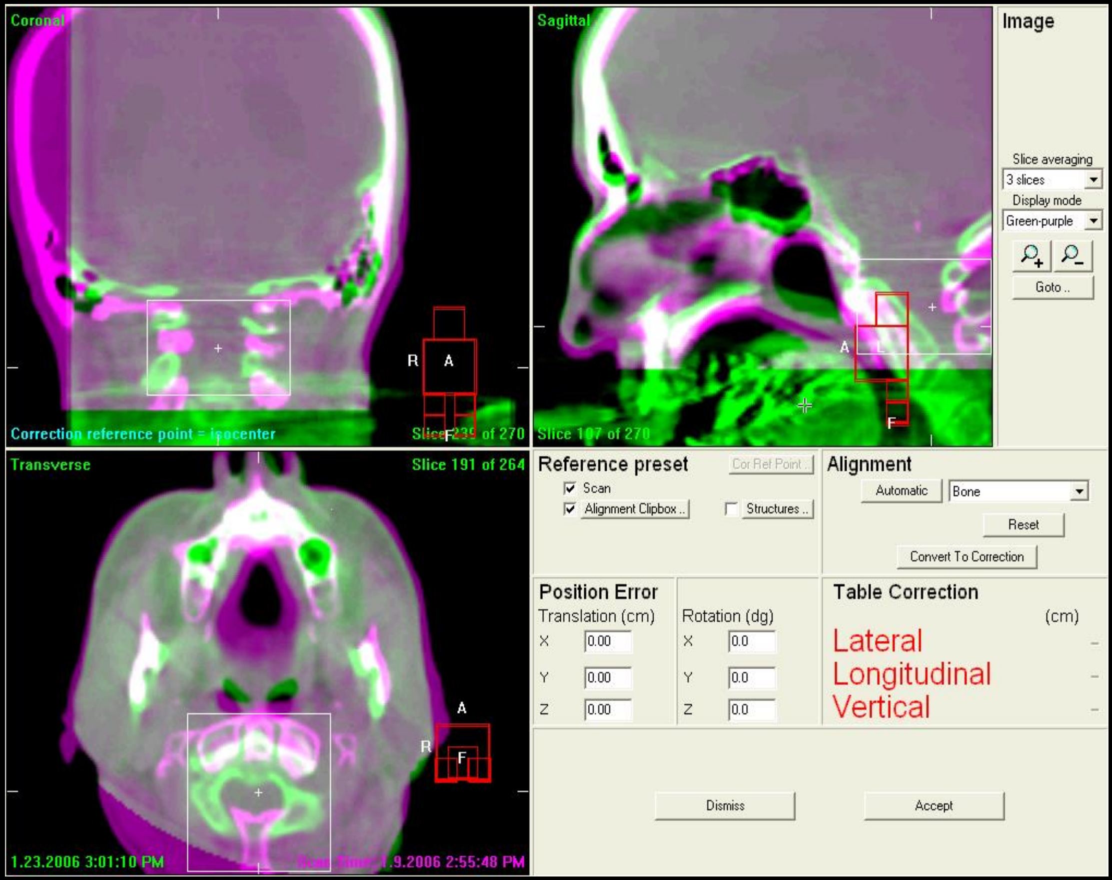
REFERENCE: Brock KK and the Deformable Registration Accuracy Consortium, Results of a multi-institution deformable registration accuracy study (MIDRAS), IJROBP, 76 (2), 583-596, 2010

Commissioning Toolbox

- What tools do we have?

Visual Verification

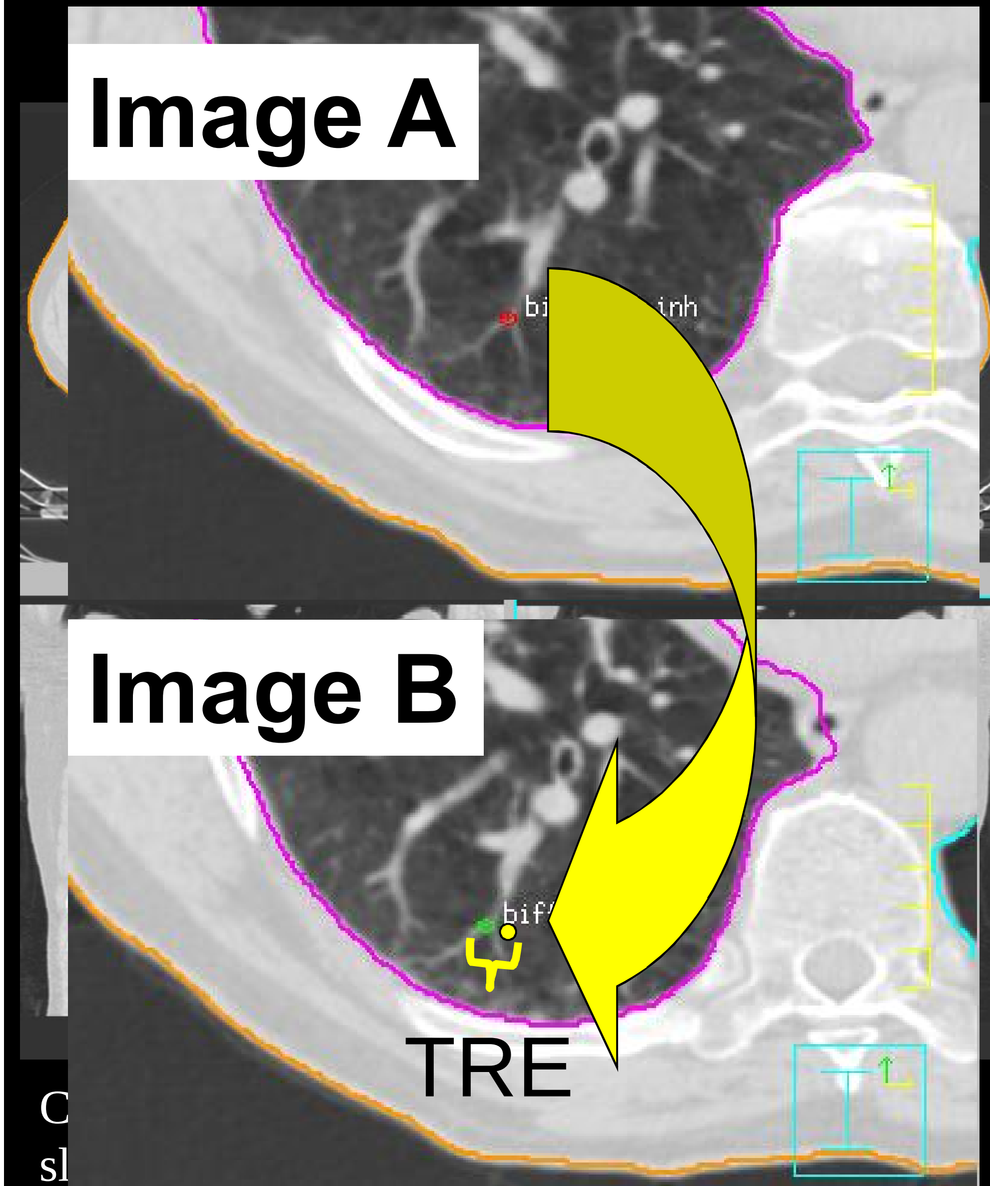
Excellent tool for established techniques
Not enough for Commissioning



Quantitative Validation Techniques

- Å Landmark Based
  - ï Does the registration map a landmark on Image A to the correct position on Image B?
  - ï Target Registration Error (TRE)
- Å Contour Based
  - ï Does the registration map the contours onto the new image correctly?
  - ï Dice Similarity Coefficient (DSC)
  - ï Mean Distance to Agreement (MDA)
- Å Digital/Physical Phantoms
  - ï Compare known motion with registration results

Landmark Based (TRE)

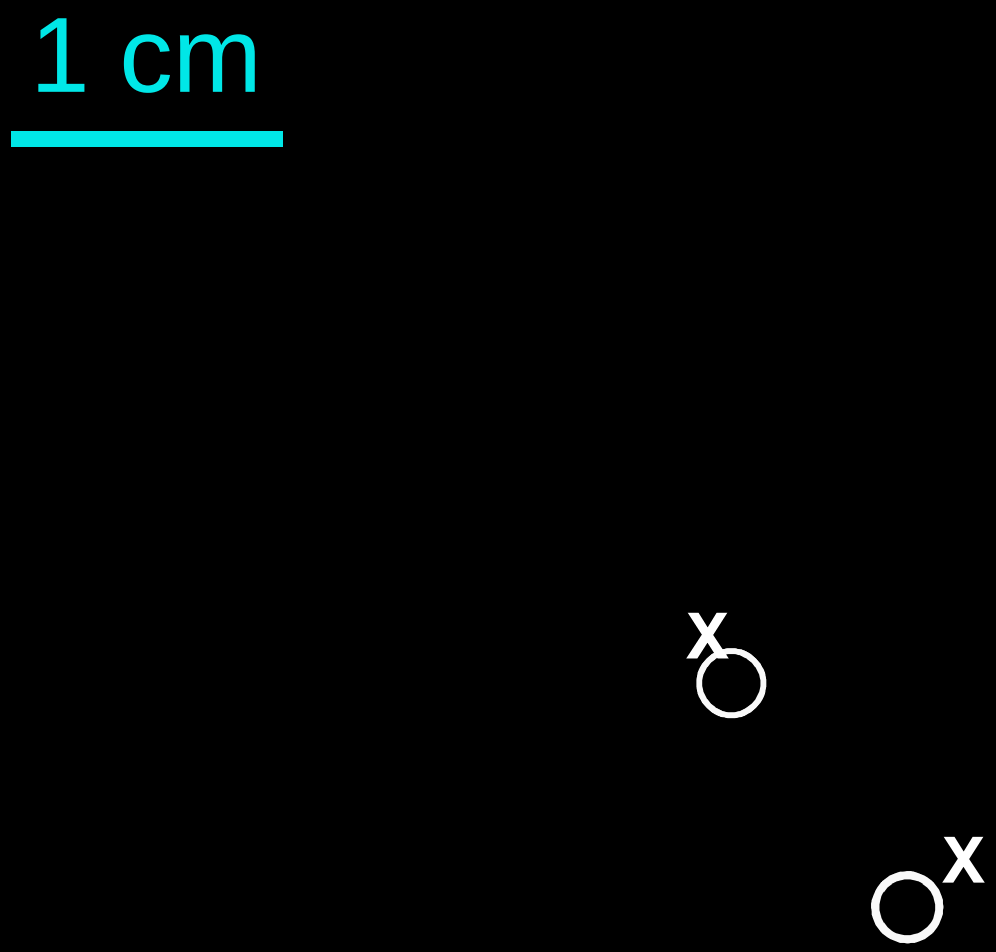


- Reproducibility of point identification is sub-voxel
  - Gross errors
  - Quantification of local accuracy within the target
  - Increasing the number increases the overall volume quantification
- Manual technique
- Can identify max errors

- Average vector distance between the points identified on Image A mapped onto Image B via the registration and the points identified on Image B = TRE

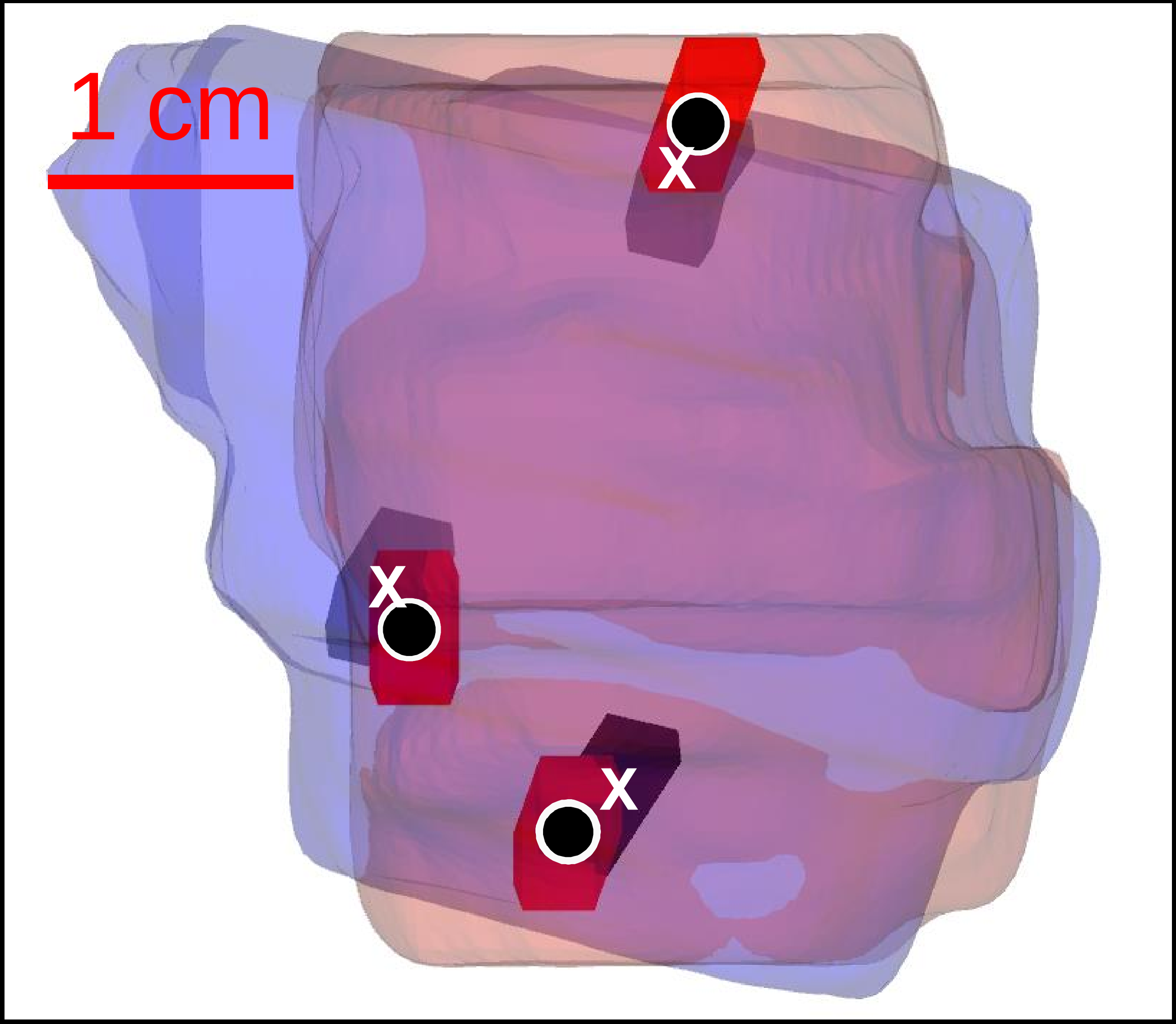
That sounds great! Is that enough?

Accuracy of Points



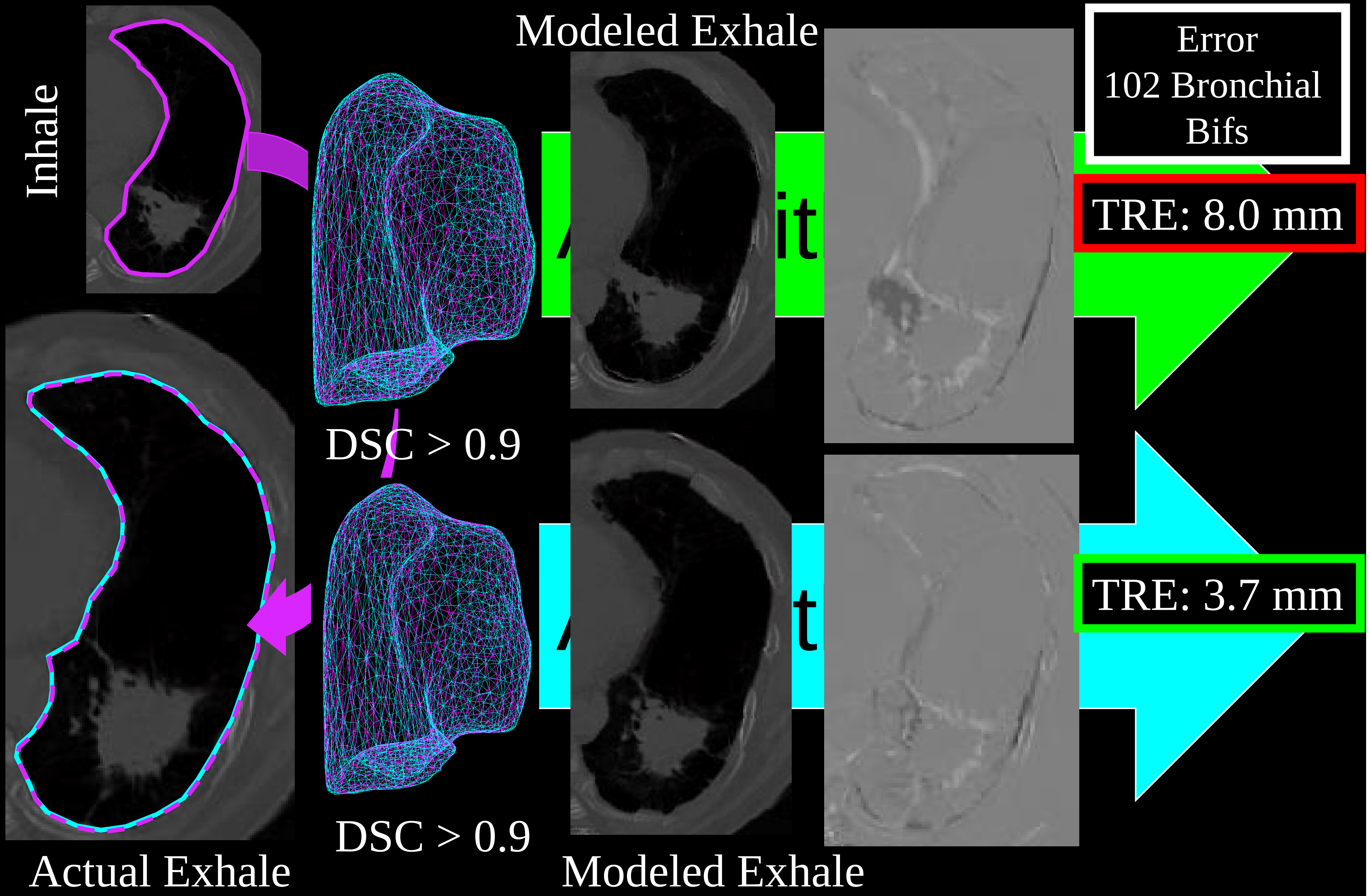
RMS = 0.3 mm

Points Donâ Tell the Whole Story



RMS = 0.3 mm

Accuracy of Contours



2. Target registration error (TRE) is defined as

20% 1. the uncertainty in selecting landmarks on an image

20% 2. the average vector distance between the points identified on Image A mapped onto Image B via the registration and the points identified on Image B

20% 3. the improvement in accuracy when using deformable registration over rigid registration

20% 4. the volume overlap of 2 contours on registered images

20% 5. the mean surface distance between 2 contours on registered images

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4. the volume overlap of 2 contours on registered images
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REFERENCE: Fitzpatrick, J.M., J.B. West, and C.R. Maurer, Jr., Predicting error in rigid-body point-based registration. IEEE Trans Med Imaging, 1998. 17(5): p. 694-702.

3. Visual verification (e.g. split screen, blended images) following image registration

20% 1. is a quick method to perform qualitative validation of image registration in a clinical workflow following the quantitative commissioning of an algorithm

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REFERENCE: REFERENCE: Kessler ML, Image Registration and Data Fusion in Radiation Therapy (Review Article), BJR 79:S99-S108 2006

4. Image registration for adaptive radiotherapy is particularly challenging because

20% 1. the images are always multi-modality

20% 2. the patient cannot be imaged in an immobilization device

20% 3. the second image must be at half-resolution

20% 4. the patient has typically responded to therapy, therefore the volume of tissue is not the same in both images

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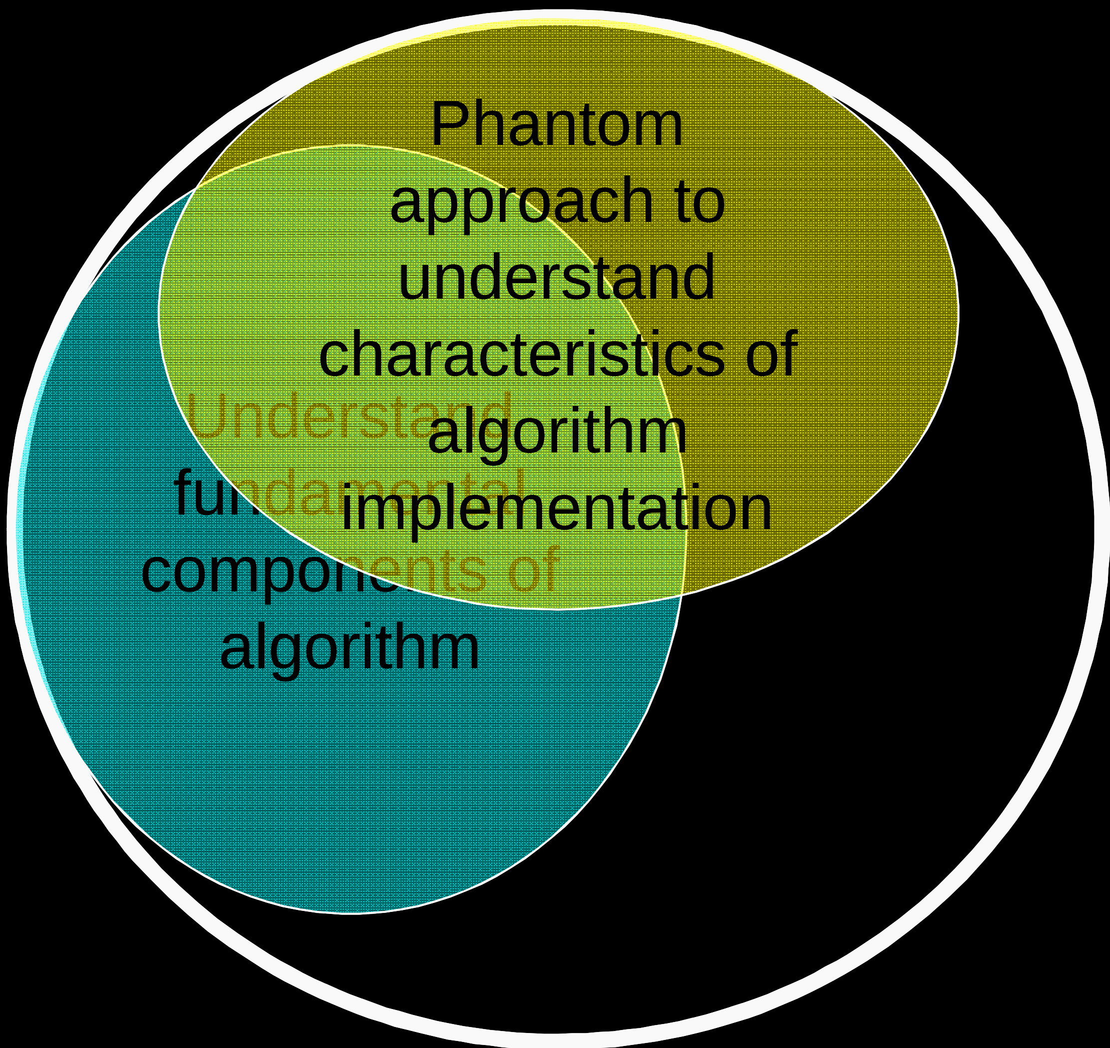
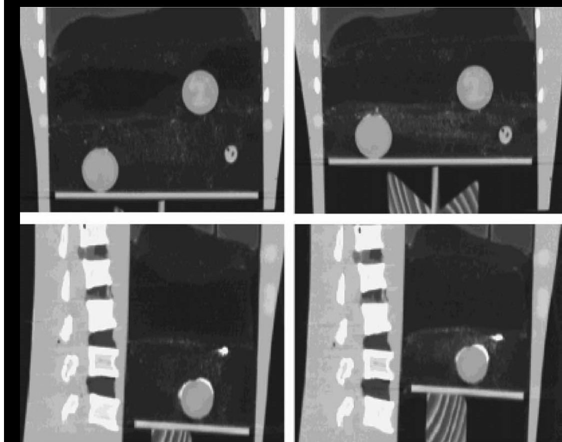
REFERENCE: Xing L, Lee, L, Timmerman R, Image-guided Adaptive Radiation Therapy and Practical Perspectives, Image-Guided and Adaptive Radiation Therapy, Lippincott Williams & Wilkins, 16-41.

Commissioning and QA

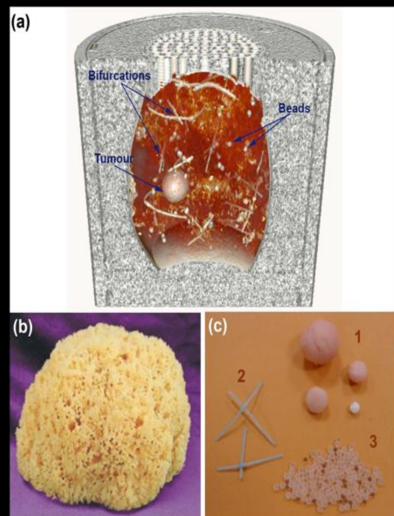
Understand the whole picture



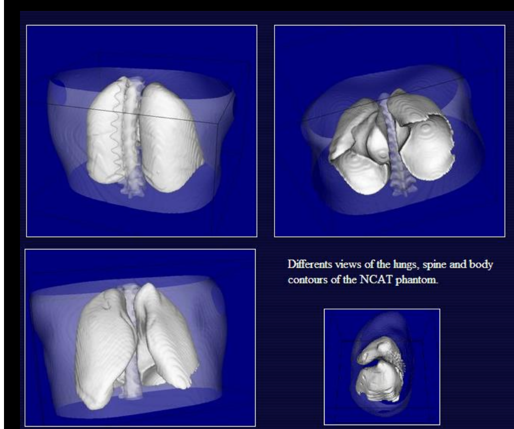
Phantoms



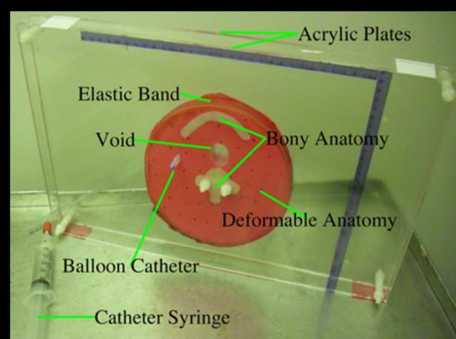
Kashani, U of M



Serban, McGill



NCAT Phantom



Pouliot, UCSF

Å Known attributes (volumes, offsets, deformations, etc.)

Å Testing standardization ï we all are using the same data

Å Helps us learn specific aspects of the algorithm that are difficult to learn on clinical data

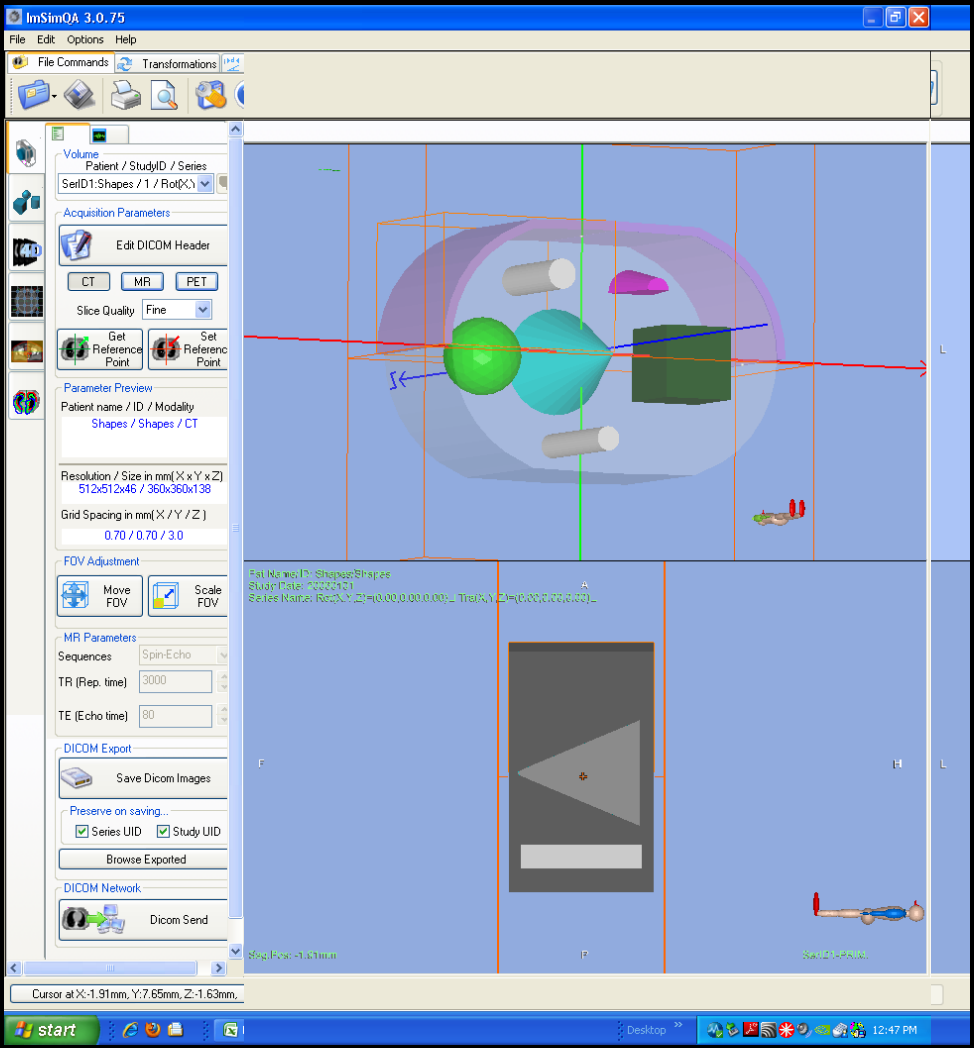
Å May not include the complexities/noise of clinical images

Rigid Geometric Data

Å Helps us to learn the impact of the ðknobsô of the registration

Å Validation of most straightforward case

Å Similar to 20x20 field profile



* Phantom Courtesy of ImSim QA, TG-132* pending AAPM approval

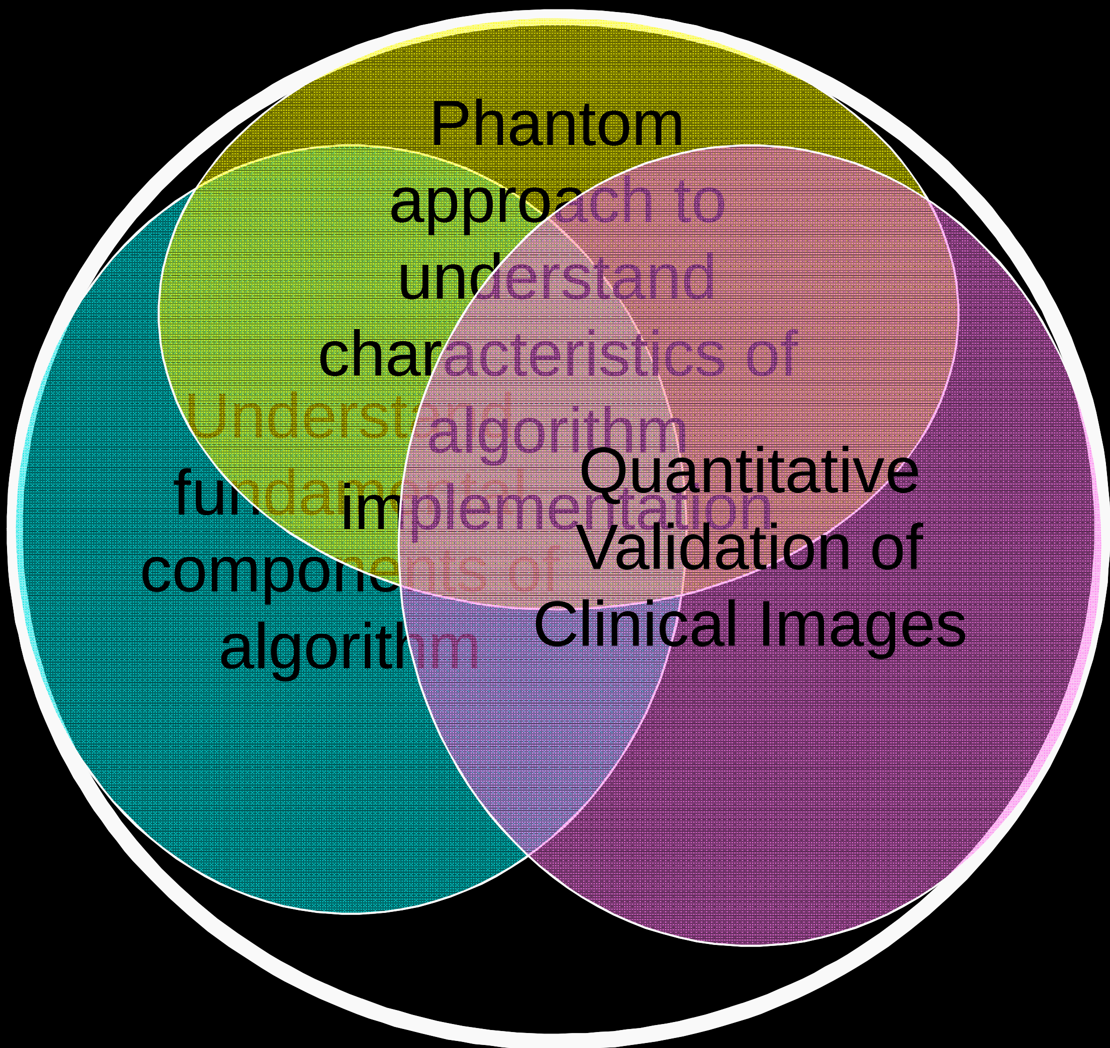
Example Commissioning Tests

KKB204 - Geometric Phantom Registration

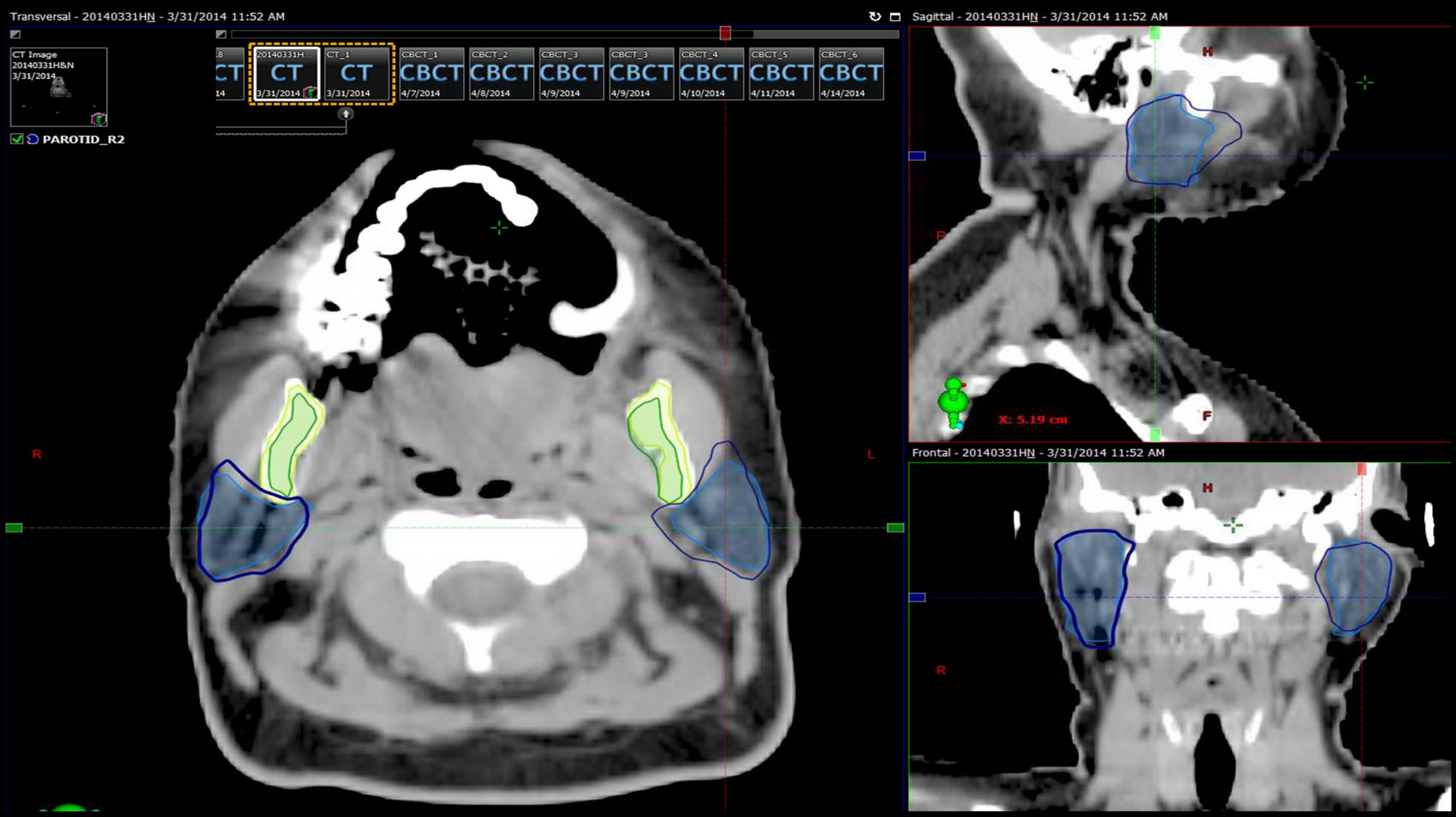
		AP	SI
Offset to Primary	**dx**	**dy**	**dz**
Defined	**-10**	**5**	**-15**
default, entire FOV	-10	5.1	-12.9
default, entire FOV	-9.9	4.5	-13.5
default, entire FOV	-10	4.9	-14.1
default, entire FOV	-10	5.2	-13.8
default, entire FOV	-8.3	4.4	-13.6
AVG	-9.64	4.82	-13.58
SD	0.75	0.36	0.44
AVG Deviation from Defined Offset	0.36	-0.18	1.42
Offset to Primary	**dx**	**dy**	**dz**
Defined	**-10**	**5**	**-15**
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15
User Defined (4th step with 1 mm resolution), entire FOV	-10	4.9	-15
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15
AVG	-10	4.98	-15
SD	0.00	0.04	0.00
AVG Deviation from Defined Offset	0	-0.02	0

Commissioning and QA

Understand the whole picture



DSC Evaluation on CT-CT DIR

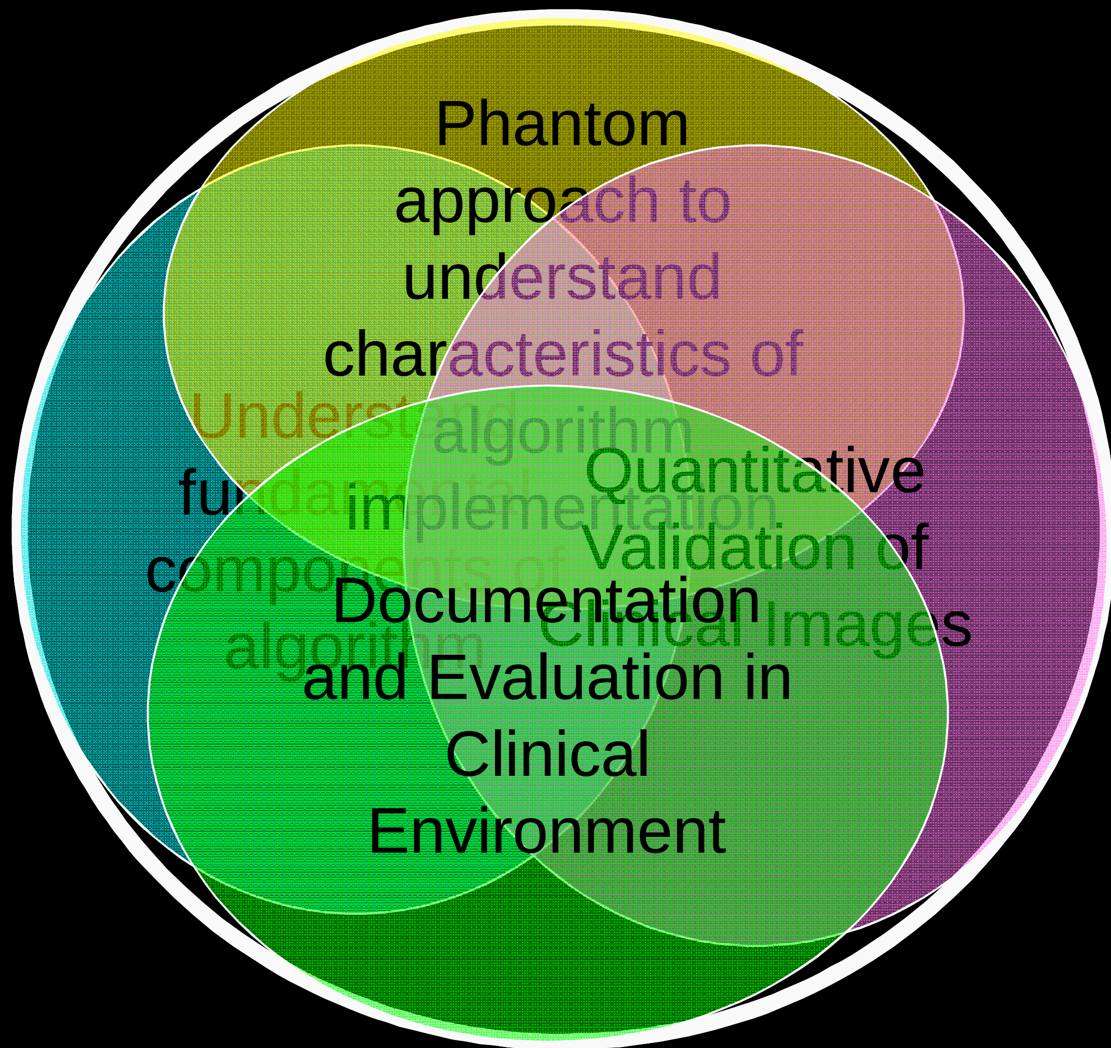


Data from 4 Clinical Cases

HN1002_REDO	DSC	DSC	DSC	DSC	AVG DSC
ORAL_CAVITY1	0.78	0.85	0.89	0.89	0.85
SUBMAND_R1	0.67	0.97		0.82	0.82
CORD_PRV6	0.72	0.86		0.81	0.80
SUBMAND_L1	0.67		0.97	0.74	0.79
PAROTID_R1	0.76	0.84	0.74	0.76	0.77
BRAINSTEM1	0.74	0.89	0.81	0.58	0.76
LARYNX1	0.68		0.86	0.69	0.74
MANDIBLE1	0.80	0.68	0.67		0.71
PAROTID_L1	0.61	0.81	0.65	0.74	0.70
ESOPHAGUS1	0.71	0.62	0.73	0.71	0.69
CORD1	0.59	0.74	0.69	0.66	0.67
COCHLEA_L1	1.00	0.43	0.28	0.68	0.60
CONSTRICTOR_SUP1	0.29	0.85	0.52	0.65	0.58
LIPS1	0.60	0.54	0.67	0.37	0.54
CONSTRICTOR_INF1	0.13	0.50	0.42	0.60	0.41
COCHLEA_R1		0.18	0.34	0.06	0.19

Commissioning and QA

Understand the whole picture



Patient-Specific Clinical Evaluation

- Multi-disciplinary education on information learned from commissioning
- Know the visual tools available in clinical system
- Develop procedure to do efficient quantitative evaluation when needed
- Documentation!

Example Implementation

Å Integrate with another document

 ï Included in the Simulation Directive

Å Use drop-downs and check boxes

Å Include visuals when helpful

Imaging and Registration

Primary Imaging:

CT **ABC:** ☐ Yes ☐ No

Secondary Imaging: ☒ MRI Date: MRI sim from perfusion protocol

Series: Images:

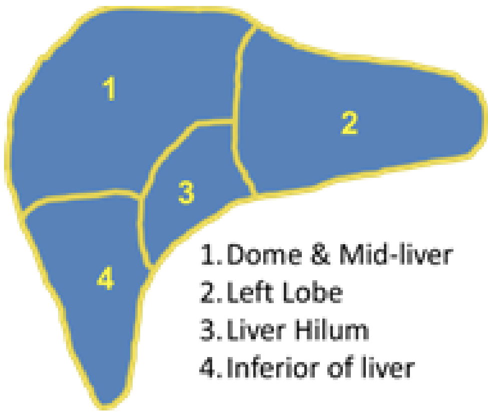
Registration Technique: ☒ Rigid ☐ Deformable

Local Region of Importance: 3 (Hepatic Duct) Comments:

Intended use of Registered Images:

☒ Tumor Definition ☐ Normal Tissue Definition

☐ Treatment Adaptation

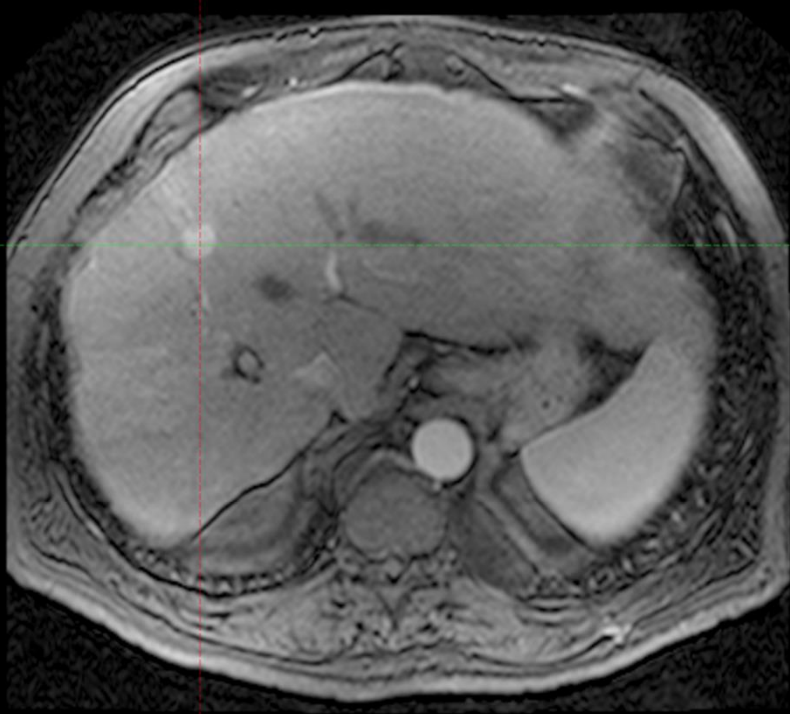


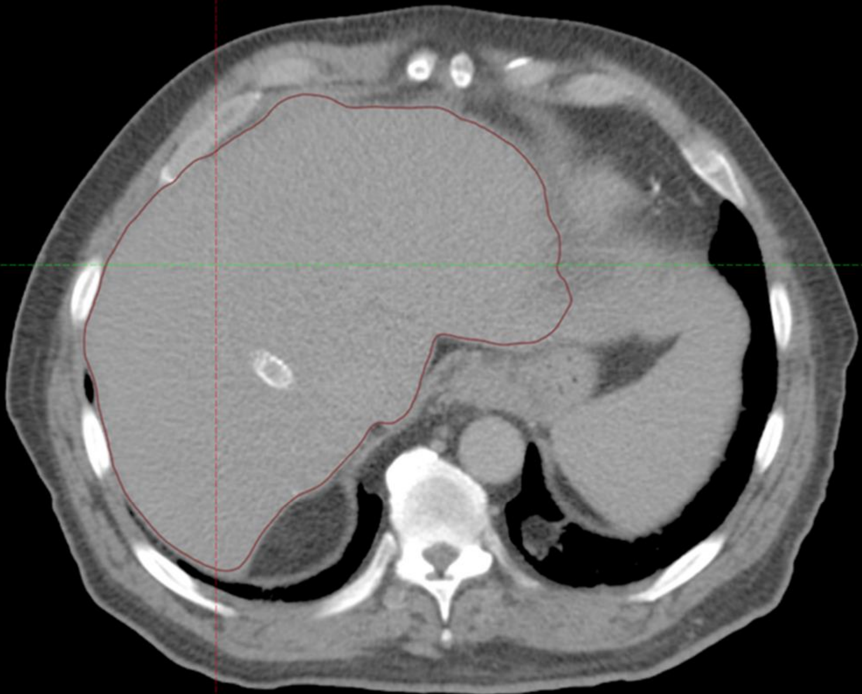
Uncertainty Assessment	Phrase	Description
0	Whole scan aligned	- Anatomy within 1 mm everywhere - Useful for structure definition everywhere - Ok for stereotactic localization
1	Locally aligned	- Anatomy local to the area of interest is un-distorted and aligned within 1mm - Useful for structure definition 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)

Preliminary (not yet approved by AAPM) Recommendations from TG 132

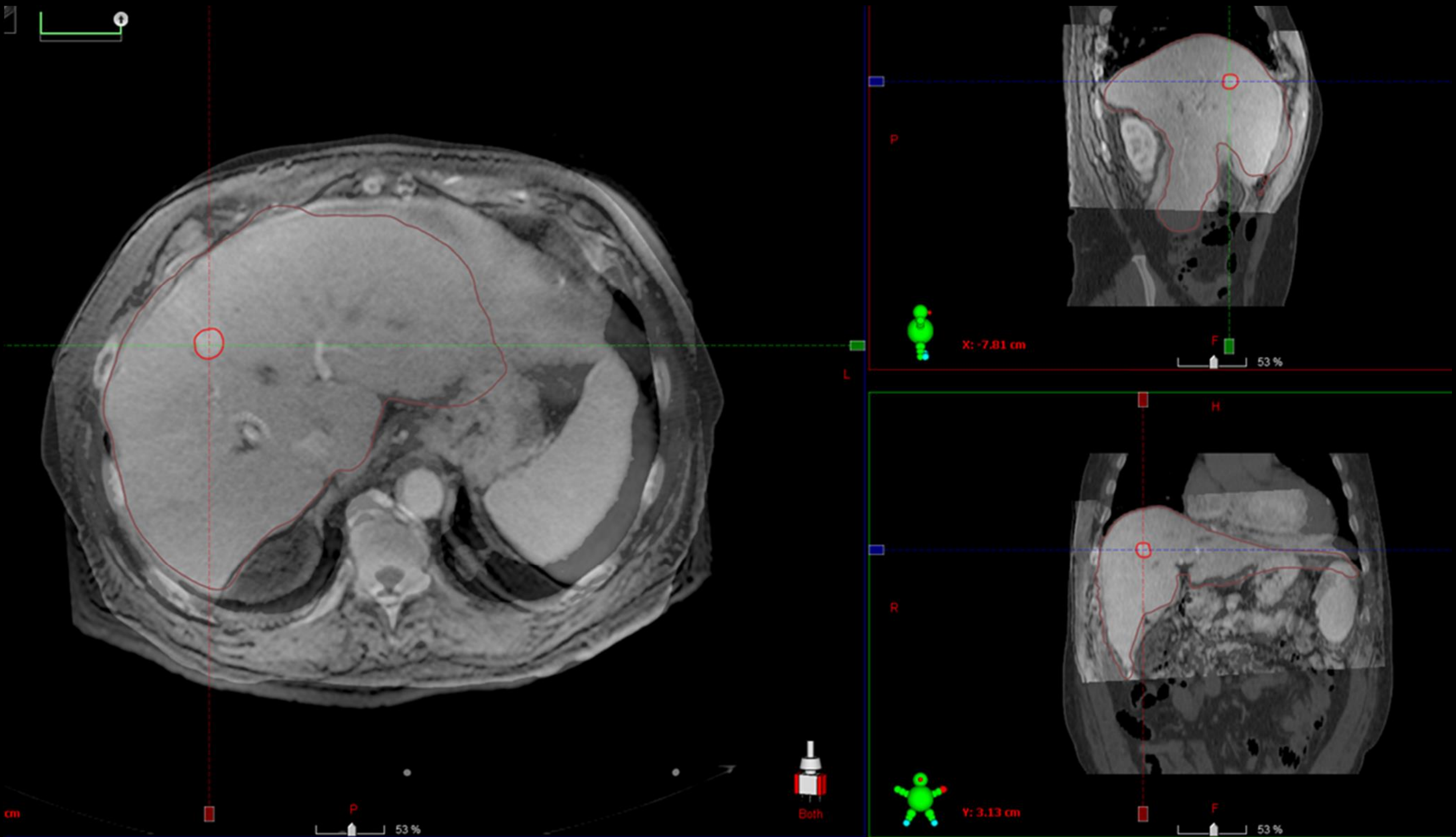
Example: Multi-modality imaging for Planning

Liver: CT (No Contrast = No visible GTV)





Liver: MR (Visible GTV)



Uncertainty Level: 2

Difficult to assess local accuracy, boundaries appear to match in local region

Deformation is clear

Summary

Å Deformable registration is a complex model

  ï Must understand the fundamentals of the model

  ï Commission and Validate the algorithm prior to clinical implementation

Å Translation of geometric uncertainties to dosimetric error is complex and depends on complexity of motion and image intensity variation in the region

Å Implementation of adaptive RT requires multi-disciplinary teamwork

Å Physicists play a critical role in adaptive RT and communicating the right information to the right person in the right way is key