Modeling Tissue Biomechanics for Image-Guided Cancer Therapy

THE UNIVERSITY OF TEXAS MD Anderson Cancer Center Making Cancer History®

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Disclosures:

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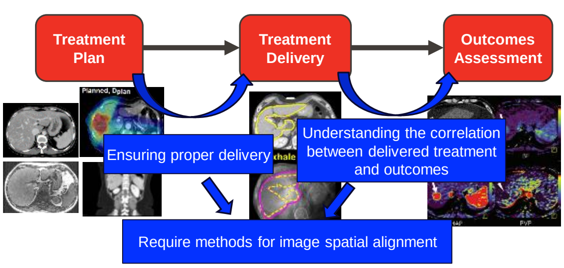
Cancer Therapy Workflow



Deformable Image Registration (DIR)

- A lot of DIR solutions are commercially available today.
- Most of them are global intensity-based methods → aim to match the mutual information (structure boundaries)

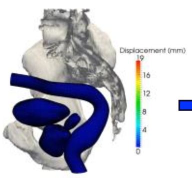
One main reason to be cautious when using standard DIR:

Matching organ boundaries does not ensure matching anatomy especially inside large areas homogenous in intensity where the deformation estimation is the result of a geometrical regularization model.

One main limitation of standard intensity-based DIR:

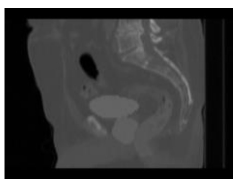
This global regularization model of the displacement field will not allow to model complex volume change or complex inter-organ interactions such as a sliding motion.

Why should we be cautious when using standard DIR?

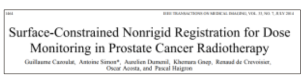


Pelvis Numerical phantom

Pressure injected in the bladder (0-5 kPa) and the rectum (0-2 kPa)

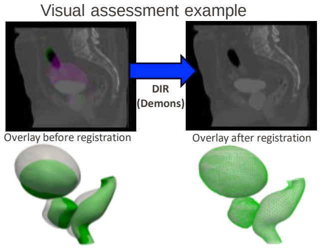


Synthetic high-contrast longitudinal images


Surface-Constrained Nonrigid Registration for Dose Monitoring in Prostate Cancer Radiotherapy

Why should we be cautious when using standard DIR?

Visual assessment example

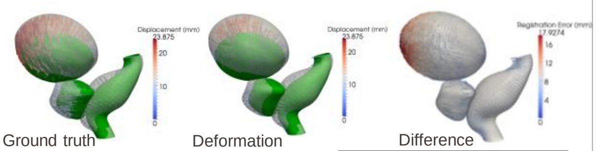


Dice scores

Prostate	0.97±0.001
Bladder	0.97±0.01
Rectum	0.97±0.01

DIR results look great

Why should we be cautious when using standard DIR?



Ground truth deformation

Deformation computed by DIR

Difference

Large anatomical point to point matching errors (due to a sliding motion of the bladder)

Surface-Constrained Nonrigid Registration for Dose Monitoring in Prostate Cancer Radiotherapy

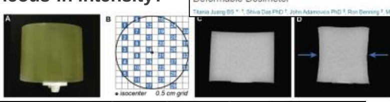
A smooth deformation vector field matching perfectly the anatomical structure boundaries does not necessarily ensure a « good » accuracy

So how to evaluate DIR accuracy for image areas homogeneous in intensity?

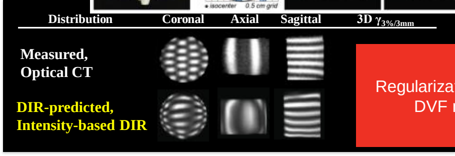
International Journal of Radiation Oncology*Biology*Physics
Volume 87, Issue 2, 1 October 2013, Pages 414-421

Physics Contribution

On the Need for Comprehensive Validation of Deformable Image Registration, Investigated With a Novel 3-Dimensional Deformable Dosimeter

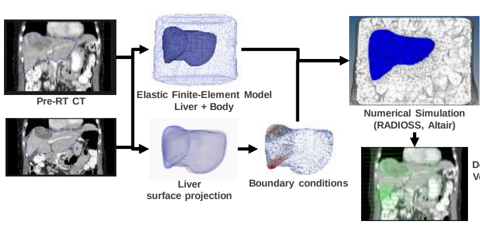


27% lateral compression

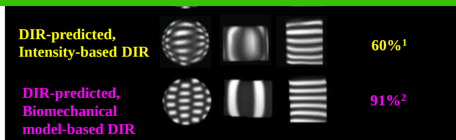


Regularization model of the DVF not adapted

Morfeus: A biomechanical model-based DIR solution



Biomechanical model-based DIR can be more accurate than classical intensity-based DIR in elastic structures homogeneous in contrast




Practical Radiation Oncology
Volume 5, Issue 4, July–August 2015, Pages e401-e408

Original Report

Utility and validation of biomechanical deformable image registration in low-contrast images

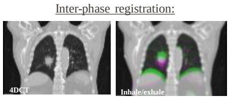
Michael Velec PhD, Titania Juang BSc, Joanne L. Moseley BMath, Mark Oldham PhD, Kristy K. Brock

1. Juang. IJROBP 2013;87(2): 414-421
2. M Velec, et al, PRO, 2015

Morfeus can be expanded to model inter-organ interactions or complex anatomical changes

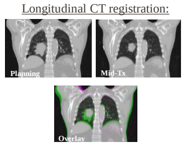
Registration of lung CT scans:

Inter-phase registration:



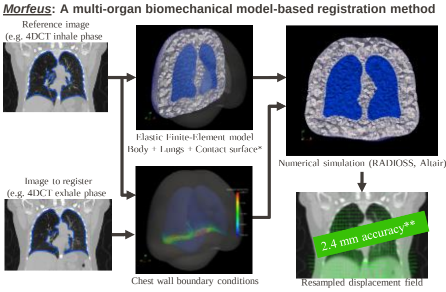
Challenges:
- expansion/contraction of the lung tissue
- Lung/chest wall sliding motion

Longitudinal CT registration:



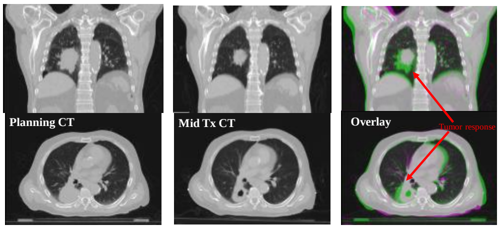
Challenges:
- Internal anatomical variations

Morfeus: A multi-organ biomechanical model-based registration method



* Contact surface and material nonlinearity modeling of human lungs, Al-Mayah *et al*, *PMB 2008*
** Biomechanical Deformable Image Registration of Longitudinal Lung CT Images Using Vessel Information, Cazoulat *et al*, *PMB 2016*

Lung biomechanical modeling for Deformable Image Registration

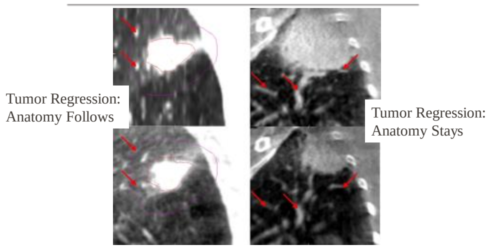


ELSEVIER

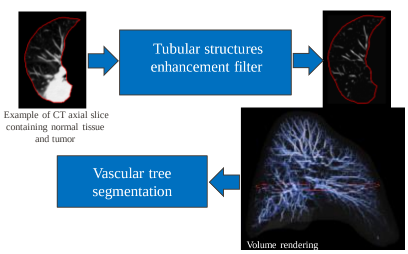
Seminars in RADIATION ONCOLOGY

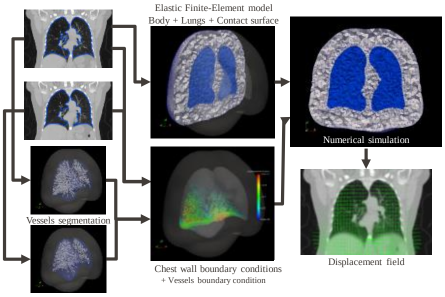
Adaptive Radiotherapy for Lung Cancer

Jan-Jakob Sonke, PhD, and José Belderbos, MD, PhD



<u>Solution to be more robust when registering tumor areas</u>:
To adjust internal deformations with consistent information in the image pairs

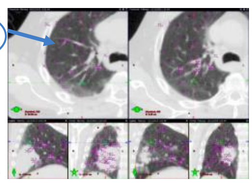




Evaluation of Morfeus accuracy:

Table 1. Patient-specifics information.

Patient	Tumor volume Plan-Follow-up (cm^3)(vol%)		Lung volume change (cm^3)(vol%)		Observations	Landmarks (tumor / normal lung)
P1	52-46	(-12%)	65	(+4%)	-	3/46
P2	54-33	(-38%)	221	(+13%)	Tumor erosion	7/59
P3	57-44	(-16%)	88	(-6%)	Emphysema	8/67
P4	431-319	(-26%)	60	(-6%)	Tumor elastic shrinkage; Pleural effusion	7/88
P5	205-128	(-39%)	238	(+16%)	Tumor erosion/elastic shrinkage	5/52
P6	189-103	(-46%)	32	(-3%)	Tumor erosion	19/28

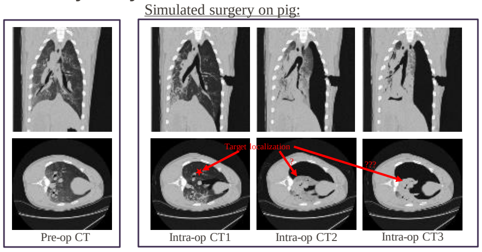


1.6 mm accuracy* (1.1mm for inter-phase registration)

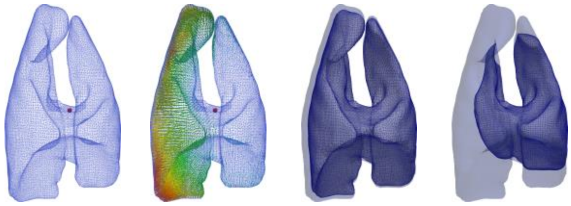
* Biomechanical Deformable Image Registration of Longitudinal Lung CT Images Using Vessel Information, Cazoulat *et al*, *PMB 2016*

Expanding the lung model to predict deflation during surgery: a preliminary study

Simulated surgery on pig:



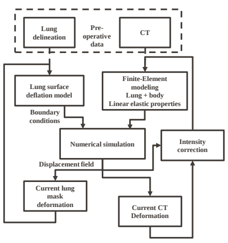
Prediction of lung deflation: Biomechanical model

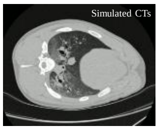


Initial lung mesh + air exit point | Boundary conditions | Morfeus 1st iteration result | Morfeus final result

More advanced model being investigated: air pressure injection through the surgical incision

Prediction of lung deflation: Biomechanical model

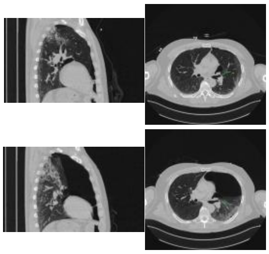


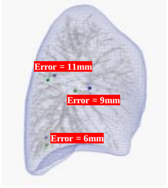


Evaluation of the predicted displacements accuracy is challenging

Development of human lung models

Example of images from a biopsy procedure:



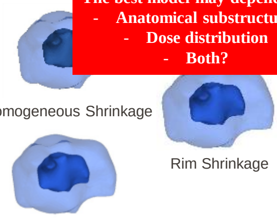


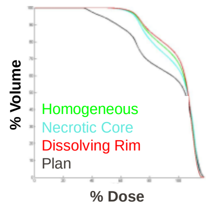
- Predicted landmark location
- Ground truth

Using FEM to locally control volume changes

Simulation of 3 shrinkage schemes of a parotid gland:

The best model may depend on:
- **Anatomical substructures**
- **Dose distribution**
- **Both?**





Morfeus expanded to model the volumetric response of tissue to radiation dose:

Int J Radiat Oncol Biol Phys. 2017 Nov 15;99(4):1004-1012. doi: 10.1016/j.ijrobp.2017.06.2455. Epub 2017 Jun 27.

Implementing Radiation Dose-Volume Liver Response in Biomechanical Deformable Image Registration.

Polan DF[1], Feng M[2], Lawrence TS[3], Ten Haken RK[3], Brock KK[4].

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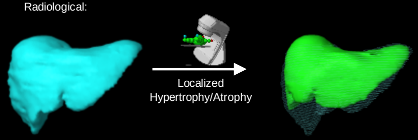
3. Department of Radiation Oncology, University of Michigan, Ann Arbor, Michigan.
4. Department of Radiation Oncology, University of Michigan, Ann Arbor, Michigan; Department of Imaging Physics, University of Texas MD Anderson Cancer Center, Houston, Texas.

Modeling Expansion/Contraction

Radiological:



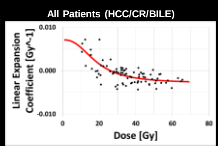
$$\alpha_L = \frac{\Delta V}{3 V_i D}$$

Dose (D) replaces Temperature Change (ΔT)

Slides Courtesy of Dan Polan, University of Michigan

Generating α_L Model

- 33 Liver Cancer Patients, 49-79 days post-RT
- Contoured Lobes on Pre and Post-treatment CT Scans
- Mean Dose to Each Lobe



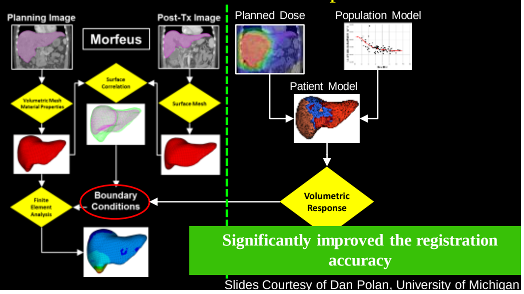
Sigmoid Equation

$$\alpha_L = (C - F)\left(\frac{(D_{50}/D)^{4\gamma}}{1 + (D_{50}/D)^{4\gamma}}\right) + F$$

C = Ceiling (max)
F = Floor (min)
D_{50} = Dose at 50% α_L range
γ = Fractional α_L change at D_{50}

Slides Courtesy of Dan Polan, University of Michigan

Addition of Volumetric Response



Significantly improved the registration accuracy

Slides Courtesy of Dan Polan, University of Michigan

Conclusions:

- The use of existing or the development of new biomechanical models for image alignment should be considered when:
  - The images present large regions of homogeneous intensities or inconsistent information content
  - Discontinuities in the deformation vector field should be allowed like in the presence of sliding motion
  - Complex anatomical changes occur (ex tumor regression)
- Finite-Element Models have also demonstrated to be promising tools to predict the behavior or tissues during treatment (ex lung deflation, brainshift, volume response to radiation…)