The ACPSEM Medical Image Registration Special Interest Group (MIRSIG) Online Webinars

The June 2020 Webinar is chaired by Laurel Schmidt and Joel Poder (2/6/20).

- Talk 1: **AAPM Radiation Therapy Committee Task Group 132: Content and Recommendations**

Presented by John Kipritidis

Webinar activities!! -Use the "Q&A" to ask questions! -"Like" questions! -Live polls!	**Post webinar survey!** -Share any insights, questions, or comments out with a post webinar survey -EOI for your presentation	**Seminar material available online!** The following material will be shared as PDFs online on the ACPSEM website MIRSIG welcomes professionals from all disciplines.	**Be more involved!** 1. MIRSIG welcomes professions from all disciplines, including radiation therapists and radiation oncologists 2. Sign up to the MIRSIG mailing list (https://www.acpsem.org.au/Home , click myACPSEM, click speciality groups, tick MIRSIG) 3. Join MIRSIG as a member, email mirsig@acpsem.org.au

AAPM Radiation Therapy Committee Task Group 132: Content and Recommendations

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Learning objectives:

- Learn about the AAPM TG-132 recommendations & guidelines for using image registration in all aspects of radiotherapy
- Describe the meaning of image registration and fusion
- Review of the components of an image registration algorithm
- Understand the difference between rigid, affine and deformable registration
- Understand key sources of error related to data acquisition and image registration
- Understand the need for QA of image datasets/ registrations:
  - Gain familiarity with methods for qualitative and quantitative assessment of image registration accuracy
- Describe frameworks and datasets available to carry out commissioning of registration software
- Be able to perform patient specific registration verification in a radiotherapy department:
  - Review key elements of the radiotherapy image registration request and report

Acknowledgements: Special thanks to the RNSH Physics team.

A guided tour of TG-132

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Use of image registration and fusion algorithms and techniques in radiotherapy: Report of the AAPM Radiation Therapy Committee Task Group No. 132

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- Stated goal of TG-132:
  - "[To] *review current approaches and solutions for image registration (both rigid and deformable) in radiotherapy and to provide recommendations for quality assurance and quality control of these clinical processes.*"

A guided tour of TG-132

TABLE OF CONTENTS

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I. Introduction

a. Image data in radiotherapy:

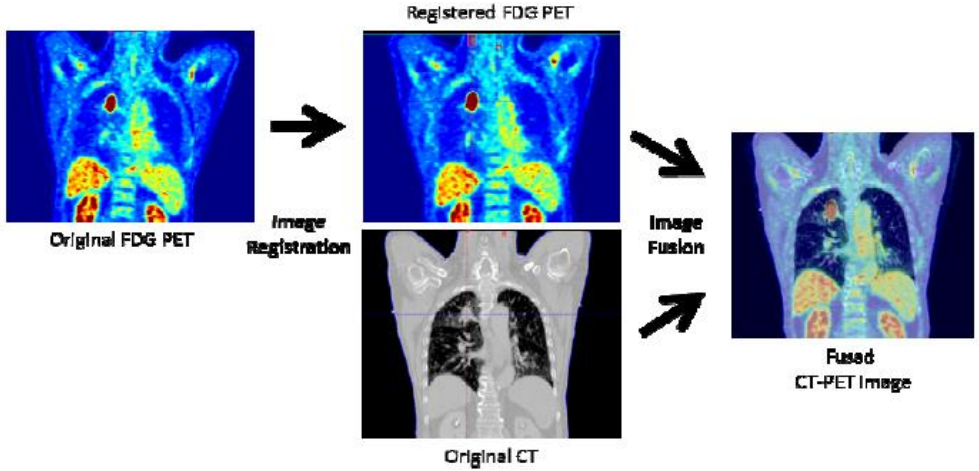
Multiple imaging modalities:

- X-ray computed tomography (CT)
- Magnetic resonance imaging (MRI)
- Positron emission tomography (PET)
- Single photon emission computed tomography (SPECT)
- In-room kilovoltage (kV) or megavoltage (MV) planar imaging
- In-room kV/MV cone beam CT (CBCT)
- Real time volumetric ultrasound (US)

b. Uses of image registration + fusion in RT:

Multiple applications:

- Segmentation
- Multi-Modality Treatment Planning
- Image-Guided Radiotherapy
- Adaptive Treatment Planning
- Response assessment



I. Introduction

d. Glossary of Terms

– **Image registration** is the process of determining a geometric transformation relating identical (anatomic) points in a `moving' dataset (*Study A*) and a `stationary' source dataset (*Study B*).

In the language of Velocity and MIM:
- Study A is the "secondary image"
- Study B is the "primary image"

Consider:
- Does an identical transform exist?
- How accurate is the transform we have derived?

– The **transformation (T)** is one of the results of image registration: it is a function applied to *Study A* to align it with *Study B.*

Mathematically:
- *Study B* = T(*Study A*)

– **Image fusion –** the combined display of mapped data from *Study A* onto *Study B* with the transformation applied.

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TABLE OF CONTENTS

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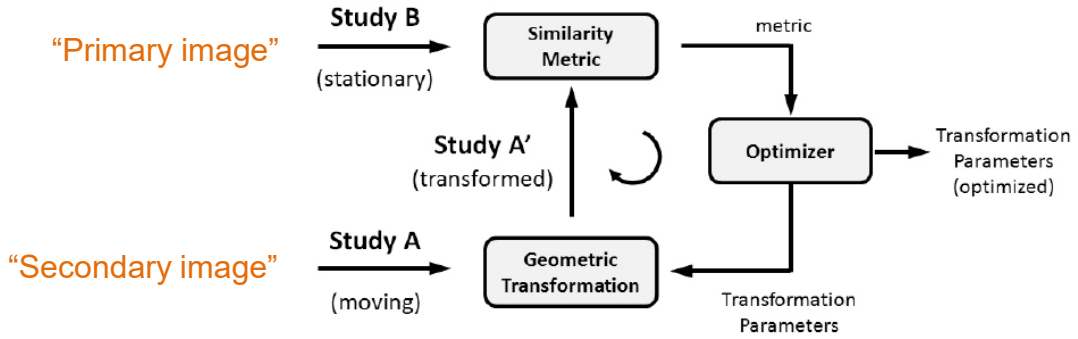
II. Techniques for image registration

- Fig. 2: Basic mechanics of an image registration algorithm:



- Characterising an image registration algorithm:

a. Dimensionality
b. Nature of registration basis
c. Nature of transformation
d. Domain of transformation
e. Interaction
f. Optimisation procedure
g. Modalities involved
h. Subject
i. Limitations and Challenges

II. Techniques for image registration

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b. Nature of the registration basis

Is the registration "*extrinsic*" (e.g. based on fiducials or other extracted geometry) or "*intrinsic*" (voxel data)?

- The ***registration metric*** quantifies the extent to which the images are aligned:

TABLE I. Similarity metrics.

Class	Metric	Description
Voxel intensity-based	Sum of the squared difference (SSD) (Mean squared difference, MSD)	$\mathrm{SSD} = \sum (I_{A'} - I_B)^2 / \mathrm{N}.$
	Correlation coefficient (CC)	$C = \sum_{\vec{x}} B(\vec{x}) \cdot T(A(\vec{x}))$
	Mutual Information (MI)	$MI(I_{A'}, I_B) = \sum_B \sum_A P(I_{A'}, I_B) \log_2 [p(I_{A'}, I_B)/p(I_{A'})p(I_B)]$
Feature-based	Point-based	$R = \sum (p_{A'} - p_B)^2 / \mathrm{N}.$
	Contour-based	$\mathrm{R} = \sum \mathrm{dist}(p_{A'}, S_B)^2 / \mathrm{N},$

II. Techniques for image registration

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c. Nature of the transformation

Considers questions like: How many degrees of freedom does the transformation have? Is it invertible?

TABLE II. Commonly used transformation models. (N = number of voxels in an image).

Class	Transformation	Maximum dimensionality of transformation	Description
Geometric	Rigid	6	Allows translation in 3 directions and rotations about 3 axes
	Affine	12	In addition to translation/rotation, allows uniform scaling and sheer (e.g., parallel lines stay parallel)[44–48]
	Free-form	3N	Local, voxel-based deformation, often regularized by a smoothing parameter
	Global spline-based methods (e.g., thin plate splines)	3N	Parameterizes deformation using a parametric grid of basis function control points with constrained global influence (e.g., deformation is global)[34,49–66]
	Local spline-based methods (e.g., B-spline)	3N	Parameterizes deformation using a weighted grid of control points of basis functions with local influence (e.g. deformation is local)[17,67–101]
Physical	Viscous/elastic/optical flow (e.g., demons)	3N	Spatially variant voxel displacement voxel displacement by a vector field in a deforming medium, by intensity gradients (deformation is local)[102–110]
	Finite element methods (FEM)	3N	Spatially variant voxel displacement voxel displacements governed by biomechanical tissue properties (deformation is local)[55,92,111–135]

III. Clinical issues of image registration in radiotherapy

- **A. Sources of error in data acquisition:**

Limitations in scan extent, slice thickness, or image quality of individual studies can affect the accuracy of their registration with other studies.

- **B. Sources of error in image registration:**

Uncertainties can arise due to image artifacts (metal or motion), contouring variability, feature selection, discontinuous motion (e.g. lung/chest wall interface), anatomic changes and interpolation/extrapolation of motion fields.

Or, in other words..

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TABLE OF CONTENTS

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IV. Methods for validation and quality assurance

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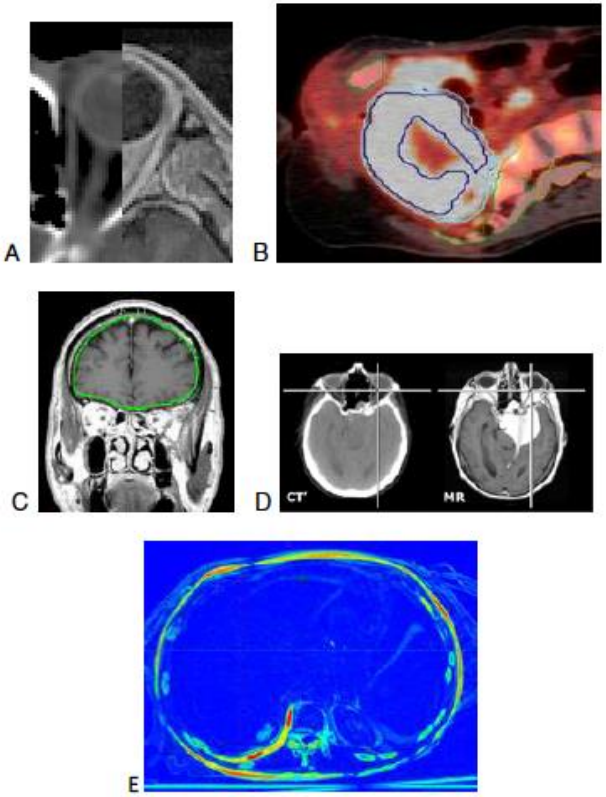
a. General concepts

Image registration errors can stem from multiple factors such as image distortions, inability to reproducibly select fiducial points represented in both image sets to be registered, registration algorithm limitations, incorrect selection of registration algorithm parameters, etc. The ability to accurately assess registration errors partially depends on the tools provided in the image registration software and the ability of the user to interact with the registration results. Other considerations include spatial distortions (e.g. MR distortion) as well as the final clinical endpoint for evaluated images. The overall image registration accuracy for the majority of clinical applications, where an in-plane resolution is ~1 mm and slice thickness is ~2-3 mm, is typically desired to be within 2 mm. Therefore, the registration evaluation process has to be able to support this accuracy and evaluation tools need to be able to detect registration errors in individual directions that are smaller than the composite error.

IV. Methods for validation and quality assurance

b. Qualitative validation and verification of image registration accuracy
(Useful in routine clinical practice)



Split Screen and Checkerboard Displays

Split screen, floating window (i.e. a window on Study B that shows Study A'), and checkerboard displays as shown in Figure 5.A are the most commonly-used form of qualitative visualization tool for detecting registration error in the clinical setting. They are particularly effective in identifying mismatches between corresponding structures at high contrast tissue interfaces. The split screen partition and checkerboard locations are typically a user-controllable aspect of these displays.[155]

Image Overlay Displays

Image overlay displays as shown in Figure 5.B produce images that are the blended composition of registered images. Often the reference image is presented in gray scale color map and the floating image is presented in a color scale. The user is typically able to control the choice of grayscale and color maps and the fraction of reference and floating image in the blended display.

Difference Image Displays

Difference image displays are useful for intra-modality visualization of registration accuracy (*e.g.*, CT/CT, MR/MR). The display is created by subtraction of co-registered voxel intensities. If the absolute value of the difference is used, a perfect intensity match at the voxel level leads to a display level of 0 (black); as the mismatch gets worse, the color displayed for the voxel gets brighter, approaching white. The utility of these displays in the clinical setting is limited as they are very sensitive to the exact voxel values of the registered datasets.

Contour/structure mapping displays

Contour overlays as shown in Figure 5.B and 5.C are useful for multi-modality image registration. Anatomical contours defined on one imaging modality can then be overlaid, in the same spatial location, on the second imaging modality. Qualitative assessment of correlation of the contour to the anatomy on the secondary image can aid in validating the registration results, although this must be interpreted in the context of the visibility of the anatomy.[156,157]

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IV. Methods for validation and quality assurance

c. Quantitative measures of registration accuracy (esp. useful for commissioning)

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TABLE III. Quantitative metrics to evaluate image registration.

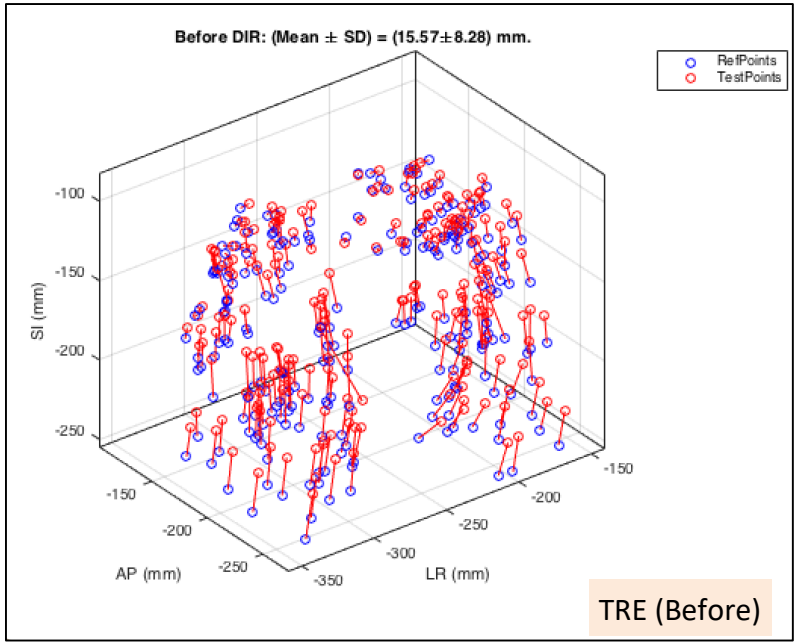
Technique	Evaluation metric	Tolerance
Target registration error (TRE)	Point-based accuracy metric using implanted or naturally occurring landmarks visualized on a pair of images	Maximum voxel dimension (~2–3 mm)
Mean distance to agreement (MDA)	Mean surface distance between 2 contours on registered images	Within the contouring uncertainty of the structure or maximum voxel dimension (~2–3 mm)
Dice similarity coefficient (DSC)	Volumetric overlap of 2 contours on registered images	Within the contouring uncertainty of the structure (~0.80–0.90[a])
Jacobian determinant	Volume expansion or contraction resulting from a deformable image registration	No negative values, values deviating from 1 as expected from clinical scenario (0–1 for structures expected to reduce in volume, greater than 1 for structures expected to expand in volume)
Consistency	Independence of an algorithm to the direction of the registration (image A to image B or image B to image A)	Maximum voxel dimension (~2–3 mm)

[a]DSC calculations are dependent on the volume of the structure, therefore very large or very small structures may have different expected DSC values for contour uncertainty.

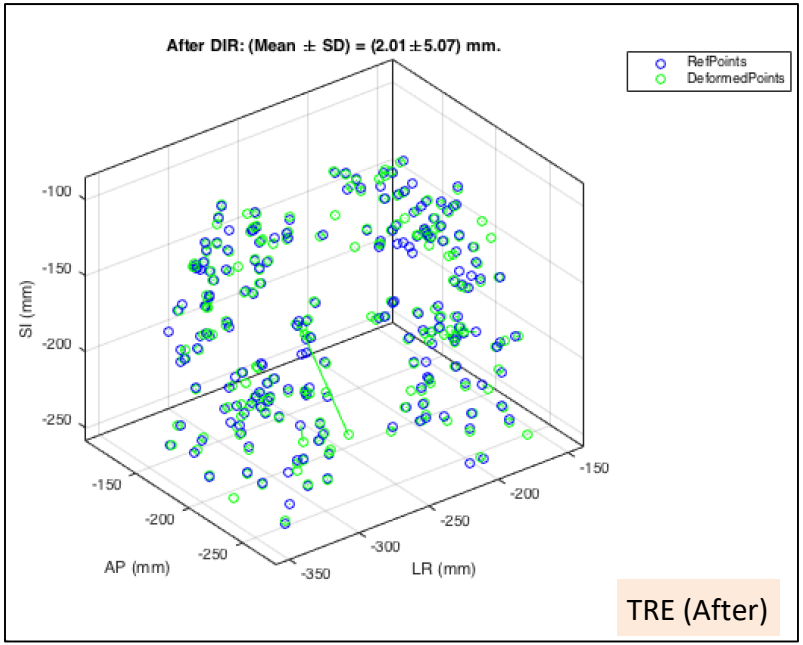
IV. Methods for validation and quality assurance

c. Quantitative measures of registration accuracy (esp. useful for commissioning)

Target registration error (Tolerance: 2-3mm)



TRE (Before)



TRE (After)

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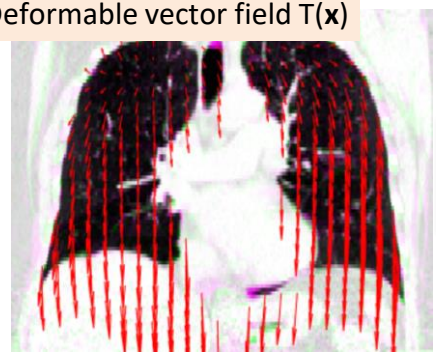
IV. Methods for validation and quality assurance

c. Quantitative measures of registration accuracy (esp. useful for commissioning)

Jacobian determinant (Tolerance: no negative values)

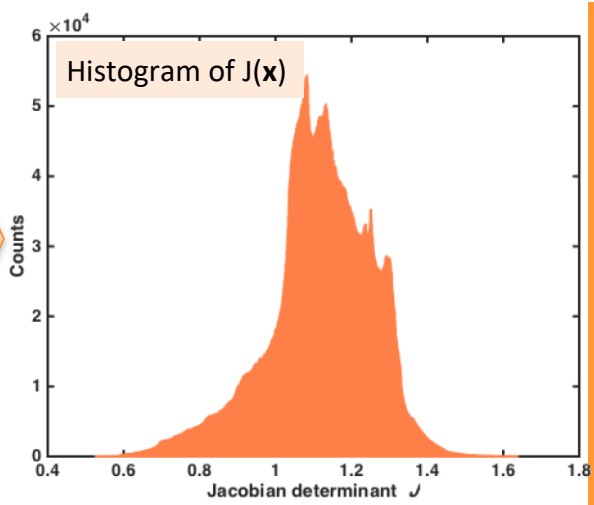
Deformable vector field T(**x**)



$$J(\mathbf{x}) = \begin{vmatrix} 1+\frac{\partial T_x(\mathbf{x})}{\partial x} & \frac{\partial T_x(\mathbf{x})}{\partial y} & \frac{\partial T_x(\mathbf{x})}{\partial z} \\ \frac{\partial T_y(\mathbf{x})}{\partial x} & 1+\frac{\partial T_y(\mathbf{x})}{\partial y} & \frac{\partial T_y(\mathbf{x})}{\partial z} \\ \frac{\partial T_z(\mathbf{x})}{\partial x} & \frac{\partial T_z(\mathbf{x})}{\partial y} & 1+\frac{\partial T_z(\mathbf{x})}{\partial z} \end{vmatrix}$$

Jacobian determinant J(**x**)

Histogram of J(**x**)



The Jacobian determinant is useful to "screen" a registration for problem areas.

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TABLE OF CONTENTS

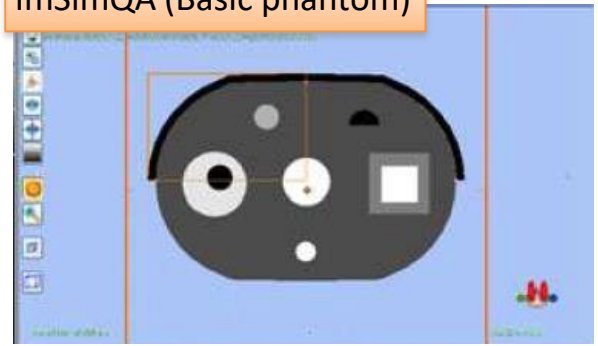
NORTHERN SYDNEY CANCER CENTRE

V. Commissioning and validation of registration software

a. Commissioning

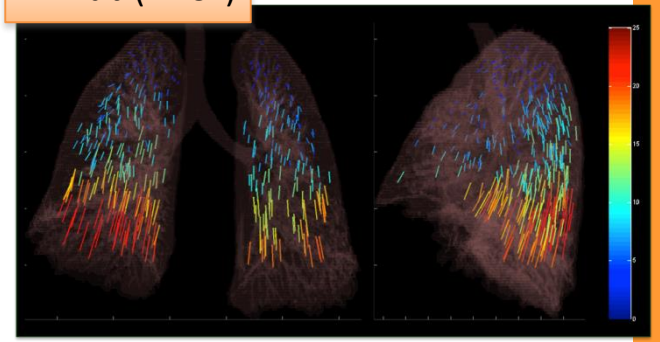
- Commissioning should make use of digital phantoms with known (synthetic) transformations and/or fiducials
- **AAPM TG-132 datasets:** https://www.aapm.org/pubs/reports/report132.asp

ImSimQA (Basic phantom)



ImSimQA (Pelvis phantom)

DIR-lab (4DCT)



The AAPM TG-132 datasets were generated using a commercial software (ImSimQA) or were contributed from the DIR-lab (www.dir-lab.com)

V. Commissioning and validation of registration software

a. Commissioning (Cont'd).

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Provided datasets

TABLE V. Digital phantom dataset generated by ImSimQA™ software (Oncology System Limited, UK (OSL, www.imismqa.com)).

Dataset	Description
Basic phantom dataset - 1	Reference dataset — HFS — black image with white and 3 shades of gray images. The voxel dimensions of all basic phantom datasets are 0.7 × 0.7 × 3 mm. Cone pointing superior, semicircle on right side, cube anterior to cylinder, 3 skin markers, and 3 internal markers, all in the same reference frame with defined perfect registration by generation of images with the following parameters: CT PET MR T1-weighted (TR = 500 ms, TE = 12 ms) MR T2-weighted (TR = 4000 ms, TE = 120 ms) CBCT (with noise added)
Basic phantom dataset - 2	Same as basic phantom dataset - 1 -CT - with the following offsets: to left = 1.0 cm, to anterior = 0.5 cm, to inferior = 1.5 cm
Basic phantom dataset - 3	Same as basic phantom dataset - 1 - CT - with the following offsets: to left = 0.5 cm, to anterior = 1.5 cm, to inferior = 2.0 cm, rotation = −5° about X-axis, +8° about Y-axis, +10° along Z-axis
Basic phantom dataset - 4	Same as basic phantom dataset - 1 - CT - except it is FFS
Basic phantom dataset - 5	Same as basic phantom dataset - 1 - CT - except it is HFP
Basic phantom dataset - 6	Same as basic phantom dataset - 1 - CT - except it is FFP
Basic anatomical dataset -1	Reference dataset – CT – HFS — the pelvis phantom provided by ImSimQA™ software (oncology system limited, UK (OSL)) with 3 markers in the region of bladder, prostate, and rectum. The voxel dimensions of the CT, CBCT, and PET basic anatomical datasets are 0.91 × 0.91 × 3 mm. The voxel dimensions of the MR basic anatomical datasets are 1.83 × 1.83 × 3 mm.
Basic anatomical dataset -2	Same as basic anatomical dataset -1 – CT - with offsets of: To left = 0.3 cm, to anterior = 0.5 cm, to inferior = 1.2 cm
Basic anatomical dataset -3	Same as basic anatomical dataset -1 - PET – HFS - with offsets of: to left = 0.3 cm, to anterior = 0.5 cm, to inferior = 1.2 cm
Basic anatomical dataset -4	Same as basic anatomical dataset -1 - MR-T1 – HFS - with offsets of: to left = 0.3 cm, to anterior = 0.5 cm, to inferior = 1.2 cm
Basic anatomical dataset -5	Same as basic anatomical dataset -1 - MR-T2 – HFS - with offsets of: to left = 0.3 cm, to anterior = 0.5 cm, to inferior = 1.2 cm
Basic deformation dataset - 1	Same as basic anatomical dataset - 1 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. Three markers were set inside the prostate, rectum, and bladder regions, prostate volume increased by 105%, −10° rotation about X-axis, +10° rotation about Y-axis, +10° rotation about Z-axis.
Clinical lung dataset – end exhalation and end inhalation	DIR-Lab 4D CT dataset (end exhalation and end inhalation reconstruction only) with semiautomatically selected bifurcation points (courtesy of the DIR-Lab, www.dir-lab.com/4DCT6.html)

HFS, head first supine; HFP, head first prone; FFS, feet first supine; FFP, feet first prone.

Recommended tests & tolerances

TABLE VI. Recommended tests and tolerances for the digital phantom test cases. See Table IV for recommended testing schedule. Here the voxel dimension should be the calculated as the 3D vector magnitude of the image with the largest voxel size to reflect the nonisotropic size of most imaging voxels.

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 the phantom within 2 mm Max error less than 5 mm
Sliding deformation dataset - 1	Sliding deformation dataset - 2	Deformable Registration	95% of voxels within the phantom 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

V. Commissioning and validation of registration software

Quality metrics & Tolerances for Commissioning, Annual QA & Patient-specific QA:

TABLE IV. Quality metrics and tolerances for commissioning, annual QA, and patient-specific QA for image registration.

Use case	Quality metric	Tolerance
Commissioning, annual, and upon upgrade	Data transfer (including orientation, image size, and data integrity), performed from end-to-end across the entire system using a physics phantom	Exact
	Rigid registration accuracy (digital phantoms, subset)	Baseline, see details in Table VI
	Deformable registration accuracy (digital phantoms, subset)	Baseline, see details in Table VI
	Example patient case verification ((including orientation, image size, and data integrity) using real clinical case	Baseline, see details in Table VI
Each patient	Data transfer	Exact
	Patient orientation	Image data matches specified orientation (superior/inferior, anterior/posterior, left/right)
	Image size	Qualitative – no observable distortions, correct aspect ratio
	Data integrity and import	User defined per TG53 recommendations
	Contour propagation	Visual confirmation that visible boundaries are within 1–2 voxels of contours
	Rigid registration accuracy	At planning: confirmation that visible, relevant boundaries of anatomy in the registered images are within 1–2 voxels of the registered image; additional error should feed into margins At treatment: confirmation that visible boundaries are within PTV/PRV margins (doesn't account for intrafraction motion)
	Deformable registration accuracy	At planning: confirmation that visible, relevant boundaries and features of anatomy in the registered images are within 1–2 voxels of the registered image; additional error should feed into margins; evaluate reasonableness of the deformation vector field; perform quantitative evaluation if results are questionable or if accuracy requirements are significant (e.g., SBRT, dose mapping for critical tissues) At treatment: confirmation that visible boundaries are within PTV/PRV margins (does not account for intrafraction motion)

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b. Patient-specific verification during clinical practice: the **request** and the **report**.

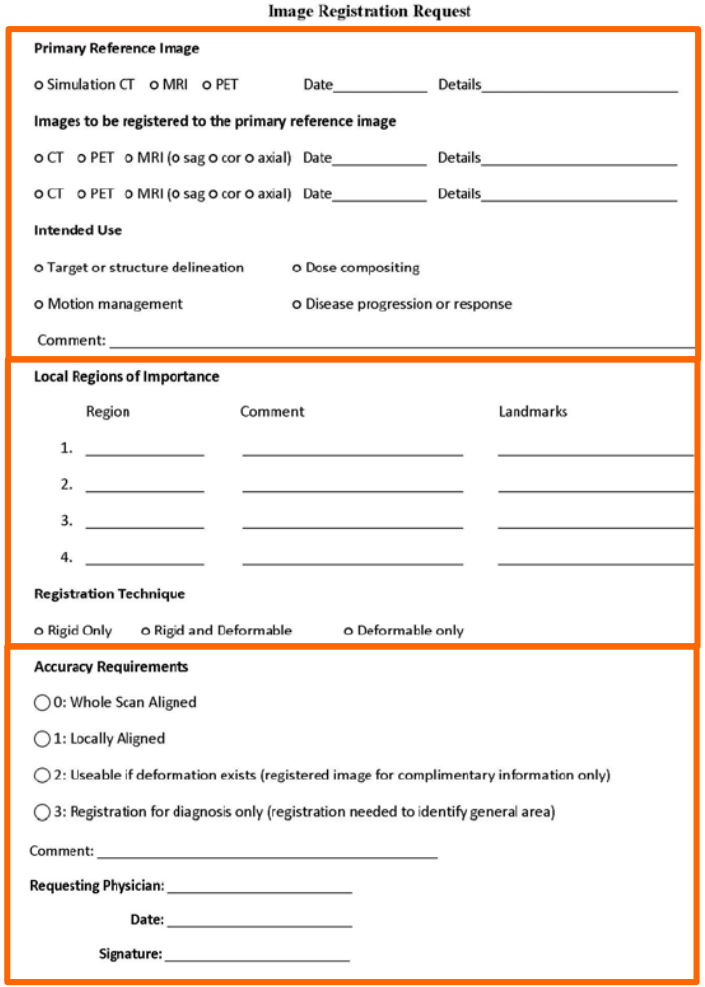

Image Registration Request

Primary Reference Image

o Simulation CT o MRI o PET Date_____ Details_____

Images to be registered to the primary reference image

o CT o PET o MRI (o sag o cor o axial) Date_____ Details_____

o CT o PET o MRI (o sag o cor o axial) Date_____ Details_____

Intended Use

o Target or structure delineation o Dose compositing

o Motion management o Disease progression or response

Comment: _____

Local Regions of Importance

	Region	Comment	Landmarks
1.	_____	_____	_____
2.	_____	_____	_____
3.	_____	_____	_____
4.	_____	_____	_____

Registration Technique

o Rigid Only o Rigid and Deformable o Deformable only

Accuracy Requirements

◯ 0: Whole Scan Aligned

◯ 1: Locally Aligned

◯ 2: Useable if deformation exists (registered image for complimentary information only)

◯ 3: Registration for diagnosis only (registration needed to identify general area)

Comment: _____

Requesting Physician: _____

Date: _____

Signature: _____

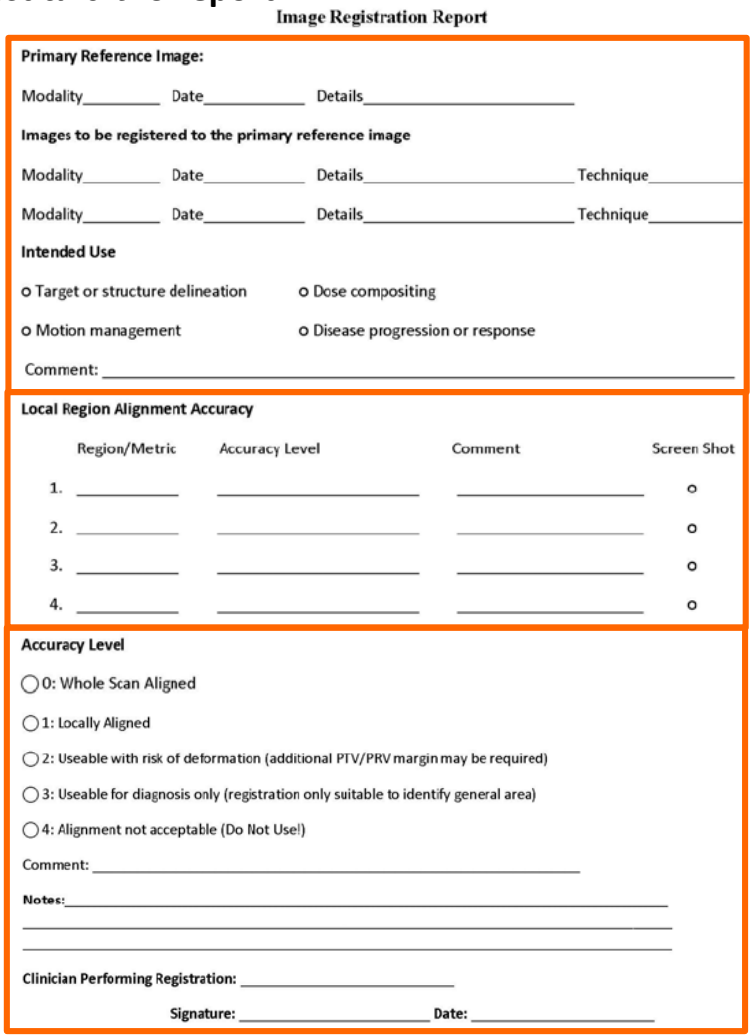

Image Registration Report

Primary Reference Image:

Modality_____ Date_____ Details_____

Images to be registered to the primary reference image

Modality_____ Date_____ Details_____ Technique_____

Modality_____ Date_____ Details_____ Technique_____

Intended Use

o Target or structure delineation o Dose compositing

o Motion management o Disease progression or response

Comment: _____

Local Region Alignment Accuracy

	Region/Metric	Accuracy Level	Comment	Screen Shot
1.	_____	_____	_____	o
2.	_____	_____	_____	o
3.	_____	_____	_____	o
4.	_____	_____	_____	o

Accuracy Level

◯ 0: Whole Scan Aligned

◯ 1: Locally Aligned

◯ 2: Useable with risk of deformation (additional PTV/PRV margin may be required)

◯ 3: Useable for diagnosis only (registration only suitable to identify general area)

◯ 4: Alignment not acceptable (Do Not Use!)

Comment: _____

Notes: _____

_____

_____

Clinician Performing Registration: _____

Signature: _____ **Date:** _____

VI. Clinical integration of registration techniques

Recommendations of the TG-132 report:

a. Treatment planning

- Processes should allow for consistent patient positioning between imaging studies.
- The image registration report should be completed prior to planning.
- Final review of the image registration should be performed by the RO.
- Unresolved registration errors should be accounted for in treatment margins (e.g. PTV).

b. Treatment delivery

- For each treatment site, a registration request should be made providing a clear directive on the region(s) of interest, important landmarks, required accuracy, etc.
- The registration should be performed by the RT, with appropriate training.
- For standard fractionation, the registration should be reviewed by the RO prior to delivery of next fraction.
- For single fractions >5 Gy, the registration should be reviewed by the RO prior to delivery.

Conclusions, I

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The recommendations of this task group can be summarized as follows:

Clinical Recommendations:

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, using a physical phantom, of imaging, registration, and planning/treatment systems if image registration is performed on a stand-alone system
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
    a. Estimation of registration error should be assessed using a combination of the quantitative and qualitative evaluation tools described in Tables 3 and 4. Regions with larger estimated errors 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

Conclusions, II

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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

Thank you!

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The ACPSEM Medical Image Registration Special Interest Group (MIRSIG) Online Webinars

Questions and Answers from the June 2020 Webinar Chaired by Laurel Schmidt and Joel Poder (Talk 1 by John Kipritidis)

Question 1: What open source software is available for investigation into DIR?

Answers: Two very good options for open source DIR software include the following US NIH-funded projects: 3DSlicer (a GUI-based software available at: https://www.slicer.org) and Plastimatch (a fully command-line software, available at: http://plastimatch.org). Both have cross-platform support (though you may have to compile source code in some cases), and both have good documentation and user forums/communities available via their respective project sites. Also interestingly, both 3DSlicer and Plastimatch have some tools/capabilities that go far beyond just DIR; for example they include many tools for basic image conversion, filtering/smoothing and contouring/segmentation in the context of developing other workflows.

Question 2: What are recommendations for dose accumulation?

Answers: The AAPM TG-132 report provides general guidelines on the uses and quality assurance for image registration; dose accumulation is recognised as one of these applications. In section 6.C. of TG-132, it is stated that dose accumulation "*has additional demands on accuracy compared to the use of deformable registration for contour propagation […] every voxel receiving significant dose should be accurately aligned, whereas for contour propagation the accuracy is most important at the boundary of the organ.*" However, TG-132 also specifically mentions that the use of DIR for dose accumulation and subsequent adaptive replanning is outside of the scope of the document, and that there should be a future report dedicated to this matter.

Question 3: What is your advice on patient specific TG132 request and report forms?

Answers: The exact form of a request / report system will depend on the infrastructure available within the department. For example one option is to create a set of electronic questionnaires or forms, linked to check-points requiring sign-off/approval at specific steps within the treatment planning process. At RNSH, an “Image Registration Review” task is part of the Care Path for all patients requiring an image registration process. It should noted that different treatment sites will have specific requirements in terms of what types of checks are required.

Question 4: What role would quantitative QA have for patient specific QA?

Answers: The ability to perform quantitative QA on a patient-specific basis (e.g. in terms of analysing target registration error, the Jacobian determinant histogram and Dice similarity index) is highly desirable but not always feasible given the manual workflows for those processes in commercial image registration software. It is nevertheless considered an essential part of commissioning for any new image registration process; the need of quantitative PSQA should also be considered during the commissioning stage.