Clinical Implementation and Commissioning of Deformable Registration for Treatment Planning

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Medical School

Disclosure

- Personal: RaySearch Licensing Agreement
- UM: Research and Development Agreement with Varian Medical Systems

- Chair, AAPM TG 132 – Image Registration and Fusion

Learning Objectives

1. Highlight the importance of understanding the image registration techniques used in their clinic.
2. Describe the end-to-end tests needed for stand-alone registration systems.
3. Illustrate a comprehensive commissioning program using both phantom data and clinical images.
4. Describe a request and report system to ensure communication and documentation.
5. Demonstrate an clinically-efficient patient QA practice for efficient evaluation of image registration.

Clinical Recommendations (1/2)

1. Understand the basic image registration techniques and methods of visualizing image fusion
2. Understand the basic components of the registration algorithm used clinically to ensure its proper use
3. Perform end-to-end tests of imaging, registration, and planning/treatment systems if image registration is performed on a stand-alone system

Clinical Recommendations (2/2)

4. Perform comprehensive commissioning of image registration using the provided digital phantom data (or similar data) as well as clinical data from the user's institution
    1. Estimation of registration error should be assessed using a combination of the quantitative and qualitative evaluation tools. Estimated errors in the area of the relevant anatomy exceeding 1-2 voxels should be accounted for in the uncertainty margins used.
5. Develop a request and report system to ensure communication and documentation between all users of image registration
6. Establish a patient specific QA practice for efficient evaluation of image registration results

1. Understand the basic image registration techniques and methods of visualizing image fusion

How?

- TG report has basic information and references
- AAPM Virtual Library
- Several books and review papers

Why? Many Image Registration Techniques

Metric	Transformation	Optimization
Your Eye		Brain-power
Least Squares (Poi	Rotation	Simplex
Chamfer Matching (surface matchi	tion	Gradient descent
Contour matching	g)	etc…
Mean Square Di	in	
Correlation		
Mutual Information	anical	

Quick, Easy, local

Surface-based

Manual or auto-segmentation

Great for 4D CT

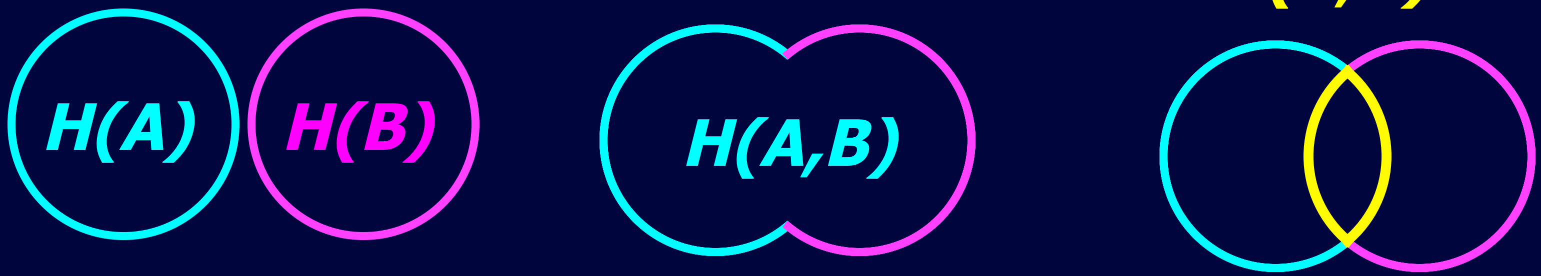
Good for same modality (x-ray), different contrast/noise (CECT, CT, CBCT)

Works for Multi-Modality

Mutual Information

- Maximise the mutual information

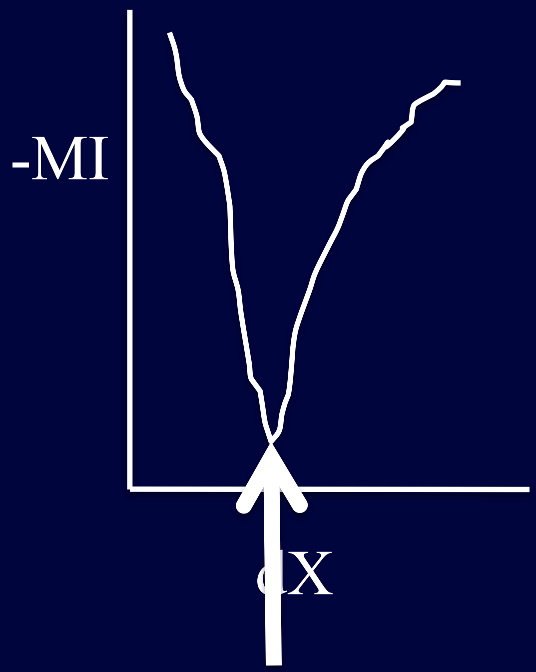
Marginal Entropies | **Joint Entropy** | **Mutual Information, *I(A,B)***



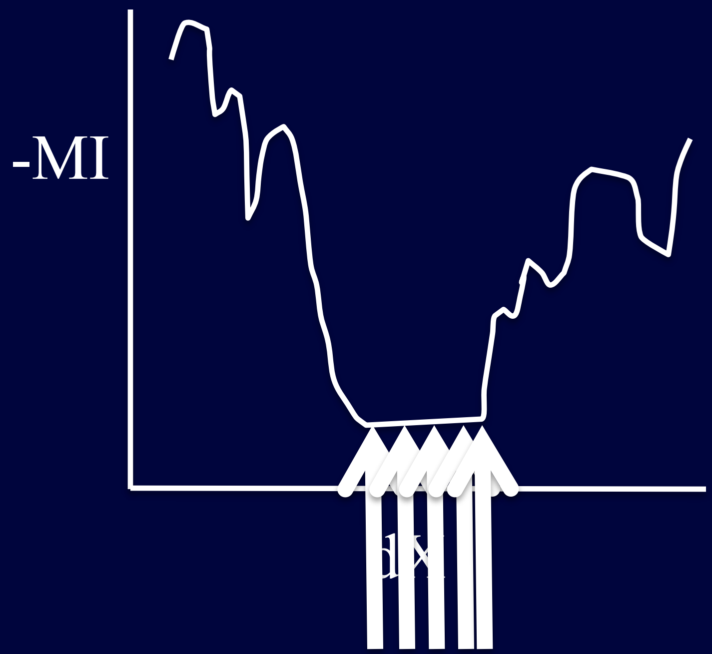
- Sensitivity of results: Vary the vector field and evaluate the change in similarity metric
  - Hub, et. al., IEEE TMI 2009

How Reliable is the Max MI?

- Actually, min -MI



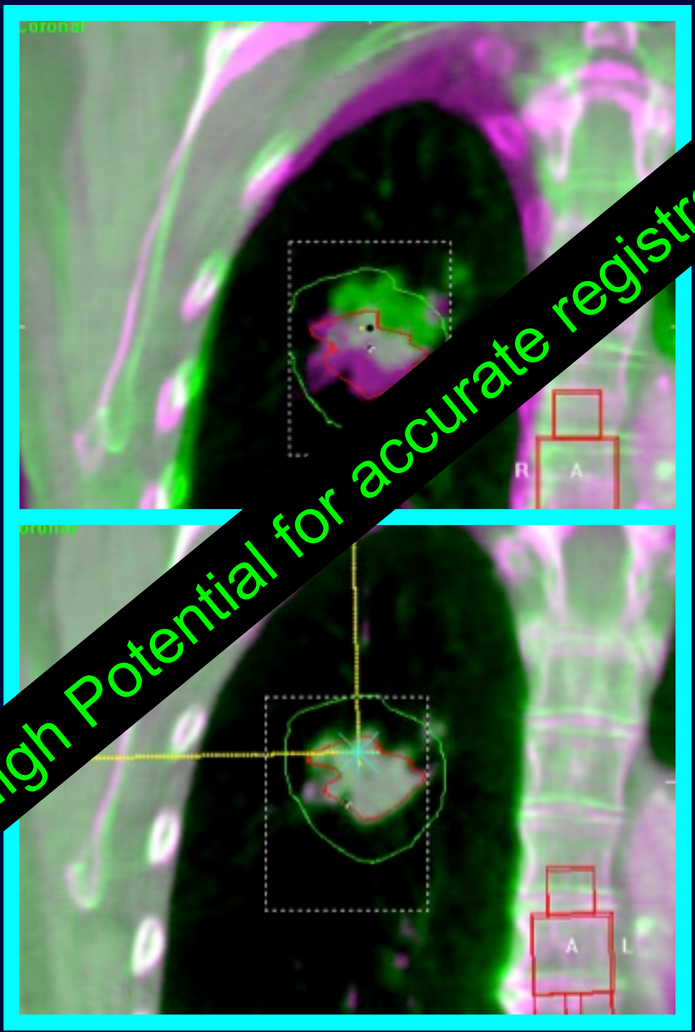
Min –MI
Best Solution



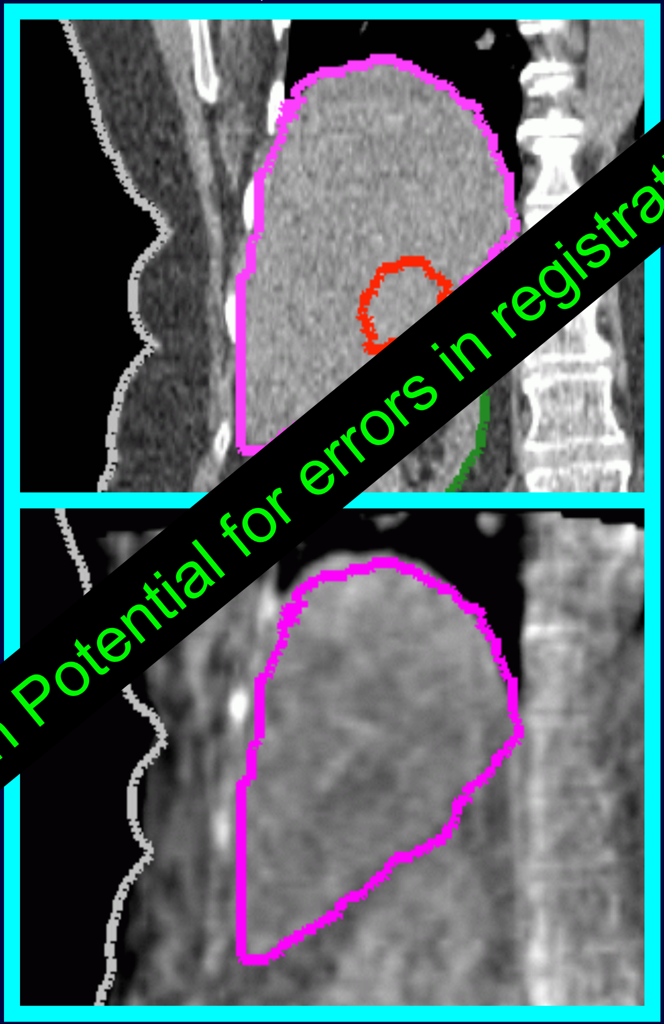
Min –MI
Best Solution

Intensity Variation: Impact on CC/MSD

Clear intensity variation

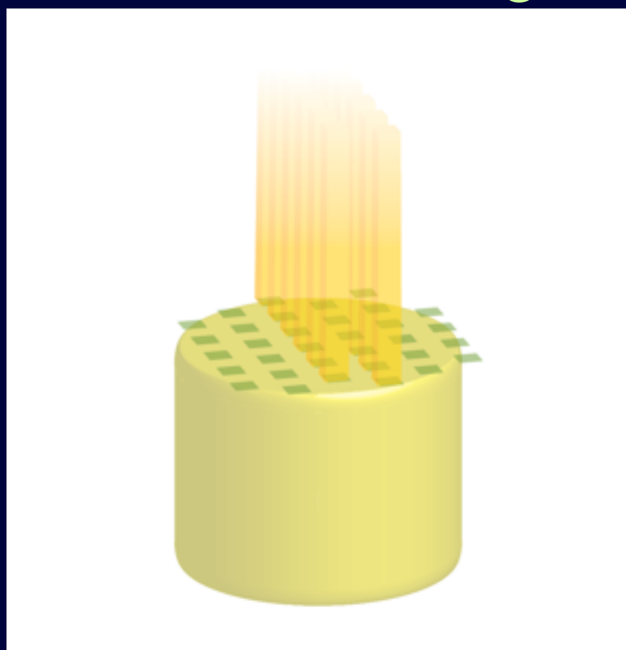


No relevant intensity variation, noise/artifact

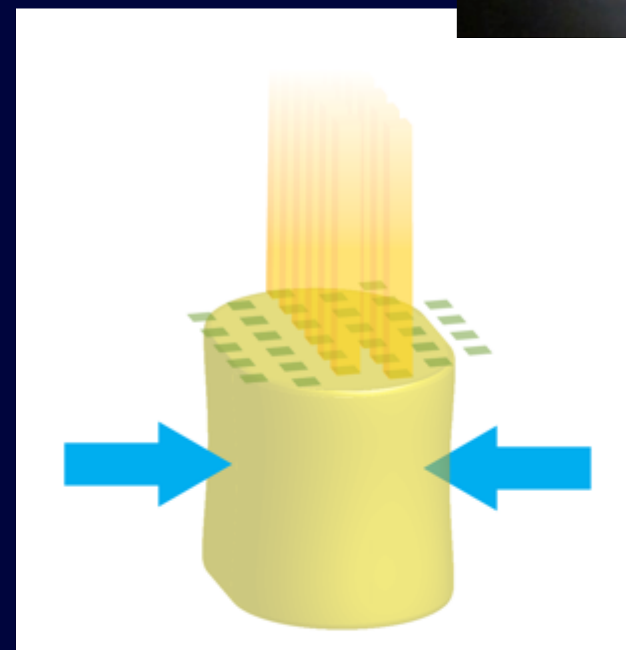


New method to validate Deformable Image Registration

Deformable 3D Presage dosimeters



Control
(No Deformation)



Deformed
(27% Lateral Compression)

DUKE UNIVERSITY MEDICAL PHYSICS GRADUATE PROGRAM

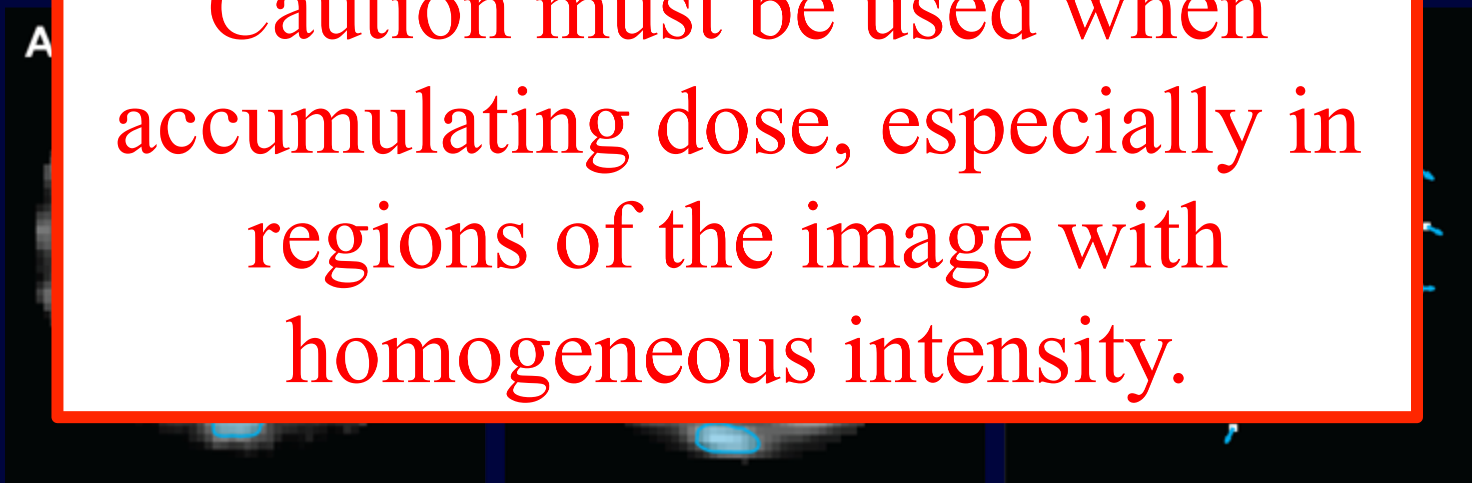
Slides Courtesy of Mark Oldham and Shiva Das

Dosimeter & Deformable Registration-based Dose Accumulation: Dose Distributions

Field Shape Differences

DVF-based

De **nts**



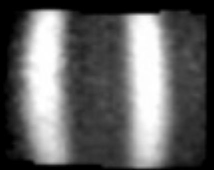
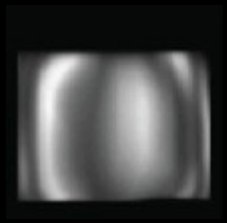
Caution must be used when accumulating dose, especially in regions of the image with homogeneous intensity.

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, et al, PRO, 2015

2. Understand the basic components of the registration algorithm used clinically to ensure its proper use

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 do we need to know the implementation?

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

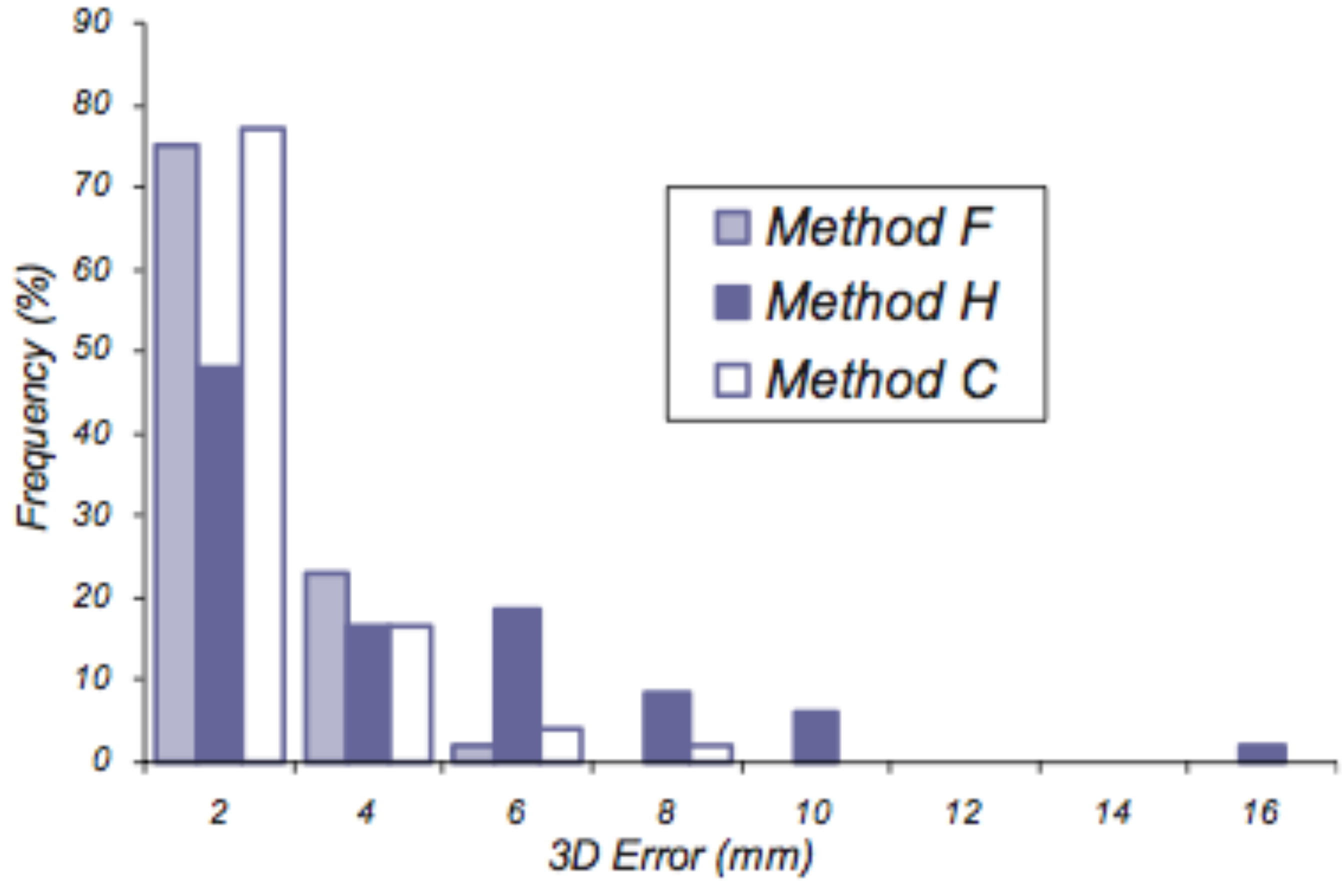
Med Phys 2008

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

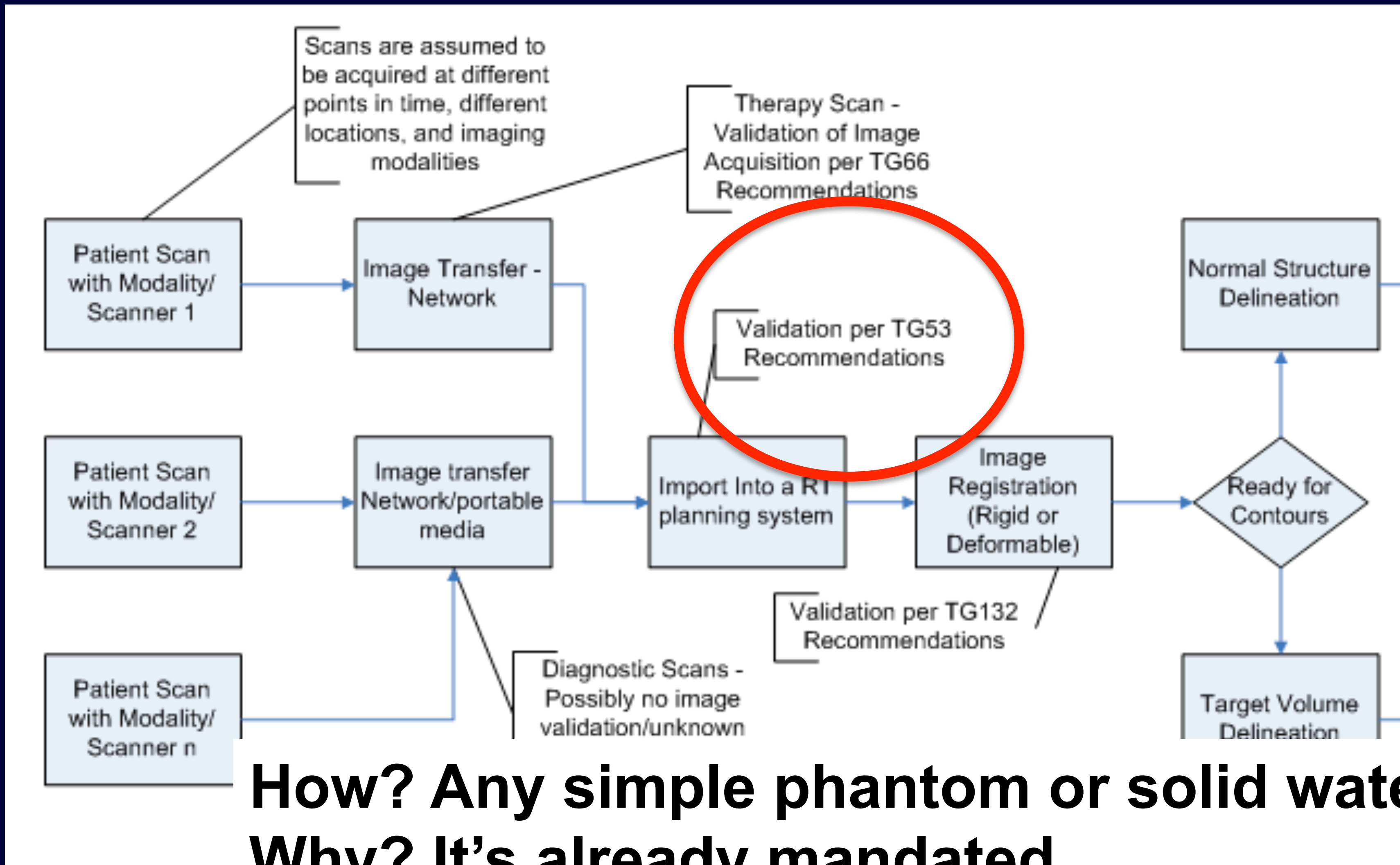
TABLE I. Summary of registration methods and references.

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

Method (k	$d_k^{\max}$ 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



3. Perform end-to-end tests of imaging, registration, and planning/treatment systems if image registration is performed on a stand-alone system



How? Any simple phantom or solid water
Why? It's already mandated

4. Perform comprehensive commissioning of image registration using the provided digital phantom data (or similar data) as well as clinical data from the user’s institution

Why? Commissioning is Important!

- 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**

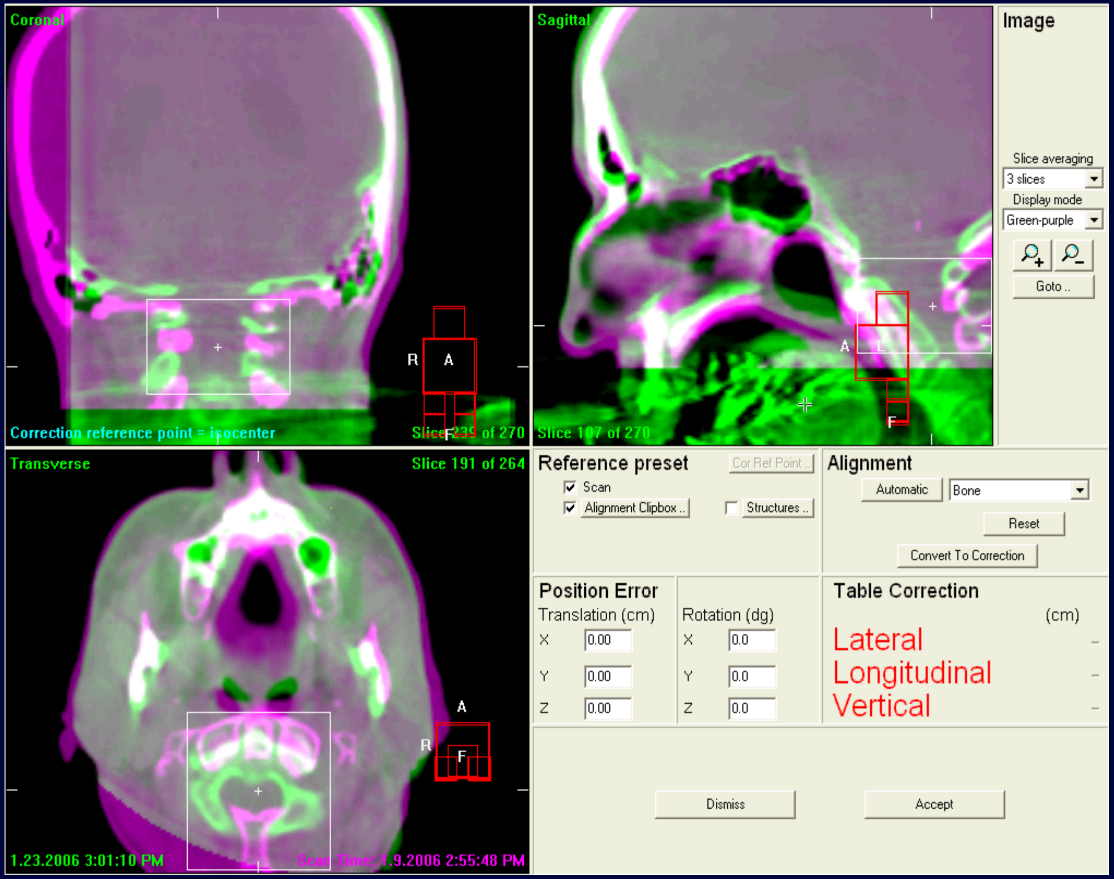
How do we do it?

- What tools do we have?

Visual Verification

Excellent tool for established techniques

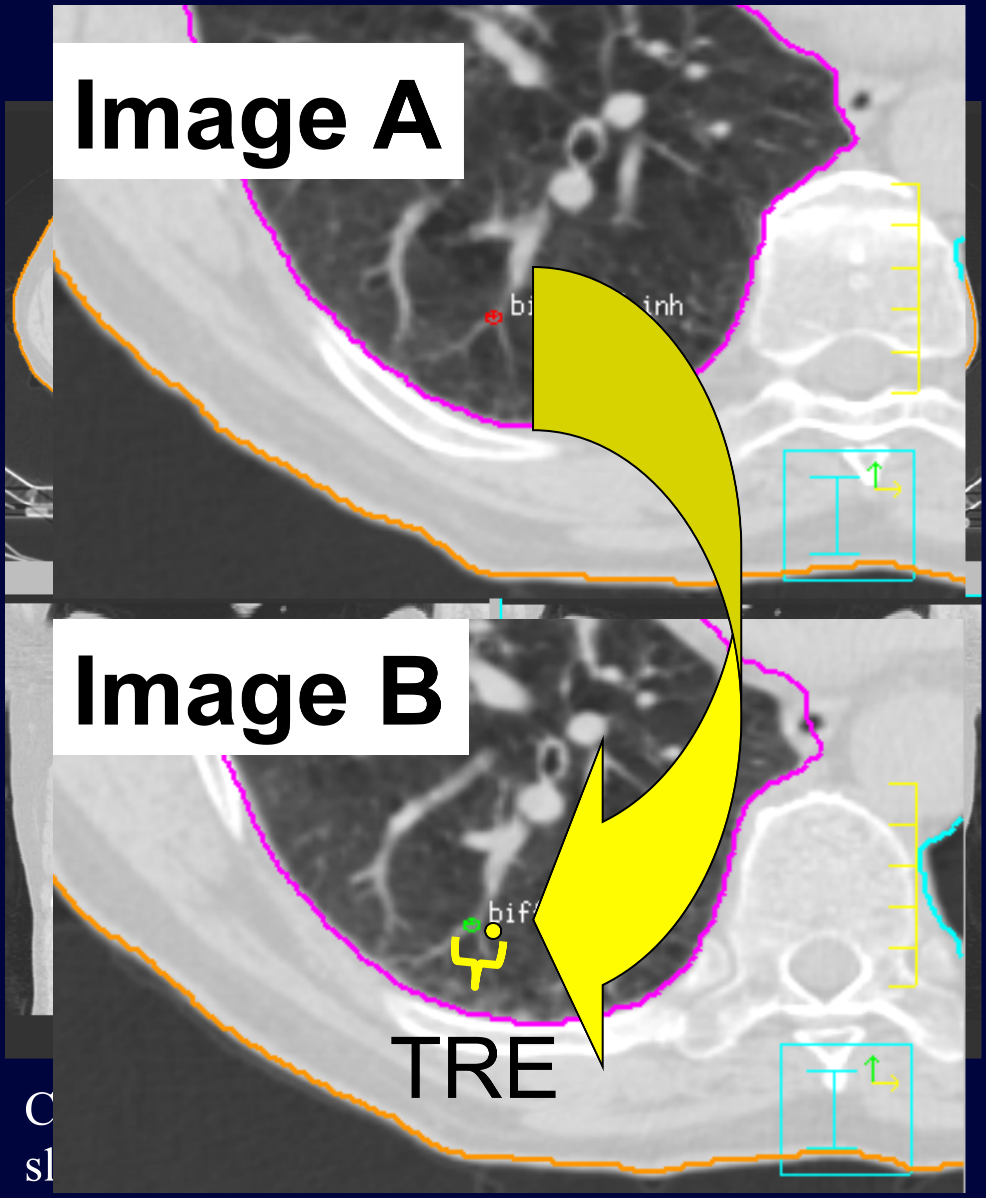
Not enough for Commissioning



Quantitative Validation Techniques

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

Landmark Based (TRE)

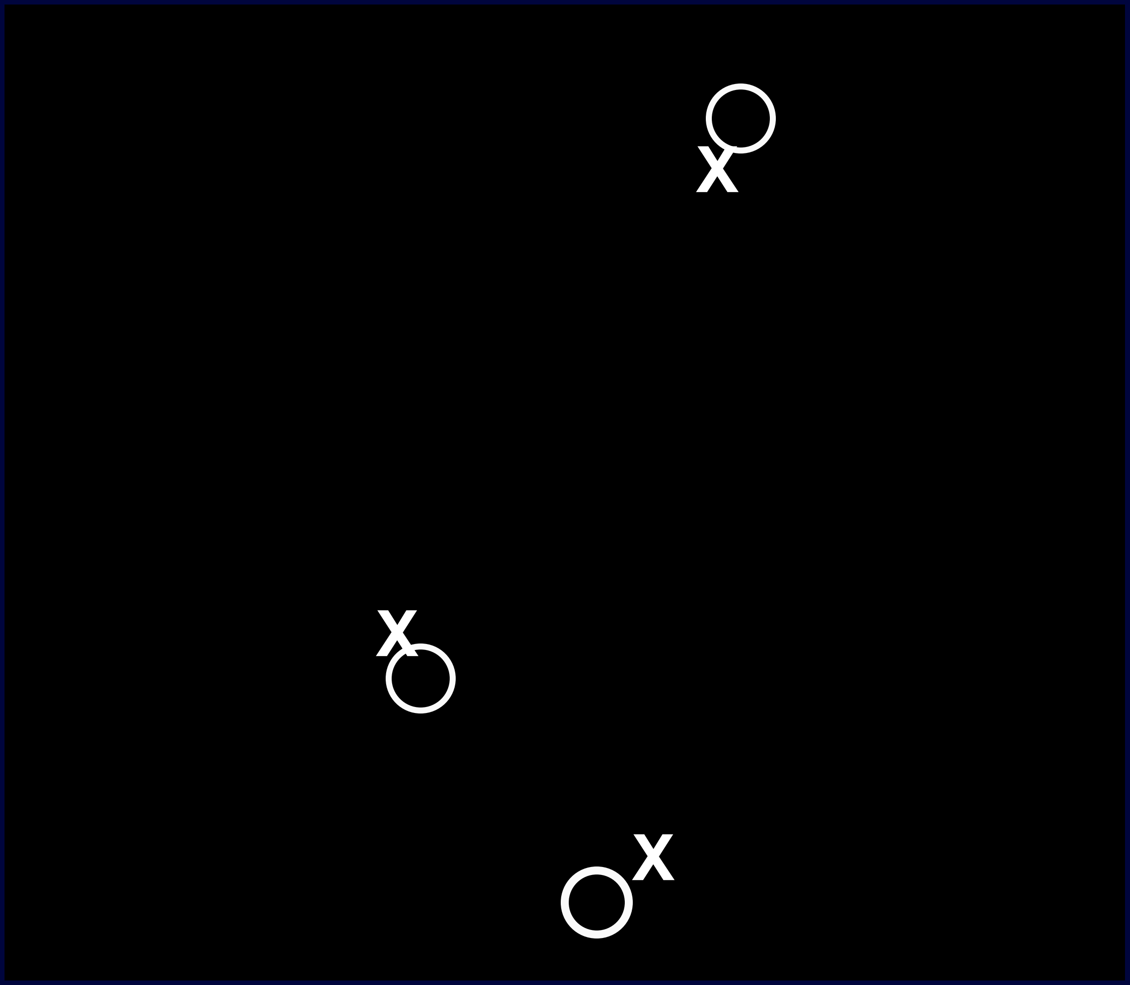


- Reproducibility of point identification is sub-voxel
  - Gross errors
  - Quantification of local accuracy within the target
  - Increasing the number increases the overall volume quantification
- Manual technique
- Can identify max errors
- Average vector distance between the points identified on Image A mapped onto Image B via the registration and the points identified on Image B = TRE

That sounds great! Is that enough?

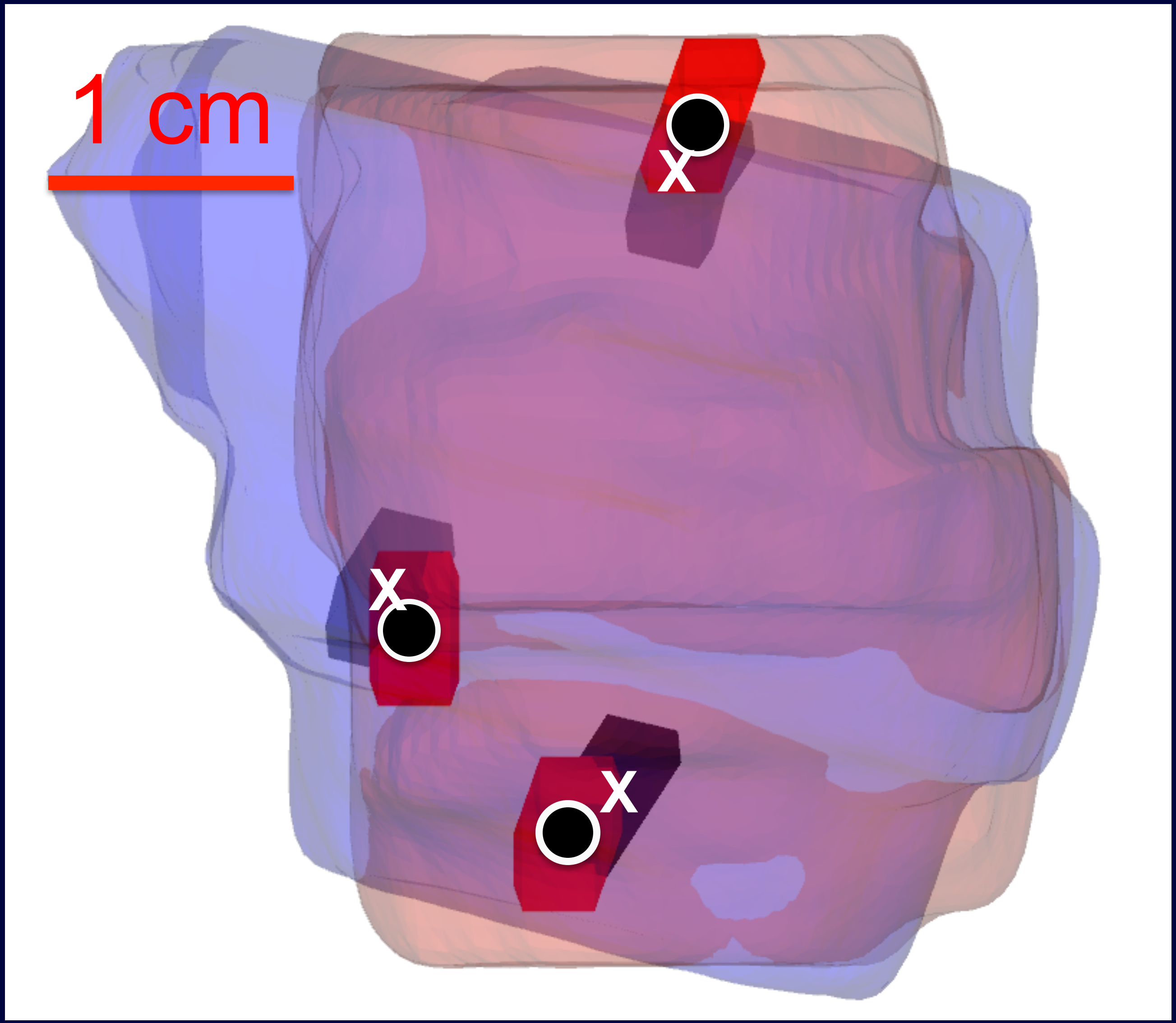
Accuracy of Points

1 cm

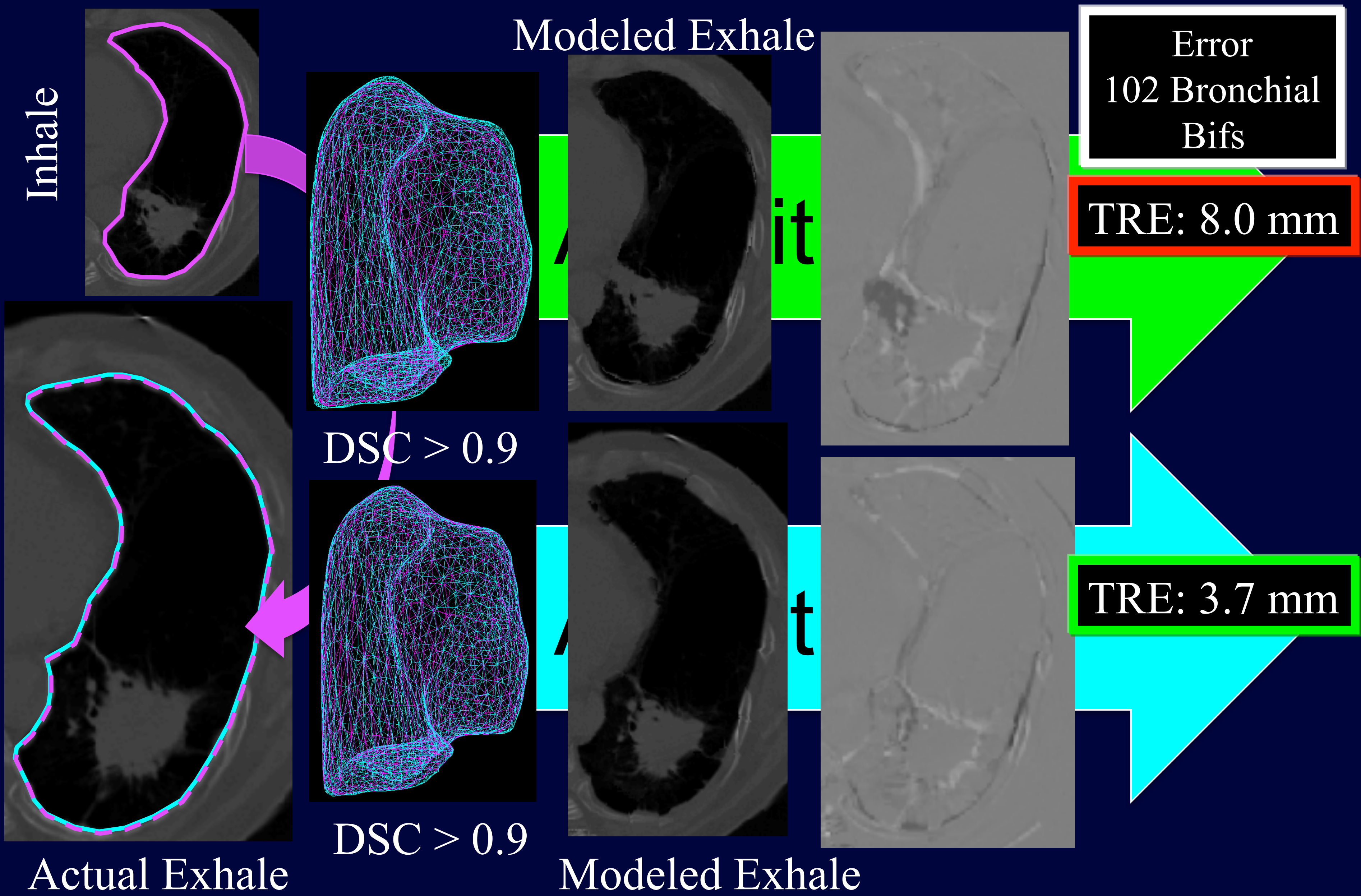


RMS = 0.3 mm

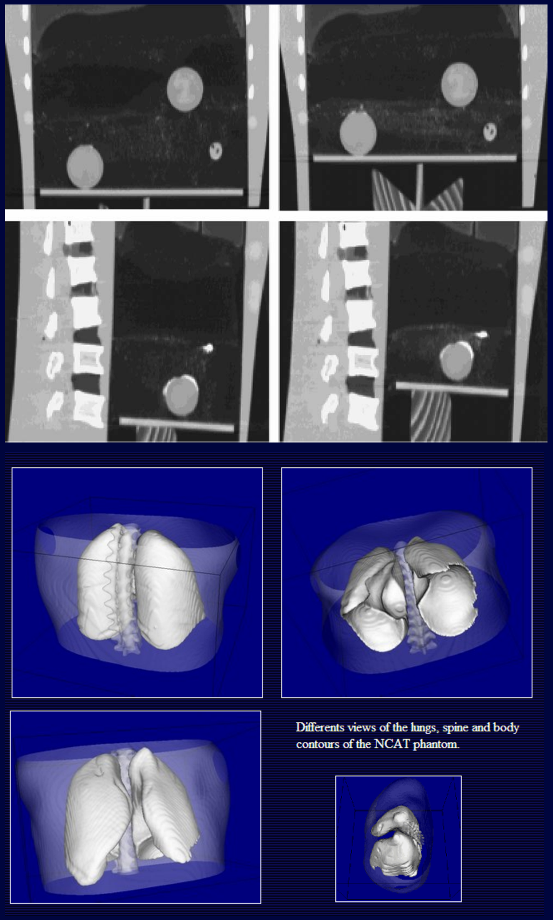
Points Don't Tell the Whole Story

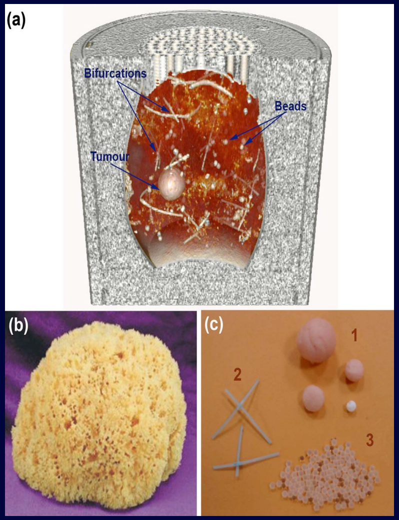


Accuracy of Contours



Phantoms

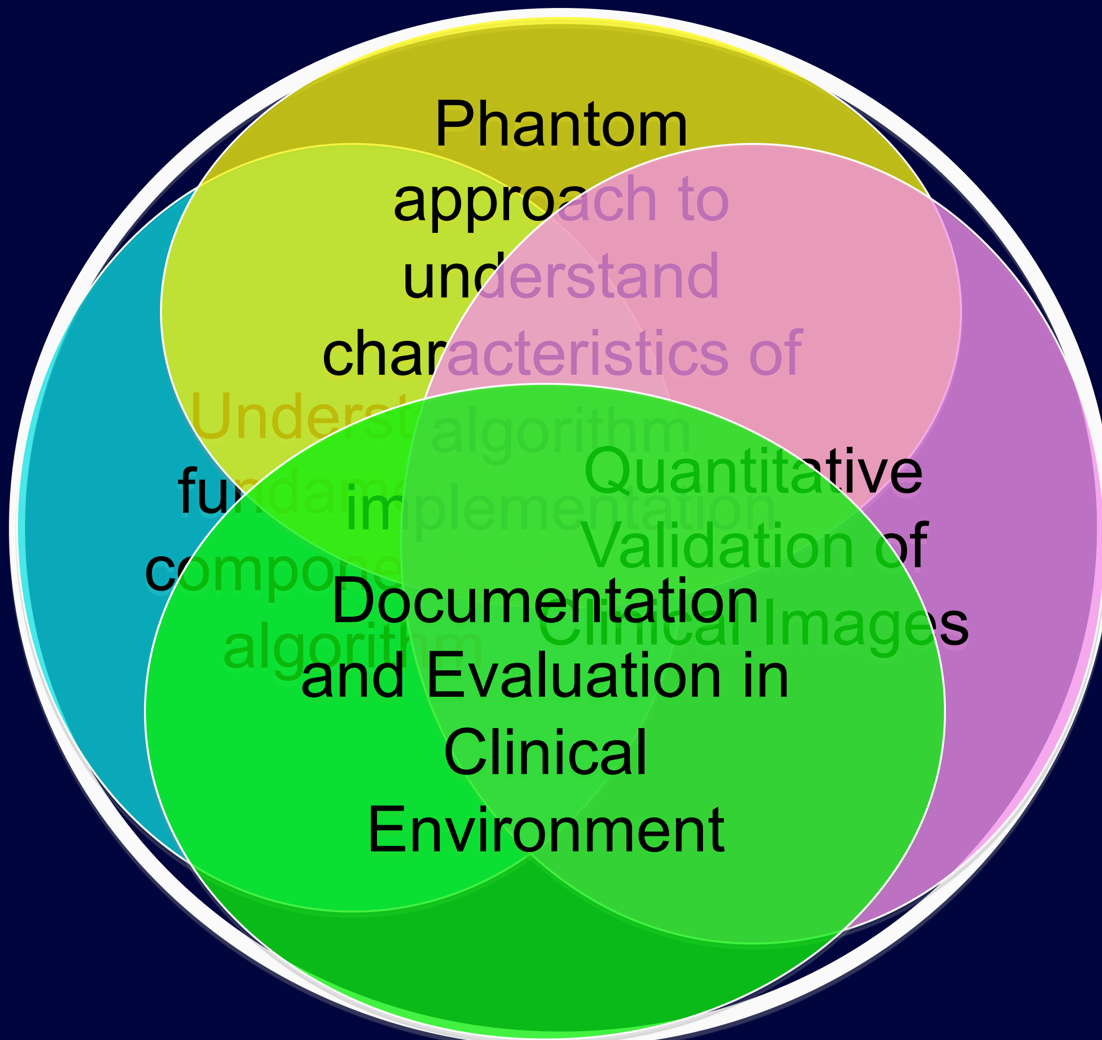




- NCAT Phantom
- U of Mich lung phantom (Kashani, Balter)
- McGill lung phantom (Serban)
- Can know the true motion of all points
- Doesn‘t include anatomical noise and variation, likely not as complex as true anatomical motion
- Does give a ‘best case’ scenario for similarity/ geometric defm reg algorithms

Commissioning and QA

Understand the whole picture



Commissioning

1. Rigid Geometric Phantom Data
2. Rigid Anatomic Phantom
3. Deformable Anatomic Phantom
4. Combined Data (Clinical & Simulation)
5. Your Clinical Data

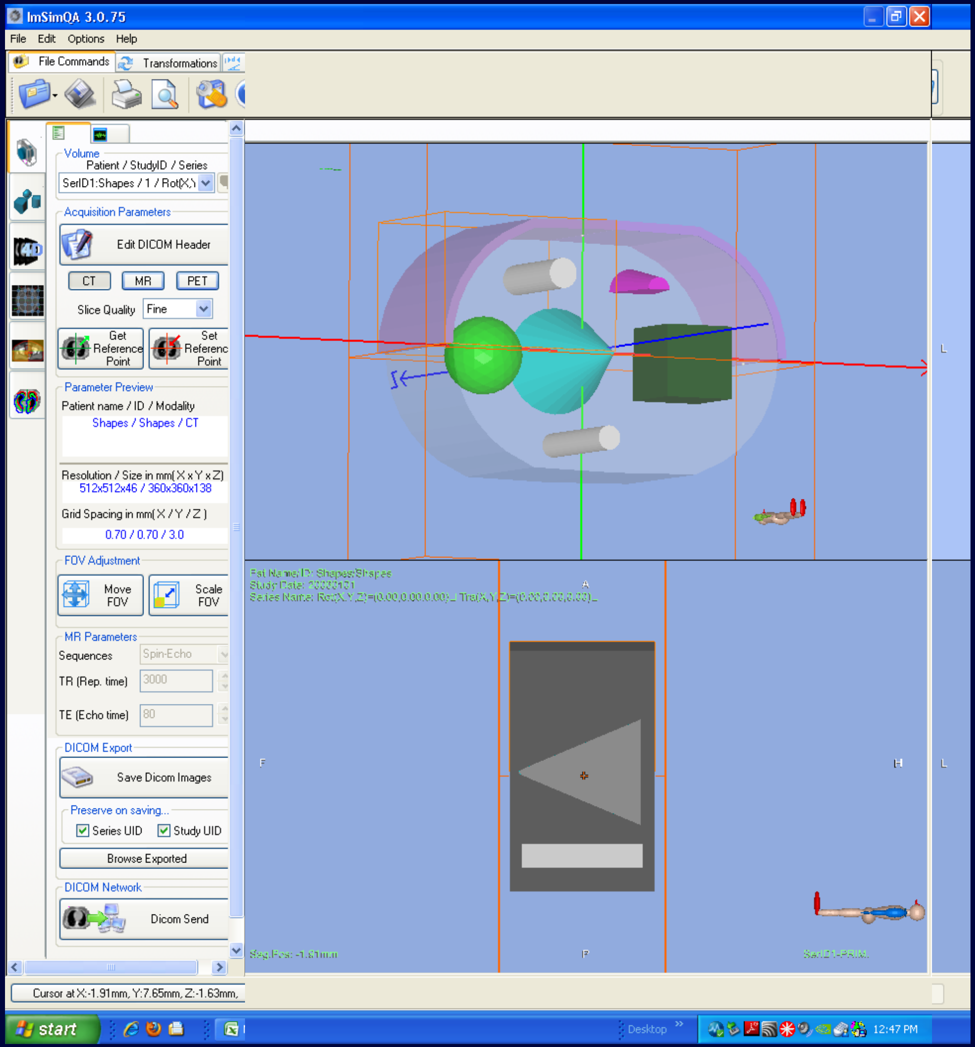
Why Virtual Phantoms

- Known attributes (volumes, offsets, deformations, etc.)
- Testing standardization – we all are using the same data
- Geometric phantoms – quantitative validation
- Anthropomorphic – realistic and quantitative

Still need end-to-end physical images

Rigid Geometric Data

- Helps us to learn the impact of the 'knobs' of the registration
- Validation of most straightforward case
- Similar to 20x20 field profile



* Phantom Data Courtesy of ImSim QA

Example Commissioning Tests

KKB204 - Geometric Phantom Registration				[mm, degrees]		
		AP	SI			
Offset to Primary	**dx**	**dy**	**dz**	**rotx**	**roty**	**rotz**
Defined	**-10**	**5**	**-15**	**0**	**0**	**0**
default, entire FOV	-10	5.1	-12.9	0.2	0	0
default, entire FOV	-9.9	4.5	-13.5	0	0	0
default, entire FOV	-10	4.9	-14.1	0	0	0
default, entire FOV	-10	5.2	-13.8	0	0	0
default, entire FOV	-8.3	4.4	-13.6	0	0	0
AVG	-9.64	4.82	-13.58	0.04	0	0
SD	0.75	0.36	0.44	0.09	0	0
AVG Deviation from Defined Offset	0.36	-0.18	1.42	0.04	0	0
Offset to Primary	**dx**	**dy**	**dz**	**rotx**	**roty**	**rotz**
Defined	**-10**	**5**	**-15**	**0**	**0**	**0**
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15	0	0	0
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15	0	0	0
User Defined (4th step with 1 mm resolution), entire FOV	-10	4.9	-15	0	0	0
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15	0	0	0
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15	0	0	0
AVG	-10	4.98	-15	0	0	0
SD	0.00	0.04	0.00	0.00	0.00	0.00
AVG Deviation from Defined Offset	0	-0.02	0	0	0	0

Rigid Anatomical Phantom

- Multi-Modality
- Translation Offset
- 1 additional (simple) layer of complexity

Offset to Primary	dx	dy	dz	rotx	roty	rotz
Defined	**-3**	**5**	**-12**	**0**	**0**	**0**
User Defined (4th step with 1 mm resolution), entire FOV	-3	4.9	-12	0	0	0
User Defined (4th step with 1 mm resolution), entire FOV	-3	4.9	-12	0	0	0
User Defined (4th step with 1 mm resolution), entire FOV	-3	4.9	-12	0	0	0
AVG	-3	4.90	-12	0	0	0
SD	0.00	0.00	0.00	0.00	0.00	0.00
AVG Deviation from Defined Offset	0	-0.1	0	0	0	0

MR1 to Primary	dx	dy	dz	rotx	roty	rotz
Defined	**-3**	**5**	**-12**	**0**	**0**	**0**
User Defined (4th step with 1 mm resolution), default FOV	-2.6	5.3	-11.5	0	0	0
User Defined (4th step with 1 mm resolution), default FOV	-2.6	5.3	-11.5	0	0	0
User Defined (4th step with 1 mm resolution), default FOV	-2.6	5.3	-11.5	0	0	0
AVG	-2.6	5.30	-11.5	0	0	0
SD	0.00	0.00	0.00	0.00	0.00	0.00
AVG Deviation from Defined Offset	0.4	0.3	0.5	0	0	0

MR2 to Primary	dx	dy	dz	rotx	roty	rotz
Defined	**-3**	**5**	**-12**	**0**	**0**	**0**
User Defined (4th step with 1 mm resolution), default FOV	-2.5	5.6	-11.4	0	0	0
User Defined (4th step with 1 mm resolution), default FOV	-2.5	5.6	-11.4	0	0	0
User Defined (4th step with 1 mm resolution), default FOV	-2.5	5.6	-11.4	0	0	0
AVG	-2.5	5.60	-11.4	0	0	0
SD	0.00	0.00	0.00	0.00	0.00	0.00
AVG Deviation from Defined Offset	0.5	0.6	0.6	0	0	0

CBCT to Offset	dx	dy	dz	rotx	roty	rotz
Defined	**3**	**-5**	**12**	**0**	**0**	**0**
User Defined (4th step with 1 mm resolution), default FOV	2.9	-5.1	12.1	0	0	0
User Defined (4th step with 1 mm resolution), default FOV	2.9	-5.1	12.1	0	0	0
User Defined (4th step with 1 mm resolution), default FOV	3	-5.1	12.1	0	0	0
AVG	2.93	-5.10	12.10	0.00	0.00	0.00
SD	0.06	0.00	0.00	0.00	0.00	0.00
AVG Deviation from Defined Offset	-0.07	-0.10	0.10	0.00	0.00	0.00

Deformable Phantom

- Run Deformable Image Registration
- Export DICOM Deformation Vector Field (DVF)
- Pseudo code provided to compare known DVF with exported DVF
- Target: 95% of voxels within 2 mm, max error less than 5 mm

PHANTOM:

Prostate with added Gaussian noise variation and the following global offsets: To left = 0.3 cm, to anterior = 0.5 cm, To inferior = 1.2 cm. 3 markers were set inside the prostate regions, prostate volume increased by105%, -10° about X-axis, +10° about Y-axis, +10° about Z-axis.

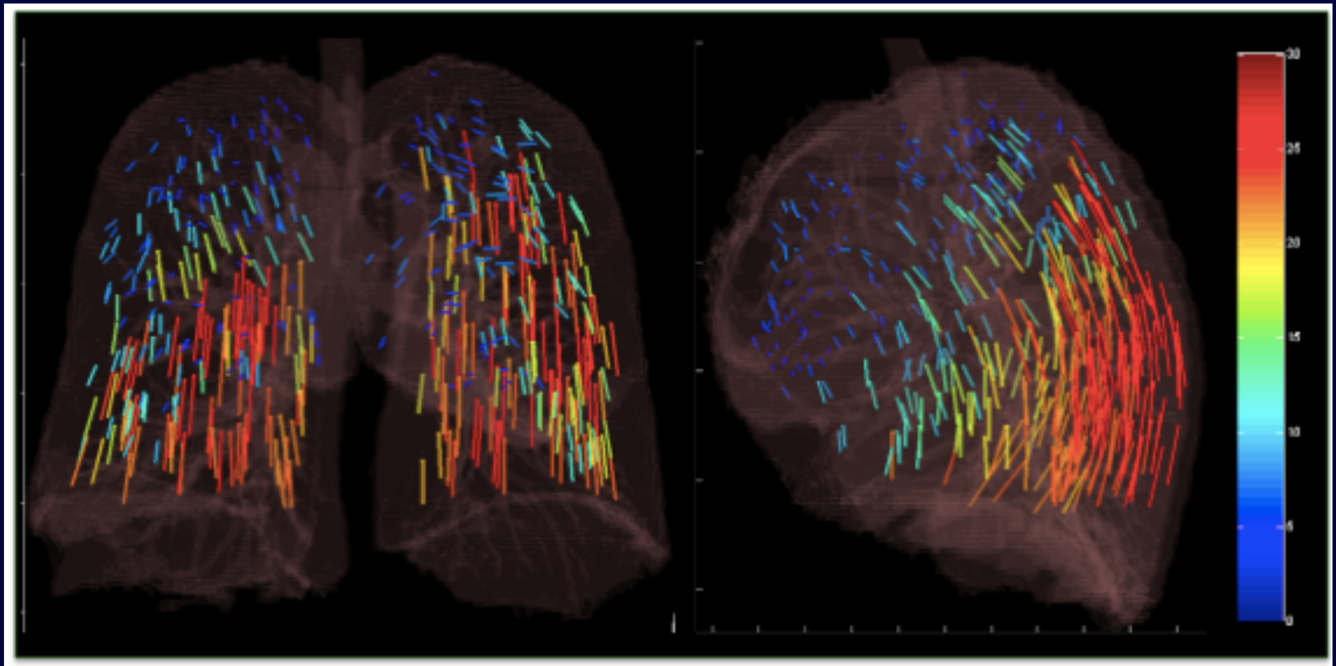
Target Tolerances for the Digital Phantom Test Cases

PHANTOM AND TEST	TOLERANCE
Basic geometric phantom registration	
Scale – Dataset 1	0.5 * voxel (mm)
Voxel value – Dataset 1	Exact
Registration – Datasets 2, 3, 4, 5, 6	0.5 * voxel (mm)
Contour propagation – Datasets 2, 3, 4, 5, 6	1 * voxel (mm)
Orientation – Datasets 2, 3, 4, 5, 6	Correct
Basic anatomical phantom registration	
Orientation - Datasets 1, 3, 4	Correct
Scale - Data sets 1, 3, 4	0.5 * voxel (mm)
Voxel value - Datasets 1, 2, 3, 4, 5	± 1 nominal value
Registration - Datasets 2, 3, 4, 5	0.5 * voxel (mm)
Contour propagation - Datasets 2, 3, 4, 5	1 * voxel (mm)
Basic deformation phantom registration	
Orientation - Dataset 2	Correct
Registration - Dataset 2	95% of voxels within 2 mm, max error less than 5 mm
Sliding deformation phantom registration	
Orientation - Dataset 2	Correct
Scale - Dataset 2	0.5 * voxel (mm)
Registration - Dataset 2	95% of voxels within 2 mm, max error less than 5 mm
Volume change deformation phantom registration	
Orientation - Dataset 2	Correct
Scale - Dataset 2	0.5 * voxel (mm)
Registration - Dataset 2	95% of voxels within 2 mm, max error less than 5 mm

Standard Clinical Data

Deformable Lung

- Clinical Lung Data
- Simulated Deformed Lung



*Courtesy DIR-lab, Dr. Castillo

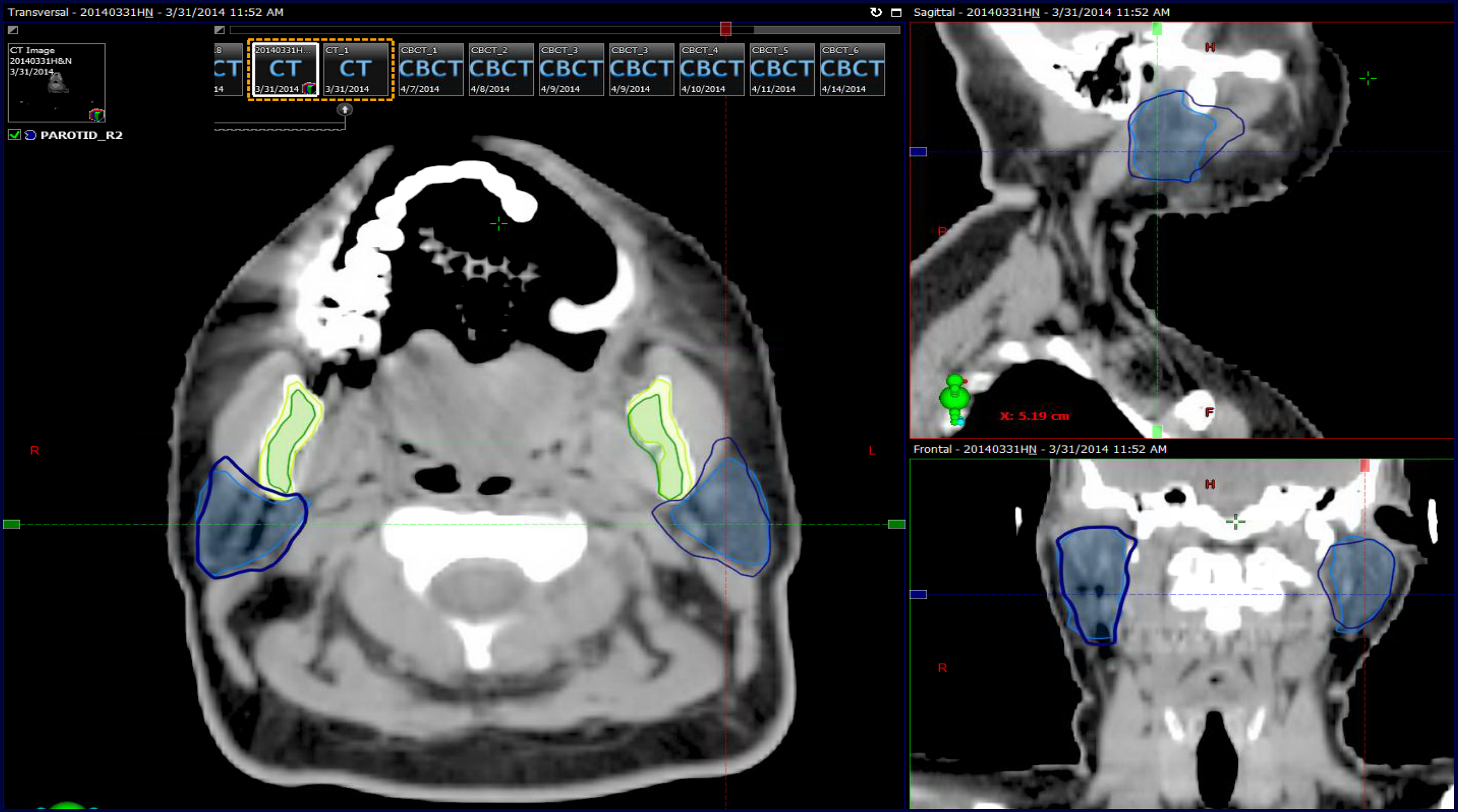
4DCT 8

Image Dims: 512 x 512 x 128
Voxels (mm): 0.97 x 0.97 x 2.5
Features (#): 476
Displacement (mm): 15.16 (9.11)
Repeats (#/#): 150/3
Observers (mm): 1.03 (2.19)

Lowest Error (mm): Observer Uncertainty Threshold

Your Clinical Data!

DSC Evaluation on CT-CT DIR

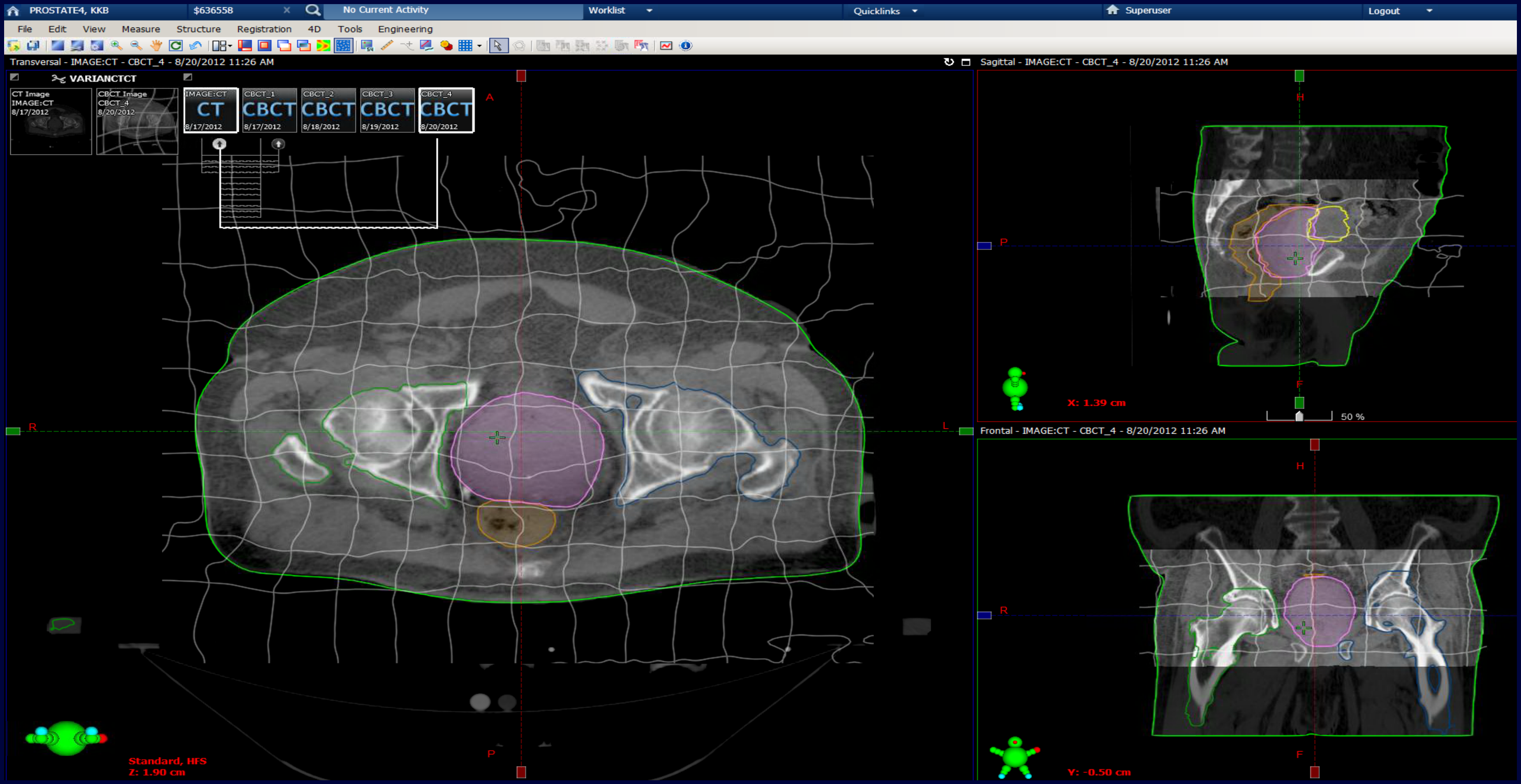


Contour structures on both CT scans, propagate via DIR

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

Clinical Deformable Registration



Identified Implanted Markers in Each Image

Clinical Deformable Registration TRE, mm

	RIGID				DEFORMABLE			
	AVG	SD	Max	Min	AVG	SD	Max	Min
P2	7.0	2.7	12.0	3.8	3.6	3.2	8.9	0.5
P3, CBCT1	4.6	3.3	11.2	0.7	2.7	1.7	6.0	0.3
P3, CBCT10	4.1	2.2	8.3	0.9	3.0	1.8	8.1	0.7
P4, CBCT1	7.1	3.5	11.8	1.7	6.8	5.5	13.7	0.2
P4, CBCT4	4.5	1.7	7.4	2.5	6.7	5.8	14.7	0.3
P5	6.7	3.3	10.6	0.8	3.7	2.7	9.2	0.5
AVG	**5.7**	**2.8**	**10.2**	**1.7**	**4.4**	**3.4**	**10.1**	**0.4**

Validation Tests and Frequencies

Frequency	Quality Metric	Tolerance
Acceptance and Commissioning **Annual or Upon Upgrade**	System end-to-end tests Data Transfer (including orientation, image size, and data integrity) Using physics phantom	Accurate
	Rigid Registration Accuracy (Digital Phantoms, subset)	Baseline, See details in Table Z
	Deformable Registration Accuracy (Digital Phantoms, subset)	Baseline, see details in Table Z
	Example patient case verification ((including orientation, image size, and data integrity) Using real clinical case	Baseline, see details in Table Z

5. Develop a request and report system to ensure communication and documentation between all users of image registration

Why?

- To create clear information and communication
- To provide documentation in the patient chart
- To ensure safety

How?

Request

- Clear identification of the image set(s) to be registered
  - Identification of the primary (e.g. reference) image geometry
- An understanding of the local region(s) of importance
- The intended use of the result
  - Target delineation
- Techniques to use (deformable or rigid)
- The accuracy required for the final use

Report

- Identify actual images used
- Indicate the accuracy of registration for local regions of importance and anatomical landmarks
  - Identify any critical inaccuracies to alert the user
- Verify acceptable tolerances for use
- Techniques used to perform registration
- Fused images in report with annotations
- Documentation from system used for fusion

Example Implementation

- Integrate with another document
  - Included in the Simulation Directive
- Use drop-downs and check boxes
- 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

6. Establish a patient specific QA practice for efficient evaluation of image registration results

Why?

- At this point we are still understanding how the the registration is performing on different types of patients

How?

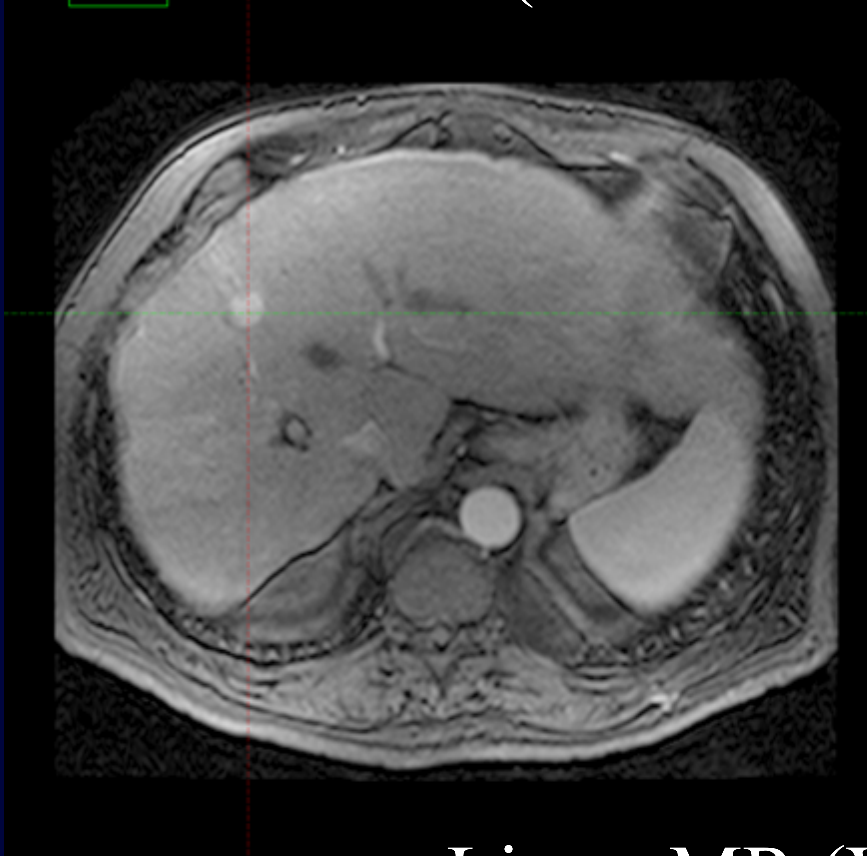
- Visual Verification
- Spot checks of landmarks
- Boundary comparison

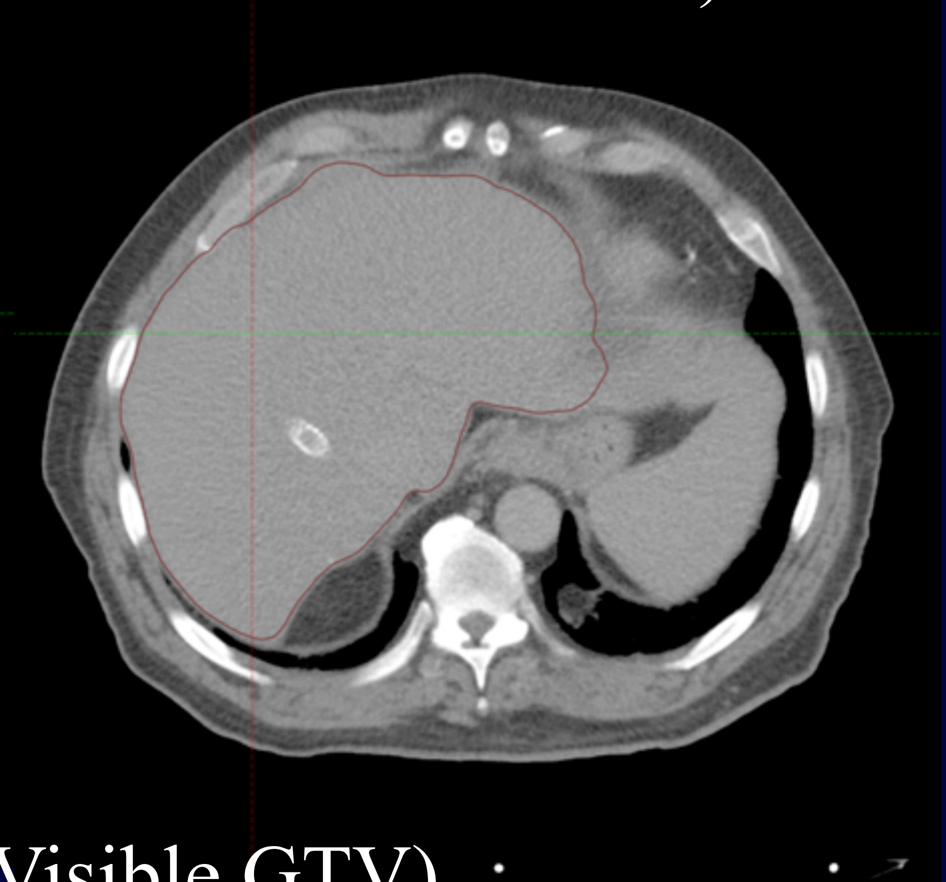
Challenge: Communicating the Uncertainty?

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)

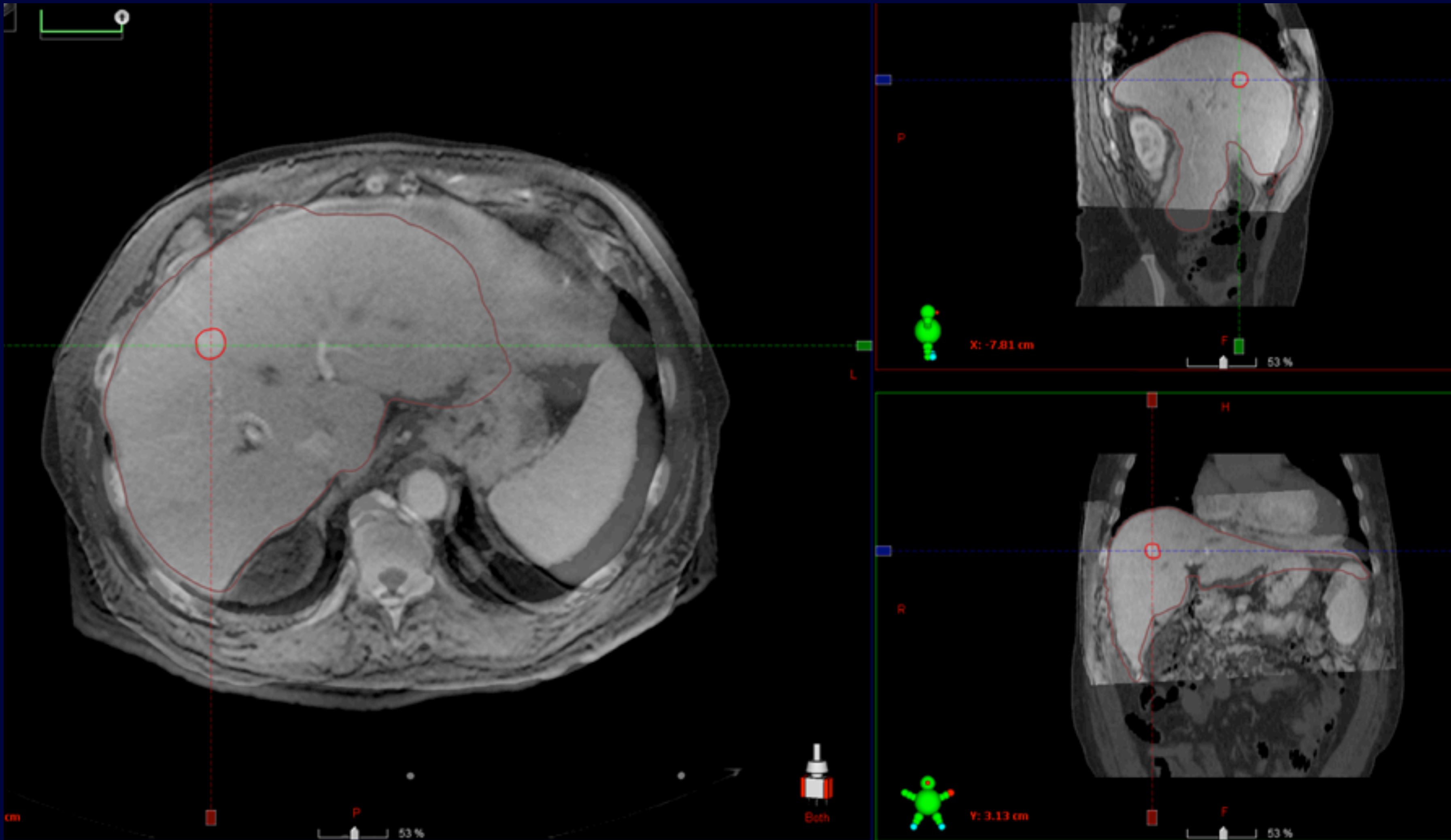
Example: Multi-modality imaging for Planning

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

Vendor Recommendations

1. Disclose basic components of their registration algorithm to ensure its proper use
2. Provide the ability to export the registration matrix or deformation vector field for validation
3. Provide tools to qualitatively evaluate the image registration
4. Provide the ability to identify landmarks on 2 images and calculate the TRE from the registration
5. Provide the ability to calculate the DSC and MDA between the contours defined on an image and the contours mapped to the image via image registration
6. Provide the ability to compare a known deformation vector field with the deformation vector field calculated by the commercial algorithm
7. Support the integration of a request and report system for image registration

TG-132 Product

Pending AAPM Approval

- Guidelines for understating of clinical tools
- Digital (virtual) phantoms
- Recommendations for commissioning and clinical implementation
- Recommendations for periodic and patient specific QA/QC
- Recommendations for clinical processes

Summary

- Deformable registration is a complex model
  - Must understand the fundamentals of the model
  - Commission and Validate the algorithm prior to clinical implementation
- Translation of geometric uncertainties to dosimetric error is complex and depends on complexity of motion and image intensity variation in the region
- Rigorous quantitative commissioning must be performed
  - Consistent with other technology in radiation oncology
- Efficient and effective QA/QC must be in place for clinical use