Image Co-Registration II: TG132 Quality Assurance for Image Registration

Preliminary Recommendations from TG 132* Kristy Brock, Sasa Mutic, Todd McNutt, Hua Li, and Marc Kessler

*Recommendations are NOT AAPM approved, Report is currently under review by AAPM



Disclosure

- Kristy Brock: RaySearch Licensing Agreement
- Sasa Mutic: Modus licensing agreement, Varian research and licensing, Radialogica Shareholder, Treat Safely Partner
- Todd McNutt: Philips Collaboration, Elekta Licensing
- Hua Li: Philips Research
- Marc Kessler: Varian research and codevelopment agreements

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 standalone 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 standalone system

Clinical Recommendations (2/2)

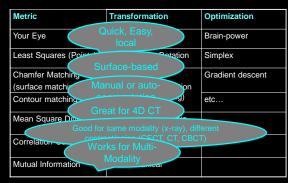
- 4. Perform comprehensive commissioning of image registration using the provided digital phantom data (or similar data) as well as clinical data from the user's institution
 - Estimation of registration error should be assessed using a combination of the quantitative and qualitative evaluation tools. 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

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



1. Measuring the similarity of alignment of multimodality images is complex, typically requiring the use of:

- 27% 1. Sum of the Squared Difference (SSD)
- ^{18%} 2. Guessing (G)
- ^{9%} 3. Mutual Information (MI)
- 32% 4. Mean Squared Difference (MSD
- ^{14%} 5. Cubed Subtracted Less One (CSLO)

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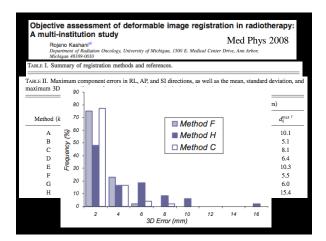
REFERENCE: P. Viola, W.M. Wells, Alignment by maximization of mutual information, International Journal of Computer Vision, 24 (1997), pp. 137–154

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

How?

- At minimum, the vendor should disclose:
 - 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?





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

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

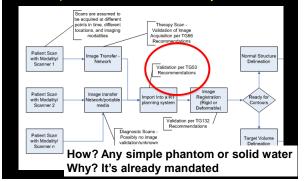
4%	1.	Not important
22%	2.	Only important for someone who wishes to write their own algorithm
11%	3.	Less important than the ability to do purple- green color blending
4%	4.	Important to know for commissioning, as they impact the accuracy of the algorithm
7%	5.	Cubed Subtracted Less One (CSLO)

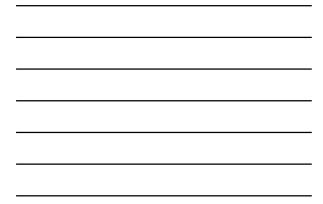
2. The subtleties in the implementation of image registration are:

- 1. not important
- 2. only important for someone who wishes to write their own algorithm
- 3. less important than the ability to have purple-green color blending
- 4. only important if it is a stand-alone image registration system
- 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

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





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

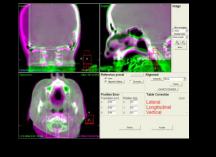
- Deformable Registration Algorithm
 - Find out how it works!
 - Accept and Commission the software
 - Perform an end-to-end test in your clinic

How do we do it?

• What tools do we have?

Visual Verification

Excellent tool for established techniques Not enough for Commissioning



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

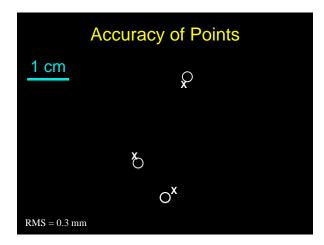
Landmark Based



- 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

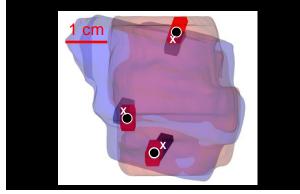
That sounds great! Is that enough?

- J J

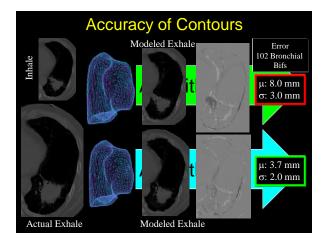


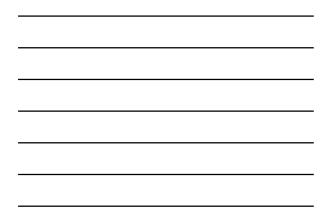


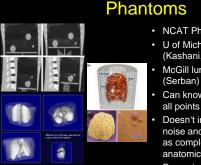
Points Don't Tell the Whole Story











NCAT Phantom

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

3. Target registration error (TRE) is defined as

11% 1. the uncertainty in selecting landmarks on an image

- 7% 2. the average residual error between the identified points on Study B and the points identified on Study A, mapped onto Study A' through image registration
- 7% 3. the improvement in accuracy when using deformable registration over rigid registration
- 11% 4. the volume overlap of 2 contours on registered images
- 18% 5. the mean surface distance between 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.

4. Visual verification (e.g. split screen, blended images, structure mapping) following image registration

- is a quick method to perform qualitative validation of image registration in a clinical workflow following the quantitative commissioning of an algorithm
- 17% 2. has no role in a well-established program
- 17% 3. should be the essential component of commissioning
- 10% 4. should never be used by the radiation oncologist
- 7% 5. should only be used by physicist with 20/20 vision

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

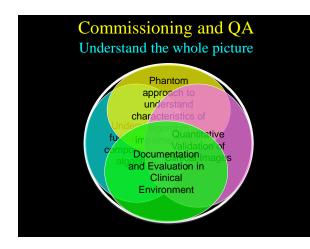
5. Image registration for adaptive radiotherapy is particularly challenging because

- 3% 1. the images are always multi-modality
- 21% 2. the patient cannot be imaged in an immobilization device
- 0% 3. the second image must be at half-resolution
- 0% 4. the patient has typically responded to therapy, therefore the volume of tissue is not the same in both images
- 7% 5. deformable registration cannot be used in this case

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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

- 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

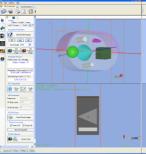
- Helps us to learn the impact of the 'knobs' of the registration
- Validation of most straightforward case
- Similar to 20x20 field profile

V Constant Landon 2 Line 2 Lin

* Phantom Data Courtesy of ImSim QA

Example Commissioning Tests

Offset to Primary d Defined default, entire FOV default, entire FOV	dx -10	AP dy 5	SI dz	rotx	roty	
Defined default, entire FOV	-10		dz	rotx	rotu	
default, entire FOV					TOLY	rotz
		5	-15	0	0	0
default, entire FOV	-10			0.2	0	0
	-9.9	4.5	-13.5	0	0	0
default, entire FOV	-10	4.9		0	0	0
default, entire FOV	-10	5.2	-13.8		0	0
default, entire FOV	-8.3				0	0
AVG	-9.64				0	0
SD	0.75				0	0
AVG Deviation from Defined Offset	0.36	-0.18	1.42	0.04	0	0
Offset to Primary d	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
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15		0	0
User Defined (4th step with 1 mm resolution), entire FOV	-10	5	-15		0	0
AVG	-10				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



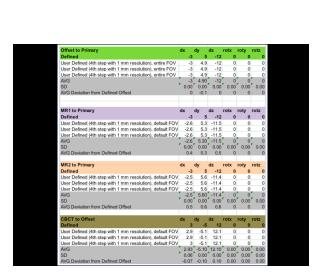


Rigid Anatomical Phantom

Multi-Modality

•

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





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:

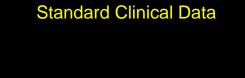
Prostate with added Gaussian noise variation and the following global offsets: To left = 0.3 cm, to anterior = 0.5cm, To inferior = 1.2 cm. 3 markers were set inside the prostate regions, prostate volume increased by105%, - 10° about X-axis, + 10° about Zaxis.

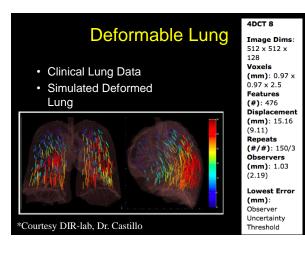
Planton And TEST Collerance Scale - Dutaset 1 Scale - Dutaset 1 Scale - Dutaset 1 Control (norm) Scale - Dutaset 1 Control (norm) Vozel value - Dataset 2, 3, 4, 5, 6 Control (norm) Control (norm) registration Control (norm) Scale - Dutaset 1 Control (norm) Registration - Datasets 2, 3, 4, 5, 6 Control (norm) Control (norm) registration Control (norm) Maxel - Dataset 1, 3, 4 Correct Scale - Dataset 1, 2, 3, 4, 5, 6 Control (norm) Control (norm) registration Control (norm) Orientation - Datasets 2, 3, 4, 5 Control (norm) Control (norpolgation - Datasets 2, 3, 4, 5 Control (norm) Control (norpolgation - Datasets 2, 3, 4, 5 Control (norm) Control (norpolgation - Dataset 2, 3, 4, 5 Control (norm) Control (norpolgation - Dataset 2, 3, 4, 5 Control (norm) Control (norpolgation - Dataset 2, 3, 4, 5 Control (norm) Control (norpolgation - Dataset 2 Correct Stale (deformation phantom registration (norpolgation - Dataset 2) Correct Stale (deformation - Dataset 2) Correct Correct

ataset 2 t 2 Pataset 2 n, max error less than 5 mm

0.5 * voxel (mm) within 2 mm, max error less

95% of



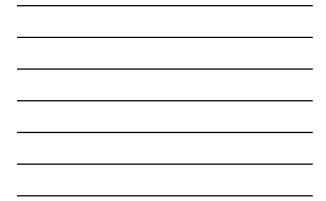


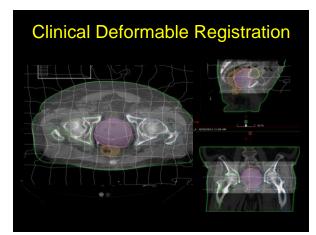
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Your Clinical Data!

Rigid Registration of Clinical Data

Patient		\$ECLIPS	E1, LIV\$II	ISBRT\$C	TMR		
User		dx	dy	dz	rotX	rotY	roZ
	1	-4.1	103.4	-58.3	0	0	0
	2	-5.7	105.5	-59.7	5.8	1.1	-1
	3	-2.7	104.9	-60.8	0	0	4.5
	4						
	5	-3.1	108.7	-58.4	1.2	-0.1	6.4
	6	-3.9	100.8	-59.5	0	0	-1.1
	7	-3.9	104.6	-56.6	0.1	-0.5	4.1
	8	-2.9	106.8	-60.4	4.4		0.4
	9	-3.7	106.3	-59.1	0	0	1.9
CT_Liver+1 cm		-4.6	109.9	-61.4	3.6	0.7	3.4
CT_GTV+1 cm		-2.5	106.4	-59.9	-1.3	-0.9	4.2
Clipbox around tumor		-2.6	110.1	-57.6	2	-0.7	4.2
AVG Users		-3.8	105.0	-59.1	1.6	0.1	1.9
SD Users		1.0	2.5	1.4	2.4	0.5	3.0
CT_Liver1-AVG		-0.7	5.2	-2.1	2.2	0.5	1.6
CT_PTV1-AVG		1.4	1.7	-0.6	-2.7	-1.1	2.4
Clipbox around tumor-AVG		1.2	5.1	1.5	0.4	-0.8	2.3

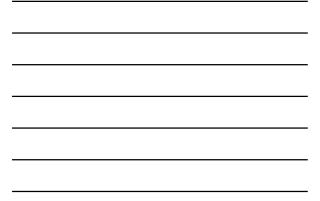




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Clinical Deformable Registration

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

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



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

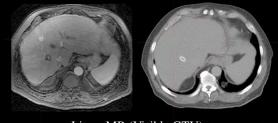
How?

- Visual Verification
- Spot checks of landmarks
- Boundary comparison

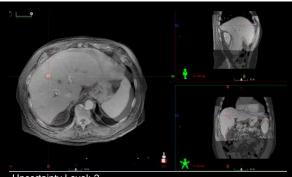
Uncertainty Assessment	Phrase	Description
0	Whole scan aligned	Anatomy within 1 mm everywhere Useful for structure definition everywhere Ok for stereotactic localization
1	Locally aligned	 Anatomy local to the area of interest is un-distorted and aligned within Imm Useful for structure definition within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

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
- 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
- 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

- 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