Deformable Registration in the Clinic:
From Commissioning To Advanced Applications

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.

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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.

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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 CTs, MRIs, CBCTs.

The deformation field is smooth.
Demons Model

Each voxel moved by
\( \text{gradient} \times \text{intensity difference} \)

- 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

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

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

Many Solutions Exists

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
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.
Solution Comparison

Demons Variants

Quality Assurance

It's easy to verify results - just have to match the anatomy as we do for manual segmentation. BSpline did not work well here.
Interactive Question:

How would you validate this segmentation in your clinic?

A. Would select the B-spline 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 mapping
Displacement field applied on the PET component of PET-CT to bring SUV’s into simulation CT

Sample Case

What’s the Deformable Thinking?

Images Uncorrelated
Air Pocket
PET-CT
Simulation -CT

I can’t see too much variation in this CT here, relatively close.

But I can see this is displaced to the right here the right amount.

Will vary also here by interpolating them, other distinct anatomy.
Would you care for these vectors here?

Large vectors in a small region should correlate with expected anatomical changes.

B-Spline always interpolates motion.

Such pockets of displacements are unnatural.

Such pockets of displacements are unnatural.
Zoom on Tumor Region

Interactive Question

What is Regularization?
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.

Multi-Modality Cost Function

Multi-modality – a pixel can change intensities between datasets.
Mix and match: can work between MRI, CT, & CBCT.

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

- Same window level used for both images.
- Artifacts
- Contrast
- CT (Anatomy Before Treatment)
- CBCT (Anatomy During Treatment)
- 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

- Displacement field applied on structures for auto-segmentation
- Applied on dose for estimating DVHs.
Demons

Deformable Applied on Dose

Checking the deformation
Checking the deformation

These vectors map to a completely different tissue. Here tissue will be ripped apart by these action forces. The voxel mapping is inconsistent.
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
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.