Deformable Registration in the Clinic: From Commissioning To Advanced Applications

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Key Technical Concepts

Dose Calculation

- **Calculation:** Monte Carlo, Pencil Beam, AAA are models of dose calculation
- **Output:** The output format is standard across models, a dose value for each pixel in the CT dataset.
- **QA:** IMRT QA uses independent tools or software to verify the linac can deliver the dose.

Deformable Registration

- **Calculation:** BSpline, demons, FEM are models of deformable registration
- **Output:** The output format is standard across models, a vector displacement associated to each pixel in the CT dataset.
- **QA:** QA should verify independently that the vector displacement correspond to expected anatomical motion.

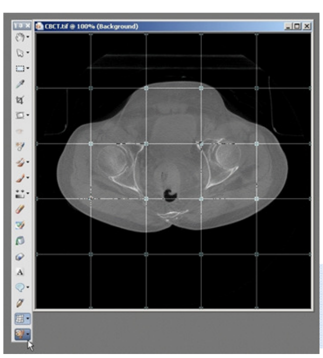
Types of Deformable Registration

BSpline – Deformation defined on a grid of nodes. Optimization finds optimal nodes displacement.

Demons – Matches intensity patterns using partial differential equations.

Finite Elements Models (FEM) – Models organ displacements using physical equations.

B-Spline Model



Displacements defined on set of control points stretched over the image

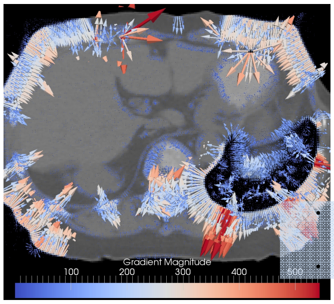
For any arbitrary location, corresponding displacements deduced by interpolation of closest control points

Optimizer finds displacements in these control points

More flexibility, being able to match CT's, MRI's CBCT's

The deformation field is smooth.

Demons Model



Each voxel moved by
gradient * intensity difference

This one defines the direction of movement, as shown in the image

This one is zero, stops the motion, when images are aligned

- Less flexibility, being able to match only same modality (CT to CT)
- High –resolution displacement field.

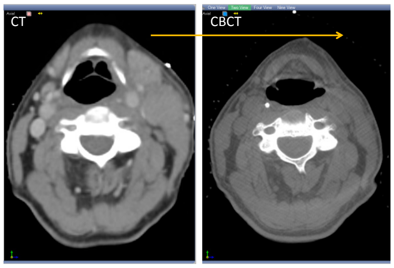
Image Registration – Key Concept

- Image registration is an approximate solution to a problem of registering multiple images together in the absence of ground truth.

Deformable Registration, From a User Perspective

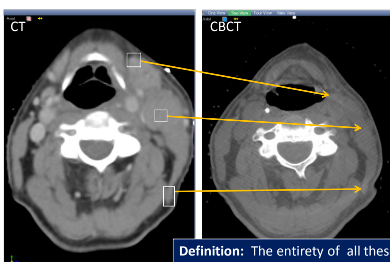
Rigid Registration

Rigid registration aligns images by global translations



Deformable Registration

Deformable registration is a rigid registration for each voxel.



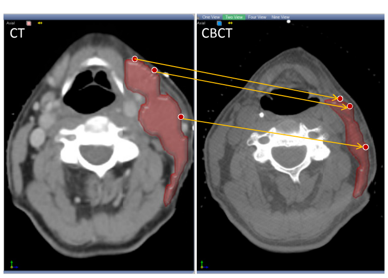
Applications :

- Auto-segmentation
- Adaptive Radiotherapy or IGRT
- Voxel-Based Treatment Response Assessment
- Dose Tracking or Summation
- 4D Motion Tracking

Definition: The entirety of all these voxel-wise displacements is called displacement field or vector field

Contour Tracking

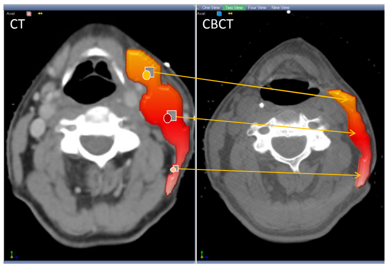
Same transform can be applied on contours for auto-contouring



The deformation field between two image scans obtained from the deformable registration can be used to deduce displacements on the contours

Dose Tracking

Dose mapped from the CT to the CBCT



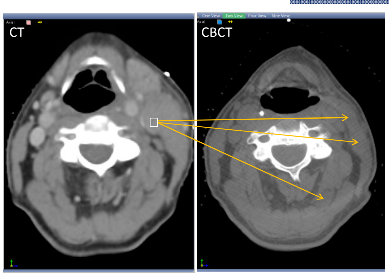
Once the voxel-by-voxel mapping is fund, it can be applied on anything associated with that voxel.

Many Solutions Exists

We don't know what really happened to the voxel inside the tumor.

Deformable registration it's just guess, using some assumptions.

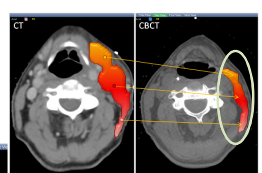
The uniform gray voxel inside the structure can be mapped anywhere. Which one of these is the correct mapping ?

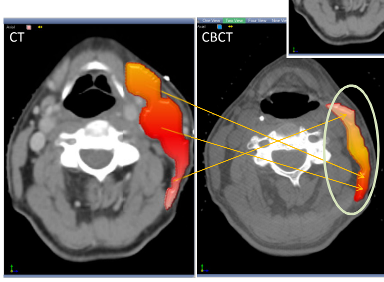


The deformable registration is guessing what happened from a multitude of mathematically equivalent solutions.

Example

These mapping are mathematically equivalent when looking at HU units. Dose-wise, significantly different.





Deformable Registration QA

Our aim is to make sure that the displacement field found by an algorithm is a reasonable guess.

As for IMRT QA, the solution is case –dependent. Therefore QA for deformable registration will be case-dependent.

Focus is on recognizing algorithm failures, in clinic, on your cases. It is not a general discussion about algorithm A is better than B.

Deformable Registration, From a User Perspective

Clinical Workflow

Case Study: SBRT Lung Case

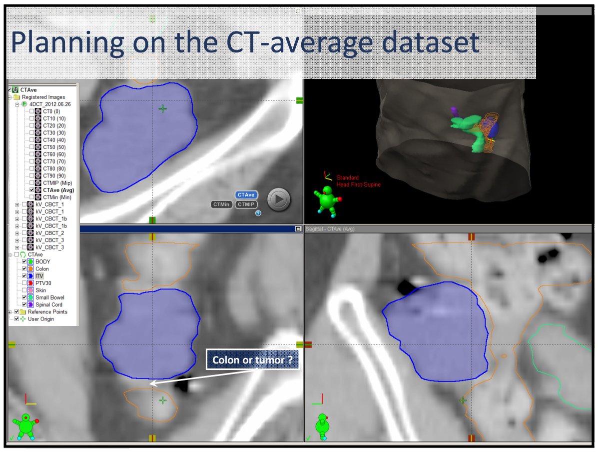
Patient had a 4D CT of the abdomen, static CTs with MIP, average and maximum projections also generated from the 4D dataset.

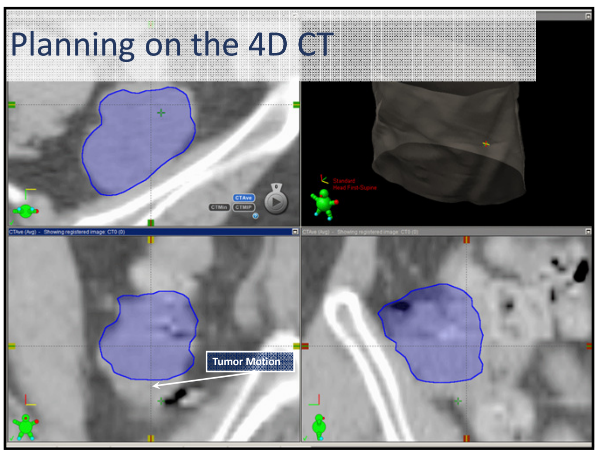
Segmentation in one phase of the 4D CT

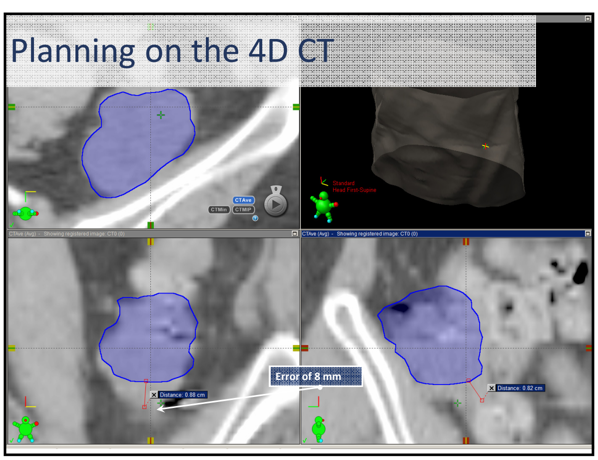
User would segment the tumor in one phase of the 4D CT dataset, such as end expiration

Deformable registration tracks motion

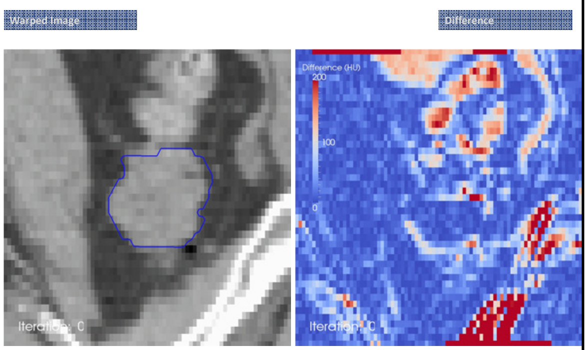
Deformable registration between the phases of the 4D CT dataset. User segmentation warped with the displacement field to the next phases.


Planning on the CT-average dataset
Colon or tumor ?

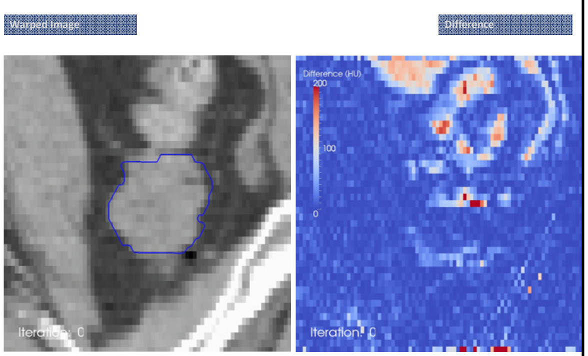

Planning on the 4D CT
Tumor Motion


Planning on the 4D CT
Error of 8 mm

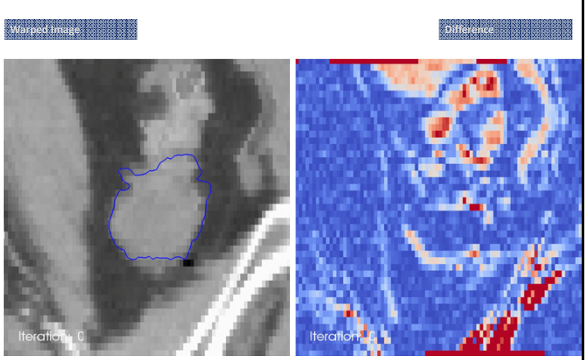
BSpline



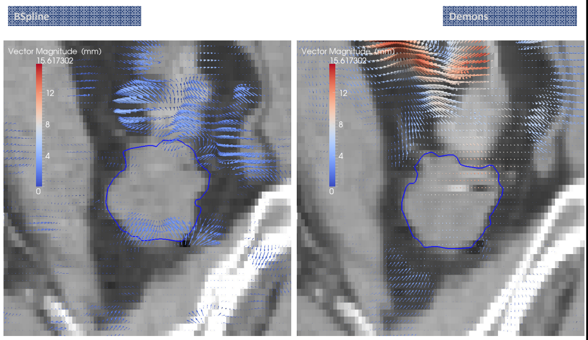
Demons – Smooth Field



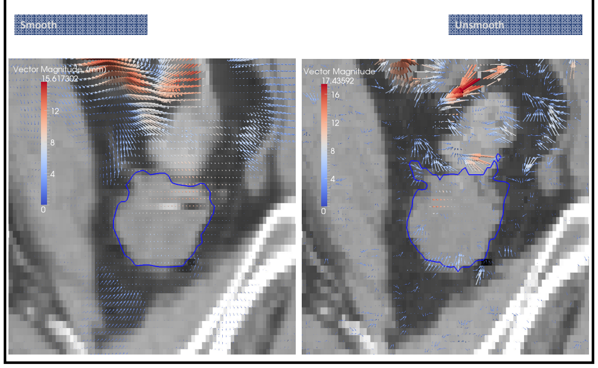
Demons – Unsmooth Field



Solution Comparison

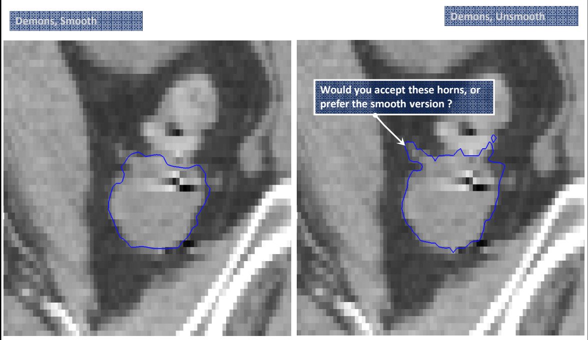


Demons Variants

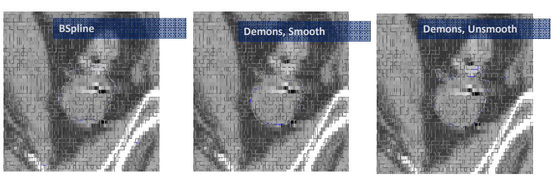


Quality Assurance

Quality Assurance



Interactive Question



Interactive Question: How would you validate this segmentation in your clinic ?

A. Would select the BSpline solution

B. Would select the demons smooth solution

C. Would select the demons unsmooth solution

D. By law, segmentations, automated or manual, should be validated by the attending physician.

Clinical Example: Integrating PET into Treatment Planning

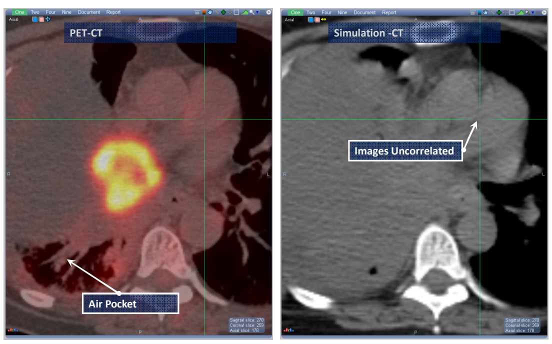
Clinical Workflow

Case Study
PET-CT case for lung case with respiratory motion displacements between PET-CT and CT-sim.

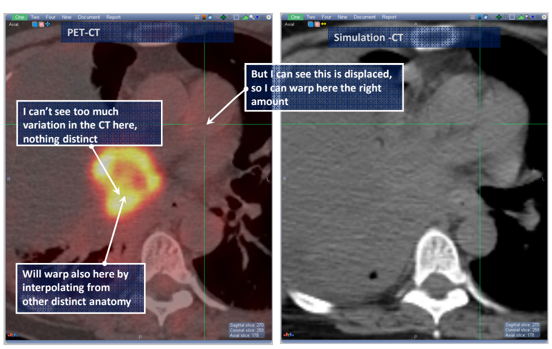
Deformable algorithm to quantify changes
Either B-Spline or Demons algorithm used to track changes between the CT component of the PET-CT, and the simulation CT

Then applying on PET for SUV's maping
Displacement field applied on the PET component of PET-CT to bring SUV's into simulation CT

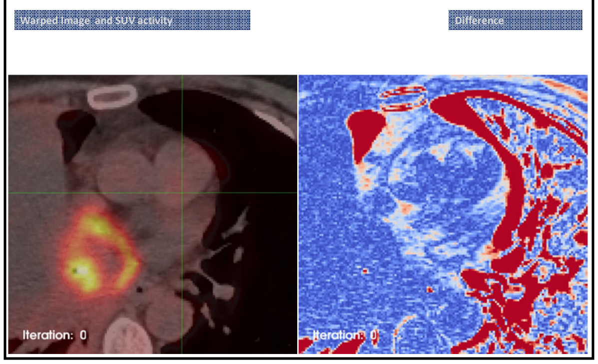
Sample Case



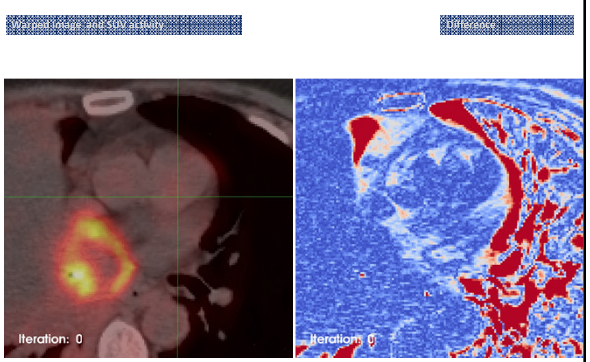
What's the Deformable Thinking ?



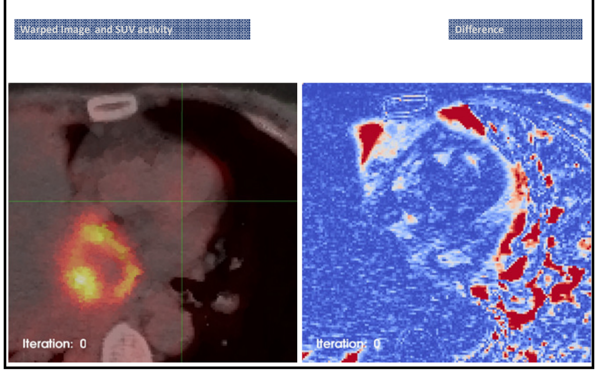
BSpline



Demons – Smooth Field

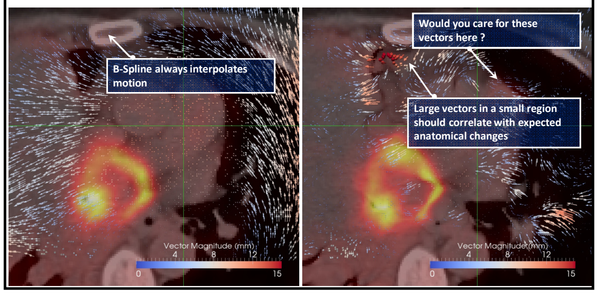


Demons – Unsmooth Field



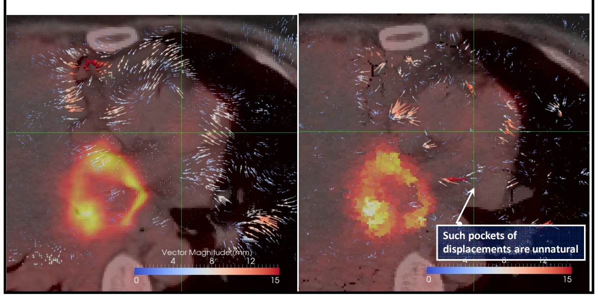
Quality Assurance

BSpline | Demons



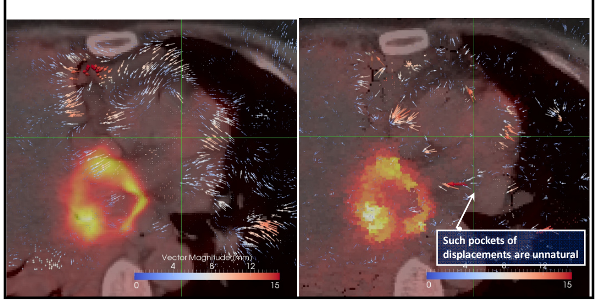
Quality Assurance

Smooth | Unsmooth

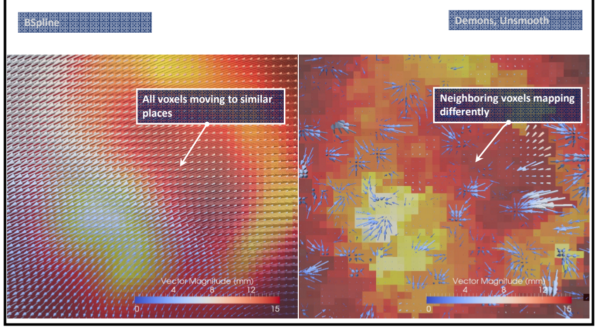


Quality Assurance

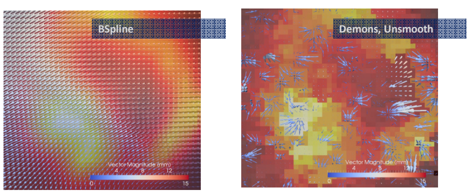
Smooth | Unsmooth



Zoom on Tumor Region



Interactive Question

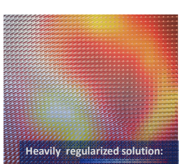


Interactive Question: Which solution would you select in this case ?

A. Would select the BSpline solution, because tumor is relatively solid tissue that is expected to deform consistently

B. Would select the demons solution, because it can warp each voxel independently.

What is Regularization ?



Heavily regularized solution:

Neighboring voxels are forced in the algorithm's mathematics to behave consistently, i.e. to map to similar places.

Most solid tissues fall under this category, deforming unitarily.

Too much regularization prevents the algorithm from modeling small deformations

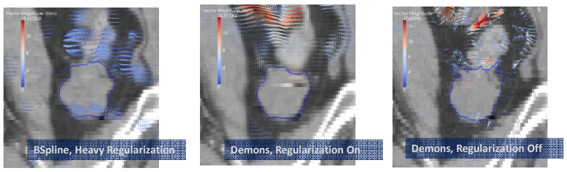
All algorithms implement this concept

Un-regularized solution:

Each voxel is allowed to move independently, it does not care how it's neighbor behave.

Sometime unregularized solutions properly model anatomical motion. For example, at the lung-diaphragm interface, lung and diaphragm slide independently.

Interactive Question



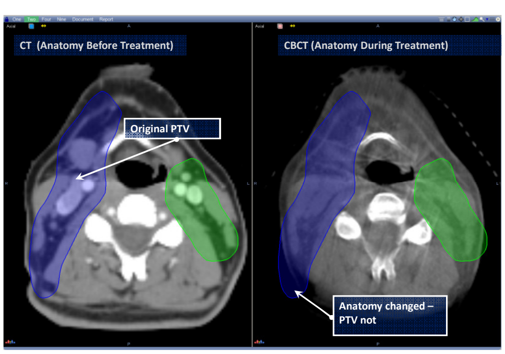
Interactive Question: For the previous case of 4D CT segmentation, would regularization obtained with these different algorithms matter ?

A. Yes, because it models tissue inside the tumor

B. No, regularization is not important here, as long as the contours match the image

Clinical Example:
Dose Tracking on CBCT

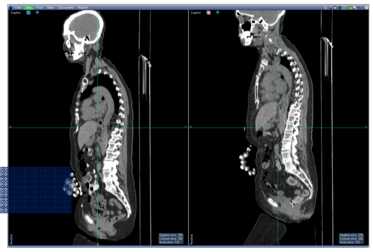
Sample Case



Mono-Modality Cost Function

Mono-modality – assume a pixel has the same intensity in both datasets to be matched.

Works only CT to CT, or MRI to MRI.



Typical cost function:
intensity difference

Multi-Modality Cost Function

Multi-modality – a pixel can change intensities between datasets.

Mix and match : can work between MRI, CT, & CBCT.

Typical cost function:
Mutual information (statistics)

Questions: Mid-Treatment Changes

Is dose still valid ?

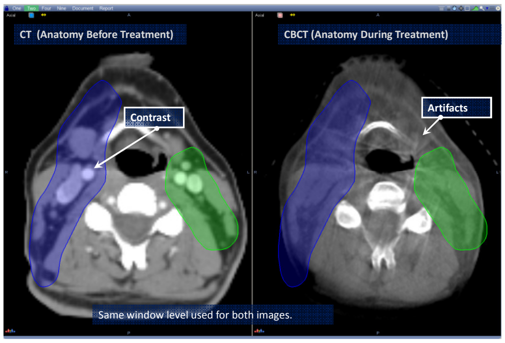
With the anatomical changes, we expect changes in the delivered dose and OAR/PTV shapes and sizes

Should re-sim ?

Is it worth going through the whole segmentation and planning process ?

Image Quality

- Assume same modality
- Different image quality



Clinical Workflow

Deformable Algorithm to quantify changes

Either B-Spline or Demons algorithm used to track changes

Then estimating dose using voxel tracking

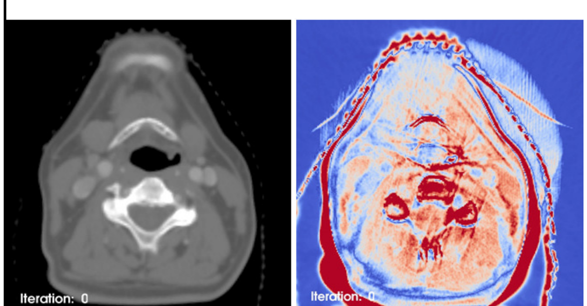
Displacement field applied on structures for auto-segmentation

Applied on dose for estimating DVHs.

BSpline

Warped Image

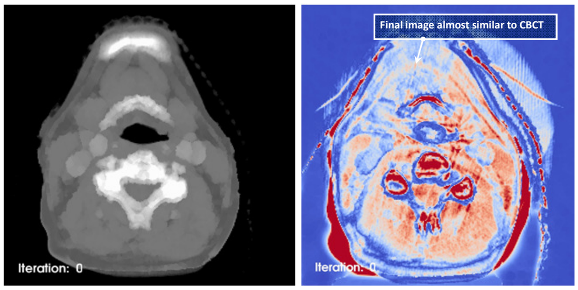
Difference



Demons

Warped Image

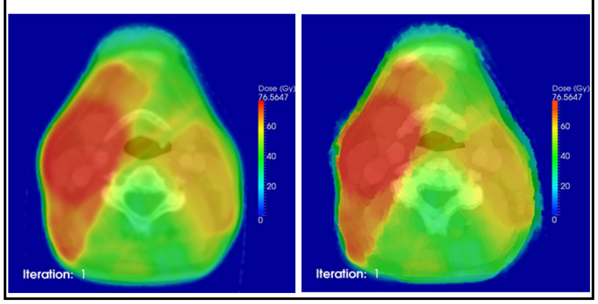
Difference



Deformable Applied on Dose

BSpline

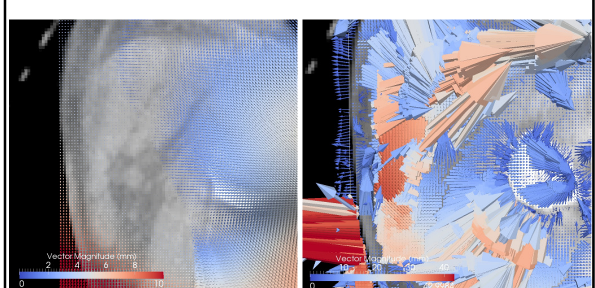
Demons



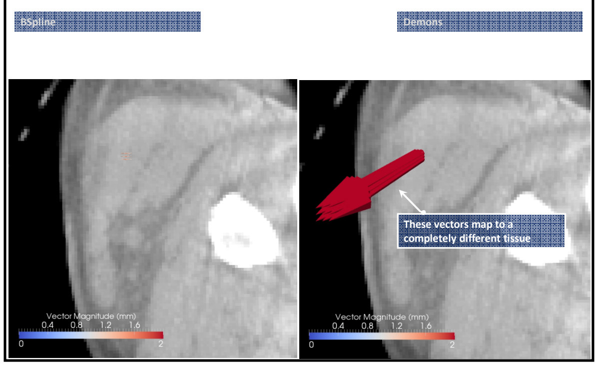
Checking the deformation

BSpline

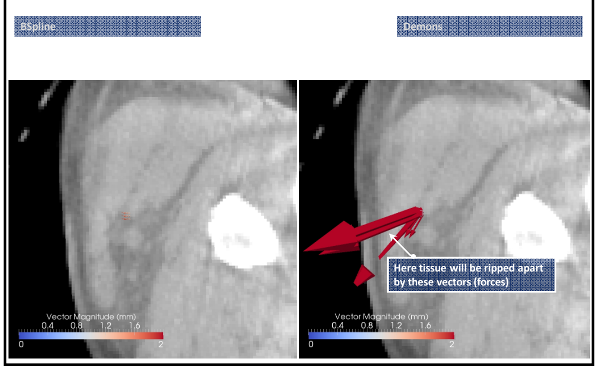
Demons



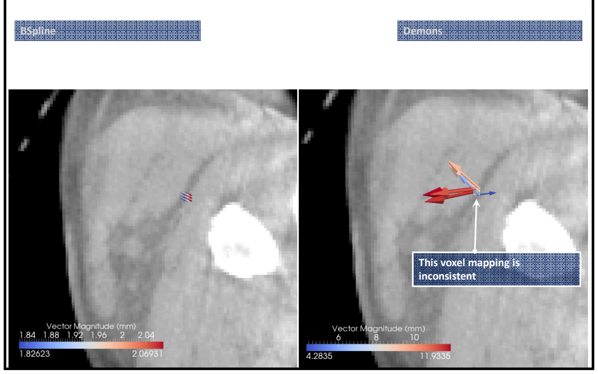
Checking the deformation



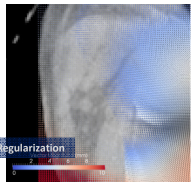
Checking the deformation

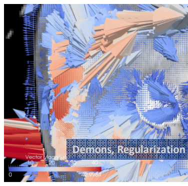


Checking the deformation



Interactive Question





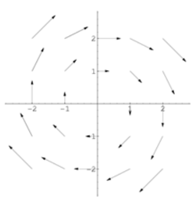
Interactive Question: For this case will you choose:

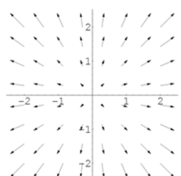
A. The BSpline solution, because it provides a vector field that is plausible

B. The demons solution, because the CT image matched with the demons is very similar to the CBCT image visually

C. It does not matter, both solutions are valid.

Measures From the Vector Field





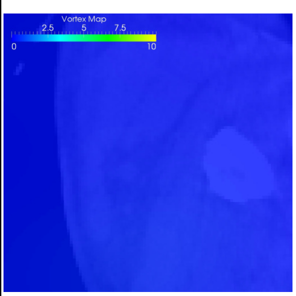
Swirls: This deformation field would cause **rotation** of an imaginary sphere placed at origin.
Mathematically detected by the **CURL** operator

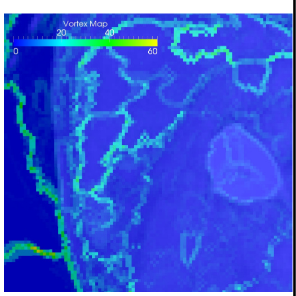
Volume Changes: This deformation field would cause **expansion** of an imaginary sphere placed at origin.
Mathematically detected by the **Jacobian** operator

Checking the CURL

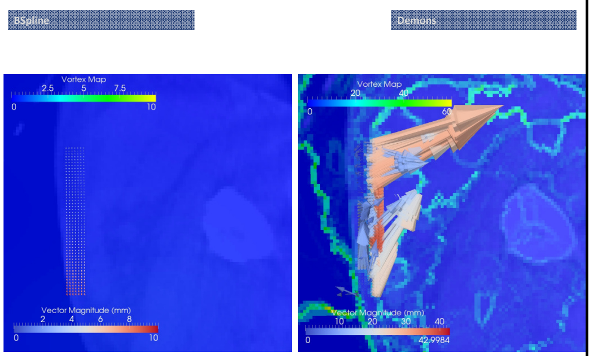
BSpline

Demons



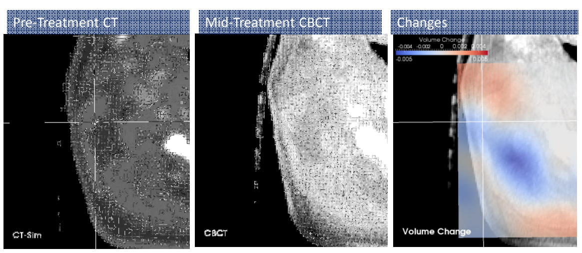


Checking the CURL



Interpretation Tool: Volume Changes

Volume changes quantified from the deformation field. Outputs map of regions expanding or contracting.



Conclusion

Flexible Tool– Clinically, deformable registration algorithm will give you the power to track and quantify anatomical changes

Interpretation Tools for QA – Inspecting the displacement field directly provides valuable information. This is independent of algorithm or settings selection

Try it ! You'll like it.