Tuesday, July 29th 2008
8:30 AM – 9:25 AM

Deformable Image Registration: Methods and Endpoints

Marc L Kessler, PhD
The University of Michigan

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By 9:25 AM, you will be able to …

- ✓ Describe the basic mechanics (*recipes*) of image registration techniques used in commercial & research planning and delivery systems
- ✓ Describe the different techniques used to combine, display & interact with multimodality and 4D image data
- ✓ Understand the clinical use & application of these techniques for treatment planning, treatment delivery & plan adaptation

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8:30 AM – 9:25 AM

What's the *recipe* for registering and fusing 3D & 4D image data?

What's the *cake*?

The Recipe

Recipe for Image Registration
2 Image Volumes
1 Transformation Model
1 Registration Metric
1 Optimization Engine
n Evaluation Tools

Recipe for Image Registration
2 Image Volumes
1 Transformation Model
1 Registration Metric
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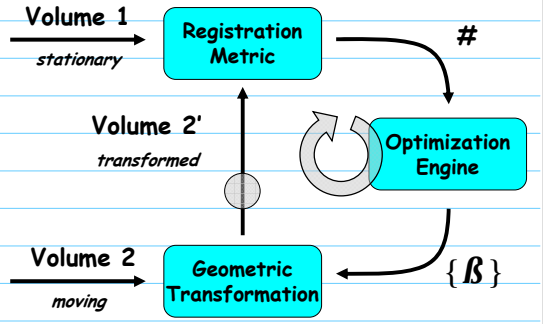
Recipe for Image Registration



Deformable Image Registration Methods and Clinical Endpoints

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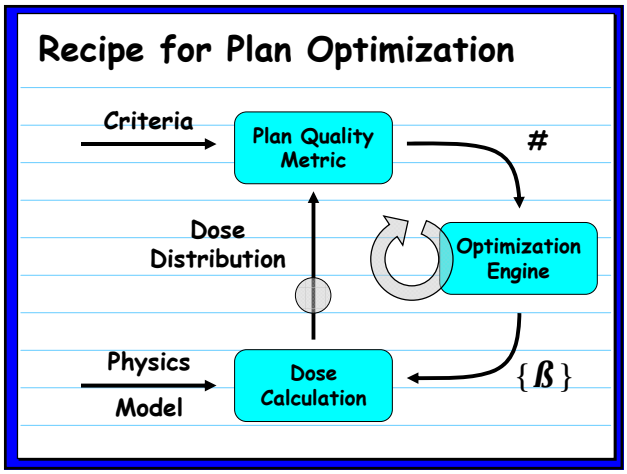

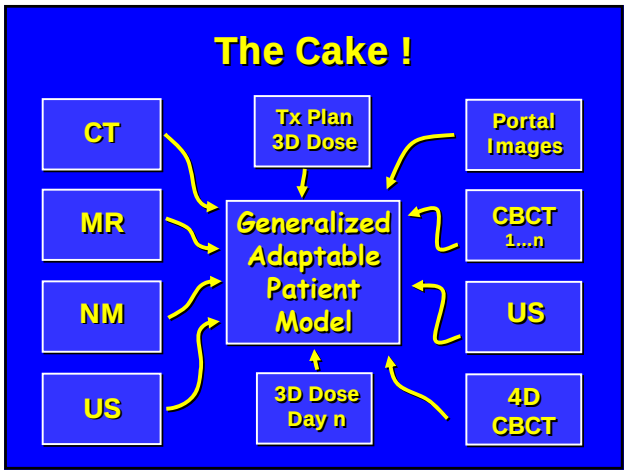

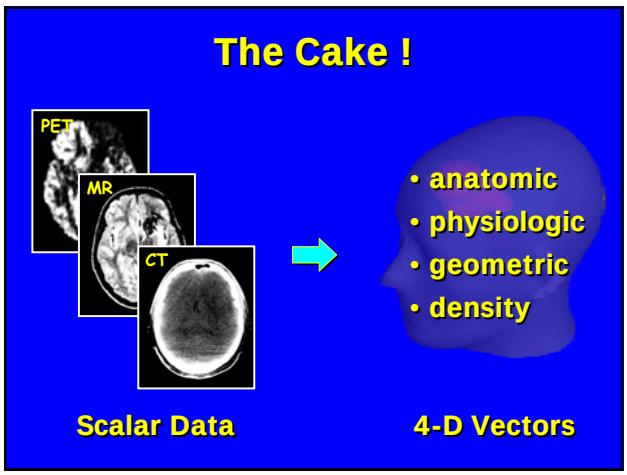

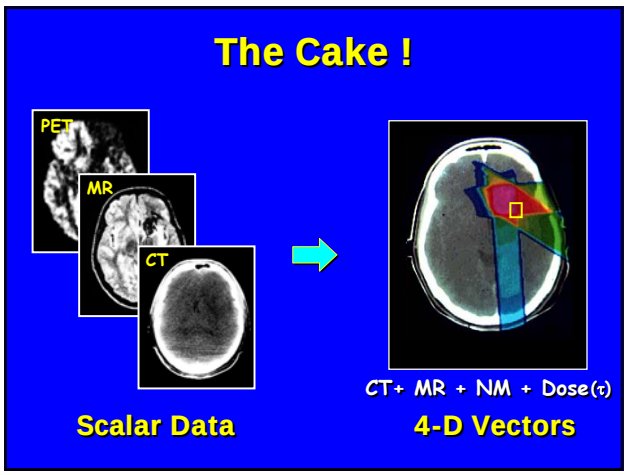

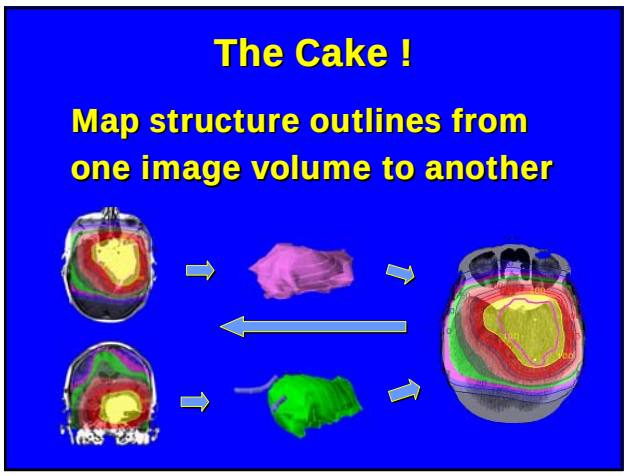

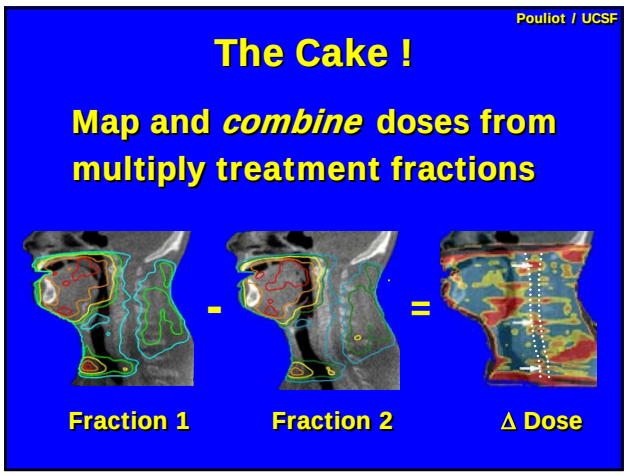

Deformable Image Registration Methods and Clinical Endpoints

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The Cake !

Dose – Function Analysis

Planning CT

SPECT Imaging

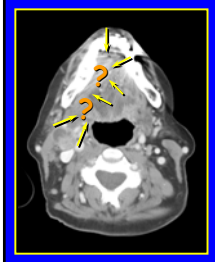
Recipe for Image Registration

- 2 Image Volumes

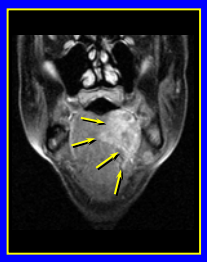
Chose 2 from the plethora of imaging volumes we now have available in radiation therapy!

Gregoire / St-Luc

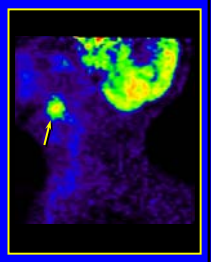
Available Image Volumes



Physics



Anatomy

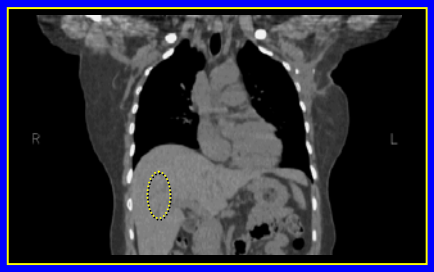


Physiology

…multiple modalities

Balter / UM

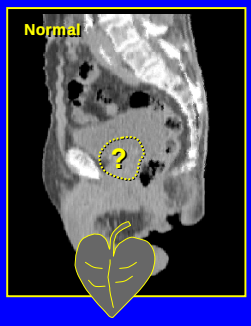
Available Image Volumes

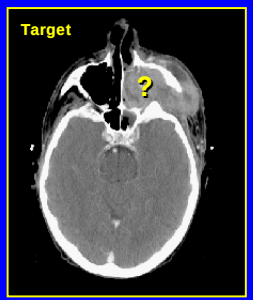


Motion Information

…4-D imaging

Available Image Volumes

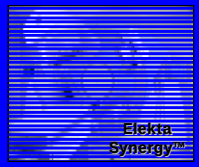




…repeat imaging during therapy

Dawson / PMH

Available Image Volumes



…at the treatment unit too!

Deformable Image Registration Methods and Clinical Endpoints

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Recipe for Image Registration

2 Image Volumes

Depending on the application,

choose either entire volumes

or the relevant sub-volumes

Prostate Example

Can you tell what is different in the 2 volumes?

Volume 1 Volume 2

Prostate Example

Bones *aligned*, prostate region *not aligned*

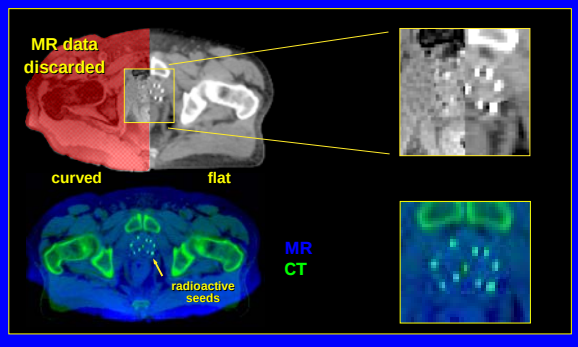
Entire Volume

Prostate Example

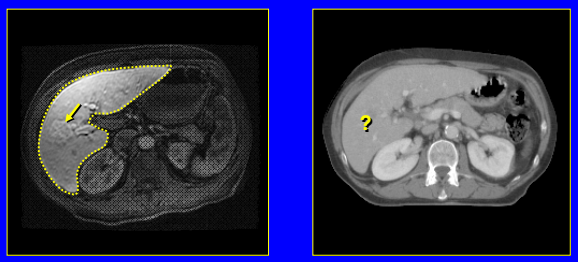
Bones *ignored*, prostate region *aligned*

Sub volumes

Prostate Example



Liver Example



anatomic-based cropping

ignore anatomy outside liver

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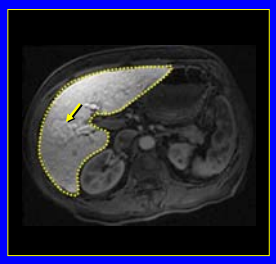
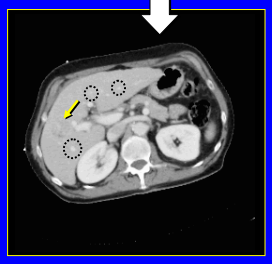
Liver Example

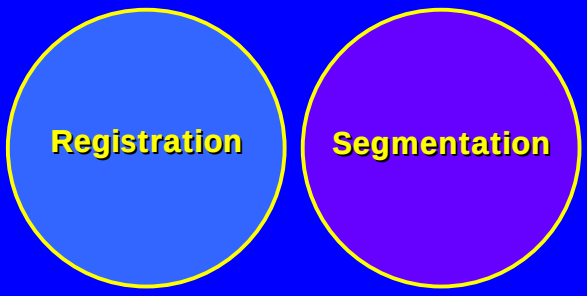




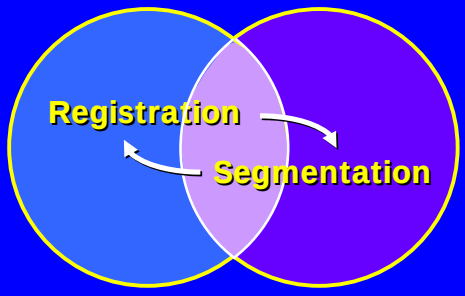
anatomic-based cropping

ignore anatomy outside liver

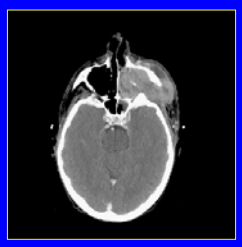
The Past / Present

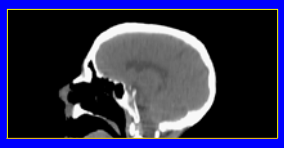


The Present / Future



Treatment Delivery Example

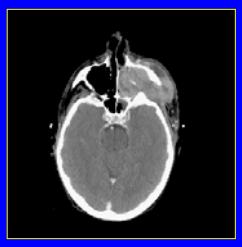


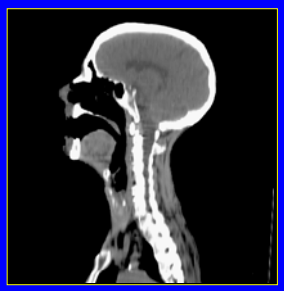


Rigid assumption used for *regional* registration

Pick Your Battles Wisely!

Treatment Delivery Example

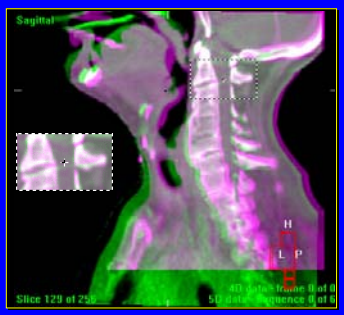




Oops!

Sonke / NKI

Registration at Delivery



Regional registration of serial CBCT scans and TP CT

6 DOF

Choose your battles wisely!

Deformable Image Registration Methods and Clinical Endpoints

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Recipe for Image Registration

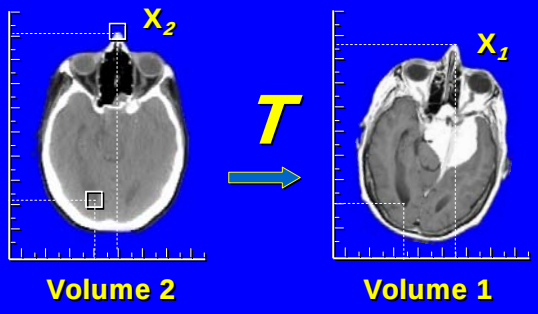
1 Transformation Model

Depending on the input data

and clinical situation, chose

a transformation model

Transformation Model



Recipe for Image Registration

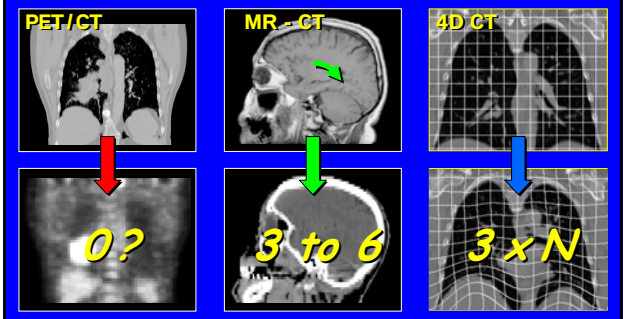
1 Transformation Model

$$x_1 = T(x_2, \{ß\})$$

Choose the flavor of T and

the set of parameters $\{ß\}$

Degrees of Freedom $\{ß\}$



Available Flavors of *T*

- **Rigid / Affine**
  - *… or regional rigid / affine*
- **Full 3D / 4D Deformation**
  - *Parametric transformations*
  - *Free-form transformations*

Available Flavors of *T*

Affine Assumption

$y = mx + b$ … in three dimensions

$x_1 = A x_2 + b$ … up to 12 DOF

Otherwise

Spatially variant transformations

Various parametric & free form models

… up to 3 x N !

… lots of degrees of freedom!

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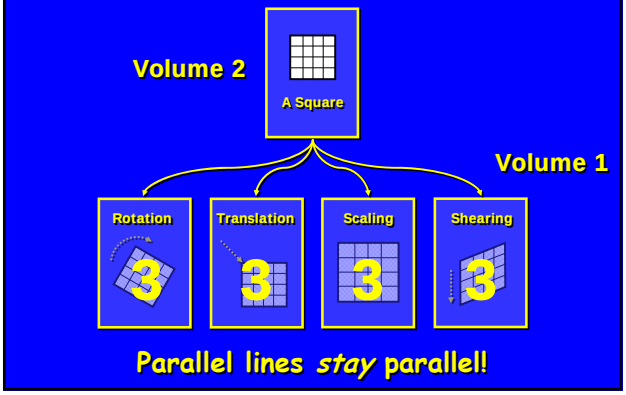
www.gnome.org

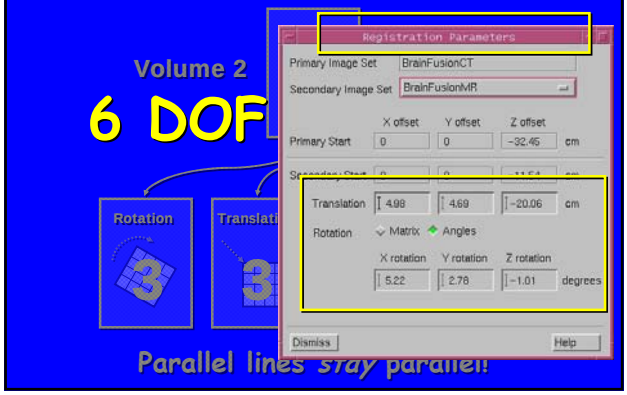
Affine Transformations



Parallel lines *stay* parallel!

www.gnome.org

Affine Transformations



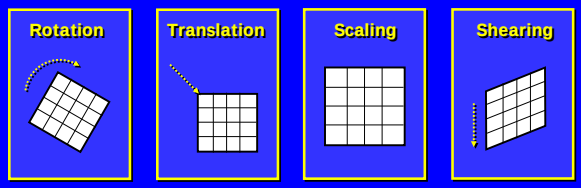
Parallel lines *stay* parallel!

Munro / Varian

Affine Transformations

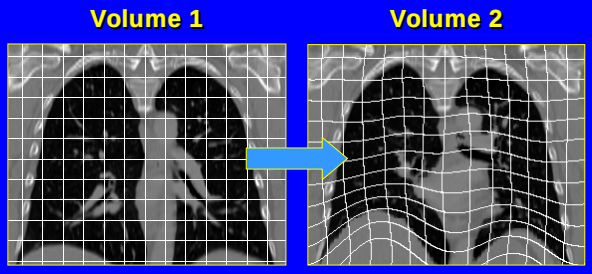
www.gnome.org

Affine Transformations



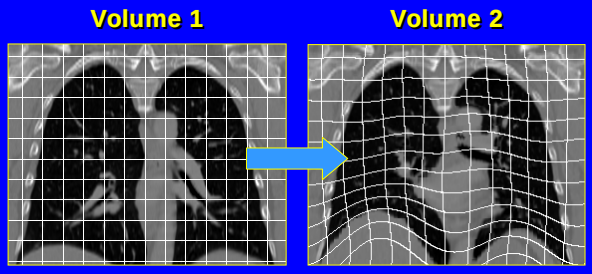
Parallel lines stay parallel!

*non-*Affine Transformations



Parallel lines *don't* stay parallel!

*non-*Affine Transformations



$x_1 = T(x_2, \{ß\})$

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*non-*Affine Transformations

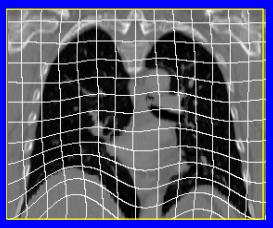
Study A Study B

Transformation parameters to apply to a particular voxel depends on the location of the voxel (spatially variant) !

$$X_1 = T(X_2, \{ß(X_2)\})$$

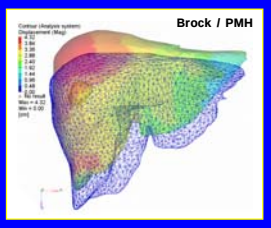
Available Flavors of *T*

Parametric Models



Warp Space / … Drag Objects

Freeform Models



Warp Objects / … Drag Space

Available Flavors of *T*

Spatially variant transformations

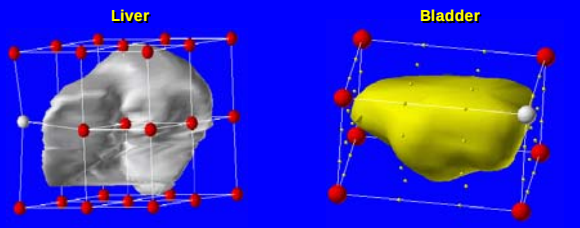
- Parametric
  - Thin-plate Splines
    - Global Deformations
  - B-Splines
    - Local Deformation

Available Flavors of *T*

Spatially variant transformations

- Free Form
  - Intensity Flow Methods
    - Fluid Mechanics-like
  - Finite Element Models
    - Account for Physical Properties

Thin-Plate Splines



$$T(P) = \underbrace{a_0 + a_x x + a_y y + a_z z}_{\text{affine}} + \underbrace{\sum_{i=1}^{n} w_i U(P - P_i)}_{\text{warping}}$$

B-Spline Deformations

Each have some distinct properties

- B-Splines

$$X_2 = X_1 + \Delta X$$
$$= X_1 + \Sigma\, w_i \cdot B(X - k_i)$$

weights basis function

(… parameters!)

Deformable Image Registration Methods and Clinical Endpoints

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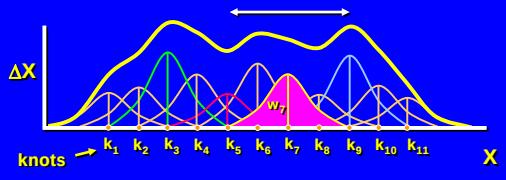
B-Spline Deformations

Each have some distinct properties

- B-Splines

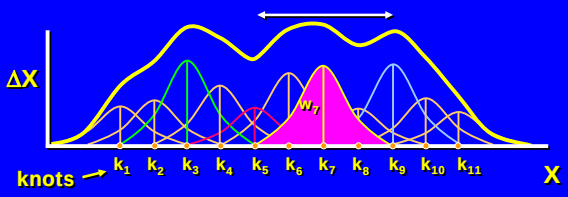
1-D Example



$X_2 = X_1 + \Delta X = X_1 + \Sigma\, w_i \cdot B(X-k_i)$

B-Spline Deformations

Construct overall function *T* from
a weighted sum of local deformations

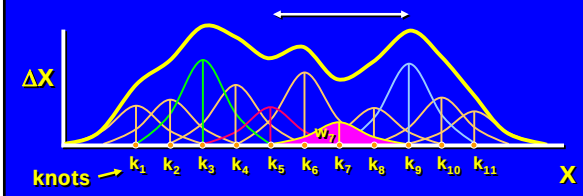


$X_2 = X_1 + \Delta X = X_1 + \Sigma\, w_i \cdot B(X-k_i)$

parameters!

B-Spline Deformations

Construct overall function *T* from
a weighted sum of local deformations

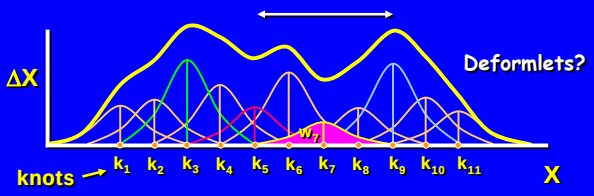


$X_2 = X_1 + \Delta X = X_1 + \Sigma\, w_i \cdot B(X-k_i)$

parameters!

B-Splines

Construct overall function from
a weighted sum of local deformations



$X_2 = X_1 + \Delta X = X_1 + \Sigma\, w_i \cdot B(X-k_i)$

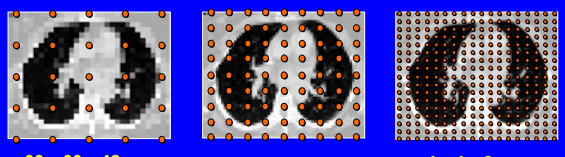
This seems a lot like intensity modulation!

B-Spline Transformation Model

3-D Grid of Knots

Multiresolution Deformations

Divide and Conquer



60 x 60 x 48 mm

4 x 4 x 3 mm

Coarse → Fine

Knot Spacing

Recipe for Image Registration

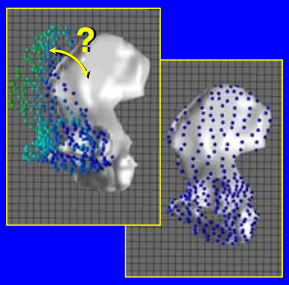
⇒ 1 Registration Metric

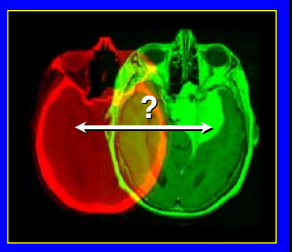
Choose a registration metric

depending on the type of

imaging data involved

Registration Metrics



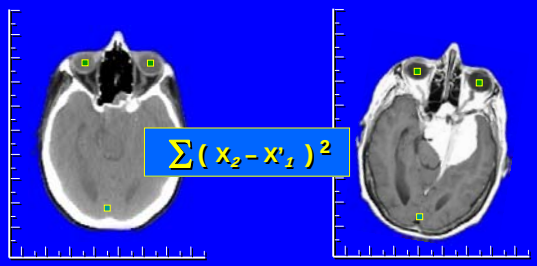


Geometry-based Intensity-based

Geometry-Based Metrics

- **Point Matching**
  Least Squares
  $\sum (x_2 - x'_1)^2$
- **Surface Matching**
  Chamfer Matching
  $\sum$ min distance ^{2}

Point Matching

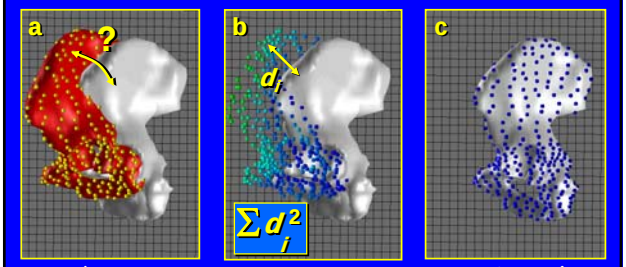


Volume 2 Volume 1

Define corresponding anatomic points

Surface Matching

Catallo / UM

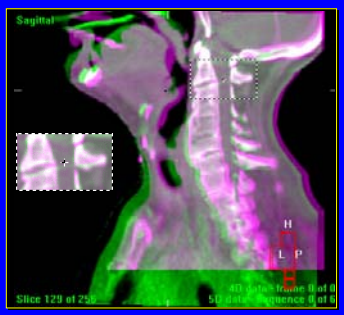


objects misaligned | compute mismatch | mismatch minimized

Define corresponding anatomic surfaces

Registration at Delivery

Sonke / NKI



Regional registration of serial CBCT scans and TP CT

6 DOF

Choose your battles wisely!

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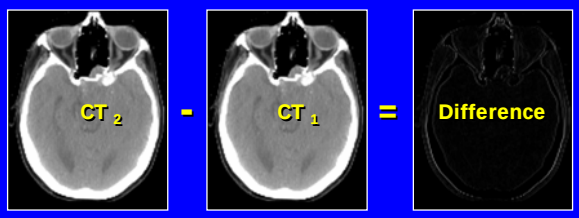
Intensity-Based Metrics

- **Mono-modality**
  Sum of Squared Diff.
  $\sum (I_2 - I_1)^2$
- **Multimodality Data**
  Mutual Information
  $\sum p(A,B) \log \frac{p(A,B)}{p(A)\,p(B)}$

Sum of Squared Differences

... subtract one image from the other



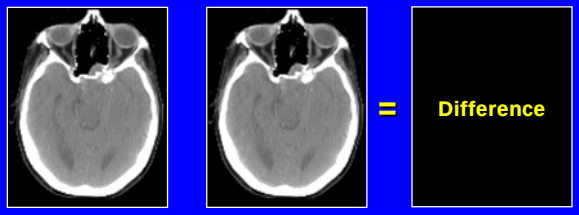
I_{CT_2} I_{CT_1} $\sum (I_{CT_1} - I_{CT_2})^2$

Individual Intensity Distributions

Sum of the Squares of the Differences

Sum of Squared Differences

... subtract one image from the other



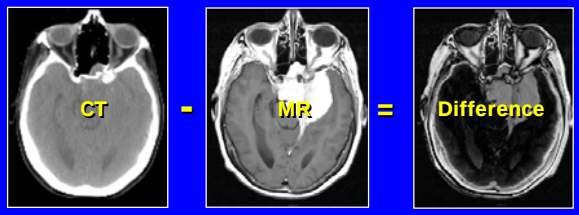
I_{CT_2} I_{CT_1} Zero

Individual Intensity Distributions

Registered

Sum of Squared Differences

... subtract one image from the other



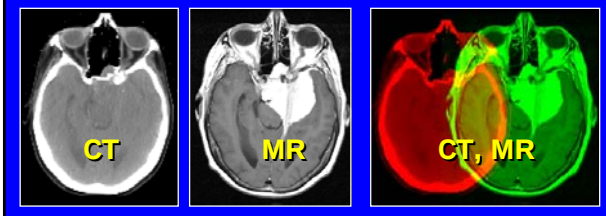
I_{CT} I_{MR} *Not* Zero

Individual Intensity Distributions

This doesn't usually make much sense

Mutual Information

... using an information theory-based approach



$H(I_{CT}) + H(I_{MR}) = H(I_{CT}, I_{MR})$?

Individual Information Contents

Joint Information Content

Mutual Information

$H(I_1, I_2) = H(I_1) + H(I_2) - MI(I_1, I_2)$

The mutual information is the information that is *common* to both image volumes!

'48 Shannon - Bell Labs / '95 Viola - MIT

Mutual Information

$$MI(I_1, I_2) = H(I_1) + H(I_2) - H(I_1, I_2)$$

The mutual information is the information that is *common* to both image volumes!

'48 Shannon - Bell Labs / '95 Viola - MIT

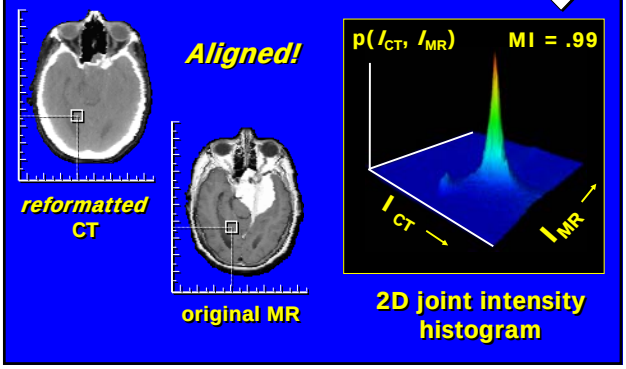
Mutual Information

$$MI(I_1, I_2) = \sum p(I_1, I_2) \log_2 \left[\frac{p(I_1, I_2)}{p(I_1)\, p(I_2)} \right]$$

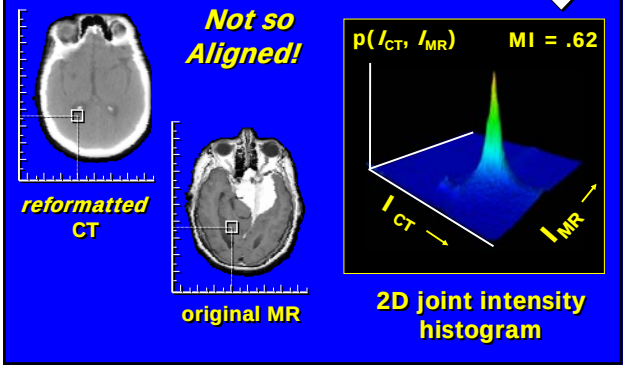
The mutual information of two image volumes is a maximum when they are *geometrically registered* ...

'48 Shannon - Bell Labs / '95 Viola - MIT

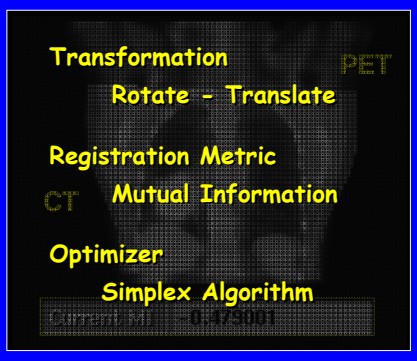
Mutual Information



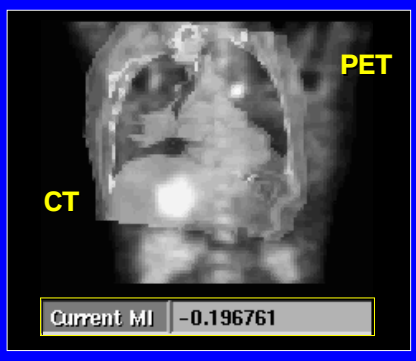
Mutual Information



How About An Example?



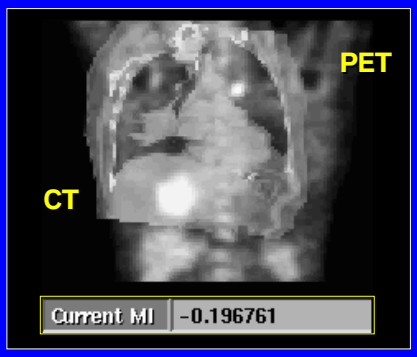
How About An Example?



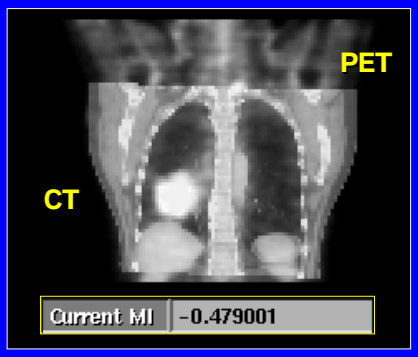
Deformable Image Registration Methods and Clinical Endpoints

Marc L Kessler, PhD

How About An Example?



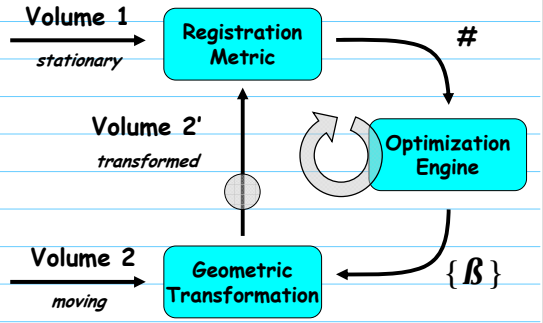
How About An Example?



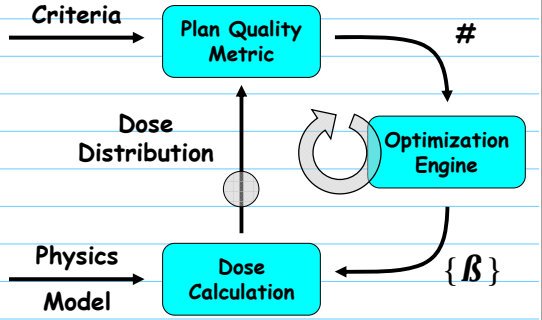
Recipe for Image Registration

- 2 Image Volumes
- 1 Transformation Model
- 1 Registration Metric
- ⇨ 1 Optimization Engine
- n Evaluation Tools

Recipe for Image Registration



Recipe for Plan Optimization



Interactive Registration

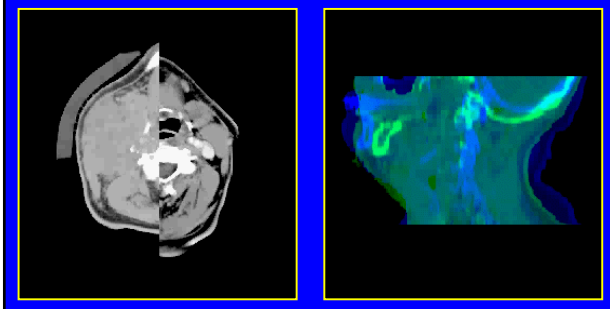
- ✓ Translate
- ✓ Rotate
- ? Deform

Provide tools to transform and visualize!

Deformable Image Registration Methods and Clinical Endpoints

Marc L Kessler, PhD

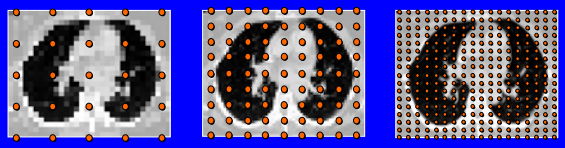
Automated Registration



Rigid first , ... then B-Spline deformation

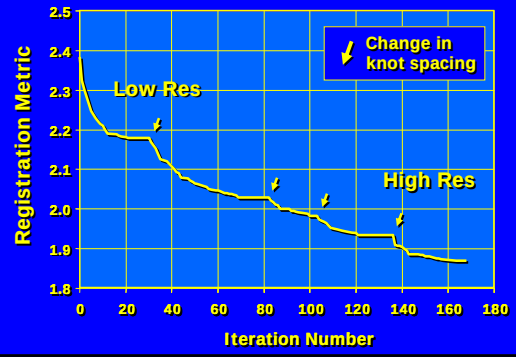
Multiresolution Deformations

Divide and Conquer



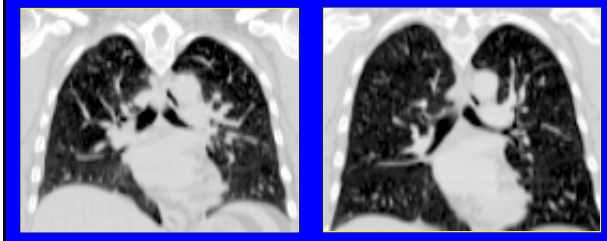
Multiresolution Deformations

Registration Metric vs. Iteration



Multiresolution B-Splines

ABC CT Example



Exhale State | Inhale State

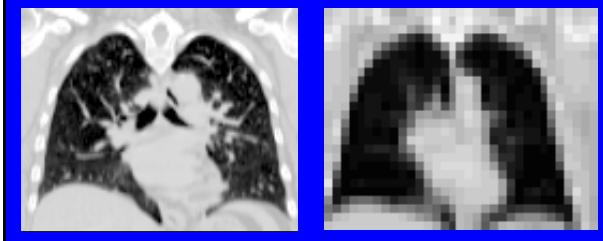
Multiresolution B-Splines

ABC CT Example

Exhale State | Inhale State deformed

Multiresolution B-Splines

Multiphasic CT Data



Exhale State | Inhale State deformed

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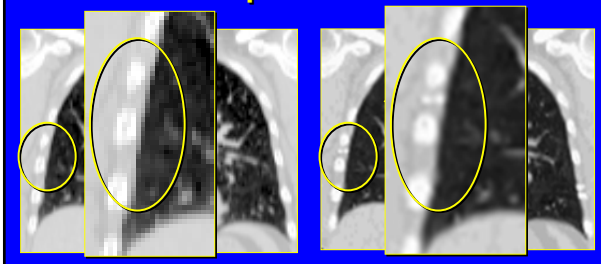
Multiresolution B-Splines

Multiphasic CT Data

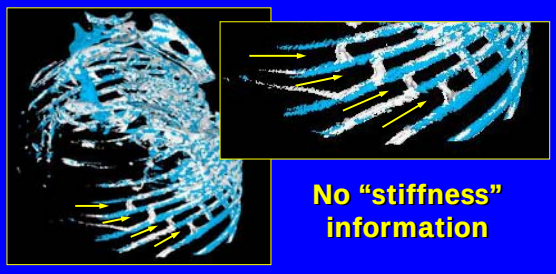


Exhale State

Inhale State deformed

Ruan / UM

We Are Not *Really* Splines !



No "stiffness" information

Extracted Ribcage

Exhale

Deform Inhale

Add Some Physics?

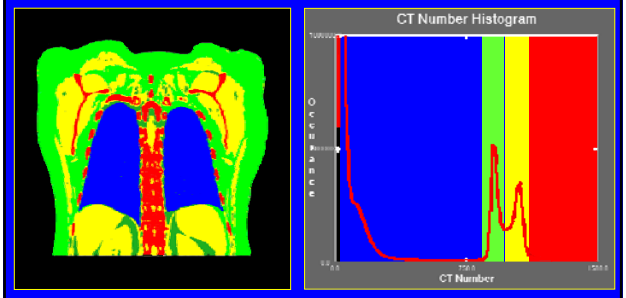
$$E_{total} = E_{similarity} + \alpha E_{stiffness}$$

intensity similarity metric

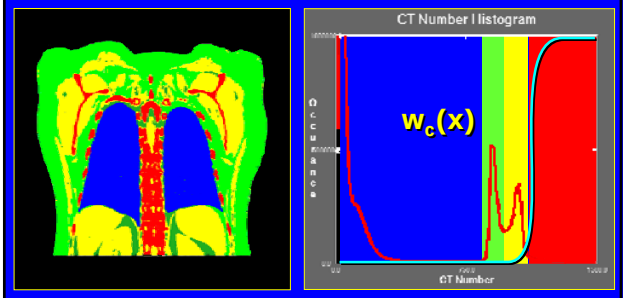
tissue-dependent regularization

$$E_{vol} = \int w_c(x) \, |\det J_T(x) - 1|^2 \, dx$$

Spatially Variant Stiffness

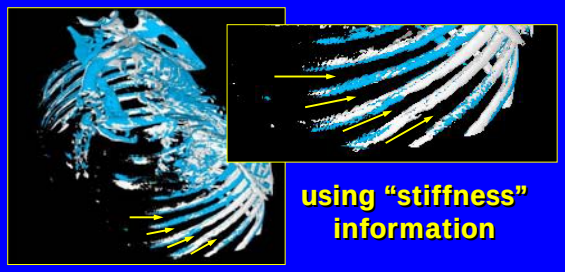


"Stiffness" Weighting



Ruan / UM

Using "Prior" Information



using "stiffness" information

Extracted Ribcage

Exhale

Deform Inhale

Deformable Image Registration Methods and Clinical Endpoints

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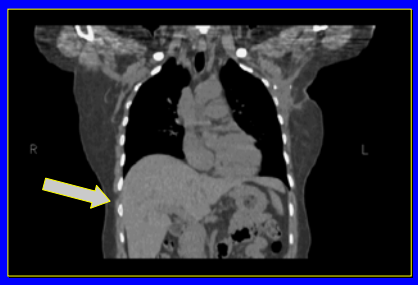
Balter / UM

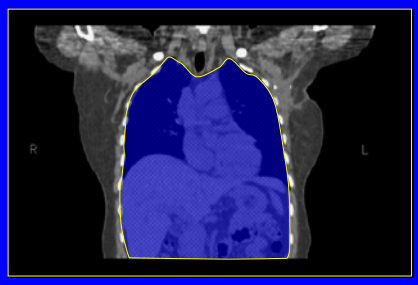
Tissue Sliding



Deal with different organs individually?

Balter / UM

Tissue Sliding



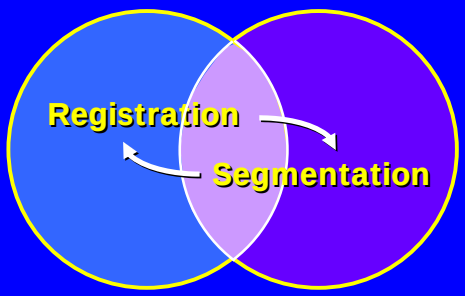
Deal with different organs individually?

Segmentation + Registration

Ribs driven by large lung deformations

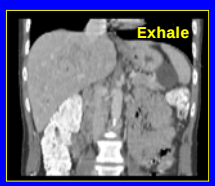
Ribs *not* affected by lung registration

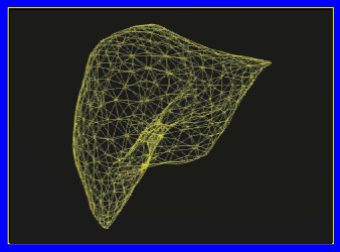
Registration / Segmentation



Brock / UM

Finite Element Modeling





Take into account physical tissue properties (directly)

Brock / PMH

Finite Element Modeling

... thorough segmentation is necessary

Deformable Image Registration Methods and Clinical Endpoints

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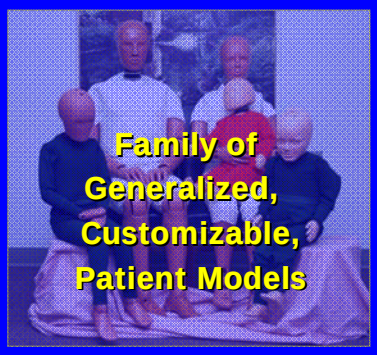
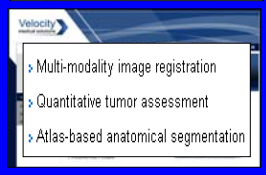
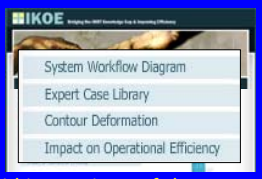
The Future ?



Are We Already There?

Several independent products are there or *almost* there!

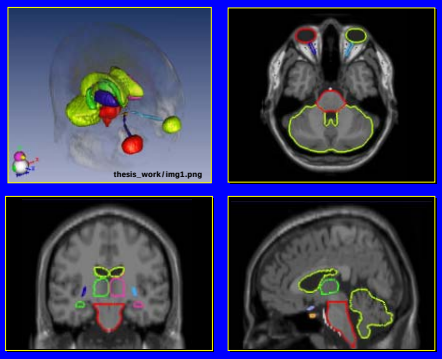




I have no commercial interest in any of these company

…*from* Atlas to Individual

olivier.commowick.org

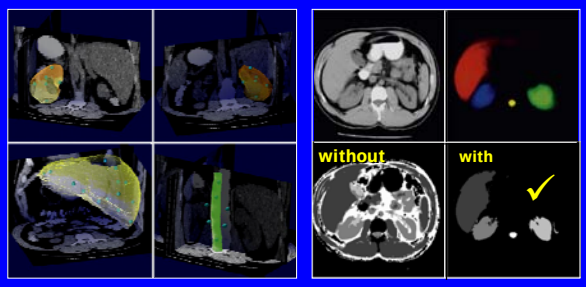


…*from* Atlas to Individual

Meyer/UM

Construction of an Abdominal Probabilistic Atlas and its Application in Segmentation

Hyunjin Park, Peyton H. Bland, and Charles R. Meyer*, *Member, IEEE*

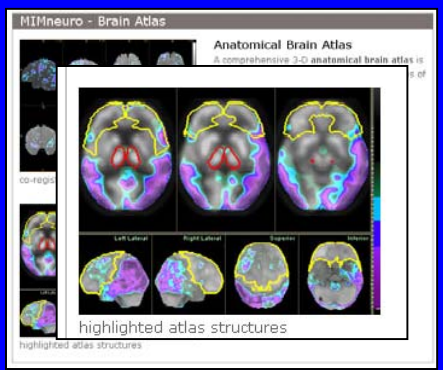


Segment /register / average

Segment using atlas

…*from* Atlas to Individual

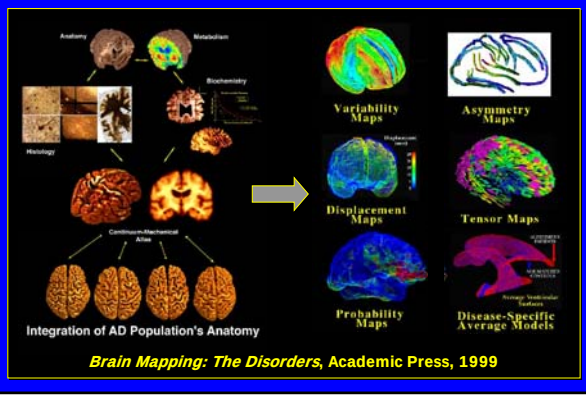
www.mimvista.com



I have no commercial interest in this company!

…*from* Individuals to Atlas

Thompson / UCLA



Brain Mapping: The Disorders, Academic Press, 1999

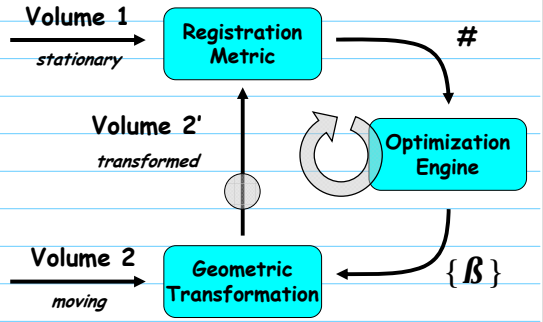
Deformable Image Registration Methods and Clinical Endpoints

Marc L Kessler, PhD

Let's Recap

- ✓ The geometric transformation ***T***
  - Affine / *not* - Affine
- ✓ The Registration Metric
  - Geometry / Intensity
- ✓ Optimization Engine
  - Interactive / Automated

Recipe for Image Registration



Recipe for Image Registration

- 2 Image Volumes
- 1 Transformation Model
- 1 Registration Metric
- 1 Optimization Engine
- ⇨ n Evaluation Tools

Evaluation Tools

How do we know how well these registration methods perform?

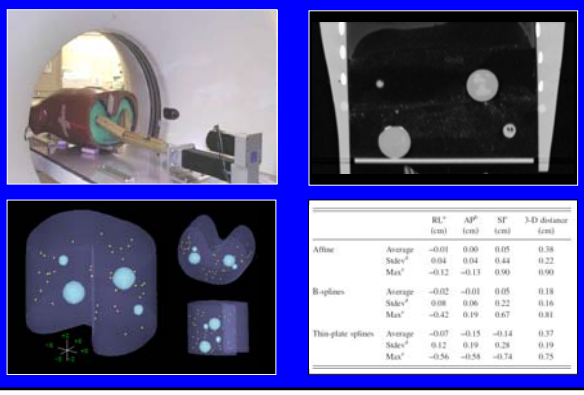
- ➢ build phantoms and test them
  we can know *the truth!*
- ➢ provide tools to examine results
  we don't know *the truth!*

Multimodality Phantoms

Circa 1986

4D Phantoms

Kashani / UM



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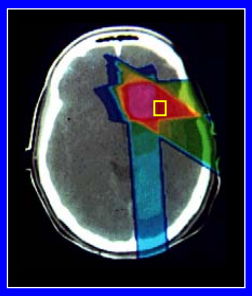
Evaluation Tools

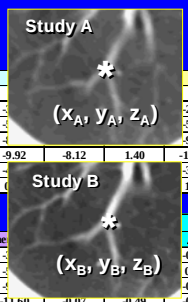
Visualization Tools



- Color gel or wash overlay
- Split / dual screen displays
- Anatomic boundary overlay!

Evaluation Tools

Numerical Tools



Point	Description	Exhale					
		X	Y				Z
1	2nd branch of bronchial tree	-5.37	0.98				-2.92
2	3rd branch of bronchial tree	-5.73	2.12				-5.92
3	4th branch of bronchial tree	-6.50	2.77				-9.42
4	Vessel bifurcation 1	-8.12	3.37	-9.92	-8.12	1.40	-11.42
5	Vessel bifurcation 2	-8.06	-1.95				-3.92
6	Vessel bifurcation 3	-10.69	2.47				1.08

all values in *cm.*

Exhale' (w/TPS alignme					ΔZ
-4.71	-0.47				-0.44
-5.35	0.58				0.09
-6.27	0.69				-0.09
-8.19	0.91	-11.60	-0.07	-0.49	-0.18
-7.27	-2.83	-3.63	0.40	0.37	0.29
-10.85	0.87	1.24	-0.07	-0.29	0.16
		σ	0.19	0.29	0.26

AAPM Task Group 132

Use of Image Registration and Data Fusion Algorithms and Techniques in Radiotherapy

- Methods to assess [illegible] image registr[illegible]
- Issues related to ac[illegible]ng and quality assu[illegible]ance for image registration and fusion

Coming Soon!

Recipe for Image Registration

- ⇒ 2 Image Volumes
- ⇒ 1 Transformation Model
- ⇒ 1 Registration Metric
- ⇒ 1 Optimization Engine
- ⇒ n Evaluation Tools

Caution: The Full Recipe?

- ✓ deformation
- ✓ weight loss
- ✓ resection
- ✓ shrinkage
- ✓ Δ vascular

Dose Mapping?

Dealing with volume elements that may:

change shape / appear / disappear

… need proper spatial re-sampling

don't necessarily add in a linear fashion

… need some sort of radiobiology

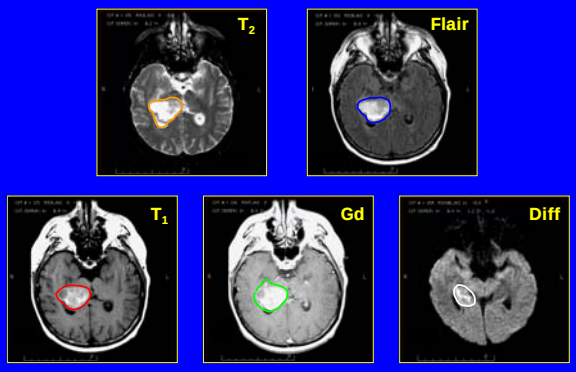
exist in homogenous intensity regions

… hard to evaluate registration

Deformable Image Registration Methods and Clinical Endpoints

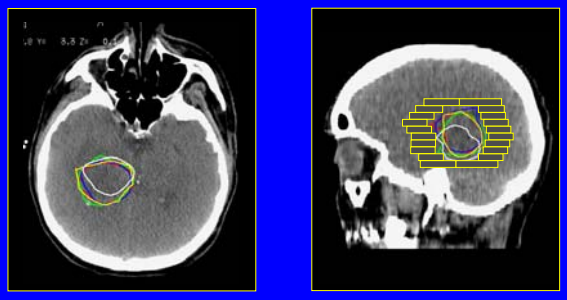
Marc L Kessler, PhD

Opportunities & Challenges



More than just mechanics!

What Now ?



MR volumes mapped to CT study

Summary

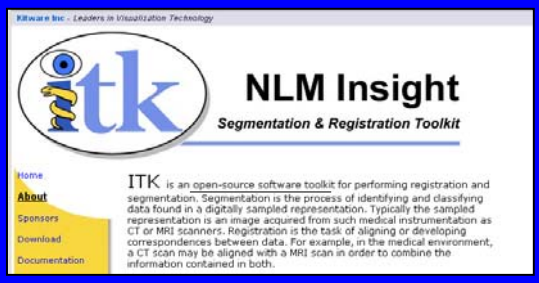
- Tools *are* now available to register and integrate image, anatomy & dose for both T_x planning and T_x delivery
- These tools can be used to help build better models of the patient and to help customize and adapt therapy
- Work towards more standard and robust tools and validations methods (for non-rigid) situations continues

Product Comparison

Imaging Technology NEWS

www.ITNonline.net

Don't try this at home!



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Wednesday , July 30th
4:00 PM – 5:30 PM

Joint Imaging -Therapy Symposium

Image Processing and Analysis for Radiotherapy Guidance

Deformable Image Registration Methods and Clinical Endpoints

Marc L Kessler, PhD