Overview of Proposed TG-132 Recommendations

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Chair, AAPM TG 132: Image Registration and Fusion

University of Michigan
Medical School

Conflict of Interest

- I have a licensing agreement for deformable image registration technology with RaySearch Laboratories.

Clinical Recommendations (1/2)

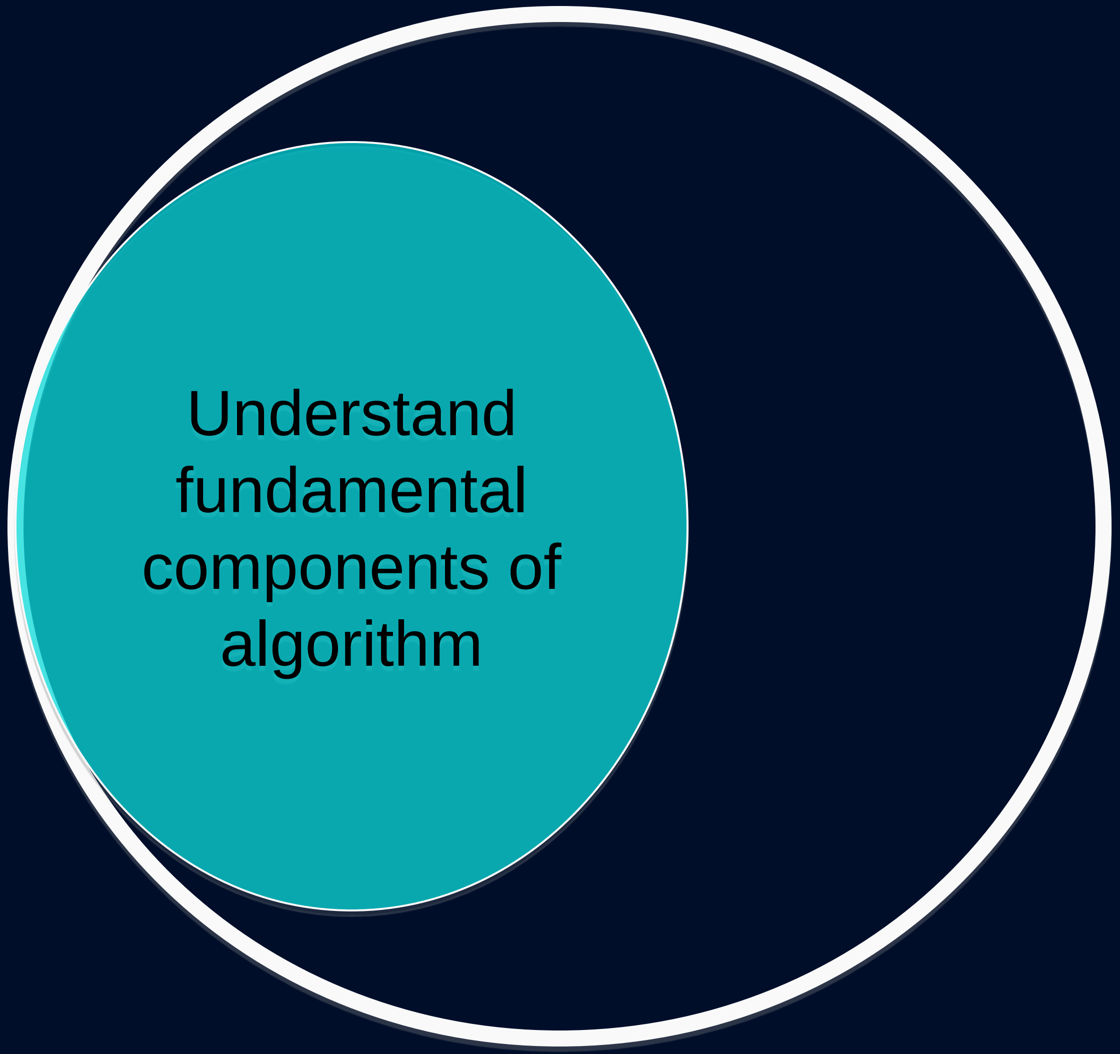
1. Understand the basic image registration techniques and methods of visualizing image fusion
2. Understand the basic components of the registration algorithm used clinically to ensure its proper use
3. Perform end-to-end tests of imaging, registration, and planning/treatment systems if image registration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

Commissioning and QA

Understand the whole picture



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 (Poin...	...otation	Simplex
Chamfer Matching (surface matchi...	...tion	Gradient descent
Contour matching	...g)	etc…
Mean Square Di...	...ain	
Correlation C...		
Mutual Information	...ical	

Quick, Easy, local

Surface-based

Manual or auto-segmentation

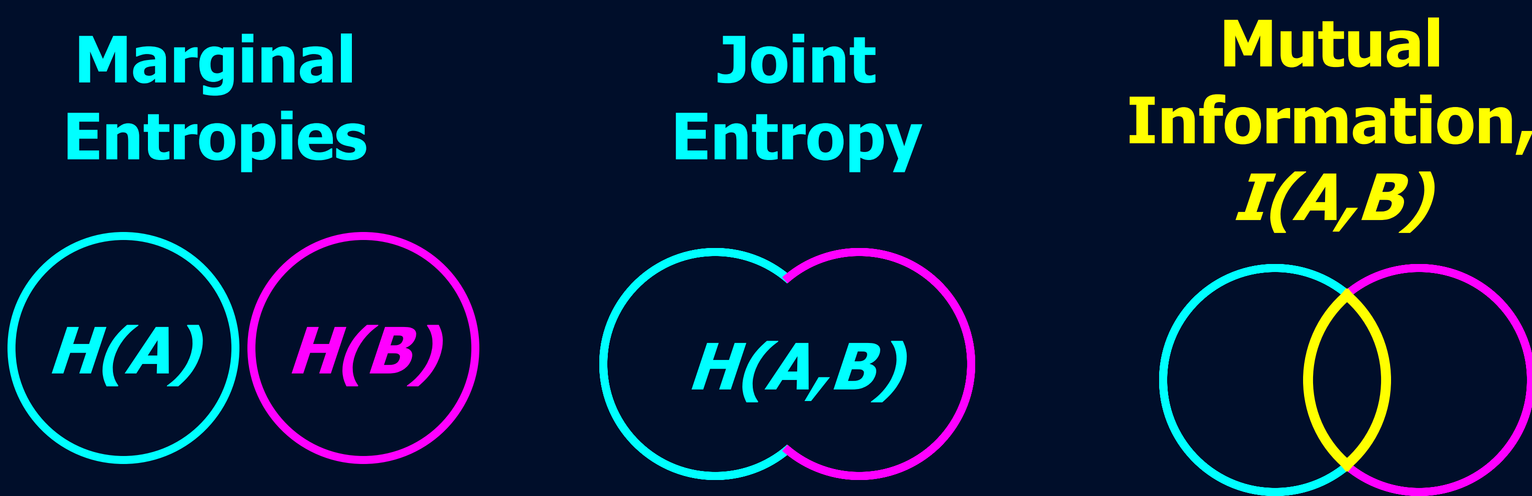
Great for 4D CT

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

Works for Multi-Modality

Mutual Information

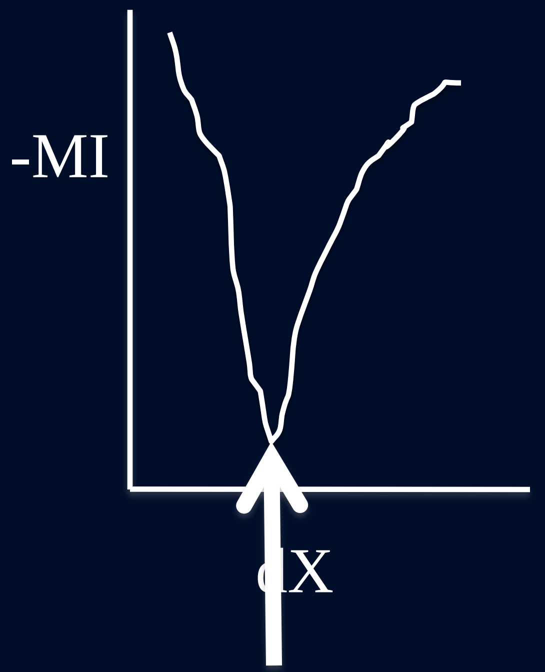
- Maximise the mutual information



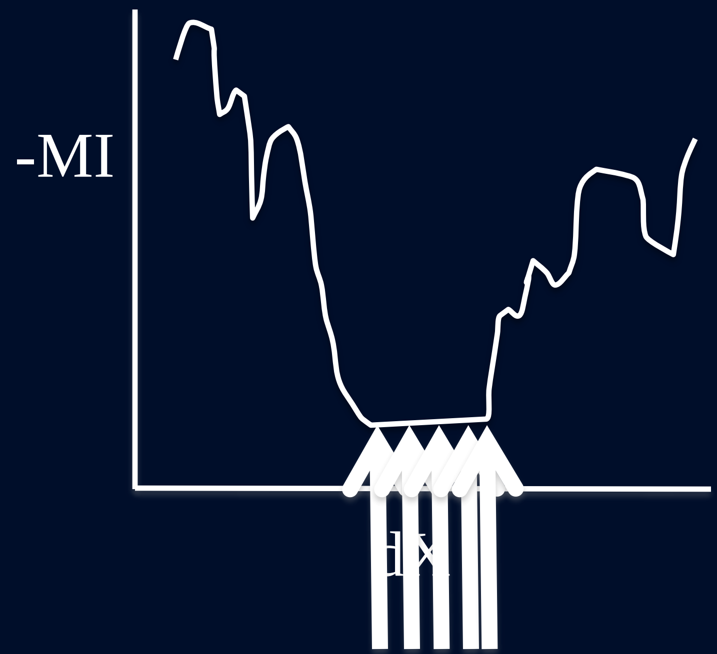
- Sensitivity of results: Vary the vector field and evaluate the change in similarity metric
  - Hub, et. al., IEEE TMI 2009

How Reliable is the Max MI?

- Actually, min -MI



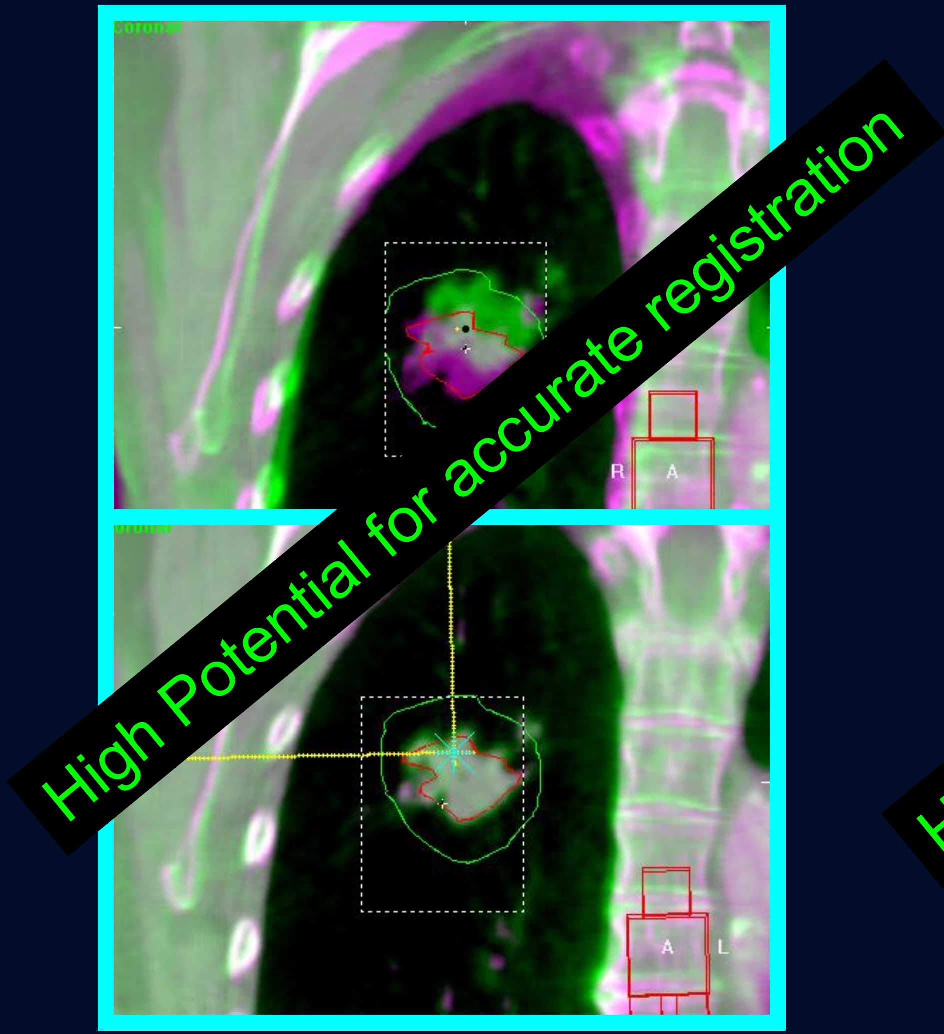
Min –MI
Best Solution



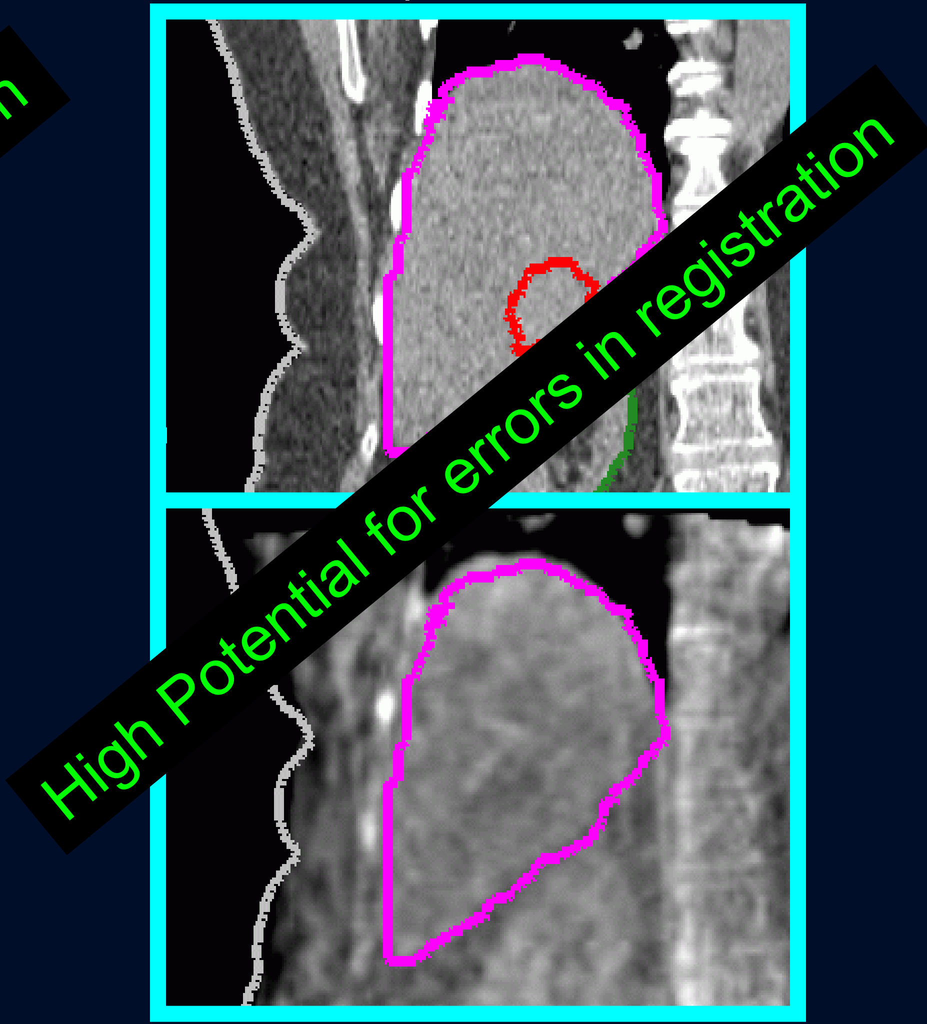
Min –MI
Best Solution

Intensity Variation: Impact on CC/MSD

Clear intensity variation



No relevant intensity variation, noise/artifact



SAMS Question

1. Measuring the similarity of alignment of multi-modality images is complex, typically requiring the use of

4%	A. Sum of the Squared Differences (SSD)
3%	B. Guessing (G)
85%	C. Mutual Information (MI)
6%	D. Mean Squared Difference (MSD)
2%	E. Cubed Subtracted Less One (CSLO)

1. Measuring the similarity of alignment of multi-modality images is complex, typically requiring the use of

A. Sum of the Squared Differences (SSD)

B. Guessing (G)

C. Mutual Information (MI)

D. Mean Squared Difference (MSD)

E. Cubed Subtracted Less One (CSLO)

REFERENCE: P. Viola, W.M. Wells, Alignment by maximization of mutual information, International Journal of Computer Vision, 24 (1997), pp. 137–154

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

How?

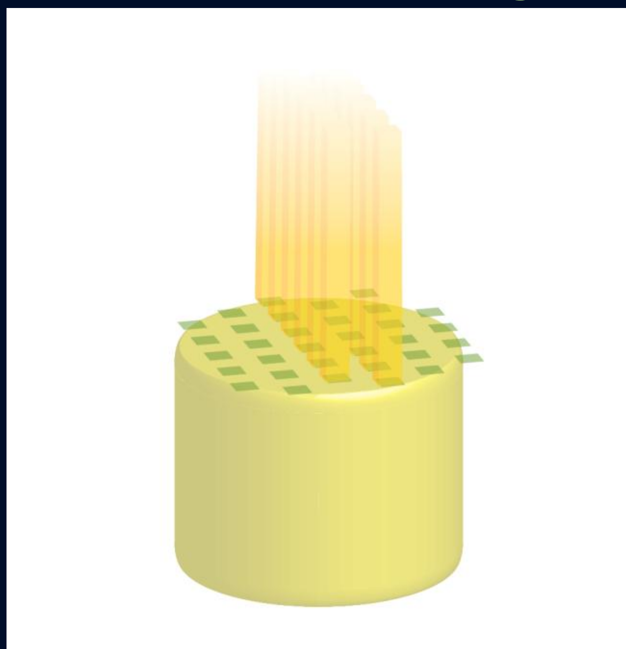
- At minimum, the vendor should disclose:

Why do we need to know the implementation?

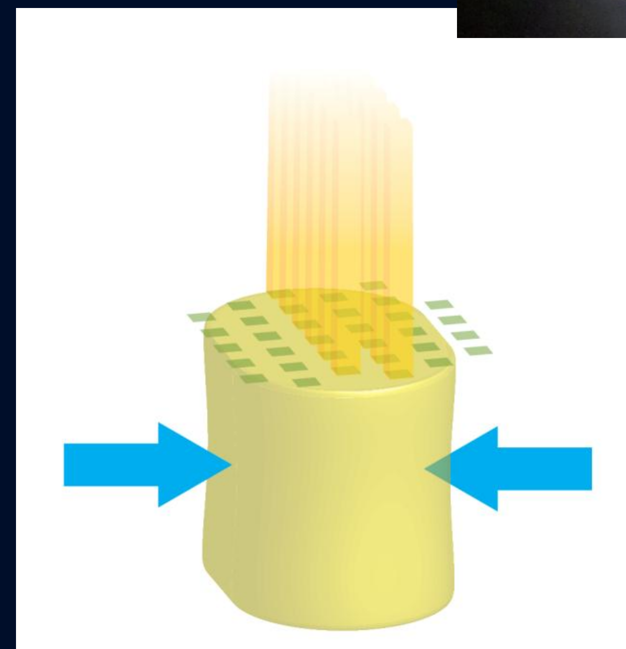
  - What knobs you can turn and what they do
- Read white papers

New method to validate Deformable Image Registration

Deformable 3D Presage dosimeters



Control
(No Deformation)



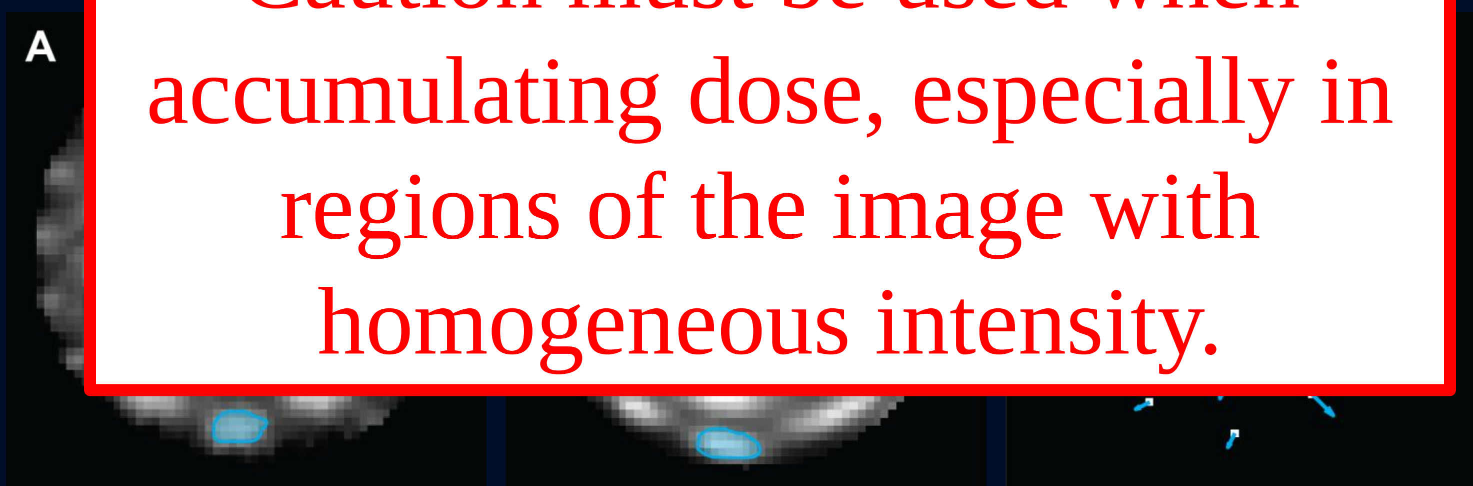
Deformed
(27% Lateral Compression)

Slides Courtesy of Mark Oldham and Shiva Das

DUKE UNIVERSITY
MEDICAL PHYSICS
GRADUATE PROGRAM

Dosimeter & Deformable Registration-based Dose Accumulation: Dose Distributions

Field Shape Differences



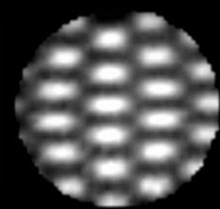
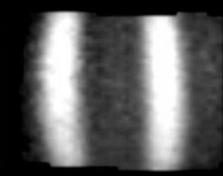
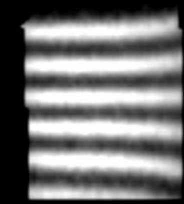
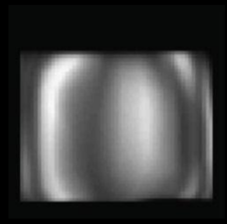
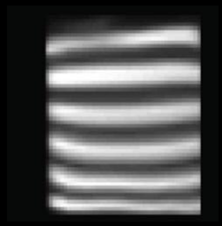
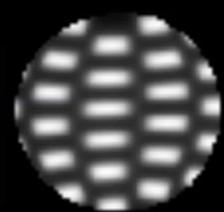
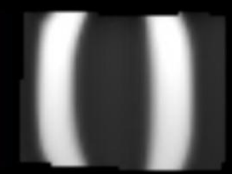
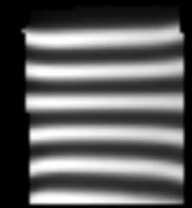
Caution must be used when accumulating dose, especially in regions of the image with homogeneous intensity.

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

Vertical → **33% shorter to 50% taller**

Slides Courtesy of Mark Oldham and Shiva Das

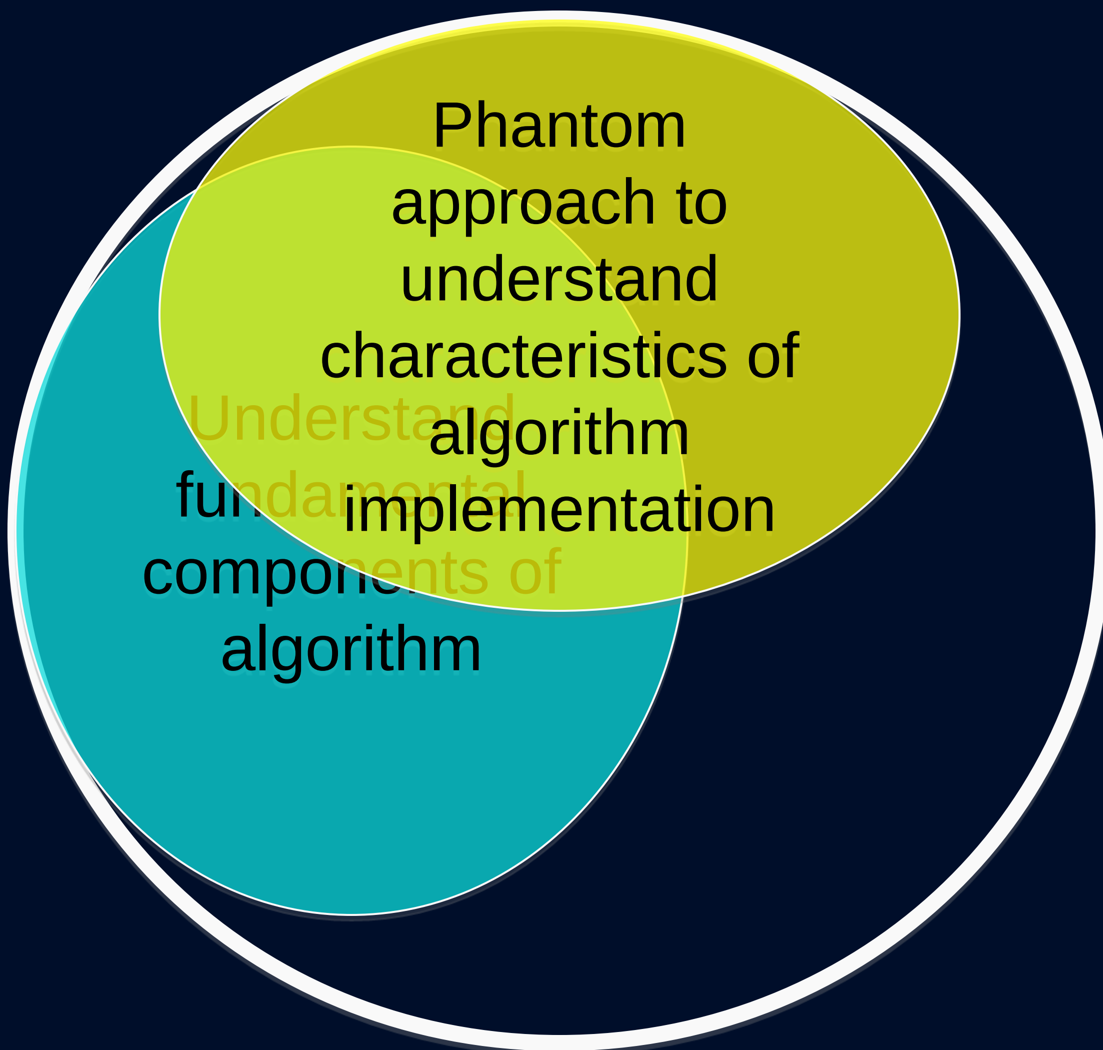
Different DIR Algorithms have Different Strengths and Weaknesses

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]

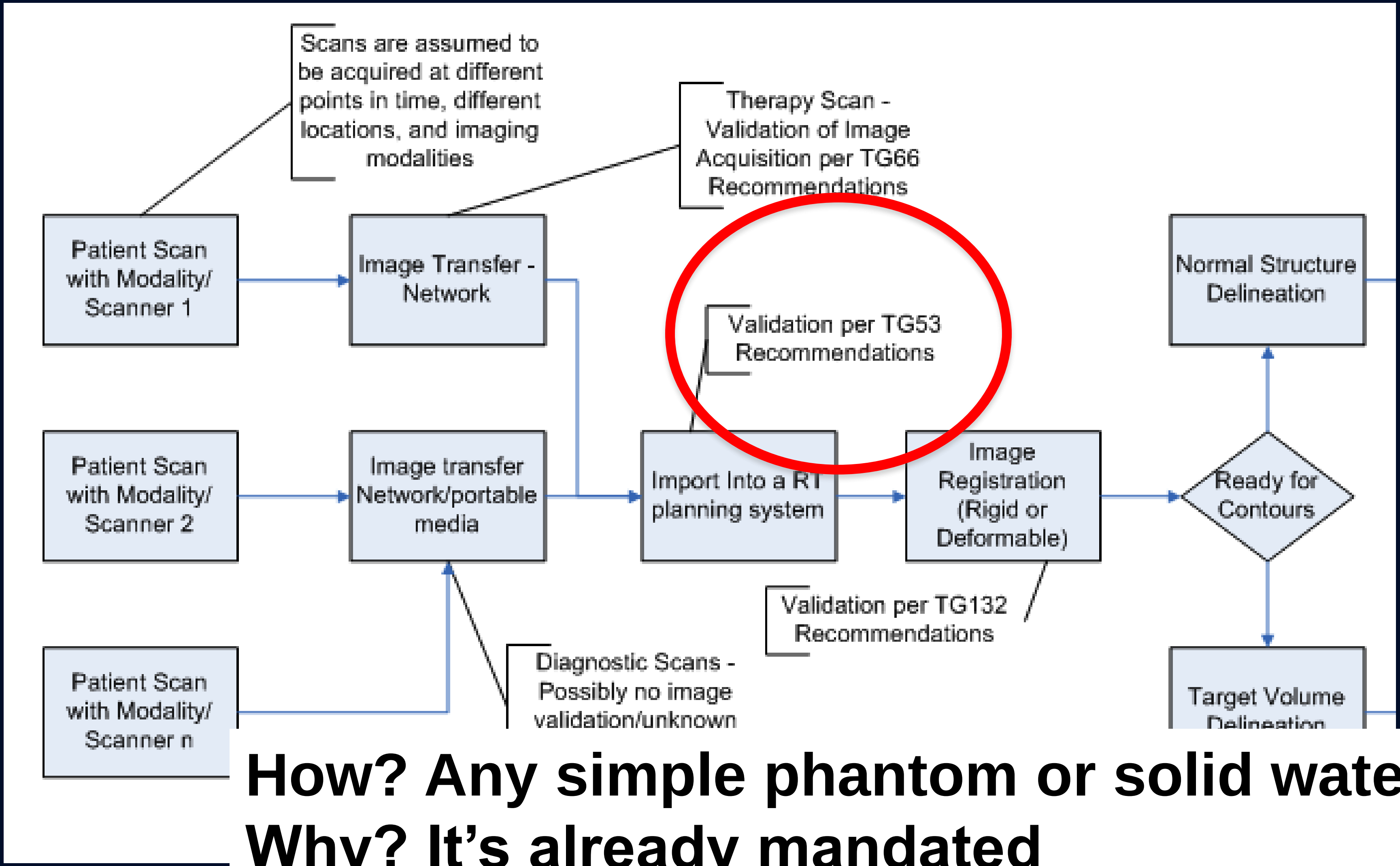
1. Juang. IJROBP 2013;87(2): 414-421
2. M Velec, et al, PRO, 2015

Commissioning and QA

Understand the whole picture



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



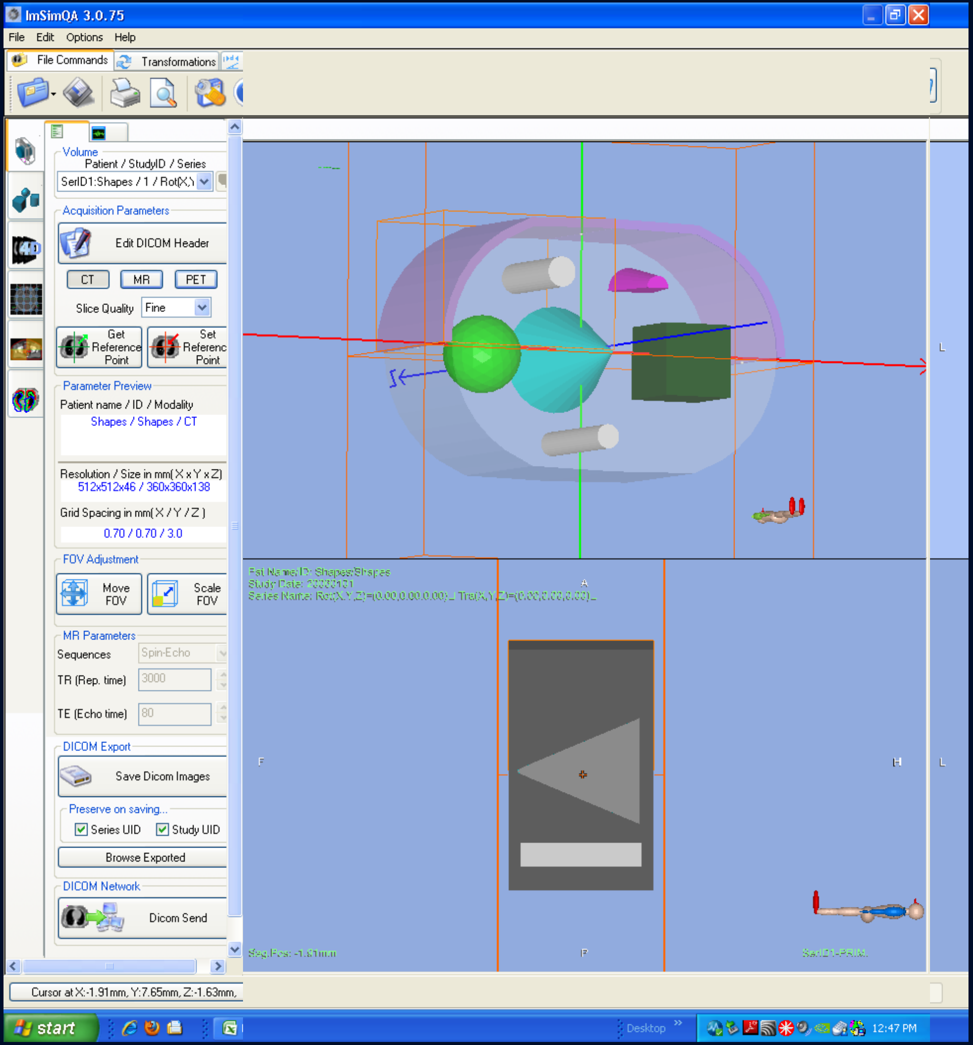
How? Any simple phantom or solid water
Why? It’s already mandated

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

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



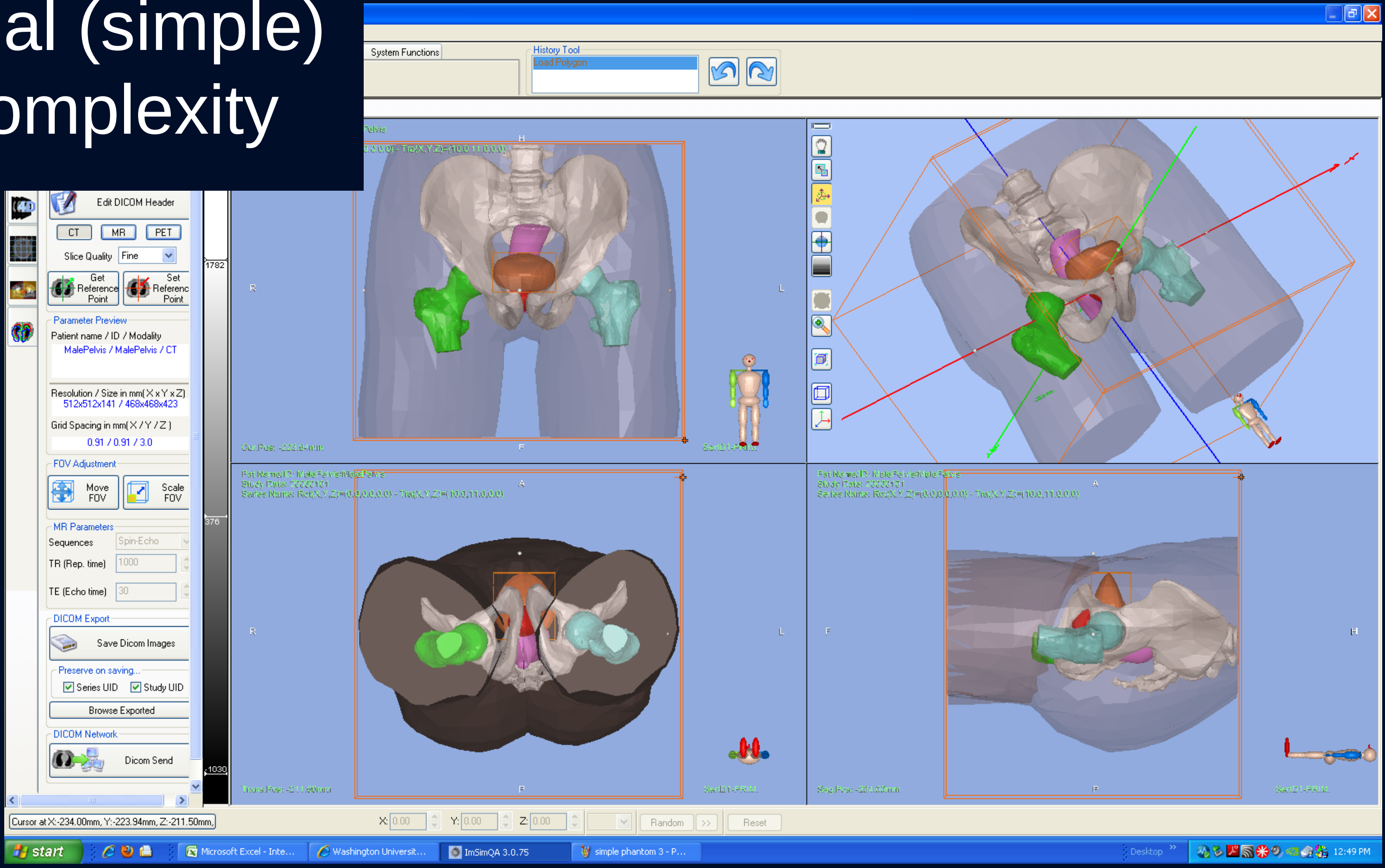
* Phantom Data Courtesy of ImSim QA

Example Commissioning Tests

KKB204 - Geometric Phantom Registration						
		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

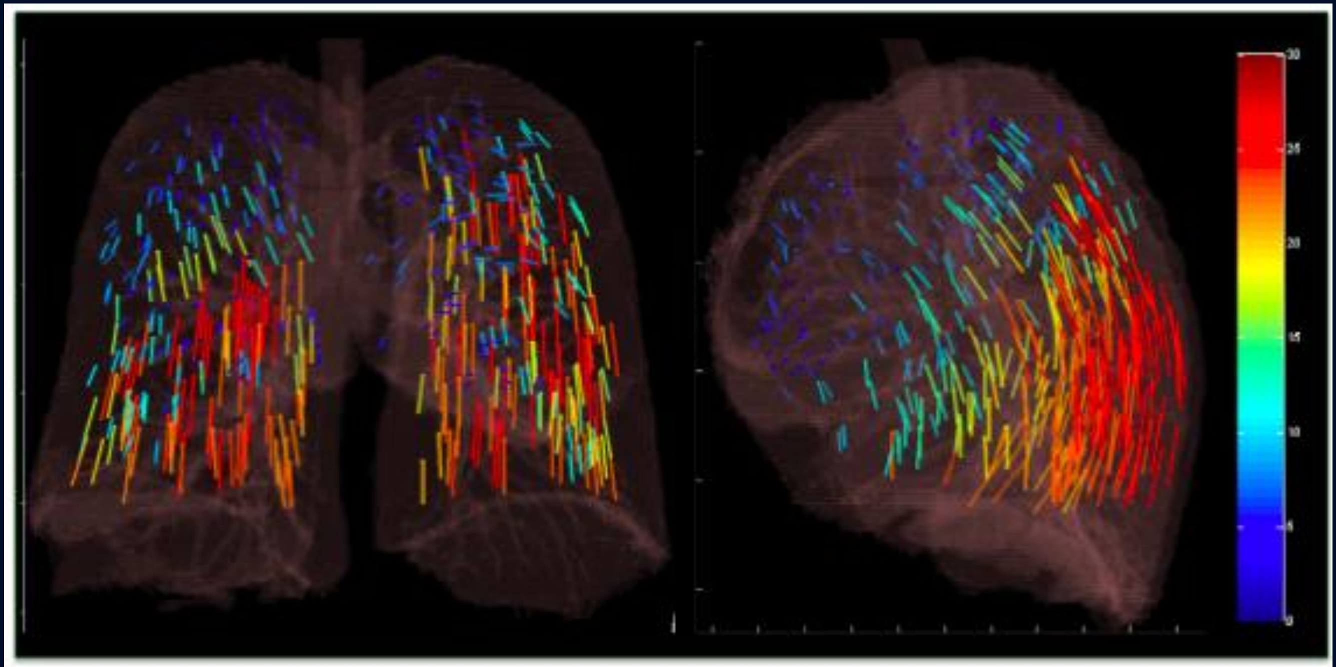
Deformable Phantom

<u>Commissioning Procedure:</u>

- 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

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

Target Tolerances

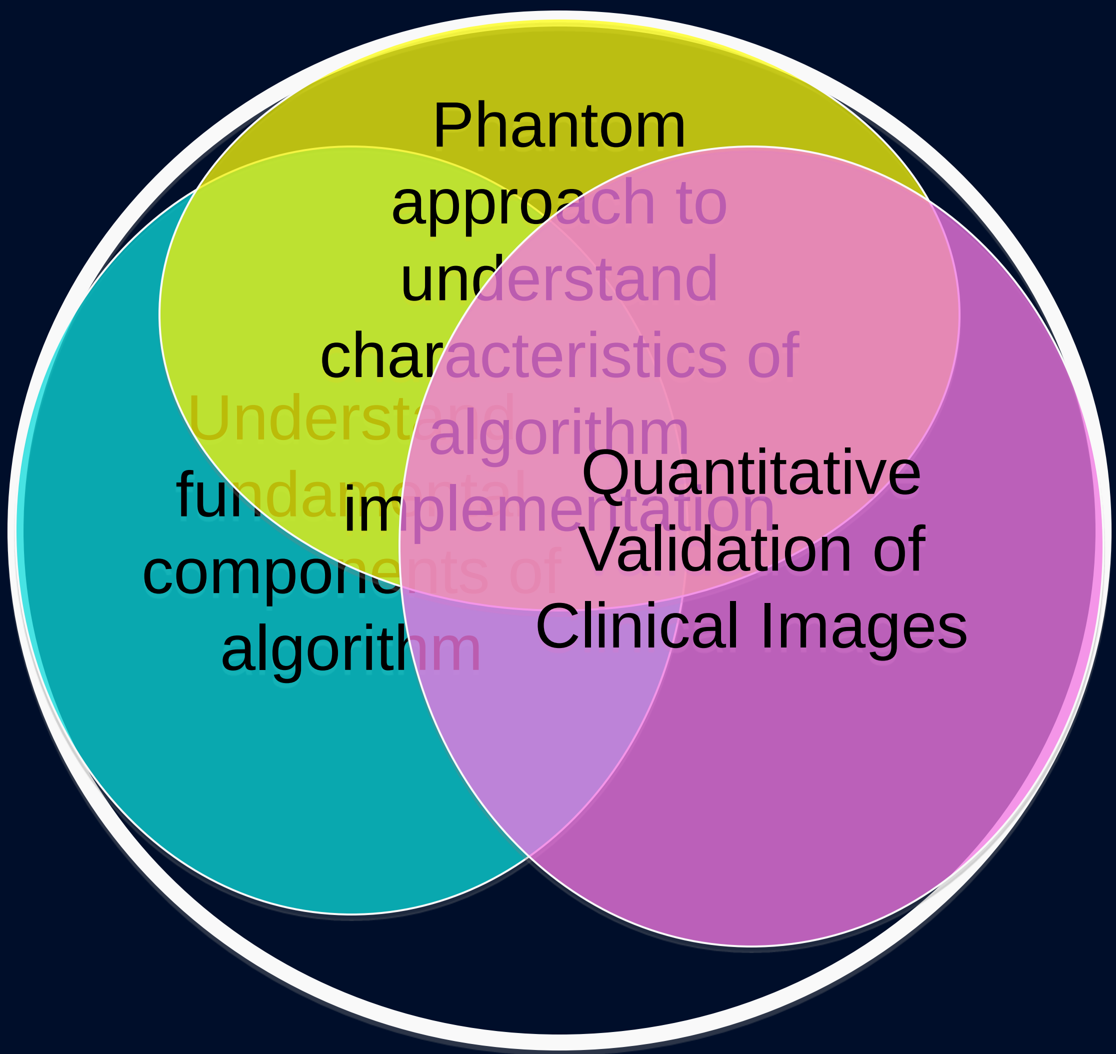
Stationary Image	Moving Image	Test	Tolerance
All Datasets		**Voxel Intensity** **Orientation**	**Exact** **Exact**
Basic Phantom Dataset - 2	Each modality image in Basic Phantom Dataset – 1	Rigid Registration – Translation Only	Maximum cardinal direction error less than 0.5*voxel dimension
Basic Phantom Dataset – 3	Each modality image in Basic Phantom Dataset – 1	Rigid Registration – Translation and Rotation	Maximum cardinal direction error less than 0.5*voxel dimension
Basic Anatomical Dataset - 1	Basic Anatomical Dataset - 2	Registration – translation only	Maximum cardinal direction error less than 0.5*voxel dimension size
Basic Anatomical Dataset - 1	Basic Anatomical Dataset - 3	Registration – translation only	Maximum cardinal direction error less than 0.5*voxel dimension size
Basic Anatomical Dataset - 1	Basic Anatomical Dataset - 4	Registration – translation only	Maximum cardinal direction error less than 0.5*voxel dimension size
Basic Anatomical Dataset - 1	Basic Anatomical Dataset - 5	Registration – translation only	Maximum cardinal direction error less than 0.5*voxel dimension size
Basic Anatomical Dataset - 1	Basic Deformation Dataset - 1	Deformable Registration	95% of voxels within 2 mm max error less than 5 mm
Sliding Deformation Dataset - 1	Sliding Deformation Dataset - 2	Deformable Registration	95% of voxels within 2 mm Max error less than 5 mm
Clinical 4DCT dataset	(Deformation can be processed in either direction)	Deformable Registration	Mean vector error of all landmark points less than 2 mm Max error less than 5 mm

Validation Tests and Frequencies

Frequency	Quality Metric	Tolerance
Acceptance and Commissioning	System end-to-end tests	Accurate
	Data Transfer using physics phantom	
Annual or Upon Upgrade	Rigid Registration Accuracy (Digital Phantoms, subset)	Baseline
	Deformable Registration Accuracy (Digital Phantoms, subset)	Baseline
	Example clinical patient case verification	Baseline

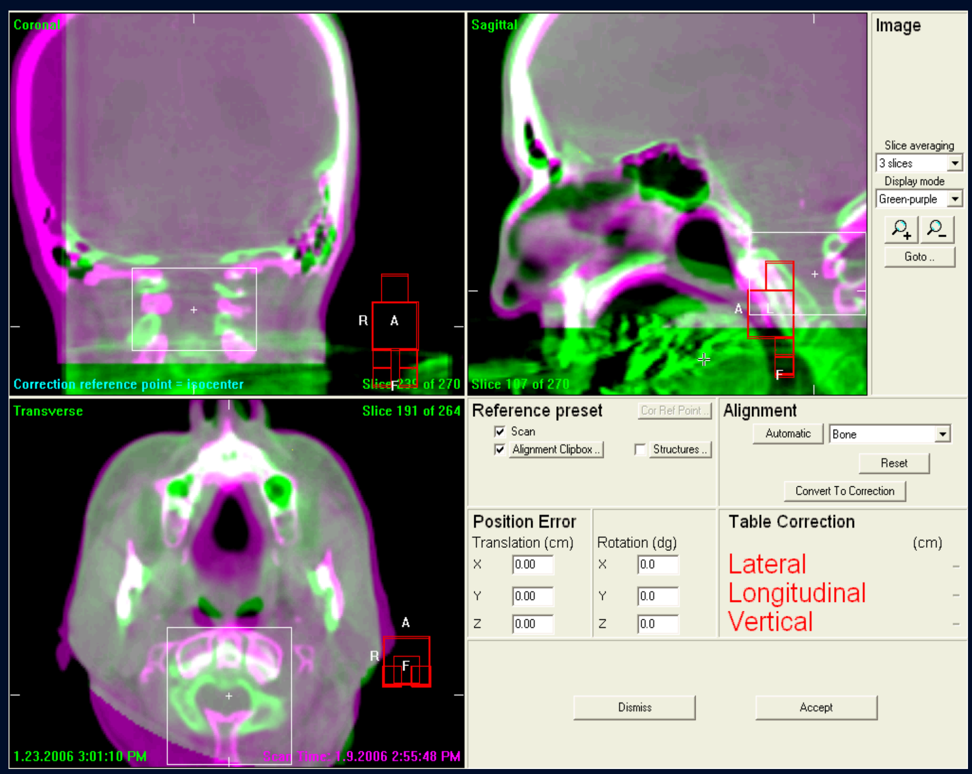
Commissioning and QA

Understand the whole picture



What Tools Do we Have?

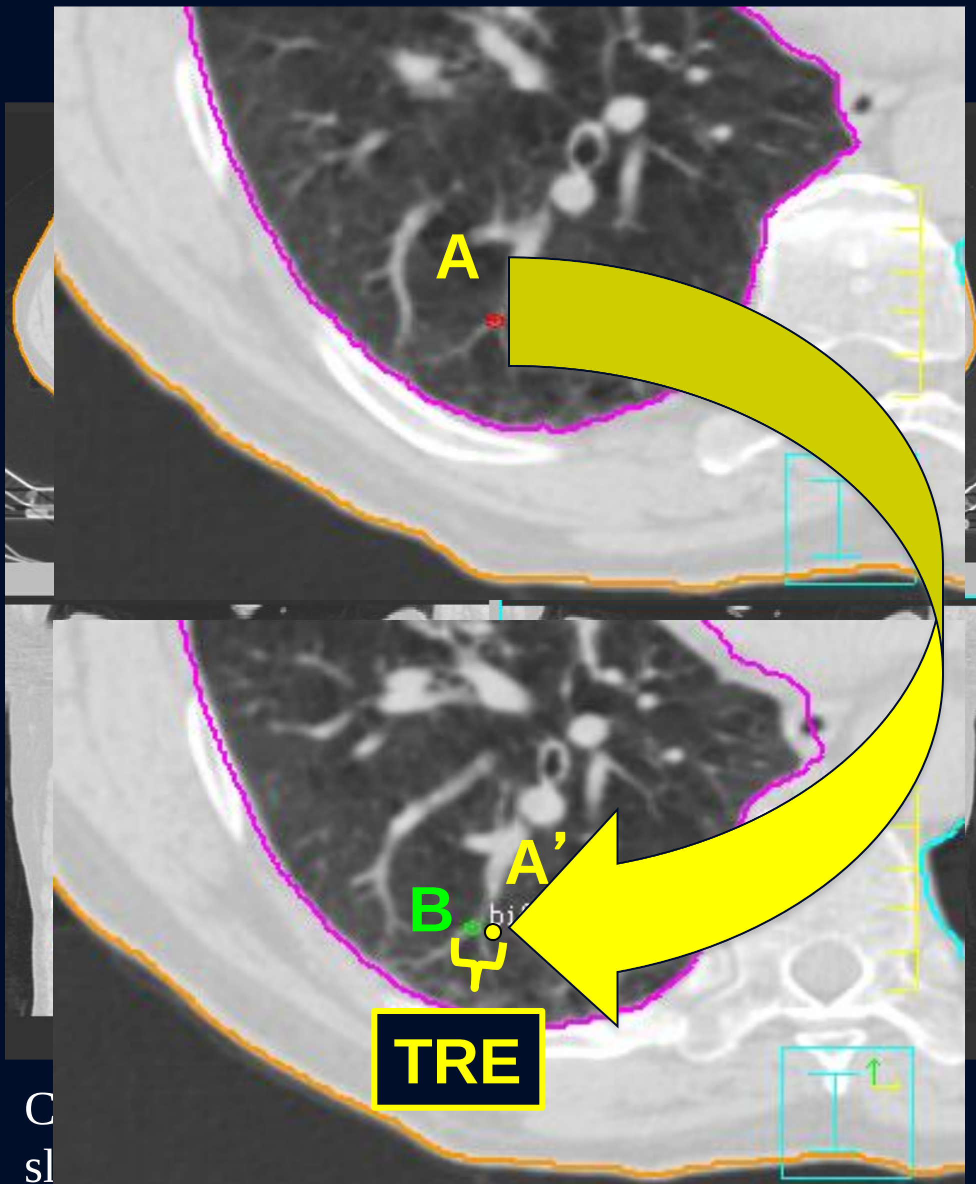
- Visual Verification: Excellent tool for established techniques.
  - Not enough for commissioning!



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)

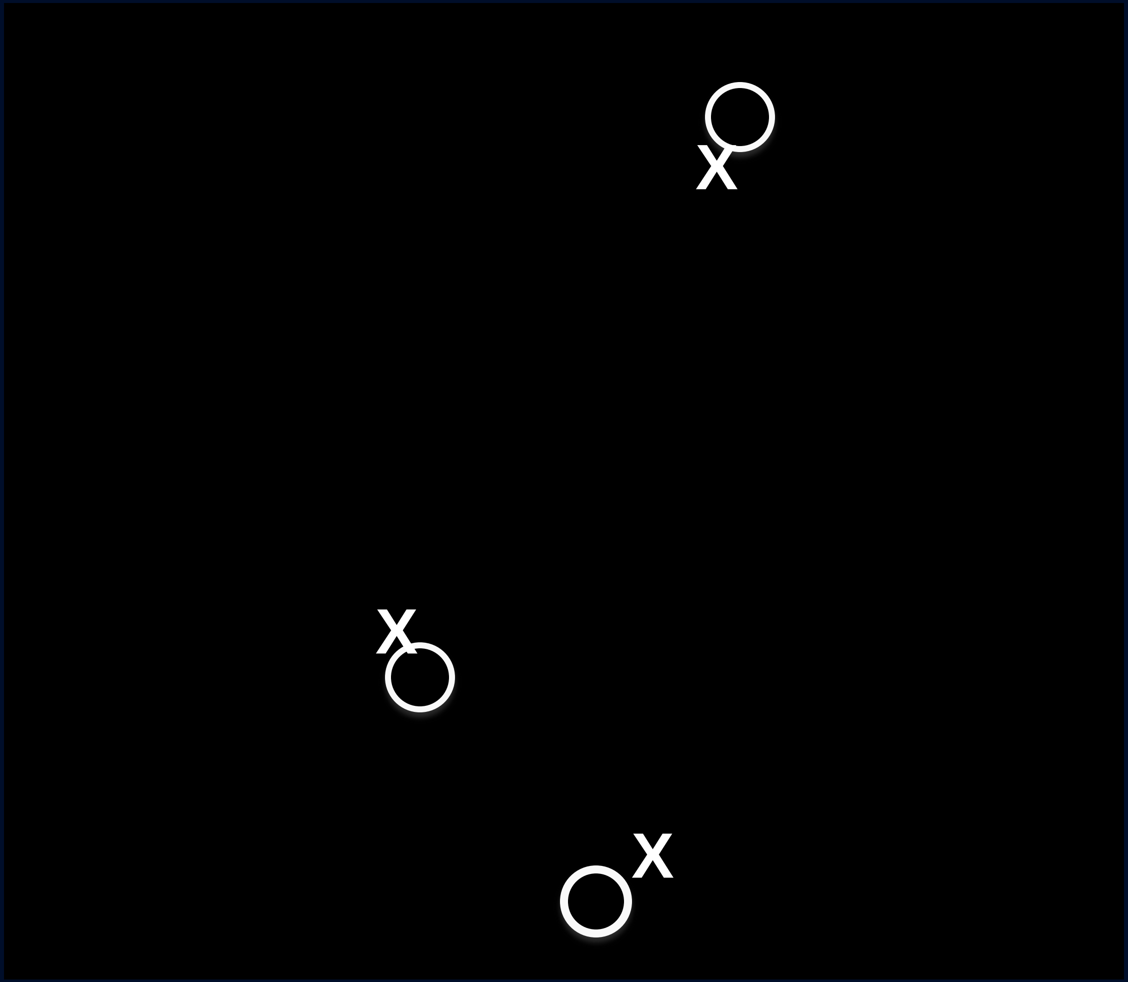


- Reproducibility of point identification is sub-voxel
  - Gross errors
  - Quantification of local accuracy within the target
  - Increasing the number increases the overall volume quantification
- Manual technique
- Can identify max errors

That sounds great! Is that enough?

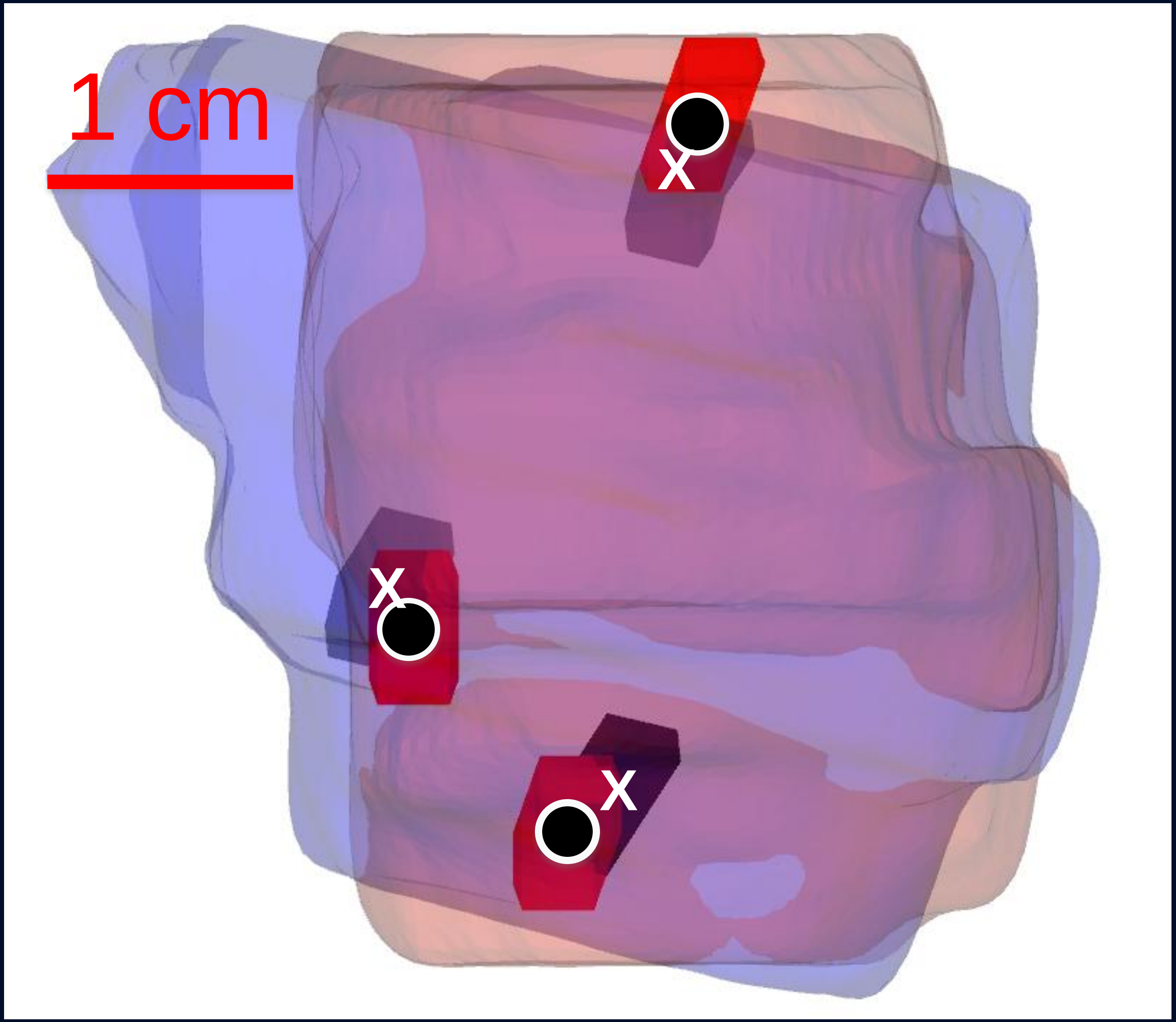
Accuracy of Points

1 cm



RMS = 0.3 mm

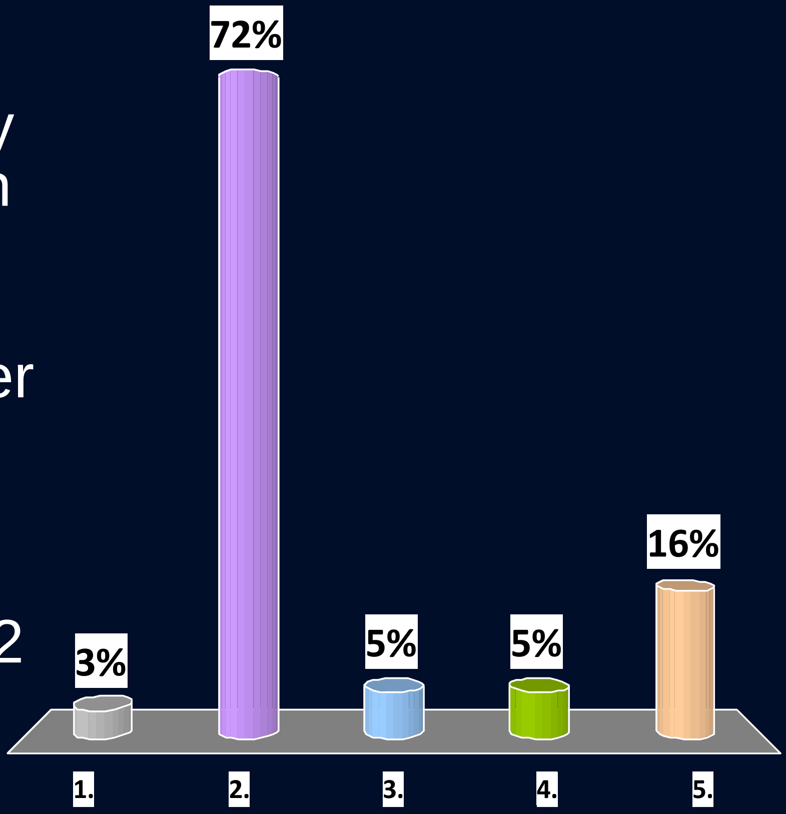
Points Don't Tell the Whole Story



SAMS Question

2. Target registration error (TRE) is defined as the

1. Uncertainty in selecting landmarks on an image
2. Average residual error between the identified points on Study B and the points identified on Study A, mapped onto Study A’ through image registration
3. Improvement in accuracy when using deformable registration over rigid registration
4. Volume overlap of 2 contours on registered images
5. Mean surface distance between 2 contours on registered images



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A. Uncertainty in selecting landmarks on an image

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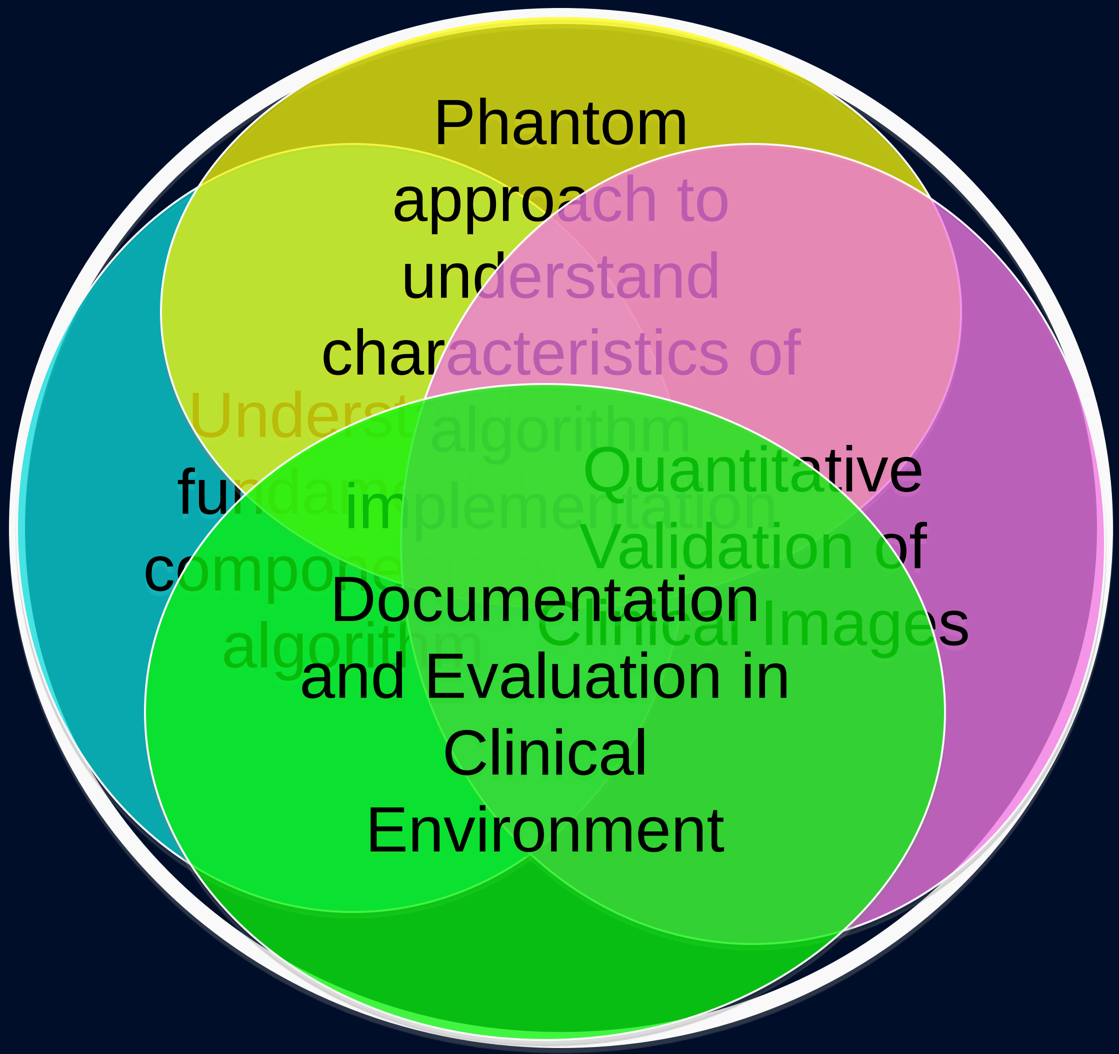
E. Mean surface distance between 2 contours on registered images

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.

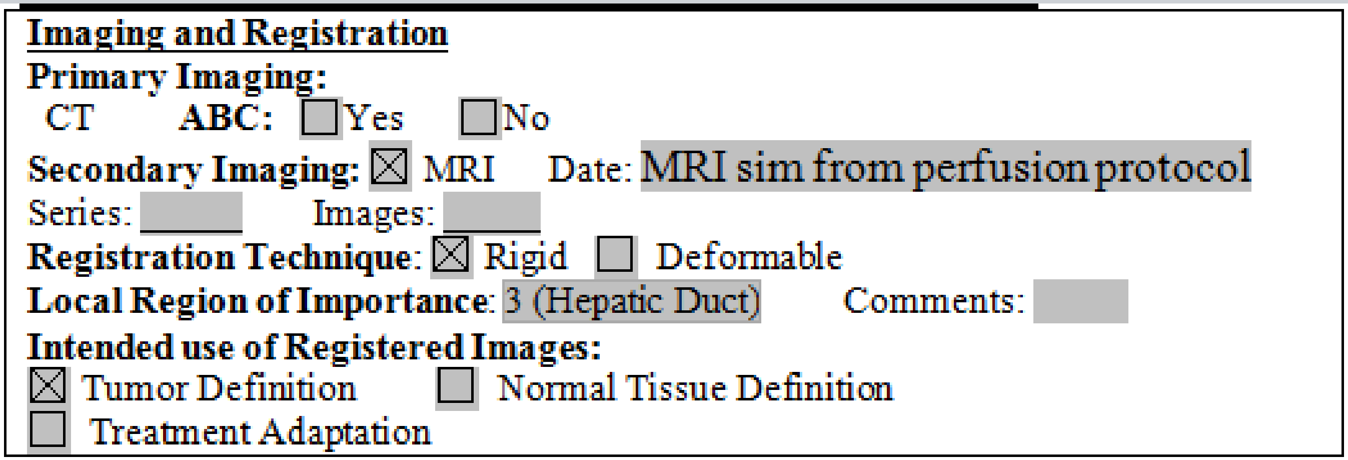
Commissioning and QA

Understand the whole picture



Request

- Clear identification of the image set(s) to be registered



Imaging and Registration

Primary Imaging:

CT **ABC:** ☐ Yes ☐ No

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

Series: ____ Images: ____

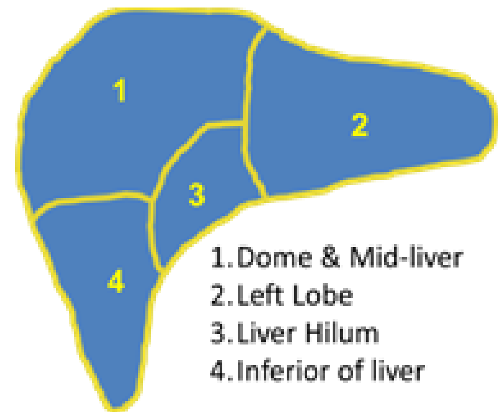
Registration Technique: ☒ Rigid ☐ Deformable

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

Intended use of Registered Images:

☒ Tumor Definition ☐ Normal Tissue Definition

☐ Treatment Adaptation



- The intended use of the result
  - Target delineation
- Techniques to use (deformable or rigid)
- The accuracy required for the final use

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)

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

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. Support the integration of a request and report system for image registration

TG-132 Product

- 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