Deformable Image Registration in Radiation Oncology

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Overview

➢ When is deformable image registration (DIR) useful?

➢ Deformable image registration basics

➢ Commercial DIR options

➢ DIR advantages/challenges
  (i.e. where things go right/wrong)
What is DIR?
Deformable Image Registration

- Deformable registration warps moving image (M) via deformation field (DF) to align (M) to the target image (T).
- DF defines the motion of each image voxel from M to T.
- This produces a registered image (R).

moving (M)  
registered (R)  
defformation field (DF)  
target (T)
When is DIR Useful?
Dose Fusions
Dose Fusions

register images
Dose Fusions

register images

map dose
Dose Fusions

- Re-treatment
- Re-planning
- Respiratory motion
- Adaptive RT
- Treatments planned on differing modalities with different clinical setup (e.g. prostate IMRT with HDR boost)

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map dose
Dose Fusions

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  (e.g. prostate IMRT with HDR boost)

Comparing/summing doses calculated on different image volumes.

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Contour Guidance

• Fuse multiple modalities to aid physician with target contours.

planning CT  diagnostic MRI

(Images courtesy of Mirada Medical)
Contour Guidance

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(Images courtesy of Mirada Medical)
Atlas-Based Contouring

- Contours are generated from patient-atlas
- Can improve contouring efficiency
- Requires building atlas
- Often requires contour corrections ("cleanup")
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*Evaluation of Commercial Solutions for Auto-seg • RO • La Macchia et al. • 2012
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Contour Propagation

- Re-treatment
- Re-planning (planning on new CT)
- Adaptive RT

*Relatively straightforward. Can speed workflow.*

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General DIR Workflow

specify moving & target image

- propagate contours
- propagate dose

choose ROI

evaluate registration

rigid registration

deformable registration

• propagate dose
To register images, a transformation is required that maps voxels of one image onto another image’s coordinate system.

1. Translations & Rotations (rigid)
2. Parameterized Basis Functions
3. Fluid/Elastic
4. Tissue Mechanics
Rigid Transformations (Global)

Rigid transformations in 2D:

\[ T(\vec{x}) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \vec{x} + \begin{bmatrix} t_x \\ t_y \end{bmatrix} \]

Rigid transformations in 3D:

\[ T(\vec{x}) = R_x R_y R_z \vec{x} + T \]

* Augmented Reality in Surgery • ARISER Summer School • Casciaro et al. • 2005
Parameterized (Local or Global)

e.g. B-Splines: piecewise polynomials that form a set of basis functions.

* Augmented Reality in Surgery • ARISER Summer School • Casciaro et al. • 2005
Borrowed from fluid and optical mechanics.

e.g.:
- Optical Flow (Fast Demons)
- Karhunan Loeve
- Horn & Schunk

* Augmented Reality in Surgery ● ARISER Summer School ● Casciaro et al. ● 2005
Biomechanical Models (Local)

Models including tissue mechanics (a set of PDEs) – discretized and solved using, e.g.:

- Finite Boundary Elements
- Finite Element Methods


Feasibility of a novel DIR technique ● Brock *et al.* ● *IJROBP* ● 2006
Once appropriate candidate transformations chosen, define cost function/error metric to identify “best” transformation.

Cost function =

image similarity
+ regularization
Choice of Optimization

While the optimizer impacts solution speed, as long as the optimizer does not stagnate in local minima, the cost function has a much greater effect on the final deformation result.

Tyler Bischel: bleedingedgemachine.blogspot.com/
Image Similarity

- Landmark-based: Distance between landmarks
- Segmentation-based: DICE-similarity between contours
- Intensity-based: Sum of squared differences between voxel HU values
  \[ \sum_{i=1}^{N} (\text{Registered}_i - \text{Target}_i)^2 \]
- Correlation-based: Mutual Information
Regularization

Constrains “bendiness” of the deformation field.

Many options exist (e.g. penalize thin plate bending energy, local Jacobian values, linear elastic energy, differences in b-spline parameters for adjacent voxels, etc.)

*Analytic Regularization Uniform Cubic B-splines ● MICCAI ● Shackleford et al. ● 2012
Landmark Registration

- Time-consuming (numerous landmarks)
- Provides only sparse data for driving the registration

* http://www.ariser.info/training/imgproc.php
Segmentation-Based

- Also termed contour guided DIR
- Differences between registered and target contours are included in the cost metric
- Requires contouring both image volumes
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Does not provide additional information internal to contours!
Voxel-Based Registration

• Sum of square differences of image intensity values (per voxel)

• When fusing images of differing modalities, (CT, MRI, PET, MVCT, etc.) mutual information metric is used.
Commercial DIR Options
MIMVista
MIMVista

- Deformation: Demons optical flow
- Image Similarity: [unimodal – least squares of voxel differences] & [multimodal – mutual information (MI)]
- Regularization: proprietary – prevents tears & folds in deformation field. Additional regularization performed after optimal deformation identified.
- Optimization: Modified gradient descent
- Reg Reveal and Reg Refine provide interactive means of assessing and altering deformation fields
Velocity

(Images courtesy of Velocity)
Velocity

- Deformation: B-splines
- Image Similarity:
  - unimodal = least squares voxel differences
  - multimodal = mutual information
- Regularization: no post-optimization regularization
- Optimizer: gradient descent

- Allows voxel-wise query of deformation fields
- Built-in QA tools (Version 3.2)
Raystation

(Image courtesy of Raystation)
• Deformation: BEM-based tissue mechanics model
• Image Similarity:
  unimodal = least squares voxel differences
  multimodal = mutual information
• Regularization: grid-based term (maintain smooth and invertible deformations) + shape based term (maintains reasonable contours when present)
Mirada RTx

(Image courtesy of Mirada Medical)
Mirada RTx

- Deformation:
  - unimodal = Lucas Kanade optical flow
  - multimodal = radial basis functions
- Image similarity:
  - unimodal = least squares voxel differences
  - multimodal = mutual information
- Regularization: penalization of diffusion PDEs
- Deformations can be signed and locked
- Can quantitatively query the deformation on a per-voxel basis
Mirada RTx

(Images courtesy of Mirada Medical)
DIR Advantages/Challenges
Contour Propagation

Contours transferred from previous to new imaging.

Because image similarity guides registration particularly at high contrast areas (edges), contour propagation is reasonably reliable.

MD second check of contours – sufficient for patient-specific QA.
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Because image similarity guides registration particularly at high contrast areas (edges), contour propagation is reasonably reliable.

*MD second check of contours – sufficient for patient-specific QA.*
Contour Guidance

More reliable than dose warping, because only need accurate deformations near contours of interest.

However, registering different modalities is challenging!

- Mutual information is not as reliable as image similarity metric
- Different patient positions, slice thickness, and resolutions further challenge the registration algorithms

Patient specific QA challenging, because no ground truth available.

(Images courtesy of Mirada Medical)
Dose Registration/Summation

More difficult than contour guidance, because deformations must be accurate across entire treated volume.

*Patient specific QA challenging, because no way to determine true deformations.*

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Transformation Type Matters!

Bspline Transform

Demons Transform

Images courtesy of Velocity
Transformation Type Matters!

Bspline Transform  

Demons Transform  

(Images courtesy of Velocity)
Deformable or Rigid?

Accuracy depends on registration method:
– Rigid registration is more accurate than deformable registration

rigid: ~1-2 mm uncertainty*
deformable: ~5-7 mm uncertainty**

*Benchmark Test of Cranial CT/MR Registration • *IJROBP* • Kenneth et al. • 2010

**Need for application-based adaptation of DIR • *Med. Phys.* • Kirby et al. • 2013

**Performance of DIR in low contrast regions • *Med. Phys.* • Supple et al. • 2013
Regions of Low Contrast

Image similarity not always sufficient to guide deformations.

Registrations accuracy is better in areas of high HU contrast (e.g. borders of organs), poor in areas of homogeneous intensity (e.g. liver)
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underconstrained/underdetermined problem: insufficient information to accurately drive the deformation
Setup Differences

Registration methods cannot differentiate between patient tissue and setup materials, (e.g. pads, bolus, etc.)

Registration may push patient tissue to match setup materials.
Setup Differences

How to address?

1. Exclude additional materials from registration ROI
2. Mask out additional material (similar to tissue override in treatment planning).

(Images courtesy of Velocity)
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Biological Changes

(1) Tumor growth/shrinkage/surgical removal
(2) Radiation induced pulmonary fibrosis
(3) Weight changes

Considerations:

(1) How to produce good registrations?
   - introduction/removal of tissue presents substantial challenge to registration methods.
(2) How to compute radiation physics?
   - Simply warping dose same as the images is insufficient.
Example: Pulmonary Fibrosis

before treatment

following treatment

(Images courtesy of Velocity)
Example: Pulmonary Fibrosis

(Image courtesy of Velocity)
Example: Pulmonary Fibrosis
Example: Pulmonary Fibrosis

(Images courtesy of Velocity)
SAMs Questions
Which of the following situations is of LEAST concern for producing inaccurate/unreliable dose deformations?

(a) rigid registration for brain
(b) deformable registration for liver
(c) deformable registration for head and neck
(d) deformable registration for lung
(e) deformable registration for prostate
Which of the following situations is of LEAST concern for producing inaccurate/unreliable dose deformations?

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Answer: (a) rigid registration for brain.

Rigid registration for small regions of bony anatomy remain higher accuracy than deformable registrations (in general). DIR should not be used when rigid registrations will suffice.

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True or False, contours fused onto a newly acquired CT are sufficiently reliable that they need not be evaluated?

(a) True
(b) False
True or False, contours fused onto a newly acquired CT are sufficiently reliable that they need not be evaluated?

(a) True
(b) False
True or False, contours fused onto a newly acquired CT are sufficiently reliable that they need not be evaluated?

Answer: (b) False.

Though the reliability of contour fusion can be higher than dose fusion, propagated contours should always be double-checked by the attending.


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Answer: (b) False.

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Which statement is MOST correct?

(a) Visual comparison of the deformed and target images is sufficient to ensure deformation accuracy.

(b) Registering with larger regions of interest boxes generally produces more accurate deformations.

(c) Image transformations are always defined globally.

(d) DIR can produce inaccurate deformations in areas of low HU contrast.
Which statement is MOST correct?

(a) Visual comparison of the deformed and target images is sufficient to ensure deformation accuracy.
(b) Registering with larger regions of interest boxes generally produces more accurate deformations.
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(d) DIR can produce inaccurate deformations in areas of low HU contrast.
Which statement is MOST correct?

Answer: (d) DIR can produce inaccurate deformations in areas of low HU contrast.

DIR in areas of low HU contrast like liver can produce inaccurate deformations because the lack of image information cannot accurately drive the inverse solver.

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Additional Resources
Practical Workflow Tips

• Use appropriate deformation direction (i.e. choice of moving and target image).
• Initial rigid registration can substantially impact deformable registration.
• Be careful of ROI box size choice.
• Keep organized and name fusions appropriately!
Image Similarity vs. Regularization

The two terms are weighted, and the relative balance substantially effects the registration outcome.

Too much regularization – the transformation motion is too constrained, which can prevent decent registrations.

Too much image similarity – registration may warp voxels in very non-physical ways to match the images on the order of noise.
Rigid vs. Deformable

In some cases, rigid is preferable to deformable.

Here, the rigid registration is sufficient, and likely more accurate than deformable.
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Evaluating Registrations: Tools for Visual Assessment
Registration Evaluation

Important to assess registration quality of each registration performed and identify and discard unacceptable registrations

(1) Visual comparison of deformed and target images  
   (insufficient to detect all possible registration mishaps)

(2) Visual inspection of deformation field  
   (potentially catch additional registration errors)
First Step: Deformed Image

(Can catch many registration errors)

blend  checker board
Visual Comparison: Example
Visual Comparison: Example
Visual Comparison: Example
Second Step: Deformation Field

(Can catch more registration errors)

warped grid  vector field  heat maps

(Images courtesy of Mirada Medical)
Some companies white papers are more informative than others. Below is a list of URLs for the major commercial options.

- **MIMVista**: Call 216-455-0600 to request white paper.
- **Mirada**: http://www.mirada-medical.com/solutions/deformable-image-registration - (white paper is located at bottom of page)