Deformable Image Registration 101

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Outline

- **Basics components of DIR**
- Demons DIR
- B-Spline based DIR
- Evaluation
- Discussions

Why do we need DIR?

- DIR is an essential component for
  - daily dose accumulations (ART),
  - 4D dose calculation,
  - structure propagations from image to image,
  - tracking anatomy changes over the course of radiation therapy,
  - and, etc.

Q) Which of the following applications does **NOT** need DIR?

- 25% 1. Daily dose accumulations for ART
- 27% 2. 4D dose calculation based on 4DCT
- 25% 3. Contour propagation from one CT to another (abdomen).
- 23% 4. Electron block cutting.

Q1) Which of the following applications does **NOT** need DIR?

- Answer: 4

What is Image Registration?

- “The process of determining the spatial transformation that maps points from one image to homologous points on a object in the second image.” - ITK[1]
- “The task of finding a spatial one-to-one mapping from voxels in one image to voxels in the other image.” – elastix[2]

1) Luis Ibáñez et al , “The ITK software guide : updated for ITK version 2.4”, 2005
2) S. Klein, M. Staring, K. Murphy, M.A. Viergever, J.P.W. Pluim, "elastix: a toolbox for intensity based medical image registration," IEEE Transactions on Medical Imaging, vol. 29, no. 1, pp. 196 - 205, January 2010.

What is Image Registration?

- Finding **T (transformation)** !

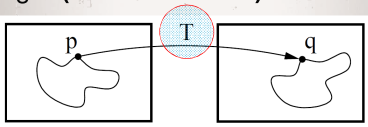


Figure 8.1: Image registration is the task of finding a spatial transform mapping on image into another.

1) Luis Ibáñez et al , "The ITK software guide : updated for ITK version 2.4", 2005

Then, How it works?

Basic Components of Image Registration

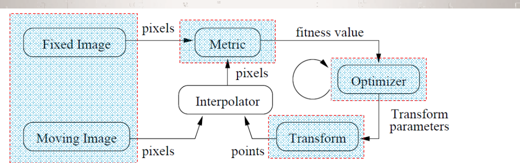
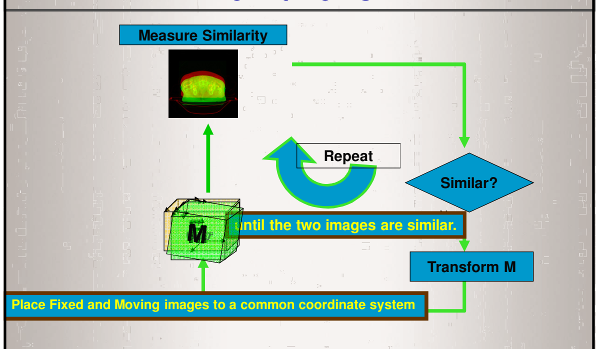


Figure 8.2: The basic components of the registration framework are two input images, a transform, a metric, an interpolator and an optimizer.

1) Luis Ibáñez et al , "The ITK software guide : updated for ITK version 2.4", 2005

How it works?



Basic Components of Image Registration

- The DIR consists of three components.
  - **Similarity Metric**
  - **Transformation**
  - **Optimization**
- **Optimization** updates the **Transformation** parameters until the **Similarity Metric** reaches maximum between two input images.

Basic Components of Image Registration

- Mathematically put:

$$\hat{T} = \arg\max_{T} S(T; I_F, I_M)$$

$$\Rightarrow \hat{T} = \arg\min_{T} \left[-S(T; I_F, I_M) \right]$$

$$\Rightarrow \hat{T} = \arg\min_{T} \left[-S(T; I_F, I_M) + \gamma P(T) \right]$$

Penalty term on T (smoothness,rigidity,etc)

Optimization

- Optimization algorithms are categorized into
  - Local optimization
    - Gradient descent, Downhill simplex, etc.
  - Global optimization
    - Simulated annealing
    - Genetic algorithm
    - Exhaustive search
- DIR mostly uses local optimization for faster conversance, although it can get trapped in a local minimum.

Gradient Descent

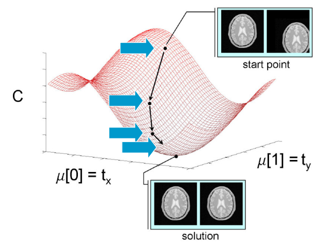


Figure 2.6: Iterative optimisation. Example for registration with a translation transformation model. The arrows indicate the steps $a_k \boldsymbol{d}_k$ taken in the direction of the optimum, which is the minimum of the cost function.

Gradient Descent Influence of Step Sizes

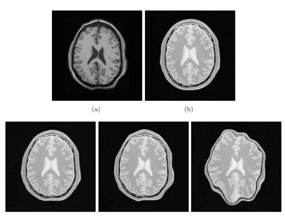
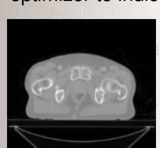
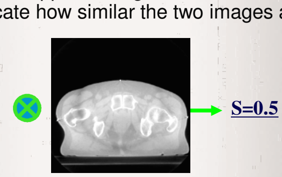


Figure 5.2: The effect of the choice of the step size a (SP_A). This example can be downloaded from the `elastix` website. (a) the fixed image, (b) the moving image. (c)-(e) show the registered images, with (c) $a = 320$ is too small, (d) $a = 3200$ as in the downloadable example is good, (e) $a = 32000$ is too large.

Similarity Metric

- Q: How do you measure the **similarity** between two images?
- Similarity metric is supposed to give **a number** to a optimizer to indicate how similar the two images are.





Similarity Metrics

- Sum of Squared Difference (SSD)
- Normalized Cross Correlation (NCC)
- Entropy Of Difference (EOD)
- Gradient Correlation (GC)
- Gradient Difference (GD)
- Pattern Intensity (PI)
- Mutual Information (MI)
- Normalized Mutual Information (NMI)
- … and More!

Mono-modal: SSD, NCC, EOD, GC, GD, PI

Multi-modal: MI, NMI

Similarity Metrics

Sum of Squared Difference

$$S_{SSD}(I_1, I_2) = \frac{1}{N}\sum_{i,j}\left(I_1(i,j) - I_2(i,j)\right)^2$$

1. Subtract pixel values
2. Square
3. Sum

→ Requires same pixel intensity between corresponding points.

Similarity Metrics

Normalized Cross Correlation

$$S_{NCC}(I_1, I_2) = \frac{\sum_{i,j}\left(I_1(i,j) - \bar{I}_1\right)\left(I_2(i,j) - \bar{I}_2\right)}{\sqrt{\sum_{i,j}\left(I_1(i,j) - \bar{I}_1\right)^2}\sqrt{\sum_{i,j}\left(I_2(i,j) - \bar{I}_2\right)^2}}$$

1. Subtract mean pixel values
2. Calculate vector inner product

→ NCC consider the image pixel array as a vector.

Similarity Metric

Mutual Information

$$S_{MI}(X,Y) = \sum_{x,y} p(X,Y) \log_l \frac{p(X,Y)}{p(X)\,p(Y)}$$

Joint prob. density function(PDF) of random variables X and Y

Marginal PDFs

→ PDF is a normalized form of image histogram.

→ MI can be used for different modality images (ex, CT/MR)

Transformation

- Rigid (translation, rotation) – 6 DOF
- Affine (translation, rotation, scale, shear) – 12 DOF
- Deformable
  - Non-parametric
    - Spatial mapping is directly represented by a deformation vector field (DVF).
  - Parametric
    - A set of parameters represent underlying deformation
      - B-spline, Thin Plate spline, radial basis functions, etc.

Q) Which of the following is NOT one of the basic image registration components?

28% 1. Image modality

26% 2. Similarity metric

23% 3. Optimization

24% 4. Transformation

Q) Which of the following is NOT one of the basic image registration components?

- Answer: 1
- Basics components: Optimization, similarity metric, and transformation

Q) Which similarity metric would you use for CT/MR registration?

24% 1. Normalized Cross Correlation

27% 2. Mutual Information

24% 3. Sum of Squared Difference

25% 4. Gradient Descent

Q) Which similarity metric would you use for CT/MR registration?

- Answer: 2
- MI is the only one that can be used for different modality image registrations.
- Gradient descent is a type of transformation, not similarity metric.

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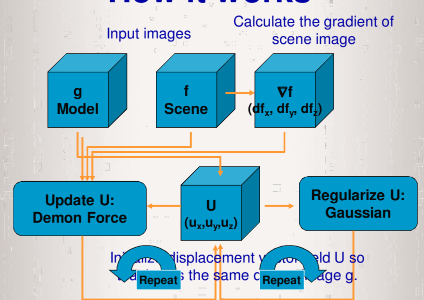
Demons

- The Demons algorithm is
  - a part of **demons framework** proposed by Thirion (1995),
  - and later mathematically proven to be similar with **viscous fluid model based registration**.
- The algorithm finds a **pixel-by-pixel displacement vector field** that overlays two input images, and
- the method consists of two components;
  - **Update using a Demon force**, and
  - **Gaussian regularization**

Demons: How it works



This process is repeated until U is stabilized.

Demons

- The **update** rule using **basic demon force** is as follow:

$$\mathbf{u}^{new} = \mathbf{u} + \alpha \frac{\left(g(\mathbf{x}) - f(\mathbf{x}+\mathbf{u})\right)\nabla \mathbf{f}(\mathbf{x}+\mathbf{u})}{\left(\nabla \mathbf{f}(\mathbf{x}+\mathbf{u})\right)^2 + \left(g(\mathbf{x}) - f(\mathbf{x}+\mathbf{u})\right)^2}$$

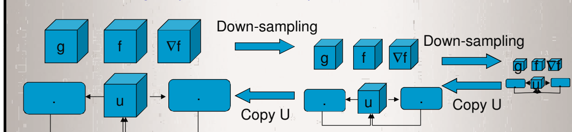
  - which involves **image difference** the **gradient of f**.

- The **Gaussian regularization** is simply a 3D convolution with Gaussian filter, and
  - it enforces the **smoothness of the vector field U** and controls the overall **freedom of transformation**.

Demons
Multi-Resolution

- Generally, **multi-resolution** approach is used for **large deformation** and **faster convergence**.

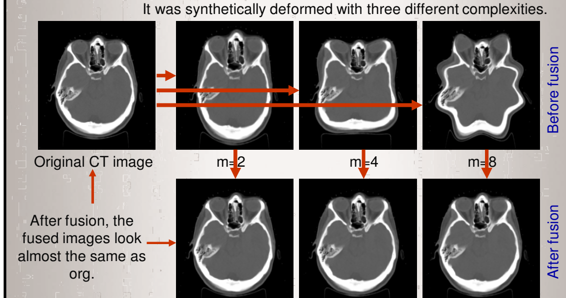
Image objects are down-sampled to coarse resolutions.



The result U of a coarse resolution is used as the initial U of the next finer resolution.

Demons
Example

It was synthetically deformed with three different complexities.

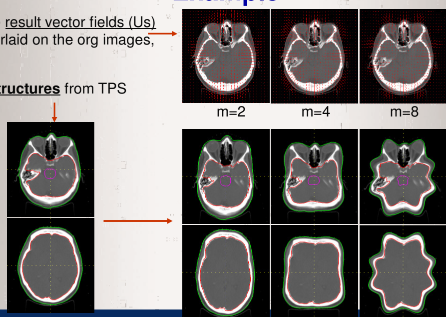


Then, they were fused back to the original image.

Demons
Example

The result vector fields (Us) overlaid on the org images,

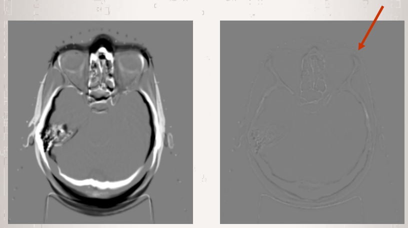
Structures from TPS



The structures were transformed using Us

Demons
Example

Residual errors



Diff. Image
Before fusion

Diff. Image
After fusion

Demons
Pros & Cons

- Pros : Fast! (<10 sec), easy to implement, and suitable for parallel architecture (GPU).
- Cons:
  - Limited applications
    - Requires same pixel intensity for same corresponding points.
    - Difficult to regularized underlying deformation
    - Expected to be sensitive to noise.

Outline

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- **B-Spline based DIR**
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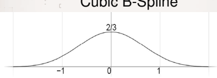
B-Spline DIR

- B-spline DIR has gained popularity because
  - B-spline is smooth, differentiable, separable, local, etc.
  - It can be used with various similarity metrics, including MI.
    - So, it can be used for multi-modal image registrations.

B-Spline DIR

Cubic B-Spline

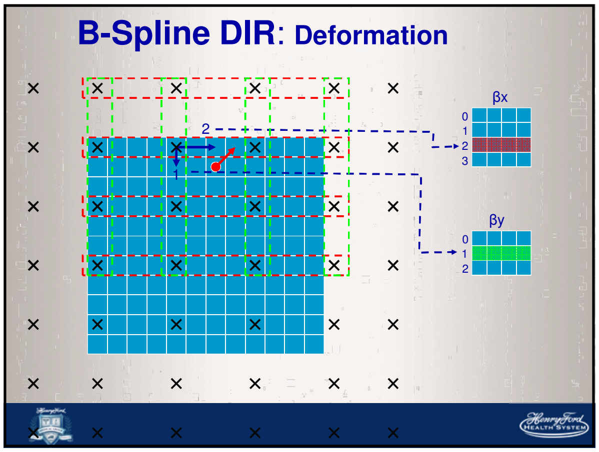


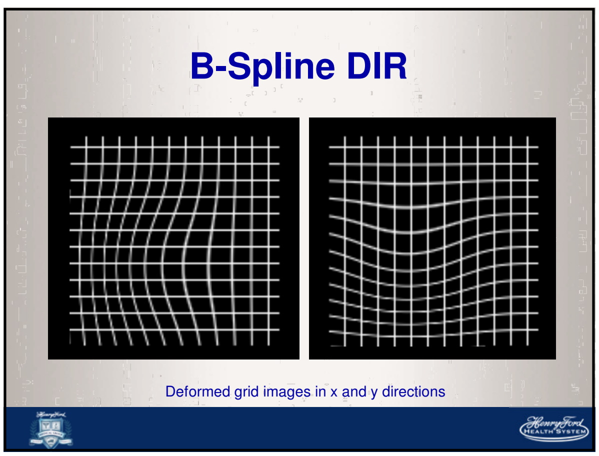
$$\beta_3(x) = \begin{cases} 0, & |x| \geqq 2 \\ \frac{1}{6} \cdot (2 - |x|)^3, & 1 \leqq |x| < 2 \\ \frac{2}{3} - \frac{1}{2}|x|^2 \cdot (2 - |x|), & |x| < 1 \end{cases}$$

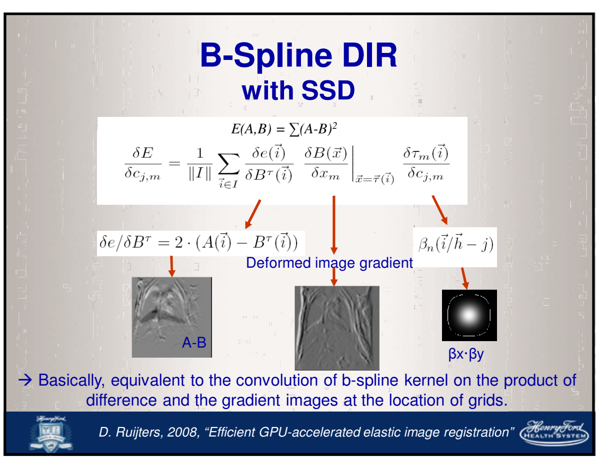
Transformation: combination of b-splines

$$\vec{\tau}(\vec{i}) = \vec{i} + \sum_{j \in I_c} \vec{c}_j \cdot \beta_n(\vec{i}/\vec{h} - j)$$

D. Ruijters, 2008, "Efficient GPU-accelerated elastic image registration", Proc. of the Sixth IASTED International Conference on Biomedical Engineering


B-Spline DIR: Deformation
βx
0
1
2
3
βy
0
1
2
2
1


B-Spline DIR
Deformed grid images in x and y directions


B-Spline DIR
with SSD
E(A,B) = ∑(A-B)²
$\frac{\delta E}{\delta c_{j,m}} = \frac{1}{\|I\|} \sum_{\vec{i} \in I} \frac{\delta e(\vec{i})}{\delta B^{\tau}(\vec{i})} \left. \frac{\delta B(\vec{x})}{\delta x_m} \right|_{\vec{x}=\vec{\tau}(\vec{i})} \frac{\delta \tau_m(\vec{i})}{\delta c_{j,m}}$
$\delta e / \delta B^{\tau} = 2 \cdot (A(\vec{i}) - B^{\tau}(\vec{i}))$
Deformed image gradient
$\beta_n(\vec{i}/\vec{h} - j)$
A-B
βx·βy
→ Basically, equivalent to the convolution of b-spline kernel on the product of difference and the gradient images at the location of grids.
D. Ruijters, 2008, "Efficient GPU-accelerated elastic image registration"

B-Spline DIR
With MI (Parzen Windowing)

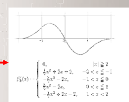
Joint PDF

$$p(\iota,\kappa|\mu) = \alpha \sum_{\mathbf{x}\in V} \beta^{(0)}\left(\kappa - \frac{f_R(\mathbf{x}) - f_R^\circ}{\Delta b_R}\right) \times \beta^{(3)}\left(\iota - \frac{f_T(\mathbf{g}(\mathbf{x}|\mu)) - f_T^\circ}{\Delta b_T}\right)$$

Direct implementation of these equations will lead to long execution time, because, for each bin, all volume pixels have to be evaluated.

Partial derivative of Joint PDF

$$\frac{\partial p(\iota,\kappa)}{\partial \mu_i} = \frac{1}{\Delta b_T(\#V)} \sum_{\mathbf{x}\in V} \beta^{(0)}\left(\kappa - \frac{f_R(\mathbf{x}) - f_R^\circ}{\Delta b_R}\right) \times \left.\frac{\partial \beta^{(3)}(u)}{\partial u}\right|_{u=\iota - \frac{f_T(\mathbf{g}(\mathbf{x}|\mu)) - f_T^\circ}{\Delta b_T}} \times \left(\left.\frac{-\partial f_T(\mathbf{t})}{\partial \mathbf{t}}\right|_{\mathbf{t}=\mathbf{g}(\mathbf{x}|\mu)}\right)^T \frac{\partial \mathbf{g}(\mathbf{x}|\mu)}{\partial \mu}$$



Deformed image gradient

βx·βy

D. Mattes, 2003, "PET-CT Image Registration in the Chest Using Free-form Deformations", IEEE Trans Med. Img.

B-Spline DIR
Pros & Cons (vs. Demons)

- Pros
  - Wider application area (mono-modal, multi-modal).
  - Easier to control the deformation complexity (achived by adjusting the B spline grid spacing).
- Cons
  - Slower in general.

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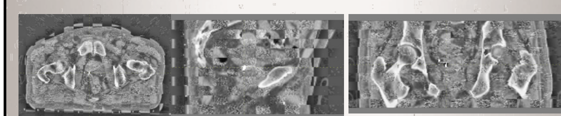
- Basics components of DIR
- Demons DIR
- B-Spline based DIR
- **<u>Evaluation</u>**
- Discussions

Evaluation
Registration is successful?

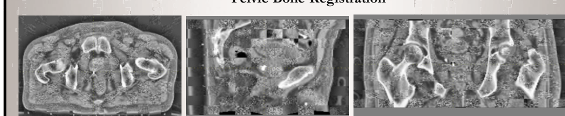
How do we know if the registration is successful?

→ First: Check if the deformed moving image looks similar to the fixed image.

Evaluation
Checker Board Blending

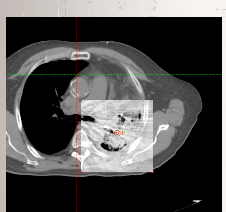


Pelvic Bone Registration

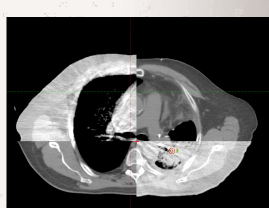


Deformable Registration

Evaluation
Registration is successful?

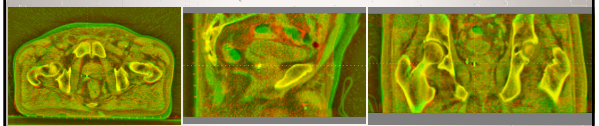


Spy glass

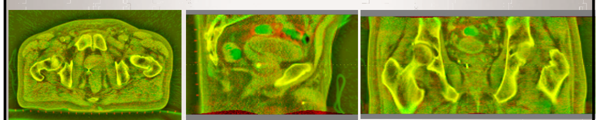


Split blending

Evaluation
Color Blending

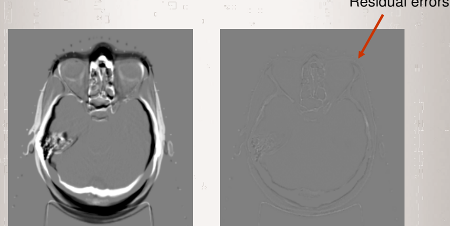


Pelvic Bone Registration



Deformable Registration

Evaluation
Image Difference



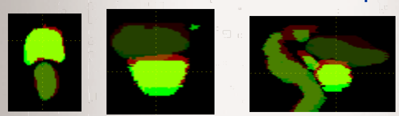
Diff. Image Before fusion

Diff. Image After fusion

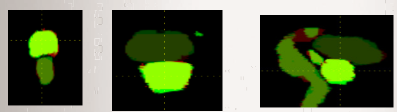
Evaluation
Registration is successful?

→ Second: Check if a set of manually segmented structures/points overlaps well after deformation.

Evaluation
Structure Overlap



Pelvic Bone Registration



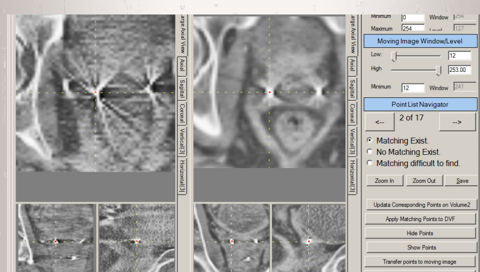
Deform Registration

DICE to quantify:

$$DSC(X,Y) = \frac{2|X \cap Y|}{|X| + |Y|}$$

DCE = 1 → perfect match
DCE=0 → no overlap

Evaluation
Point Set Overlap

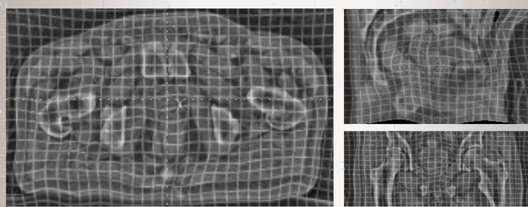


Distinct points can be segmented and used to calculate registration error.

Evaluation
Registration is successful?

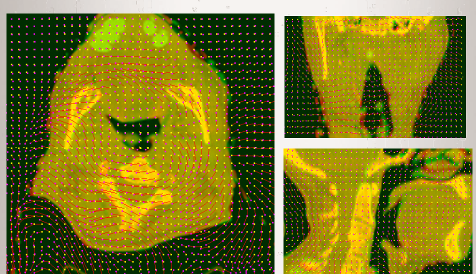
→ Third: Check if the result deformation physically make sense.

Evaluation
Grid deformation overlay

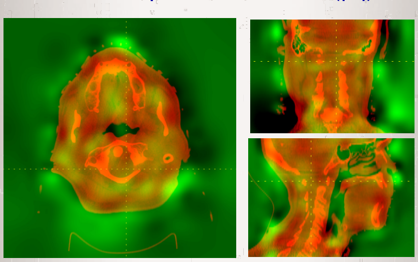


Check if the deformation make sense.

Evaluation
Vector flow overlay



Evaluation
Determinant of spatial Jacobian (|J|) overlay



|J| is a measure of compressing and expansion.

|J|< 1 → compressed, |J|> 1 → expanded, |J|= 1 → no volume change

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Tip 1. Use multi-resolution approach.

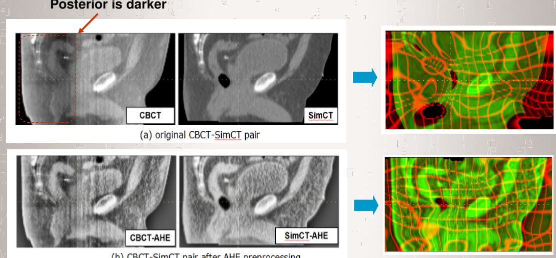
- Use multi-resolution approach
  - Coarse to fine image resolution
  - Low to high DOF transformation
    - Ex) Rigid-body → Affine → coarse resolution grid → fine resolution grid.

→It will lead to faster and robust registration.

- →Faster, because large difference are handled in the low resolution.
- →Robust, because the lower resolution has wider capture range that provides good starting point for the following resolution stage.

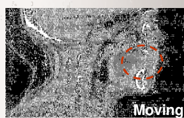
Tip 2. Preprocess input images if needed.

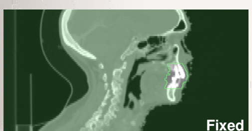
Posterior is darker



AHE – Adaptive Histogram Equalization

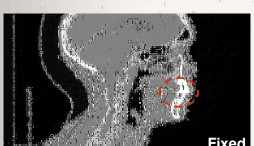
Tip 3: Remove exterior objects.

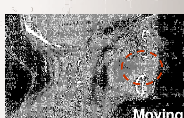


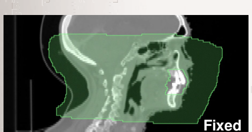


Remove objects that exist only one image from registration, such as contrast agent, surgical clips, rectum gas, etc.

Tip 3: Remove exterior objects.

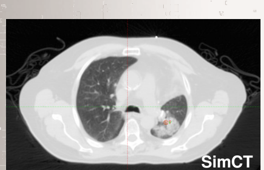


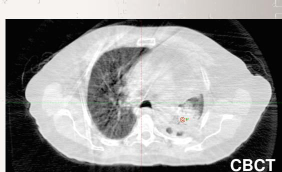




Remove image information from fixed image which does not exist on the moving image.
→If not, moving image often stretched up/down.
→It is because the transformation is defined over the fixed image.

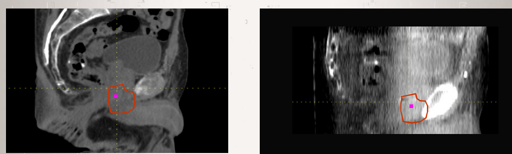
Tip 5: If the image is noisy, use lower DOF transformation.





- B-spine: try larger grid spacing.
- Demon: Use more smoothing regularization (larger Gaussian sigma).

Tip 6: Use manually segmented objects to guide registration



As a last resort, if DIR does not work, we need to provide some guidance by providing segmentations on the both images.

Enjoy!

Thanks for your attention!