Image Registration & Deformable Image Registration

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DEPT OF RADIATION ONCOLOGY

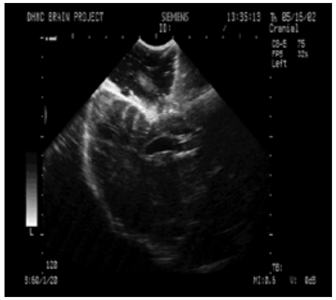
Outline

- Discuss the key components of image registration
- Discuss two basic deformable image registration (DIR) techniques
- Discuss DIR recent development
- Discuss DIR new/future direction

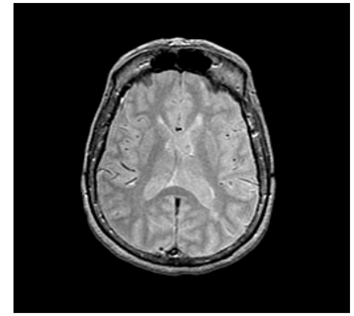
BASIC OF IMAGE REGISTRATION

Images in radiation therapy

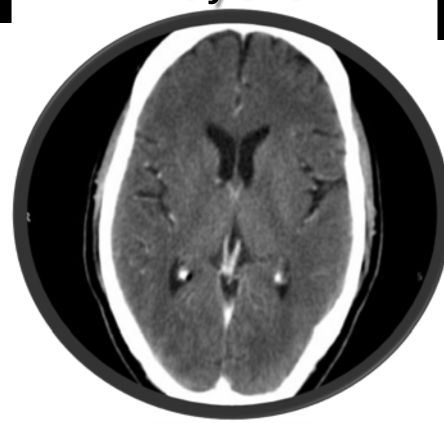
Ultrasound



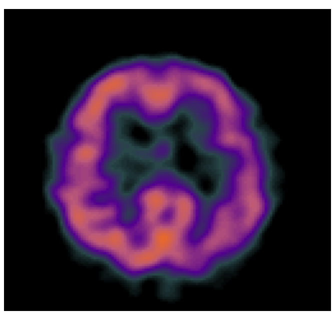
MRI



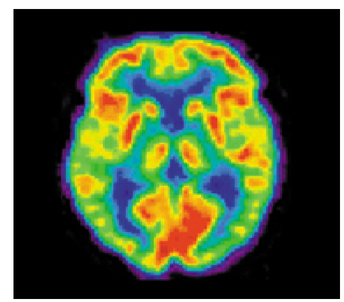
X-rays CT



SPECT



PET



Angiography

How to deal with these images

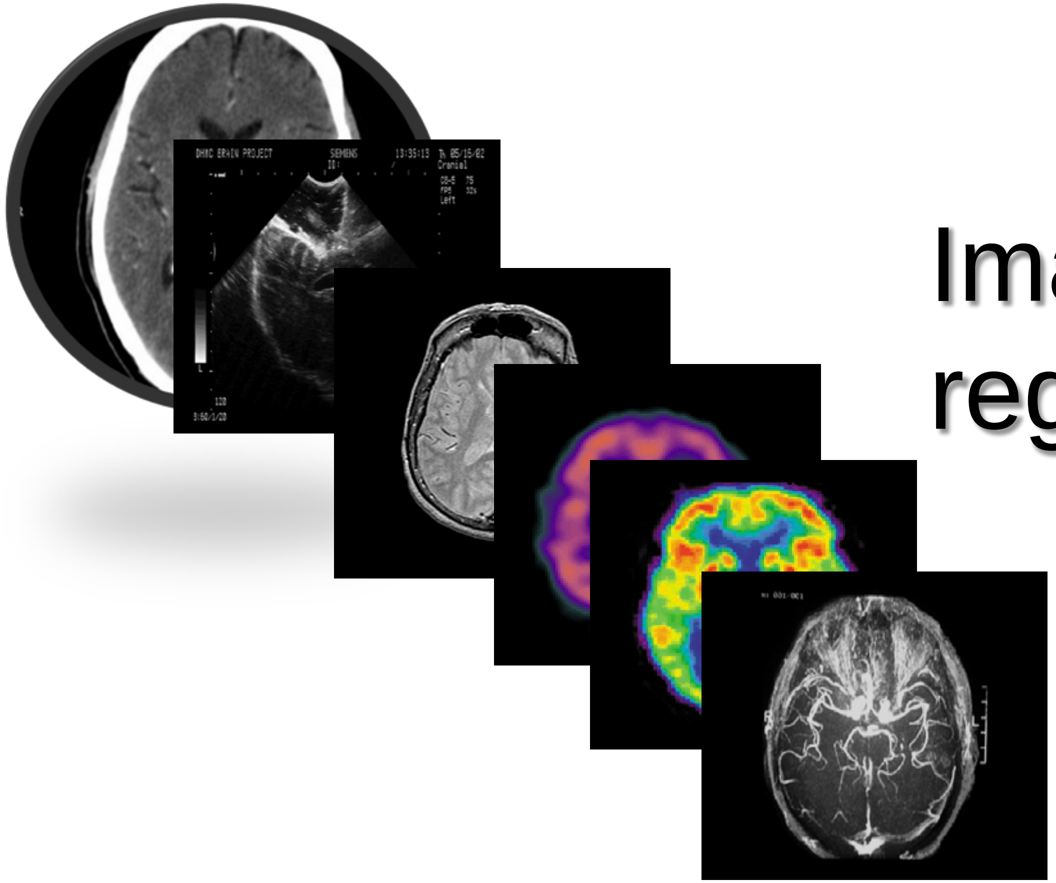
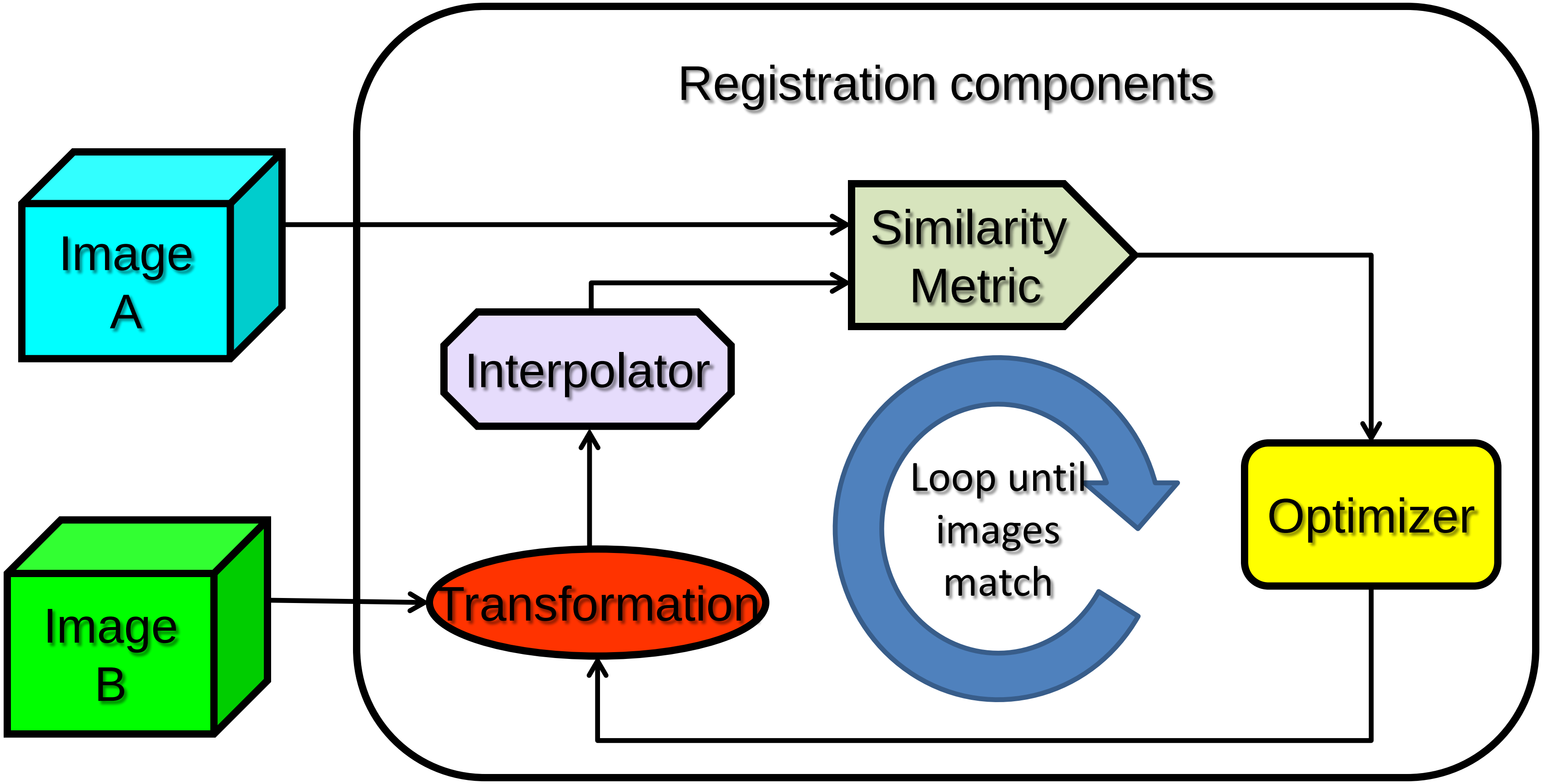


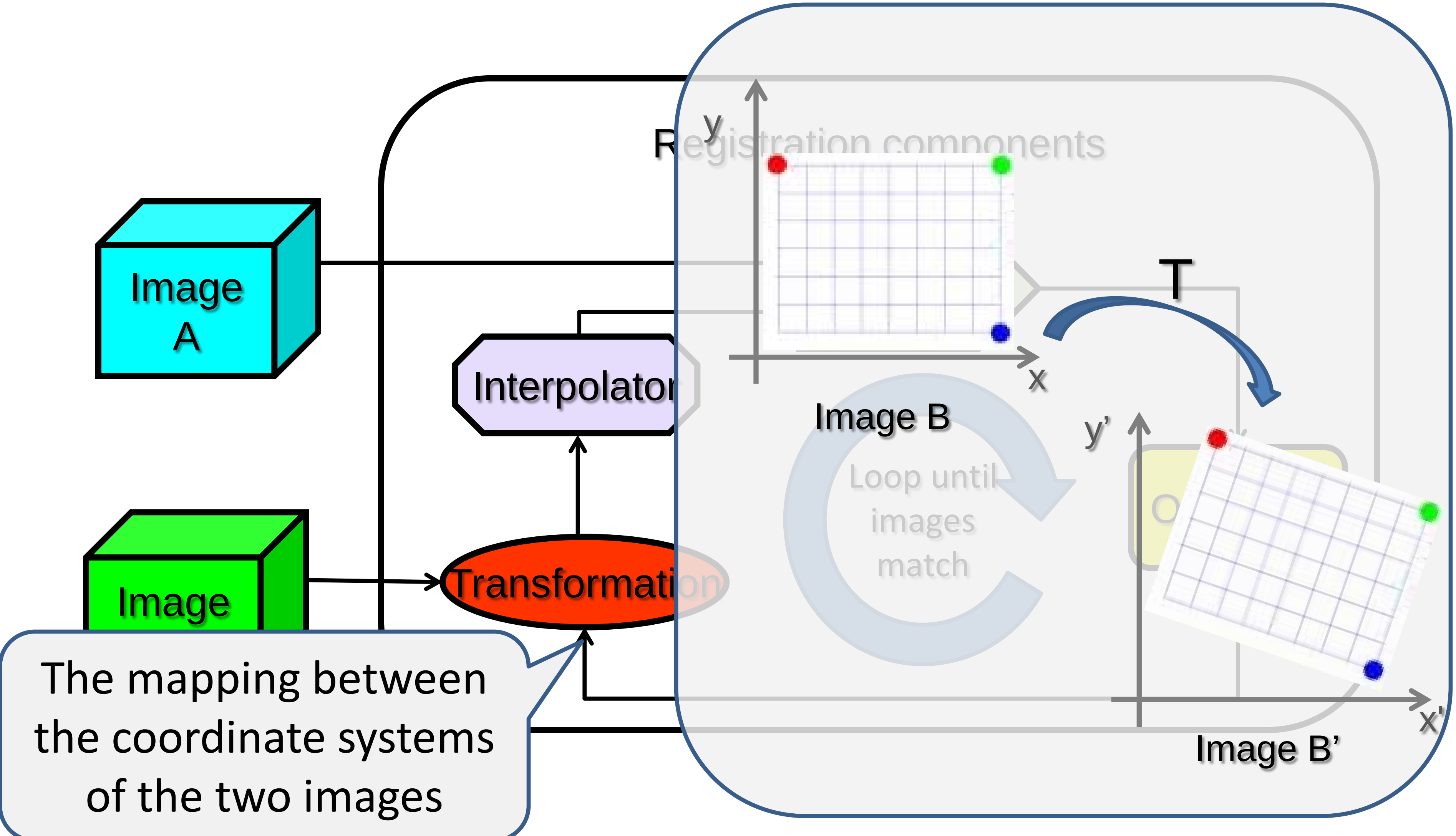
Image registration !!!

How dose image registration work?

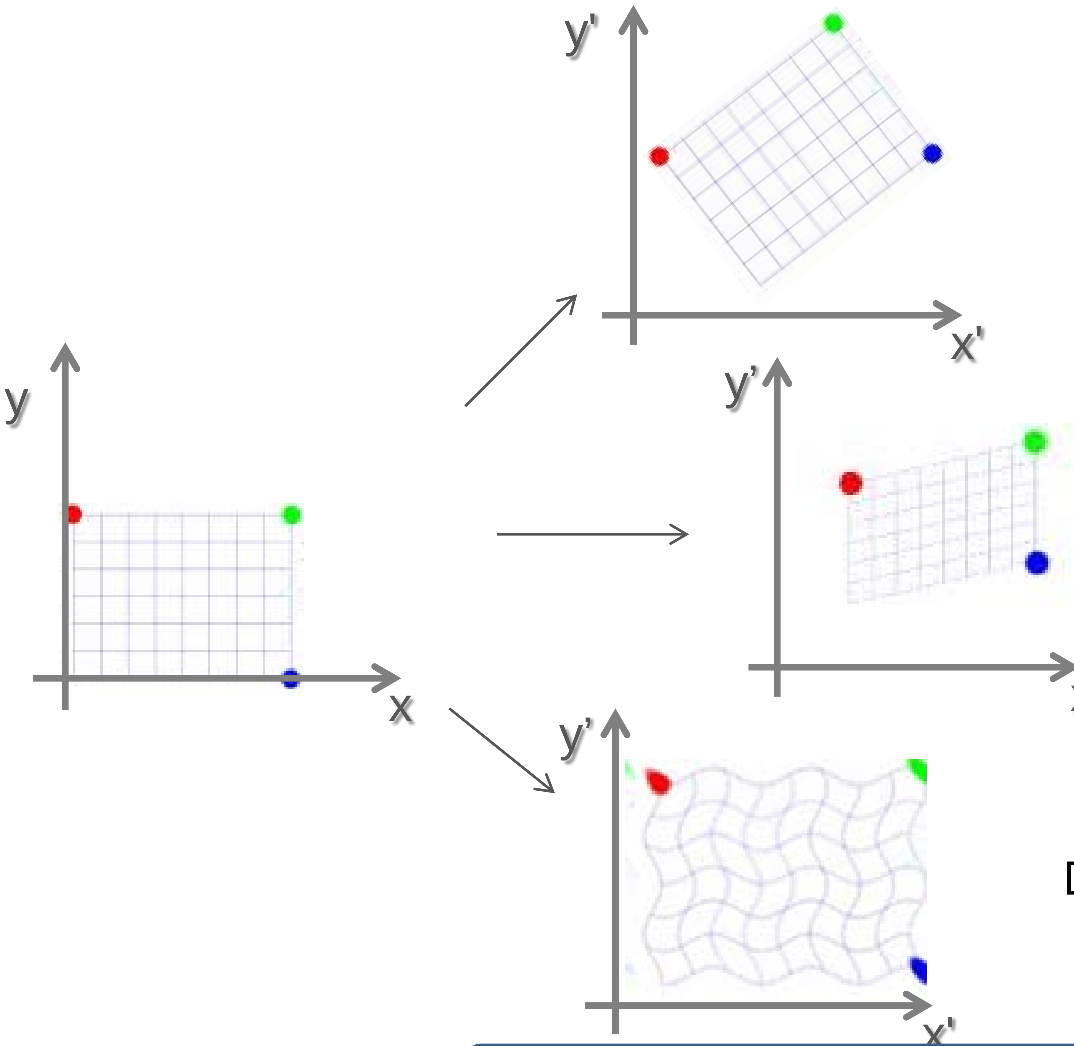


Question 1

1. Transformation



1. Transformation



Rigid Transformation
Degrees of freedom: 6

- Translation
- Rotation

Affine Transformation
Degrees of freedom: 12

- Translation
- Rotation
- Scaling
- Shear

Deformable Transformation
Degrees of freedom: $3N^3$

Rigid $\subset$ Affine $\subset$ Deformation

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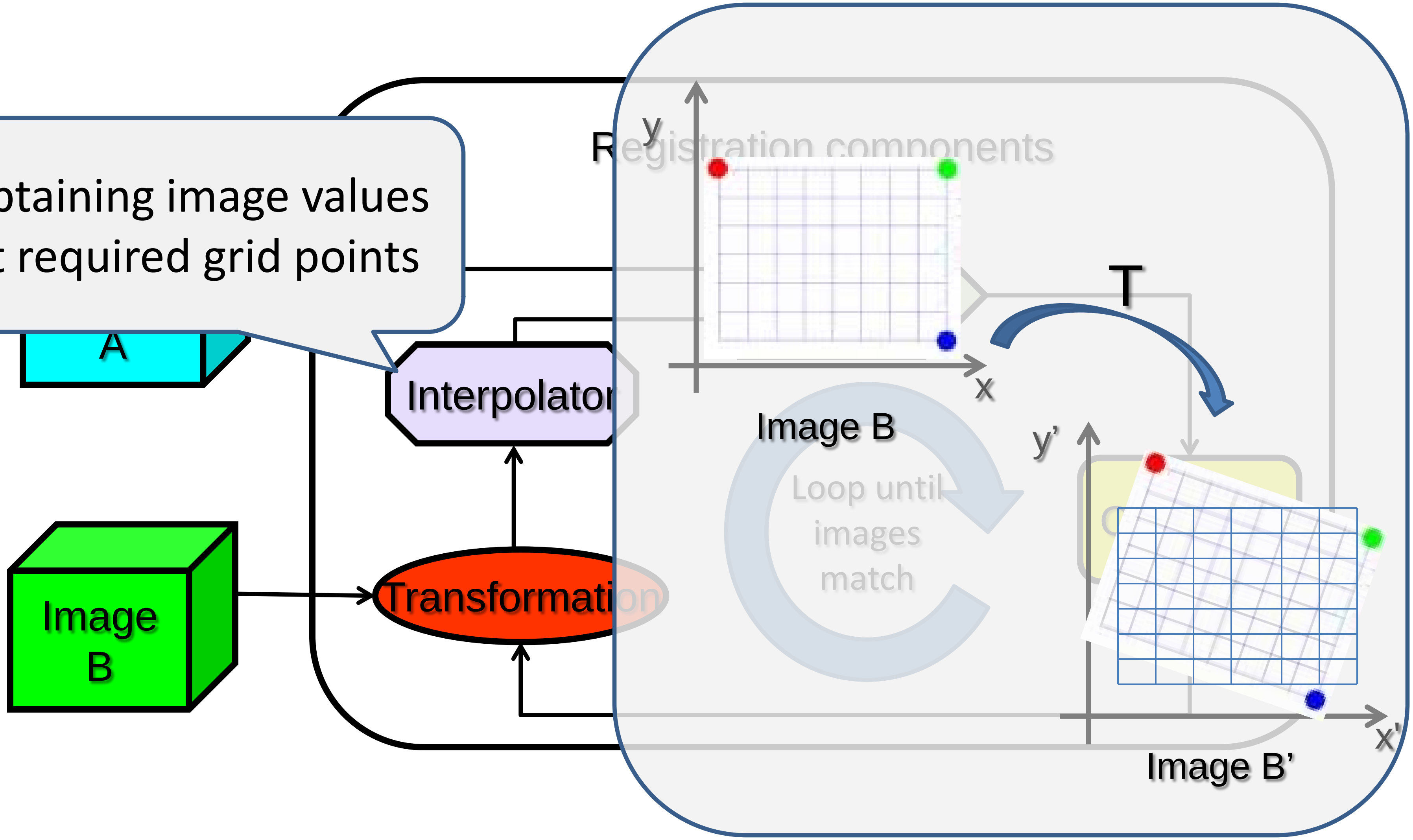
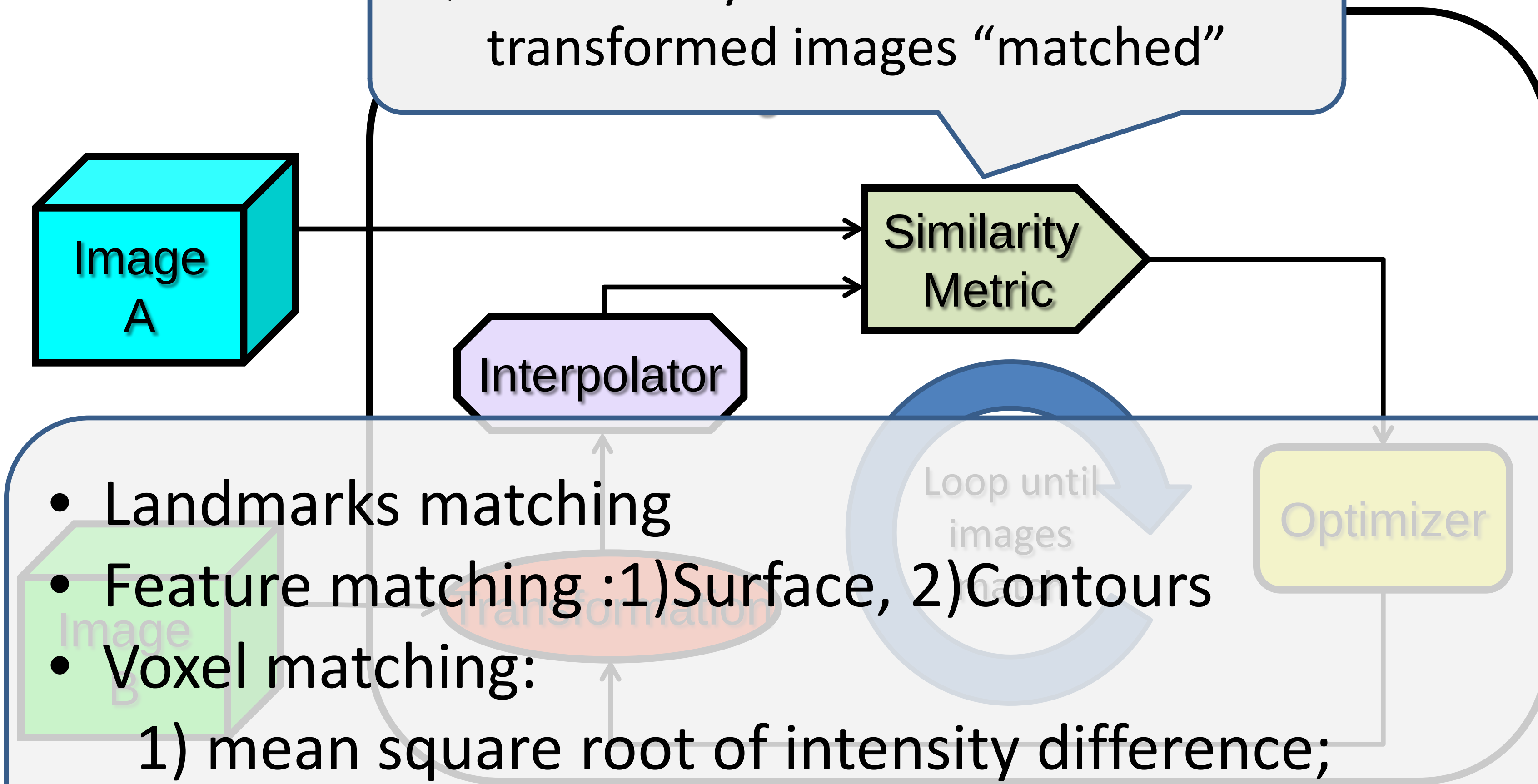
2. Interpolator

Obtaining image values at required grid points



3.Similarity Metric

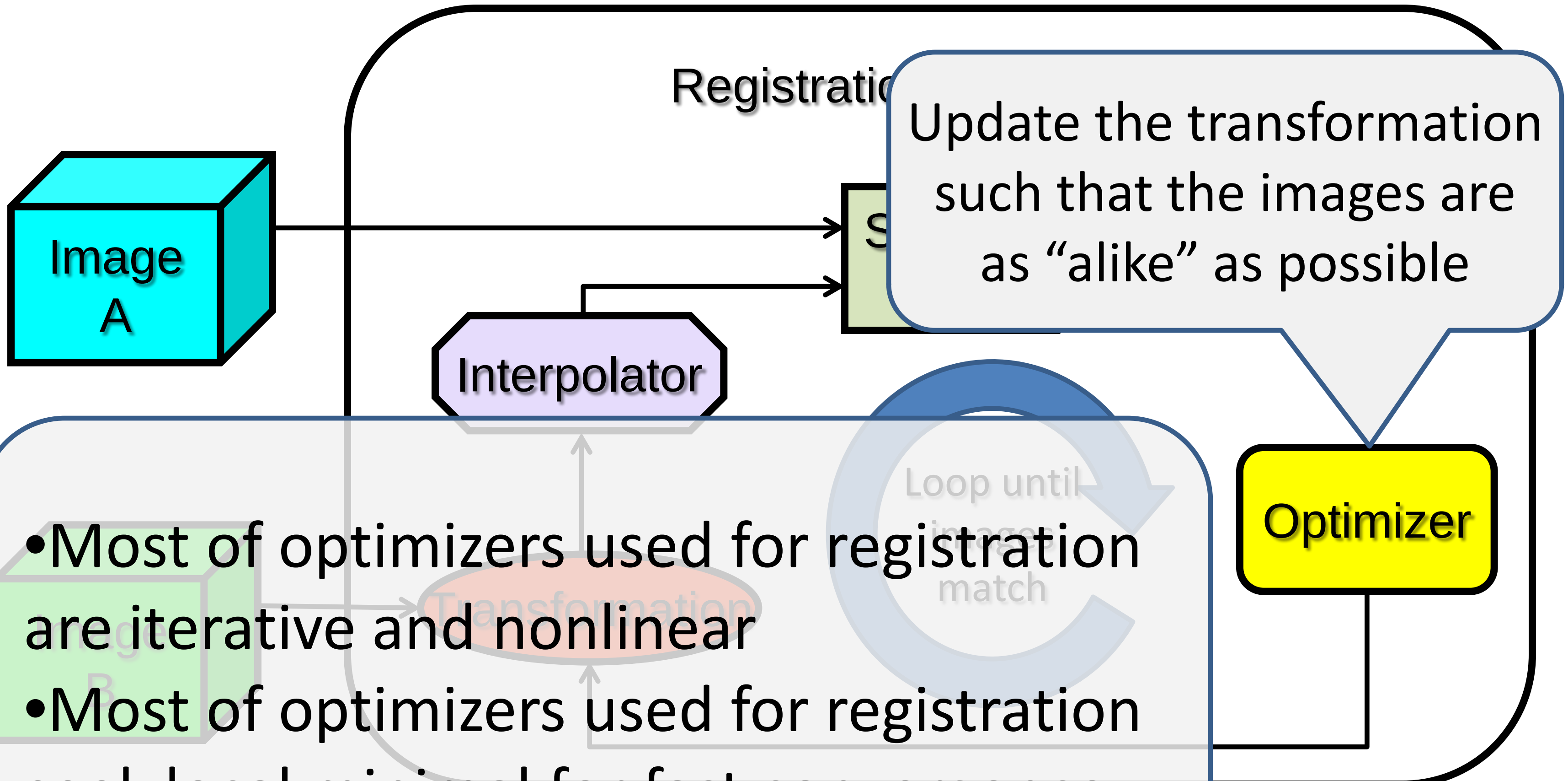
Quantitatively measures how well the transformed images "matched"



- Landmarks matching
- Feature matching :1)Surface, 2)Contours
- Voxel matching:
  1) mean square root of intensity difference;
  2)cross correlation ; 3)mutual information

Question 2

4.Optimizer



•Most of optimizers used for registration are iterative and nonlinear

•Most of optimizers used for registration seek local minimal for fast convergence

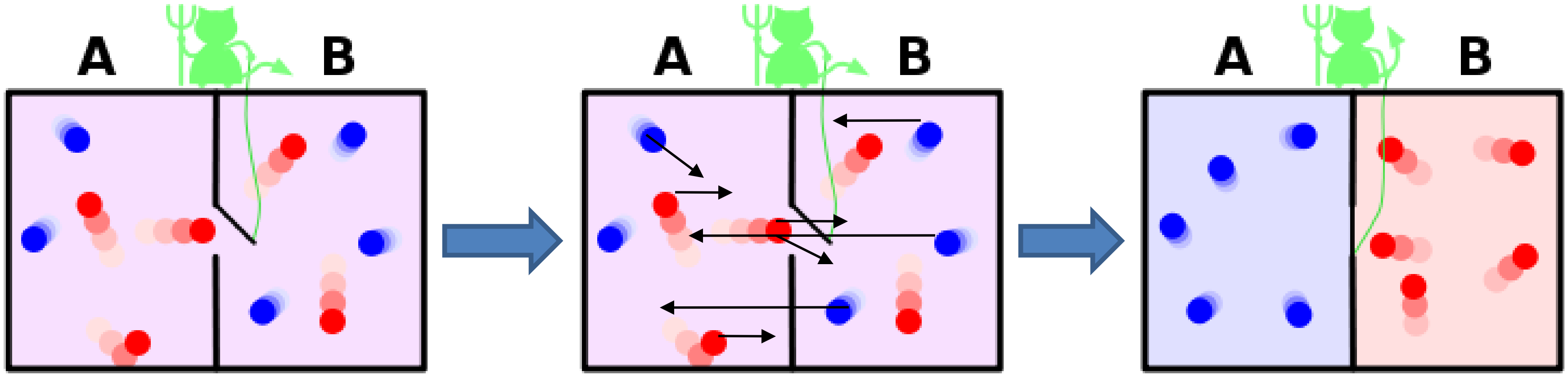
Roles of Image Registration in Radiotherapy

- Treatment planning
  - Image fusion – multimodality images (RIGID)
  - Segmentation, 4D treatment planning (DIR)
- Treatment delivery
  - 2D and 3D image-guided radiotherapy (RIGID)
  - 4D image-guided radiotherapy (DIR)
- Treatment adaptation
  - Off line contours adaptation and dose accumulation (DIR)
  - Online adaptive radiotherapy (DIR)
- Treatment evaluation
  - Off line tumor and normal tissue response assessment (DIR)
  - Online treatment monitoring and evaluation (DIR)

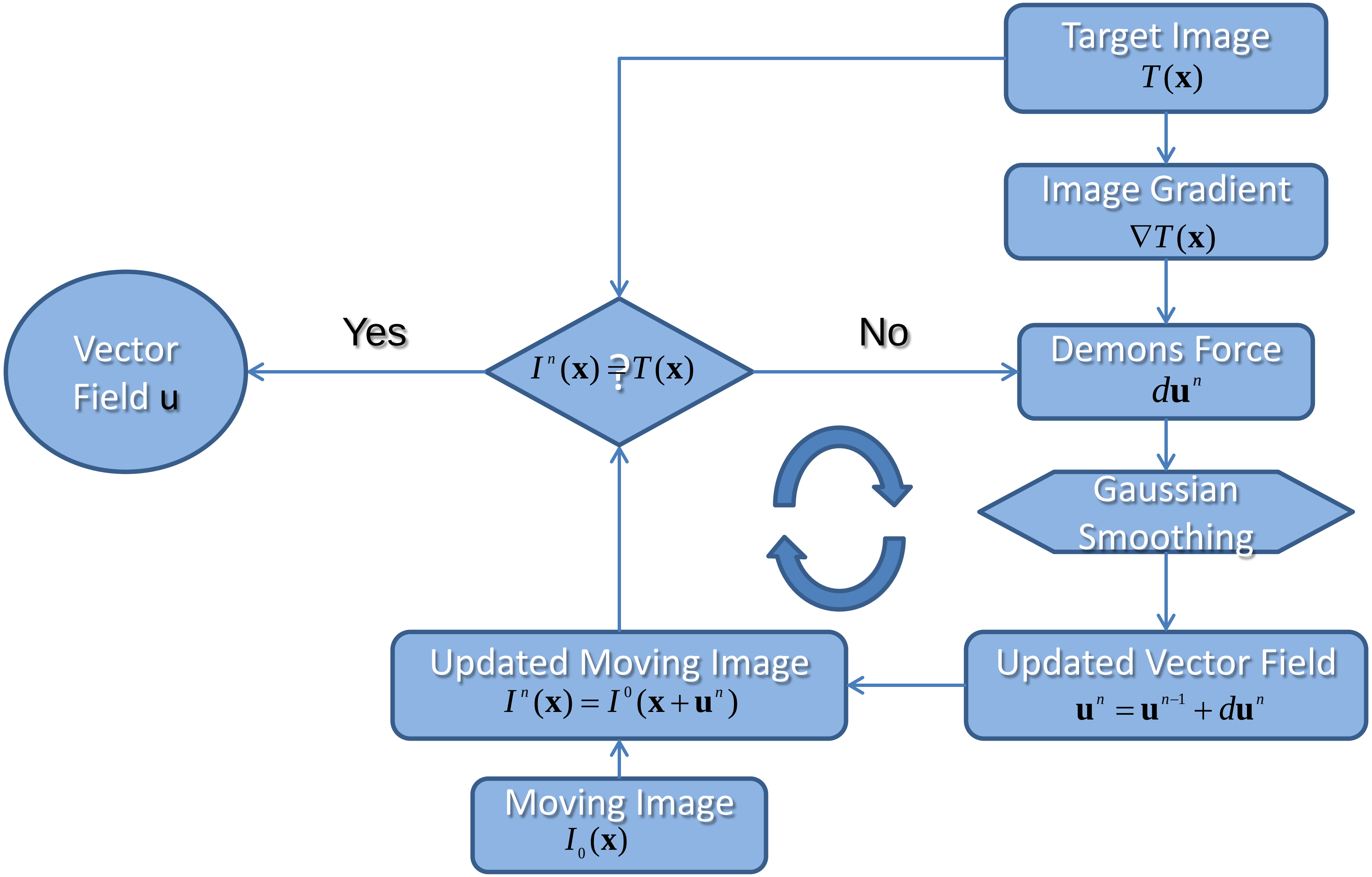
BASIC DEFORMABLE IMAGE REGISTRATION (DIR) TECHNIQUES: DEMONS & DISC

Demons DIR

- Demons Algorithm
  - Originally demons framework proposed by Thirion
    - Thirion J P 1998 Image matching as a diffusion process: an analogy with Maxwell's demons *Med Image Anal* **2** 243-60
  - Mathematically cast into an optimization framework
    - Vercauteren T, Pennec X, Perchant A and Ayache N 2009 Diffeomorphic demons: Efficient non-parametric image registration *Neuroimage* **45** S61-S72



Demons Workflow



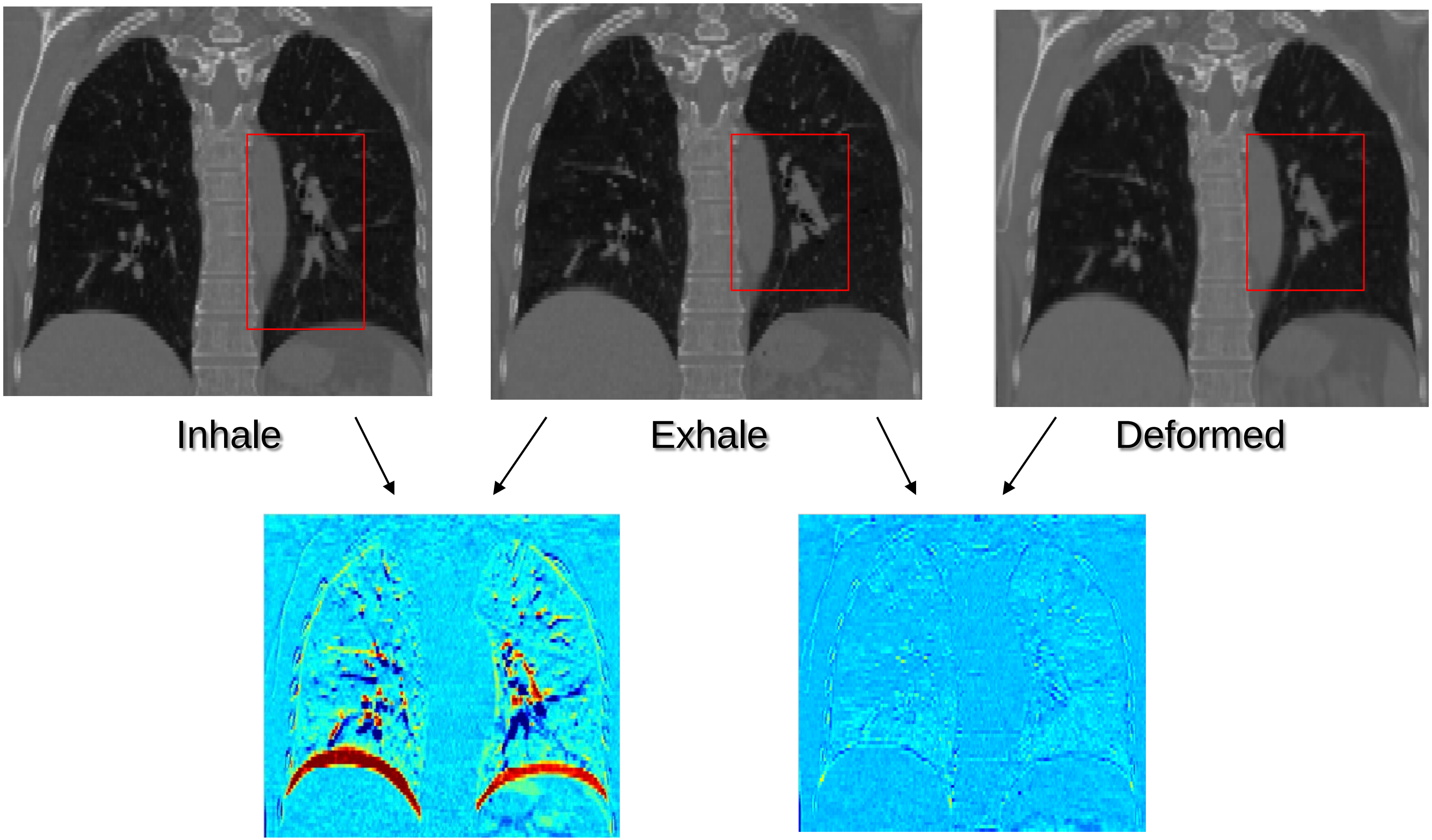
Key components of Demons

- Demons force
  - Updating vector field through a Demons force

$$d\mathbf{u} = \frac{\left(I^n(\mathbf{x}) - T(\mathbf{x})\right)\nabla T(\mathbf{x})}{\left|\nabla T(\mathbf{x})\right|^2 + \alpha\left(I^n(\mathbf{x}) - T(\mathbf{x})\right)^2}$$

  - Various demons force was proposed
- Gaussian smoothing
  - is simply a 3D convolution with Gaussian filter, and it enforces the smoothness of the vector field **u**
- Multi-resolution
  - Used for large deformation

Demons Examples

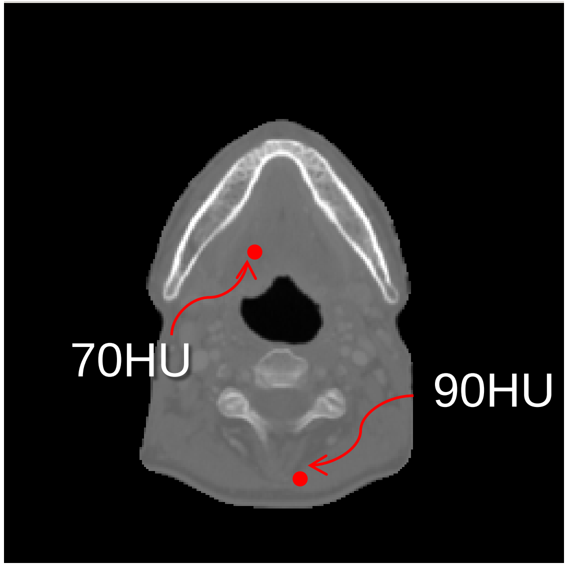


Demons Pros & Cons

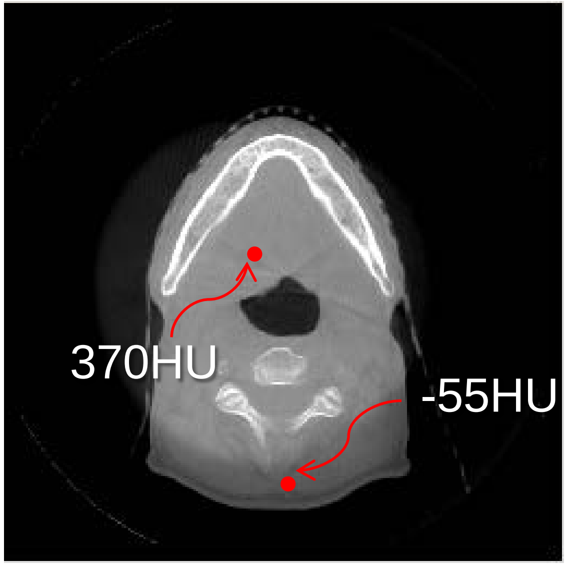
- Pros
  - Fast
  - Suitable for GPU parallelization
  - g-Demons can complete registration ~10 seconds
- Cons
  - Limited to the same modality , eg. CT-CT
  - Sensitivity to noise
  - Gaussian regularization controls the smoothness of vector field

CT→ CBCT Deformable Image Registration

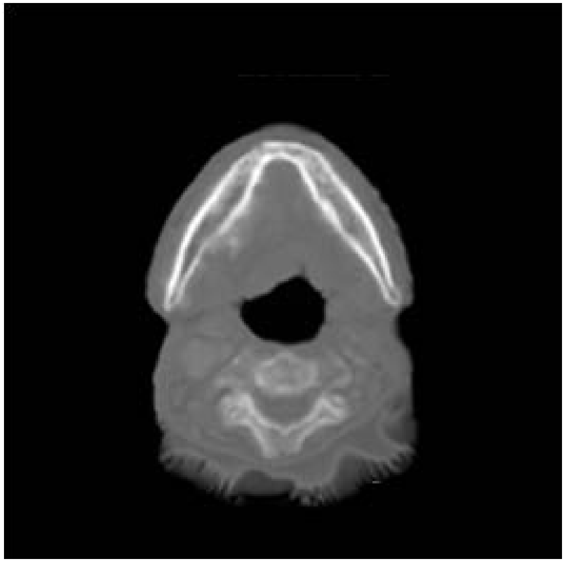
- Problems: Intensity inconsistency between CT and CBCT
  - *Different scan geometry*
  - *Scatter artifacts in CBCT*
  - *Bowtie filter artifact*
  - *Different level of noise, beam hardening, motion etc*



CT



CBCT

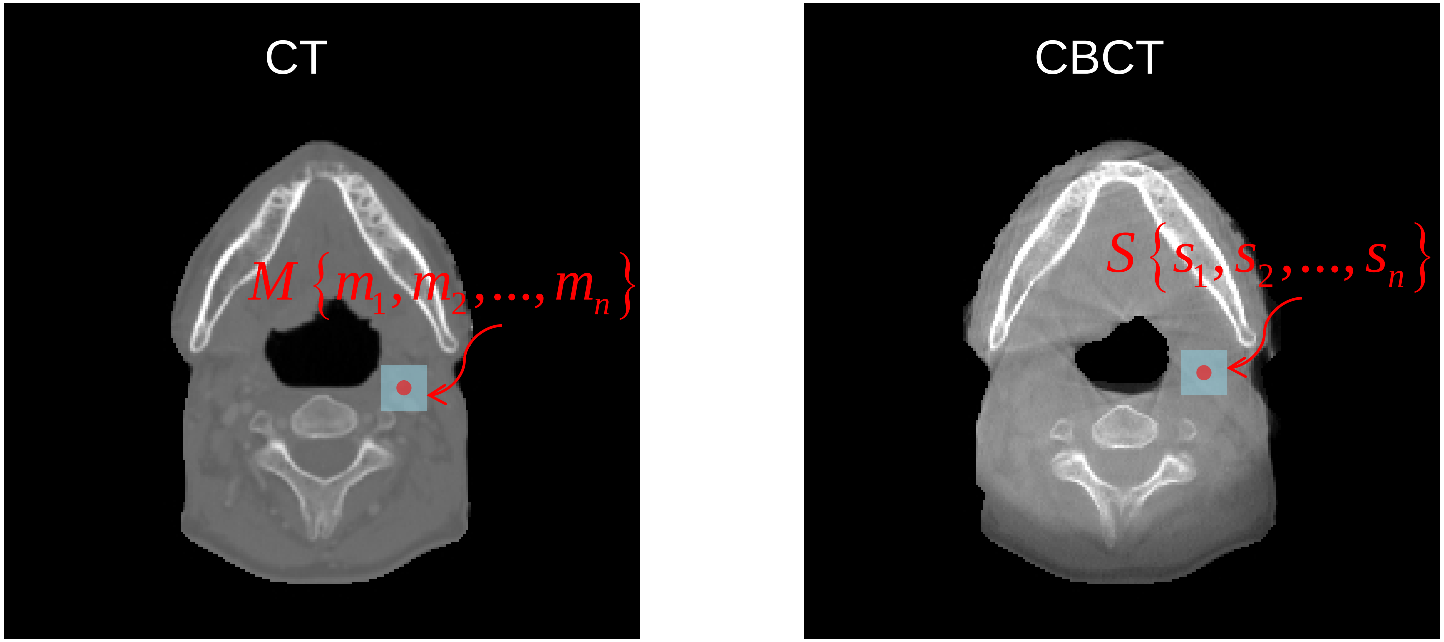


Demons: Deformed CT

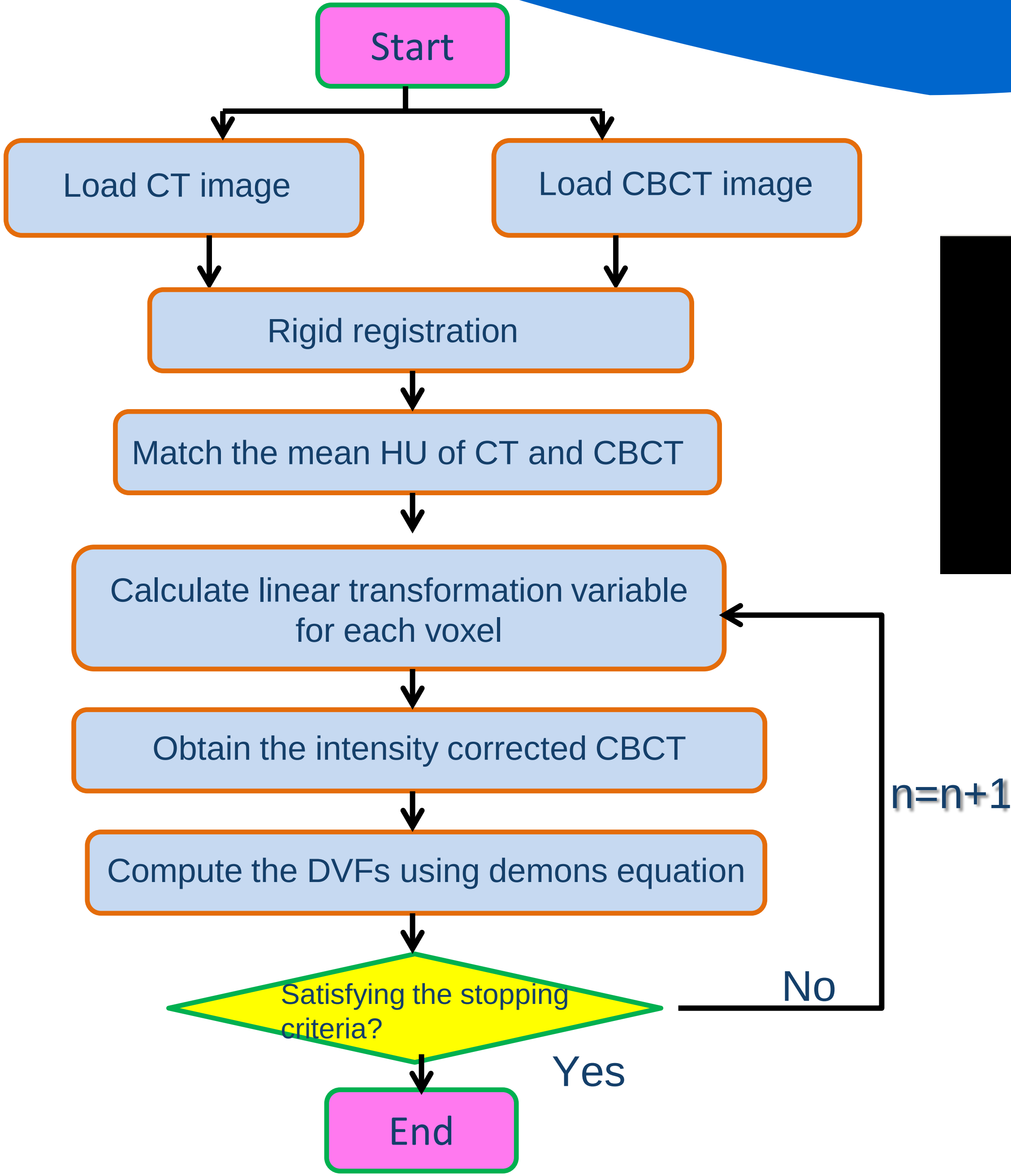
Demons Extension---DISC DIR

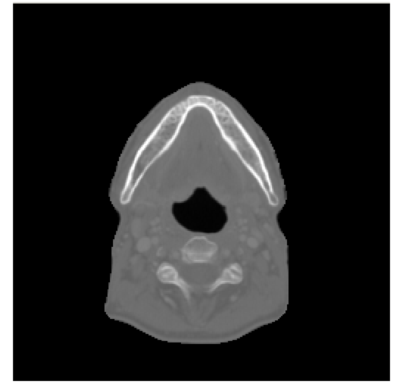
(***D**eformation with **I**ntensity **S**imultaneously **C**orrected*)

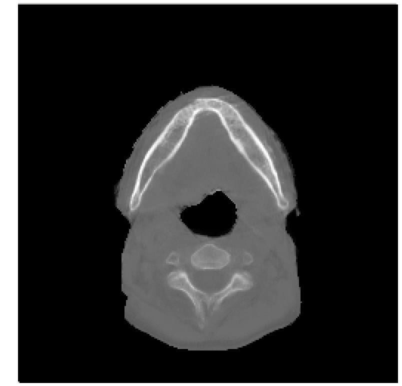
- DISC is a modified g-Demons algorithm embedded with a simultaneous intensity correction step.
- DISC corrects CBCT intensity of each voxel at every iteration step of demons by matching the *first* and the *second* moments of the voxel intensities inside a patch around this voxel with those in the CT image.

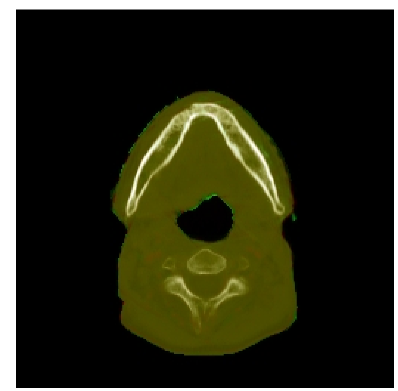


X. Zhen, et. al., "CT to Cone-beam CT Deformable Registration With Simultaneous Intensity Correction", *Phys. Med. Biol.* 57, 6807-6826(2012)

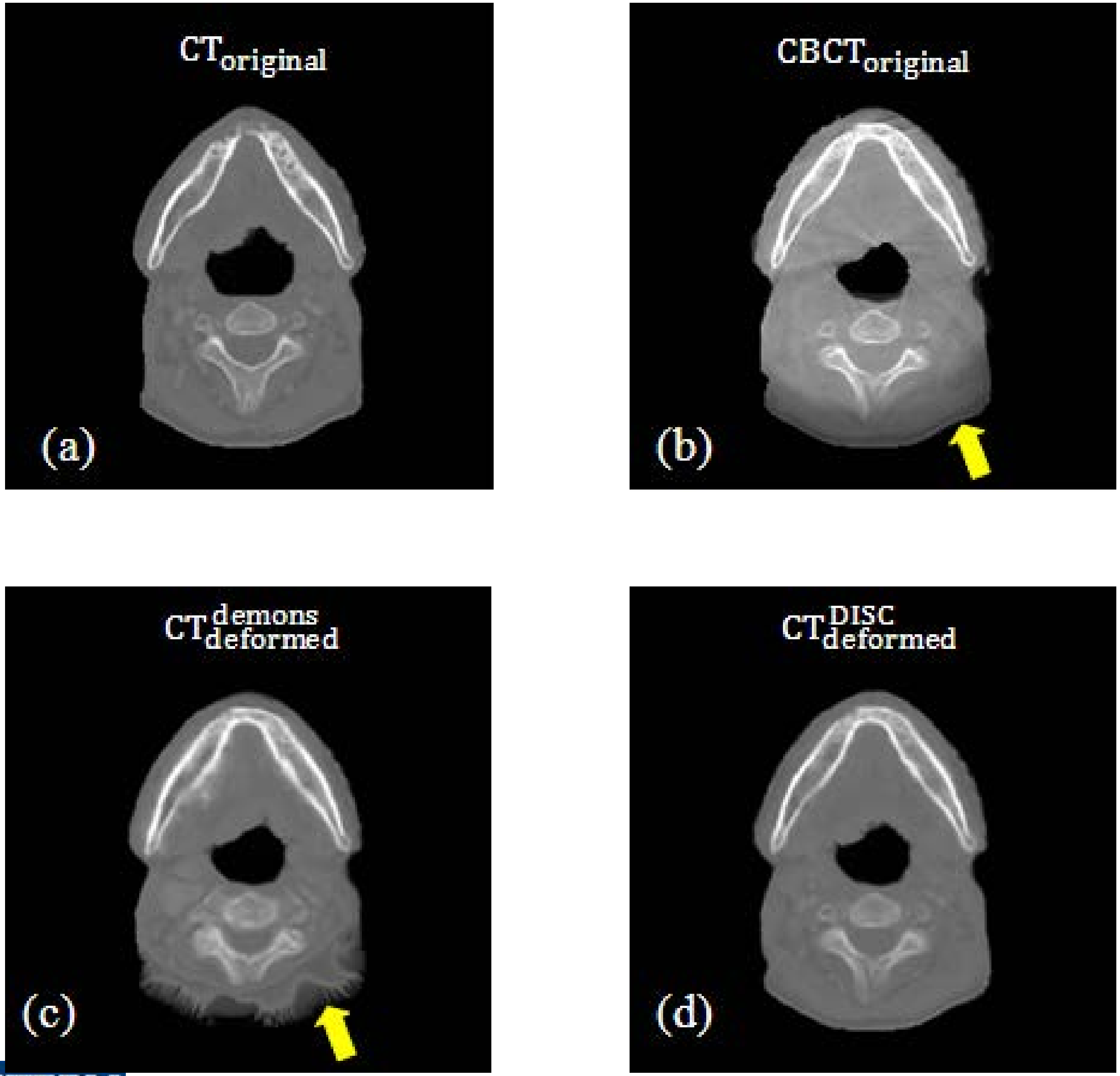


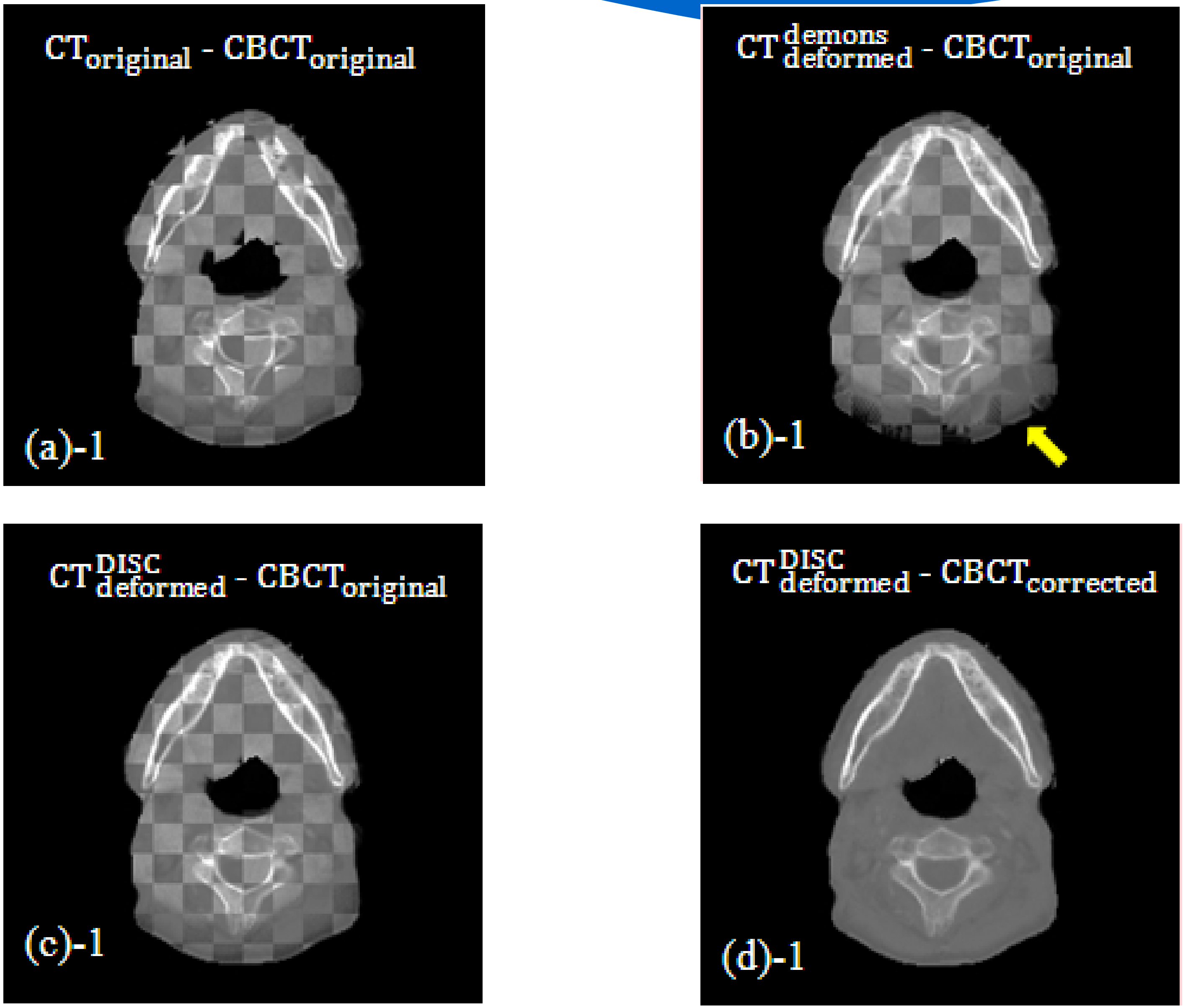

CT


CBCT

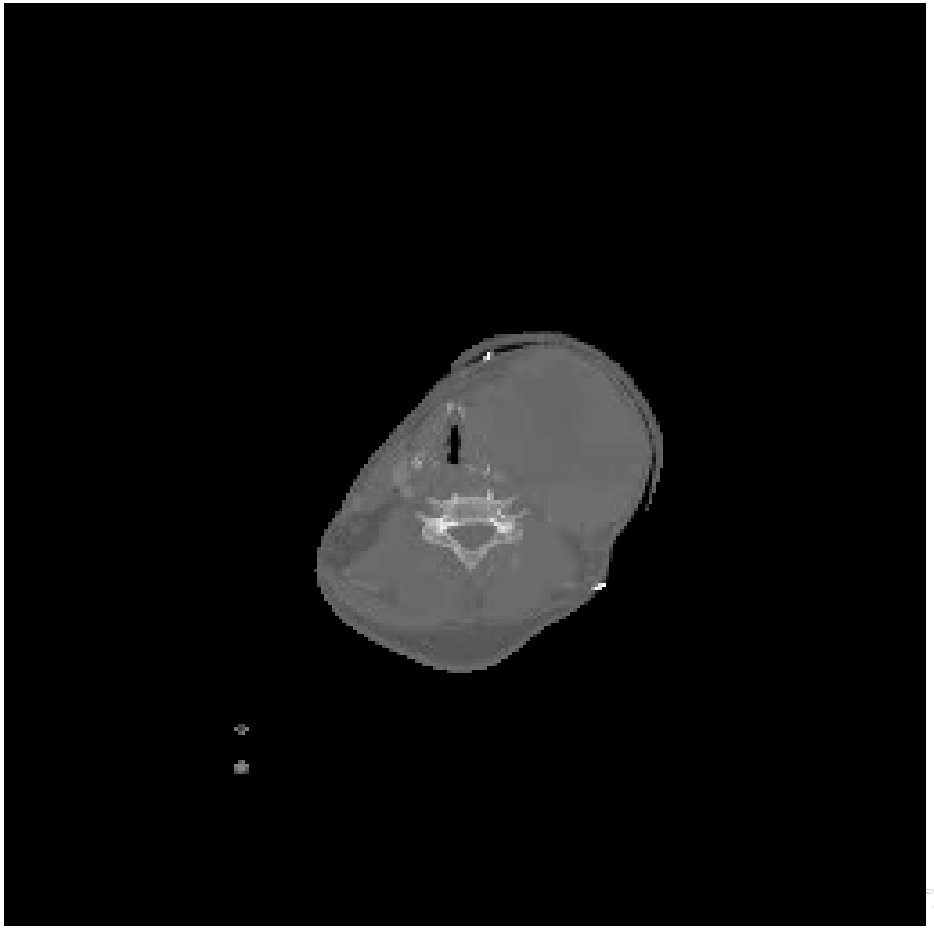

Overlap of CT and CBCT

Results---Clinical data

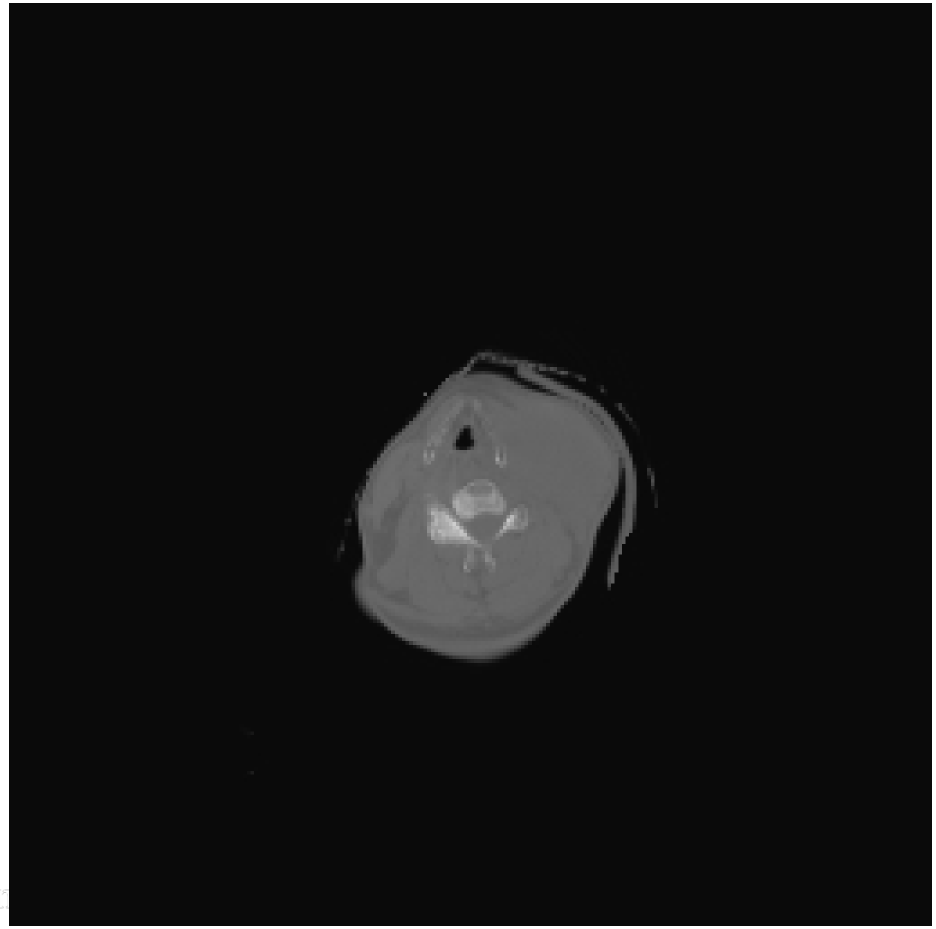



$CT_{original}$ - $CBCT_{original}$
(a)-1
$CT^{demons}_{deformed}$ - $CBCT_{original}$
(b)-1
$CT^{DISC}_{deformed}$ - $CBCT_{original}$
(c)-1
$CT^{DISC}_{deformed}$ - $CBCT_{corrected}$
(d)-1

Results



Movie- deforming CT



CBCT

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DISC-advantages

- DISC is robust against the CBCT artifacts and intensity inconsistency
- DISC significantly improves the registration accuracy when compared with the original demons.
- DISC can generate the intensity corrected CBCT image

DIR RECENT DEVELOPMENT

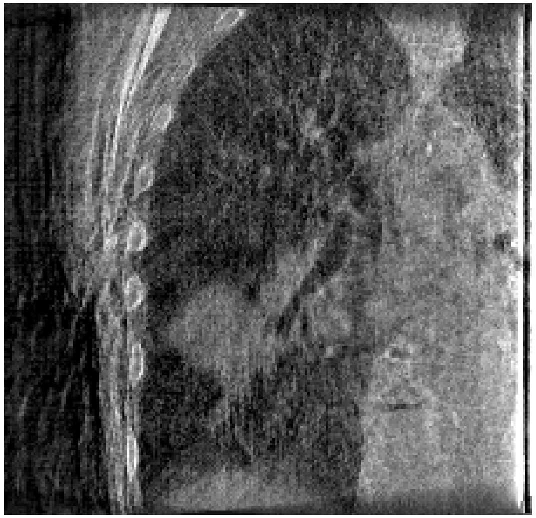
Project I: DIR for 4D CBCT Reconstruction SMEIR

---- J. Wang, X. Gu, "Simultaneous Motion Estimation and Image Reconstruction (SMEIR) for 4D Cone-beam CT", ***Med. Phys*** **40:101912:1-11(2013)**

Rationale

Image reconstruction and motion model estimation in four dimensional cone-beam CT (4D-CBCT) are handled as two sequential steps.

- Once the image is reconstructed, the accuracy of subsequent motion modeling will be limited by the quality of the reconstructed images.
- Due to the limited number of projections at each phase, the image quality of 4D-CBCT is often degraded which decreases the accuracy of subsequent motion modeling.

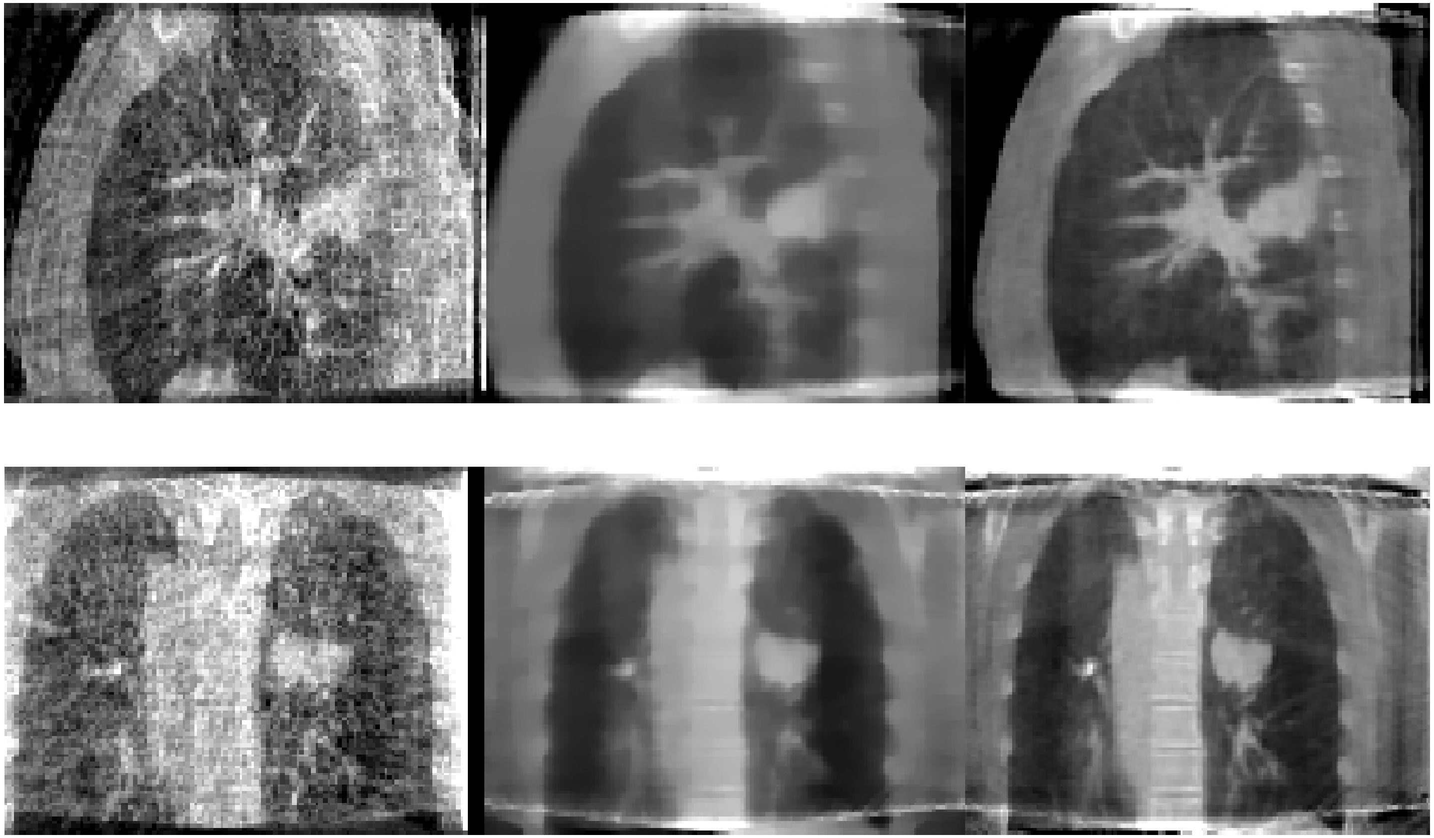


Simultaneous Motion Estimation and Image Reconstruction (SMEIR)

- Motion compensated image reconstruction
  – Reconstruct a motion-compensated primary CBCT (m-pCBCT) by using the projections from all of the phases with explicit consideration of the deformable motion between different phases.

- Motion model estimation/updating
  - Matching the forward projections of the deformed m-pCBCT and measured projections of other phases of 4D-CBCT.

Patient Study



FDK
24 projections

TV
24 projections

SMEIR
24 projections

Project 2: DIR for 4D Treatment Planning

--- Modiri, Sawant, Gu, “4D IMRT Planning Using Highly-Parallelizable Particle Swarm Optimization”, AAPM 2014

4D treatment planning

4D planning technique to be used (beyond the current scope) in conjunction with real-time MLC tracking in order to deliver the optimal dose distribution that

– accounts for real-time motion and deformation of the tumor target as well as surrounding structures

– uses motion to our advantage i.e., as an additional degree of freedom rather than a constraint, by modulating the dose-weights per respiratory phase

Optimization Step (1)

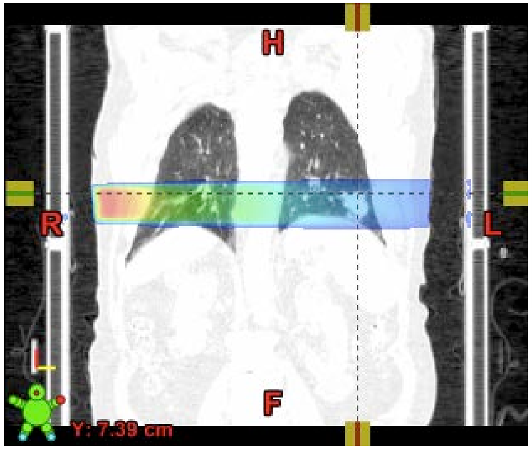
Load CT data, structure data, and all individual dose data corresponding to the beams over 10 phases

Resample CT data based on dose grid

Deform dose distributions from individual phases to the reference phase

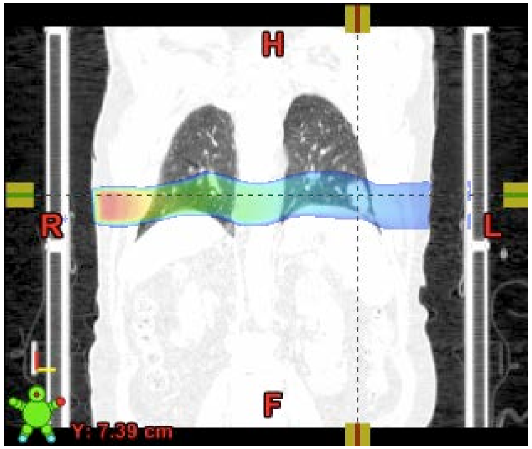
Example)

0% Dose distribution



50% phase CT

0% Deformed dose distribution

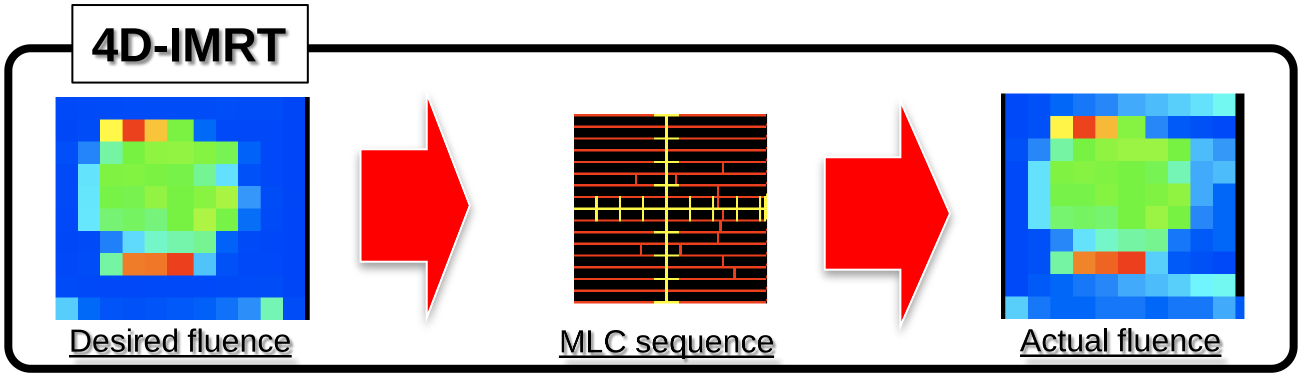


50% phase CT

Optimization Step (2)

Calculate optimal beamlet intensities for each treatment field over the phases using the particle swarm optimization algorithm

- Dose deposited to each voxel i in 4D
- Dose matrix elements a_{ij}^{p} , dose delivered by beam j to voxel i per unit beam fluence for respiratory phase p.
- The 4D optimization was performed using reference-phase structure datasets with all phase dose distributions.



Sum the dose data with the optimal beam intensities

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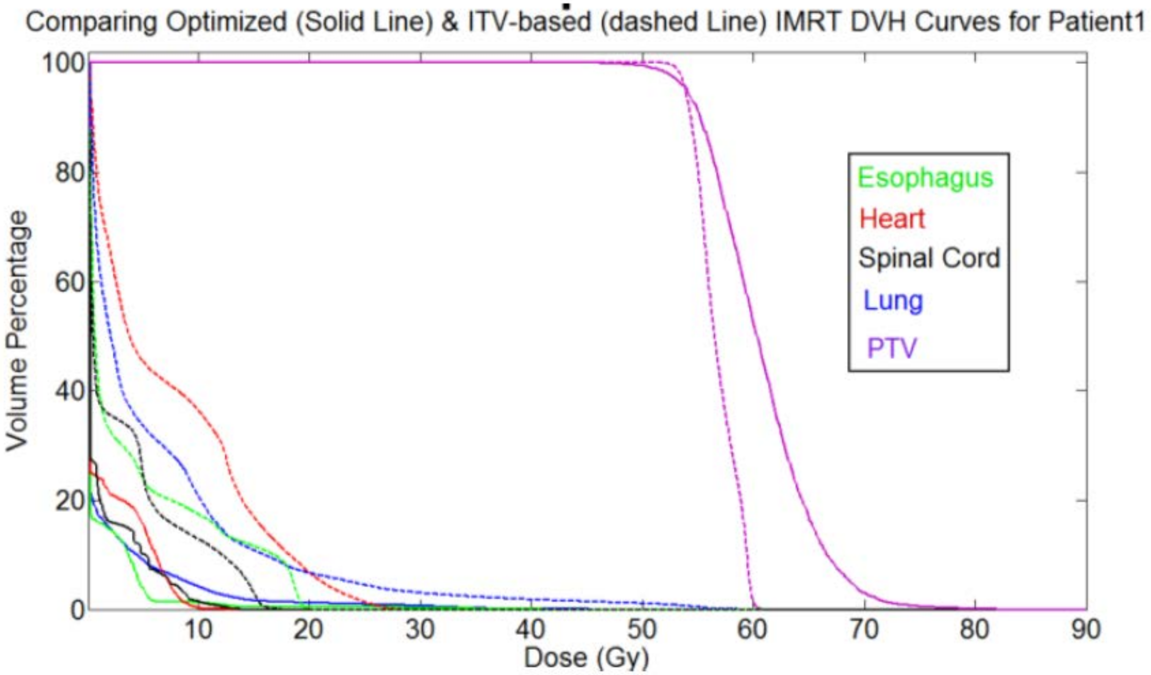
Results: Lung SBRT



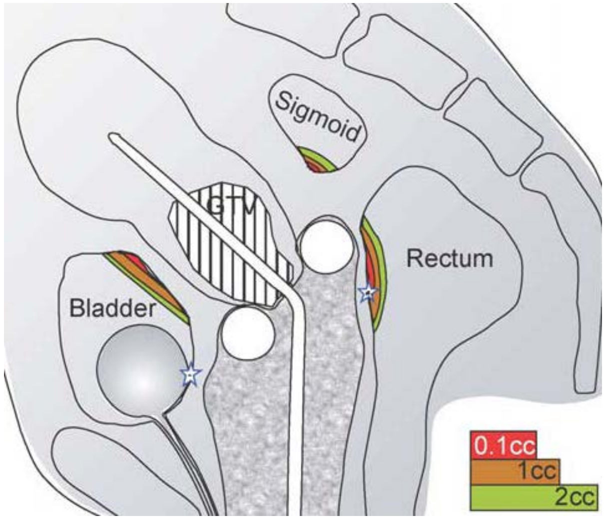
The dose comparison between ITV-based and our optimized plans

	Lung mean dose (Gy)	Lung V20% (Gy)	Spinal cord max dose (Gy)	Esophagus max dose (Gy)	Heart max dose (Gy)	Heart mean dose (Gy)
ITV-based IMRT plan	11.2	10.5	17.7	19.7	26.5	13.7
Our Optimized 4D IMRT plan	8.1	1.0	13.7	13.5	13.1	5.0

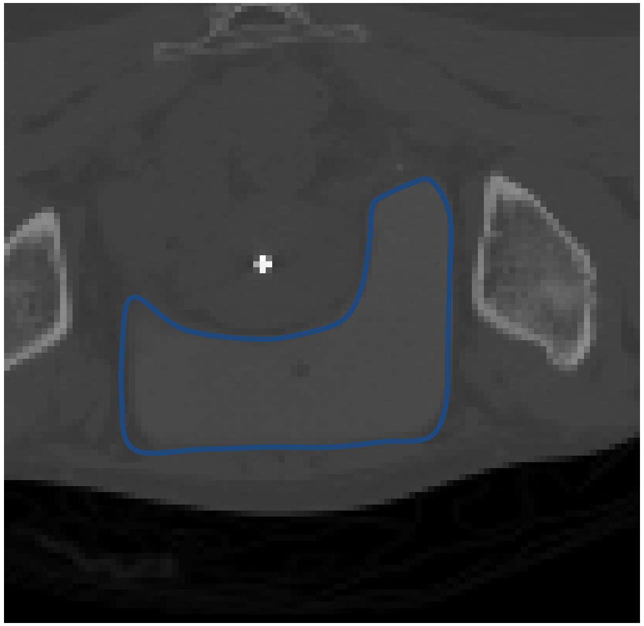
Project 3: DIR for OAR dose summation in HDR

---- X. Zhen, X. Gu "Towards accurate OAR dose summation in cervix HDR brachytherapy: applying a non-rigid point matching method to bladder deformation" ABS 2014

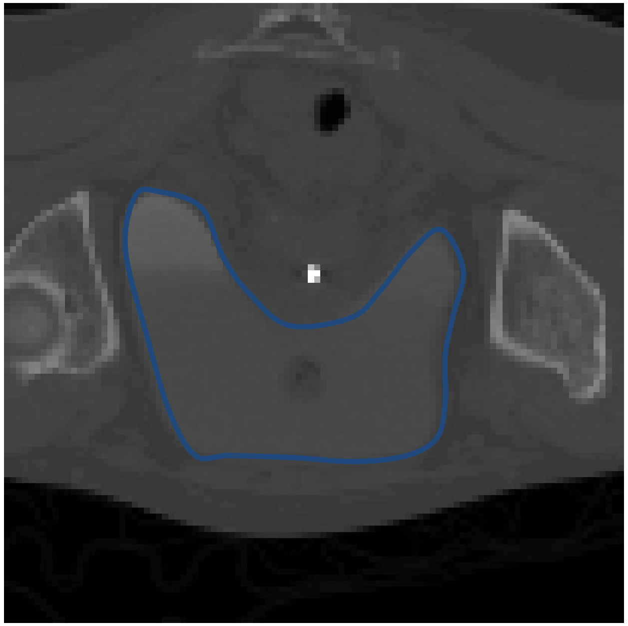
D_{2cc} Challenges in Brachy



Radiother. Oncol. 78 (2006) 67-77

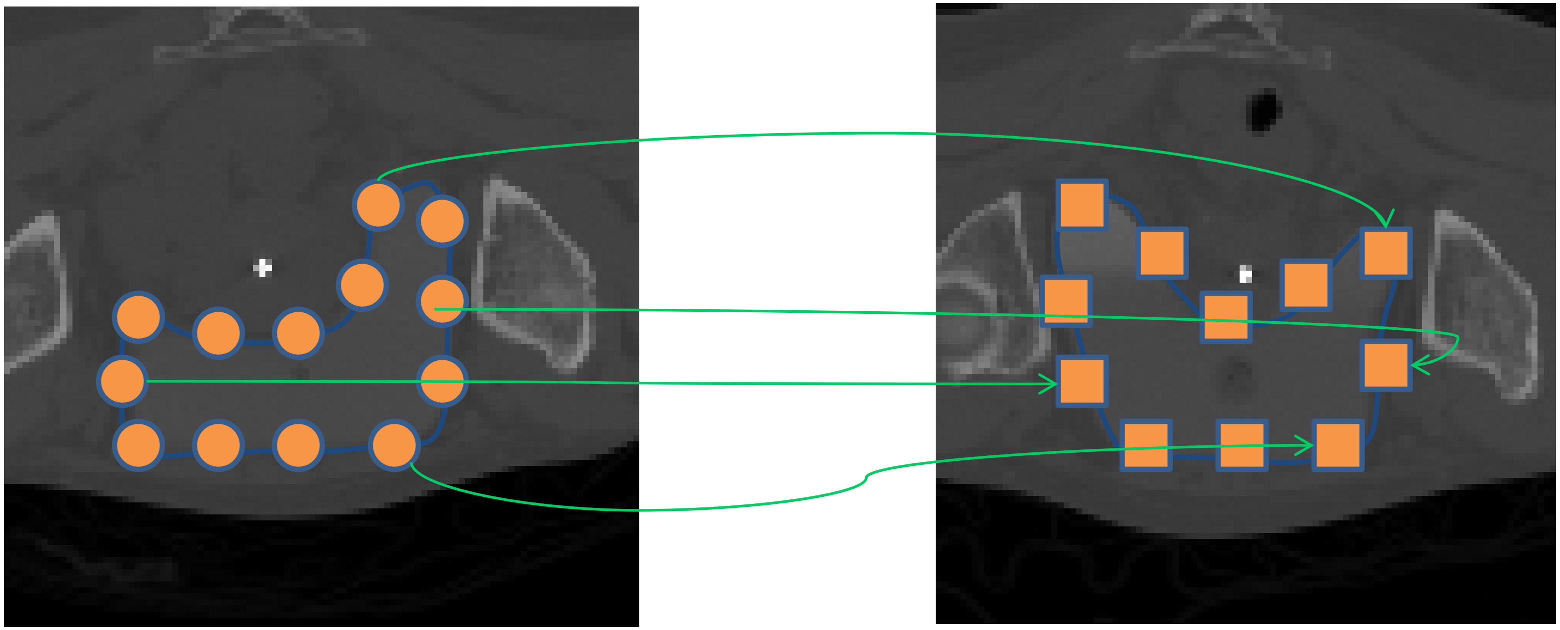


Bladder in Fraction 1



Bladder in Fraction 2

Non-rigid point matching: TPS-RPM*
(thin-plate spline robust point matching)



*Not only accurate DVFs, but also one-to-one point correspondence

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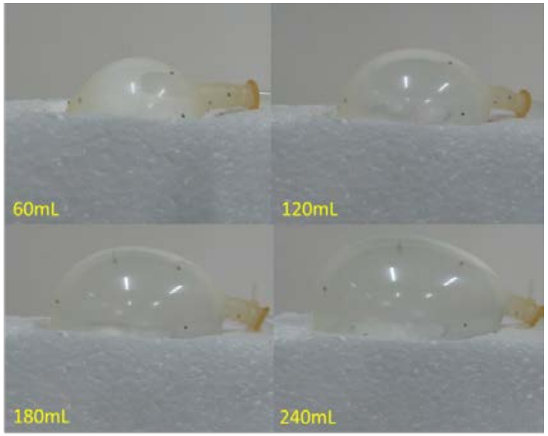
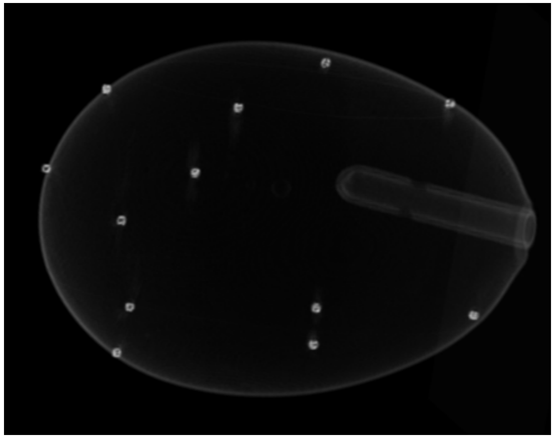
Phantom Study Results

- A homemade balloon phantom for bladder deformation simulation
  - A balloon with 12 BBs (0.5mm in radius) attached on the balloon surface as landmarkers.
  - 60mL, 120mL, 180mL and 240mL water was injected sequentially with a syringe
  - Corresponding CT scans were performed with resolution of 0.429×0.429×0.25 mm^3





CT image(240mL, rendered in 3D)

Table 1. The mean Euclidean distance (mm) of the 12 fiducials after rigid and TPS-RPM matching

	120mL→ 60mL	180mL→60mL	240mL→60mL
Rigid	7.26±0.87	12.18±1.65	15.86±1.93
Demons	4.62±2.32	7.53±3.02	10.01±3.77
TPS-RPM	2.47±1.25	4.25±1.75	5.90±2.24

DIR FUTURE DEVELOPMENT

DIR in RT

- Goal:
  - 4D CBCT: achieve better image
  - 4D planning : achieve hig... treatment plans
  - Treatment evaluatio... dose accumulation

Validation and QA

How do we make sure we are achieving improvement and not introducing more errors?

Current Validation Techniques

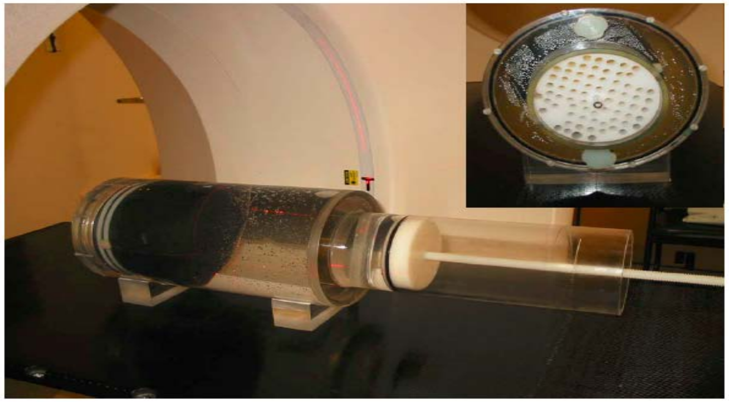
- Visual comparison
- Landmark matching
- Boundary matching
- Volume overlapping
- Image intensity correlation

Qualitative evaluation

Not guarantee inside matching

Not guarantee DVF accuracy

Develop QA phantoms



Deformable phantom

Monica Margeanu, Medical Physics Unit, McGill University

Deformable Gel Dosimeter

Oldham lab in Duke Radiation Oncology

Thank you!

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