Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

Marc Kessler, PhD
The University of Michigan

Jean Pouliot, PhD
University of California

Learning Objectives

1. Understand the basic (101) and advanced (201) principles of deformable image registration, contour propagation and dose mapping
2. Understand the sources and impact of errors in registration and data mapping and the methods for evaluating the performance of these tools
3. Understand the clinical use and value of these tools, especially when used as a "black box"

Outline

Image Registration
- The applications
- The basics – 101 and 201

Validation and Adaptation
- What are the errors
- Dose Accumulation

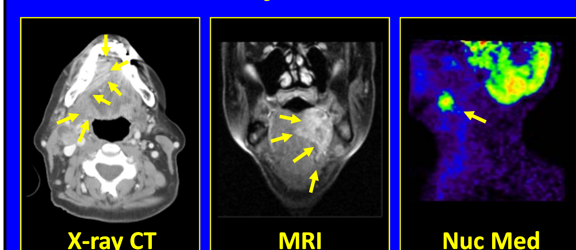
Clinical Decision Making
- Clinical examples from the real, error laden world

Data in Radiation Therapy

Gregoire / St-Luc

Data in Radiation Therapy

Lots of Cameras!

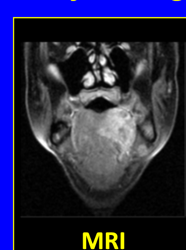


Physics | Anatomy | Function

Gregoire / St-Luc

Data in Radiation Therapy

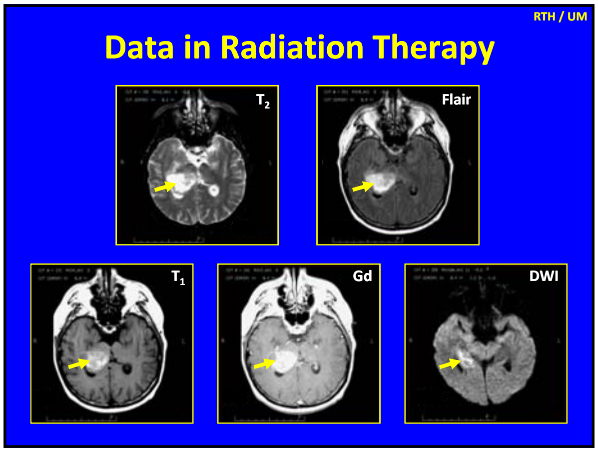
Lots of Settings!

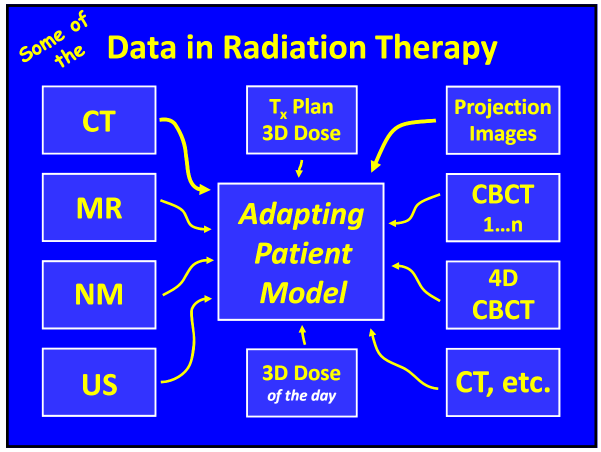


Pulse Sequence Mania!

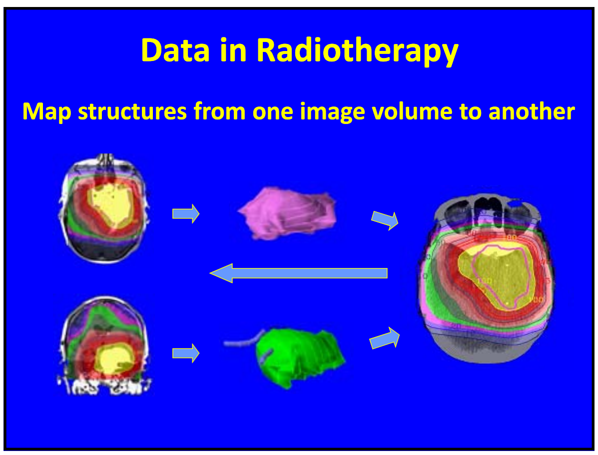
Anatomy

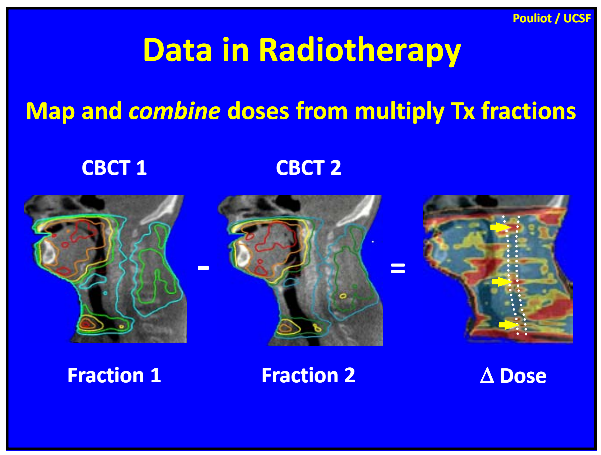
Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

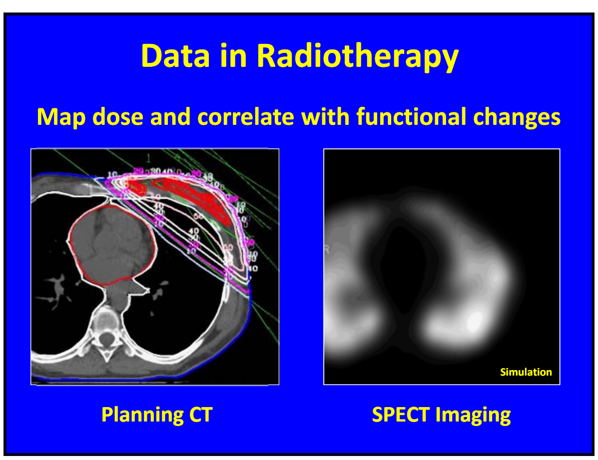


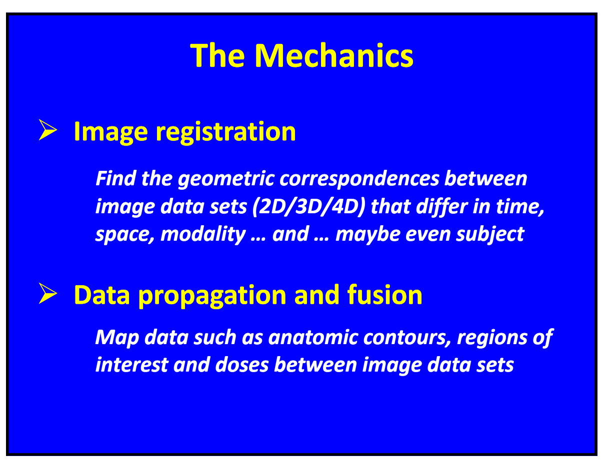


Please do not (re)redistribute

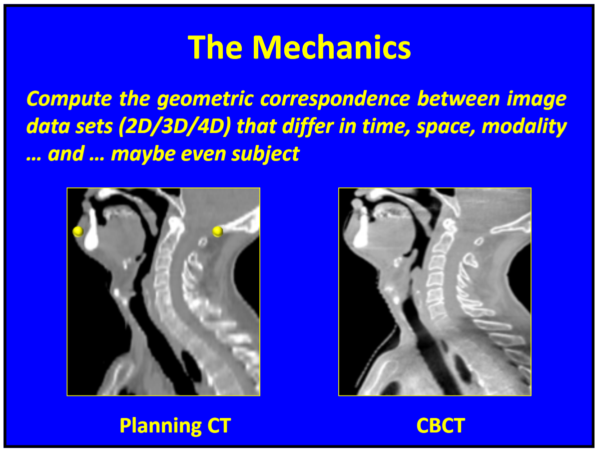


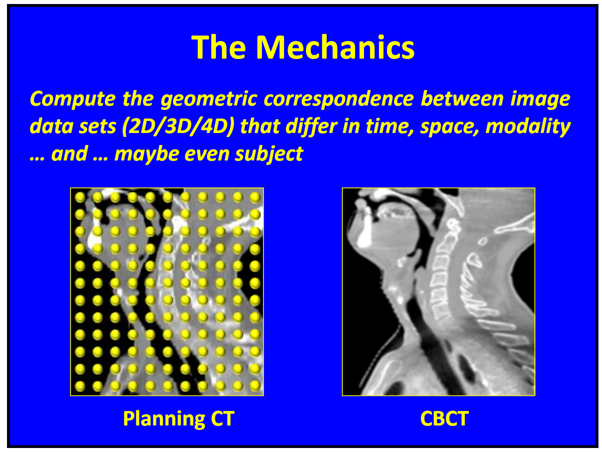




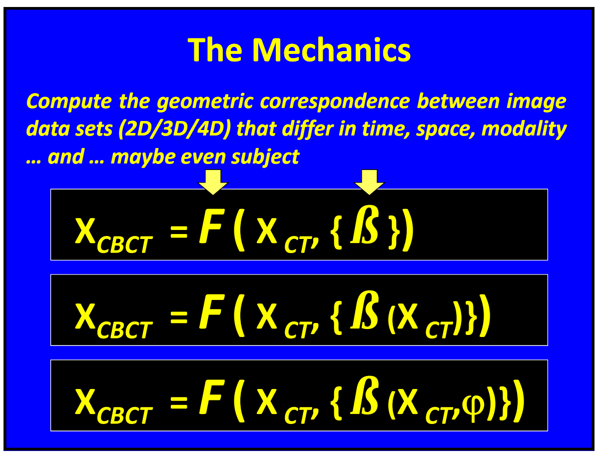


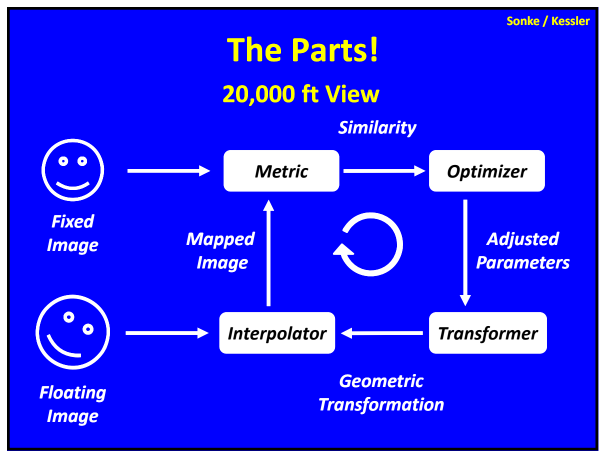
Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

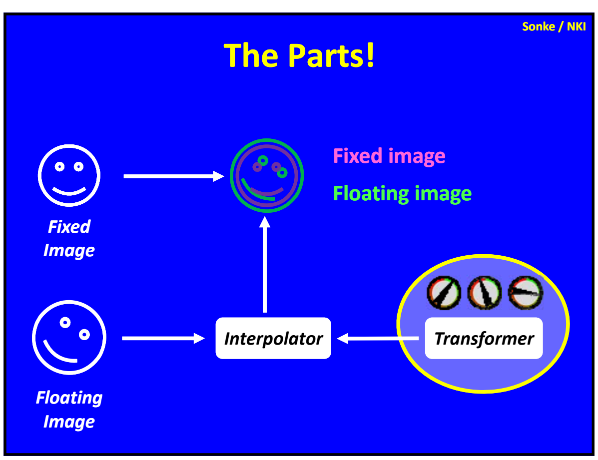


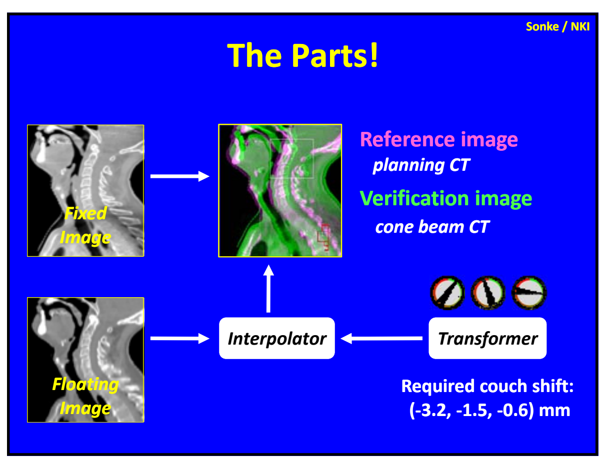


Please do not (re)redistribute

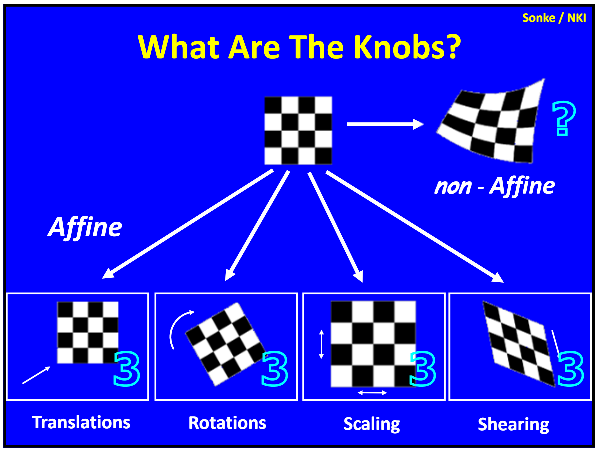


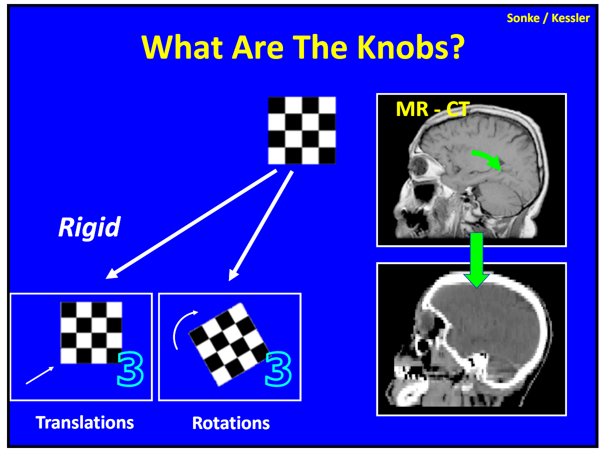


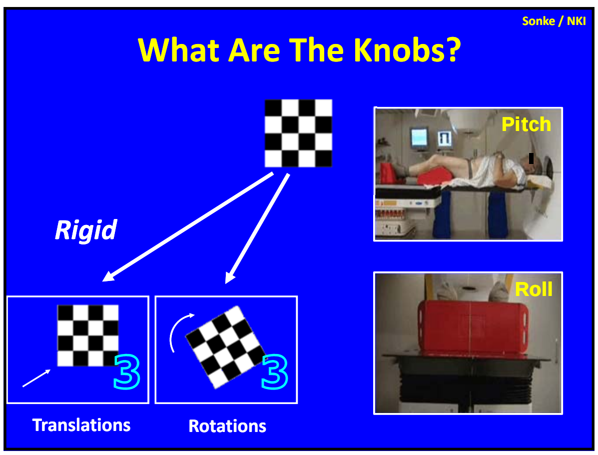


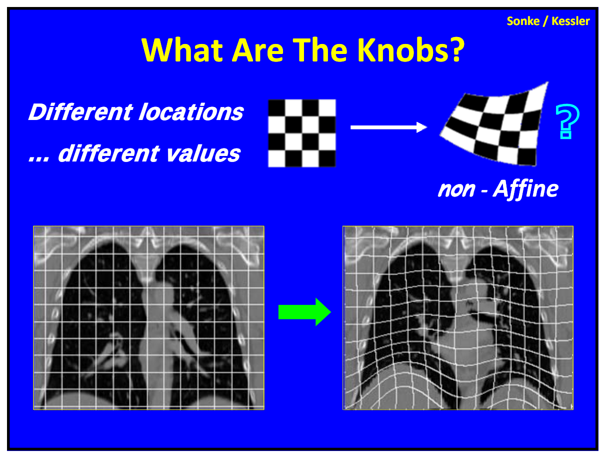


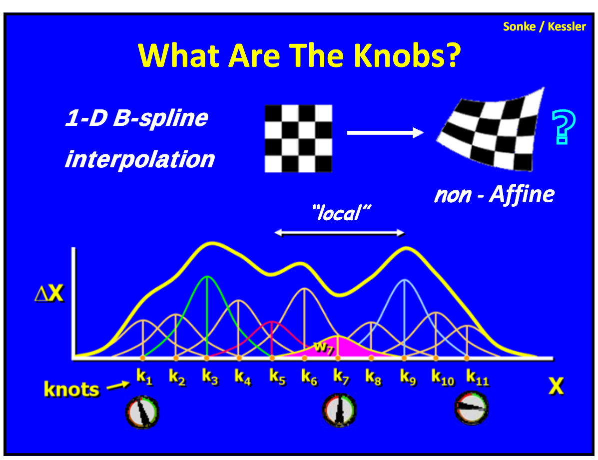
Marc L Kessler, PhD - AAPM 2013

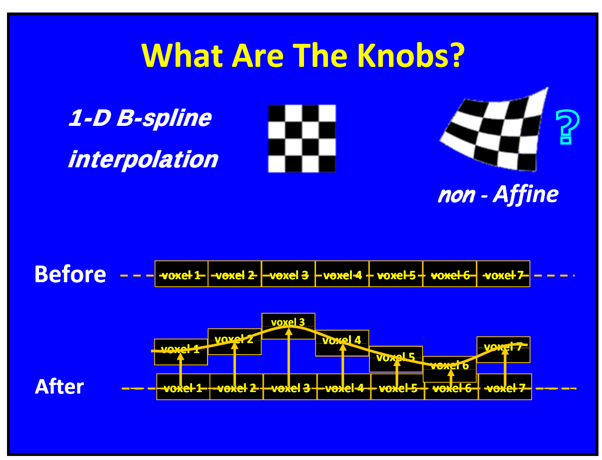

Sonke / NKI
What Are The Knobs?
non - Affine
Affine
Translations
Rotations
Scaling
Shearing


Sonke / Kessler
What Are The Knobs?
MR - CT
Rigid
Translations
Rotations

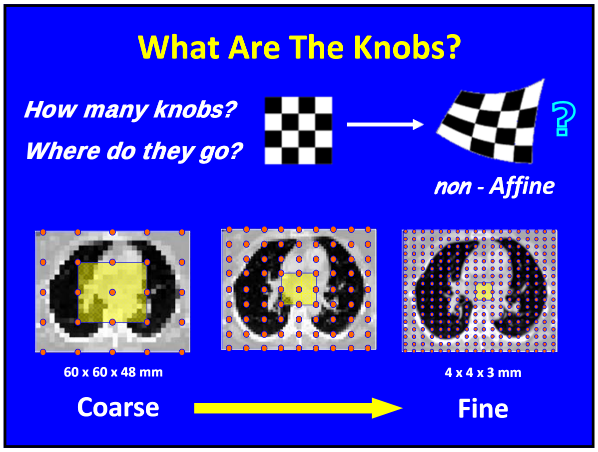

Sonke / NKI
What Are The Knobs?
Pitch
Roll
Rigid
Translations
Rotations

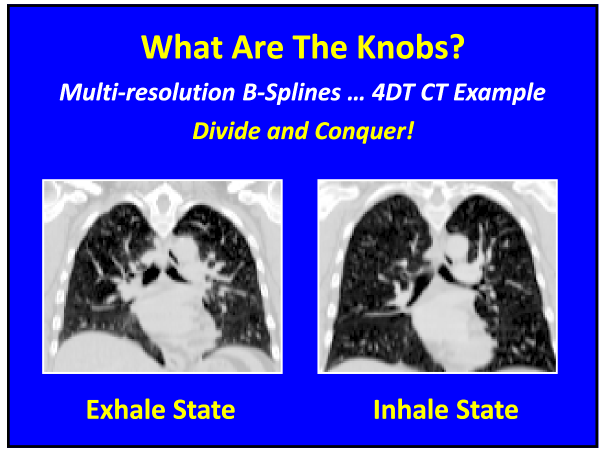

Sonke / Kessler
What Are The Knobs?
Different locations
… different values
non - Affine


Sonke / Kessler
What Are The Knobs?
1-D B-spline
interpolation
non - Affine
"local"
ΔX
knots
X

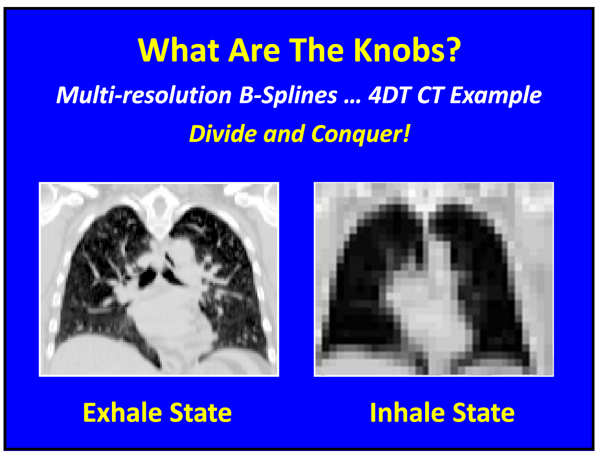

What Are The Knobs?
1-D B-spline
interpolation
non - Affine
Before
After

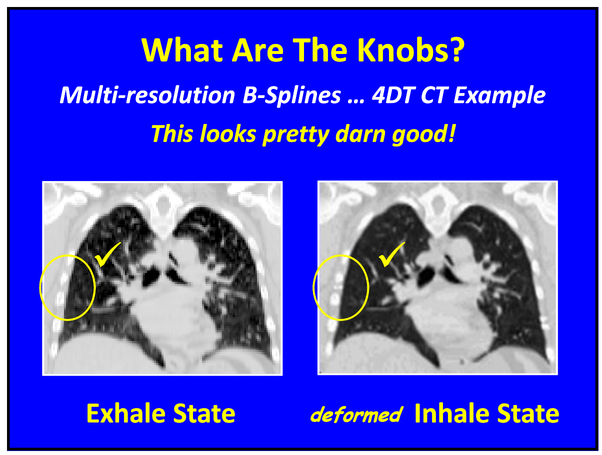
Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

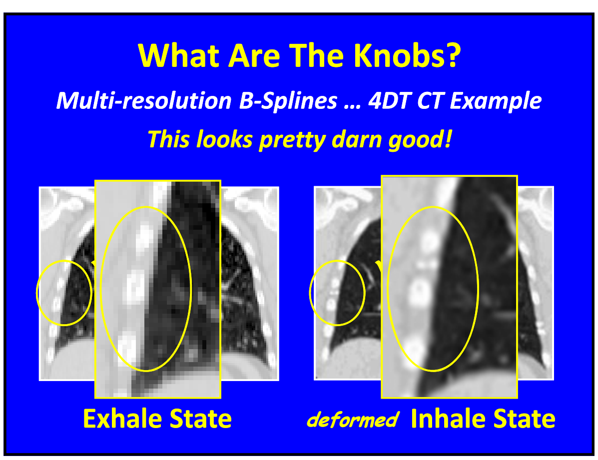


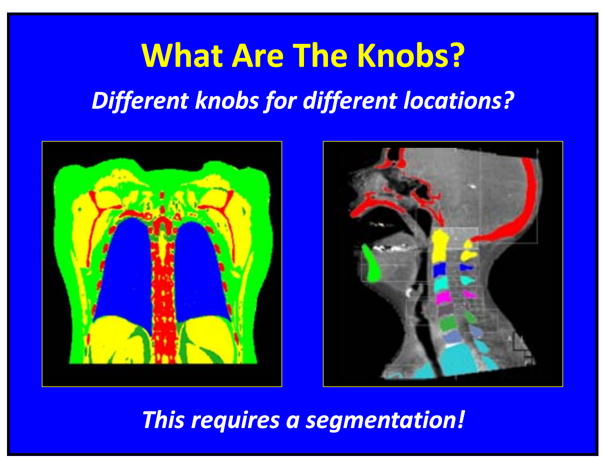


Please do not (re)redistribute





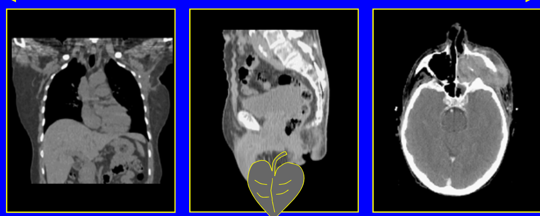




What Are The Knobs?

Different knobs for different time-scales?

Seconds — Minutes — Hours — Days — Months



Intra - fraction | Inter - fraction

How Many Knobs?

Spatially invariant *... global*
- Rigid ... to full Affine
  - *... rotate, translate, scale, shear*

Spatially variant *... local*
- B-splines, Cubic, Thin-plate
- Finite element models
- Dense deformation fields
  - *... dx, dy, dz for every voxel!*

fewer knobs ↕ *more knobs*

How Many Knobs?

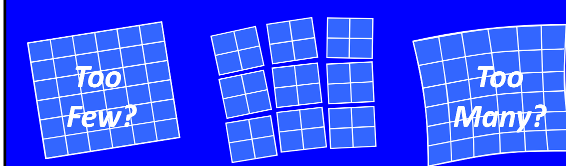
Spatially invariant *... global*
- Rigid ... to full Affine
  - *... rotate, translate, scale, shear*

Spatially variant *... local*
- B-splines, Cubic, Thin-plate
- Finite element models
- Dense deformation fields
  - *... demons, other free form*

fewer knobs ↕ *more knobs*

How Many Knobs?

Global rigid — Locally rigid — Deformable



3, 6, ... ⟷ 3 x # voxels

How many knobs (degrees of freedom) are needed to carry out (accurate) deformable image registration?

0% 1. 6

0% 2. 12

0% 3. 42

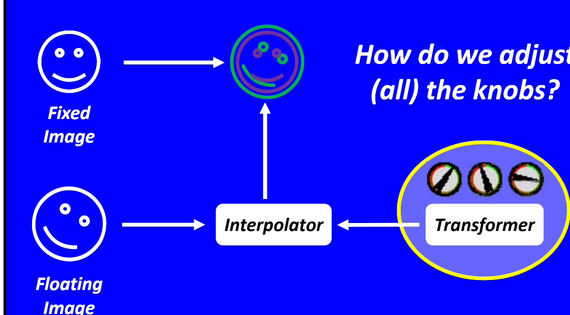
0% 4. 3 x number of voxels

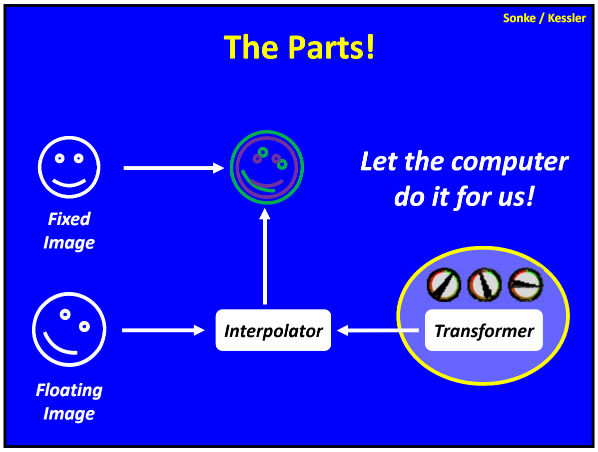
0% 5. More than 12 and less than 3 x # voxe[ls] ✓

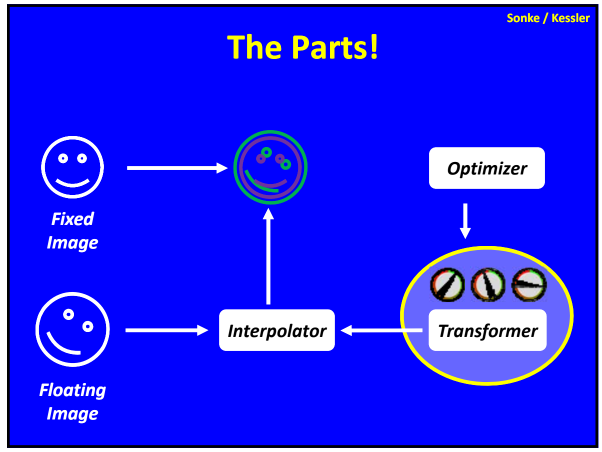
10 Countdown

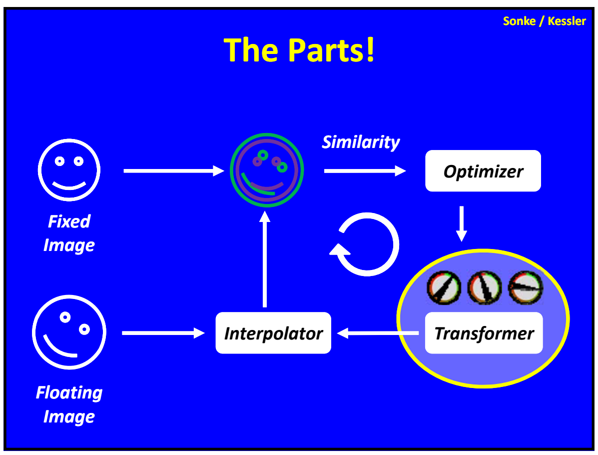
Sonke / Kessler

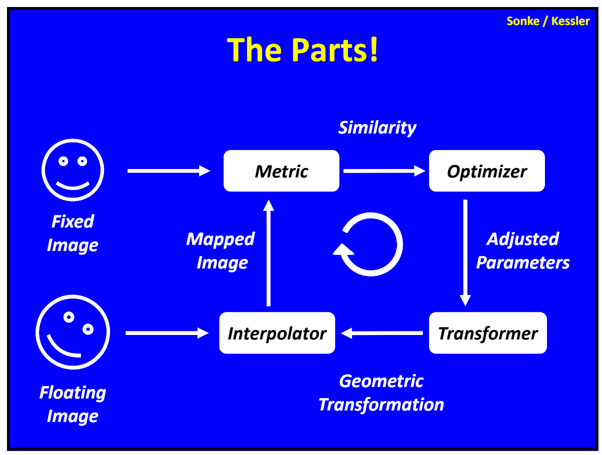
The Parts!

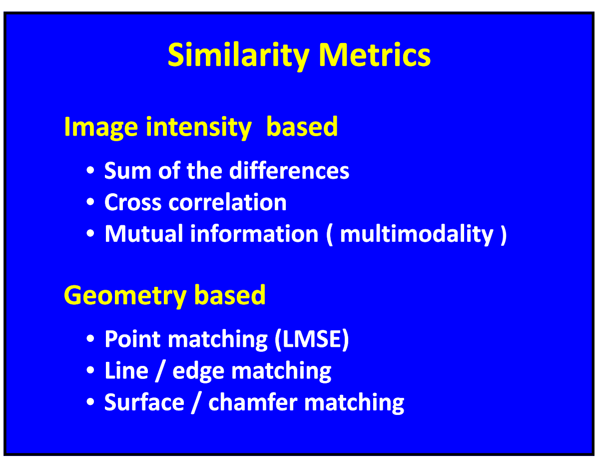


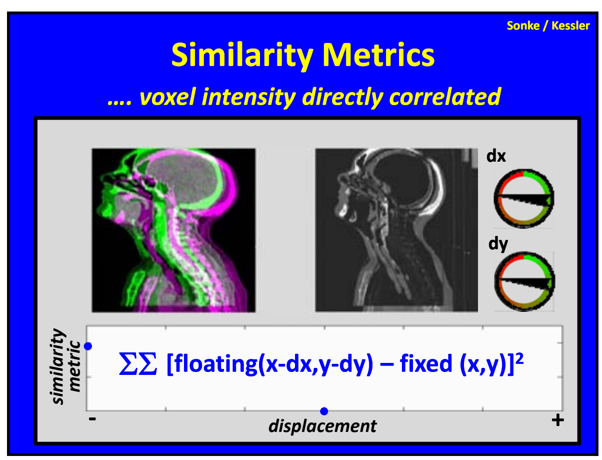

Sonke / Kessler
The Parts!
Let the computer do it for us!
Fixed Image
Floating Image
Interpolator
Transformer

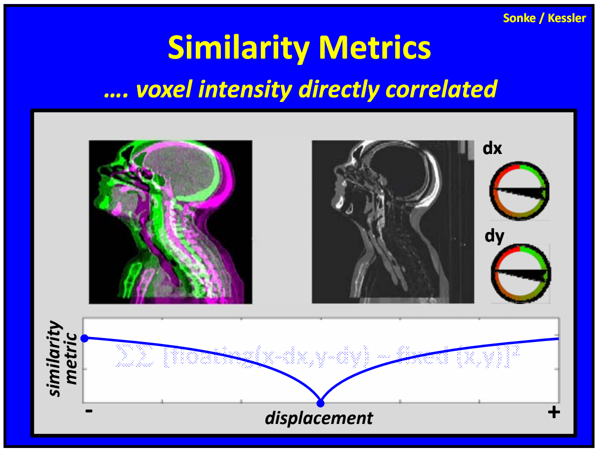

Sonke / Kessler
The Parts!
Optimizer
Fixed Image
Floating Image
Interpolator
Transformer

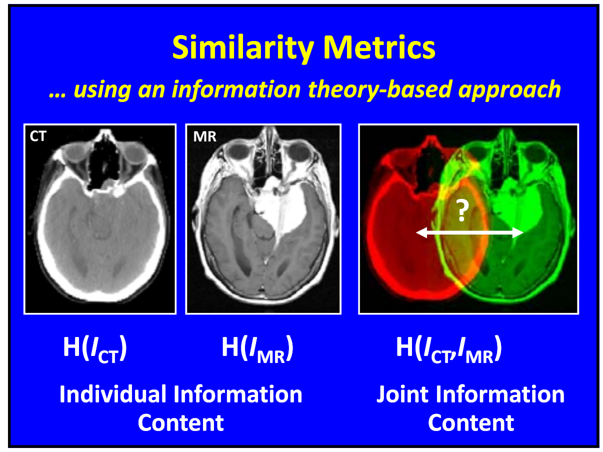

Sonke / Kessler
The Parts!
Similarity
Optimizer
Fixed Image
Floating Image
Interpolator
Transformer


Sonke / Kessler
The Parts!
Similarity
Metric
Optimizer
Fixed Image
Mapped Image
Adjusted Parameters
Floating Image
Interpolator
Transformer
Geometric Transformation

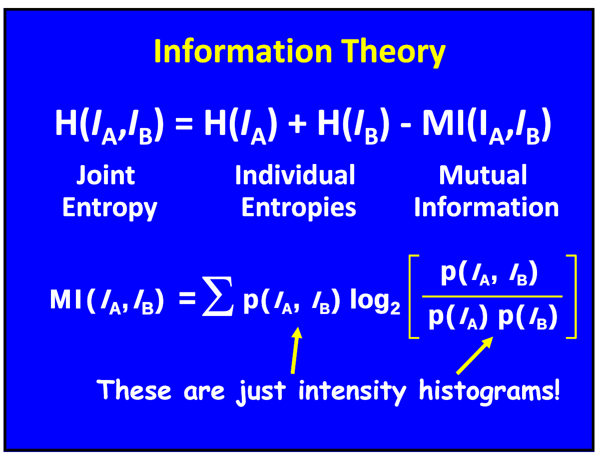

Similarity Metrics
Image intensity based
• Sum of the differences
• Cross correlation
• Mutual information (multimodality)
Geometry based
• Point matching (LMSE)
• Line / edge matching
• Surface / chamfer matching

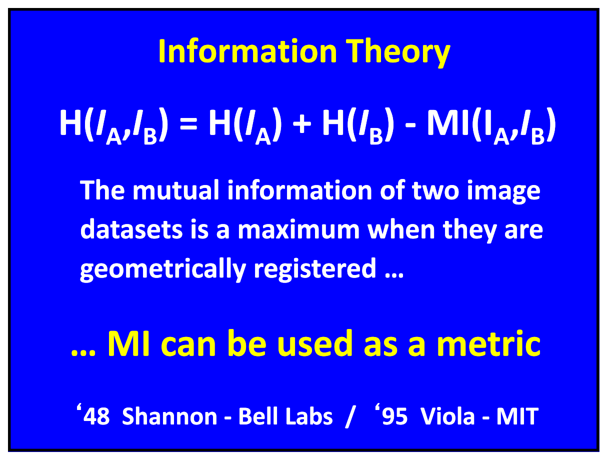

Sonke / Kessler
Similarity Metrics
.... voxel intensity directly correlated
dx
dy
similarity metric
ΣΣ [floating(x-dx,y-dy) – fixed (x,y)]²
-
displacement
+

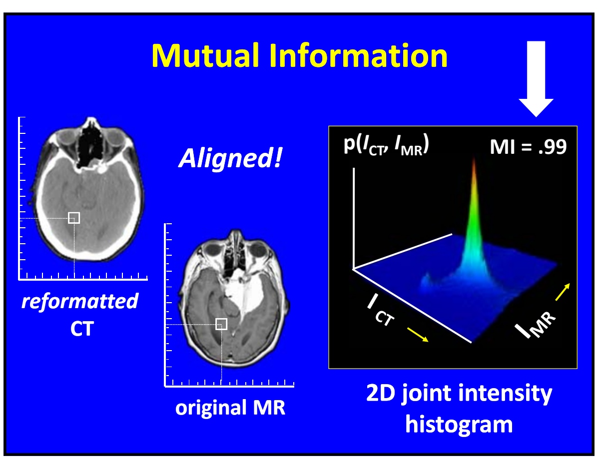


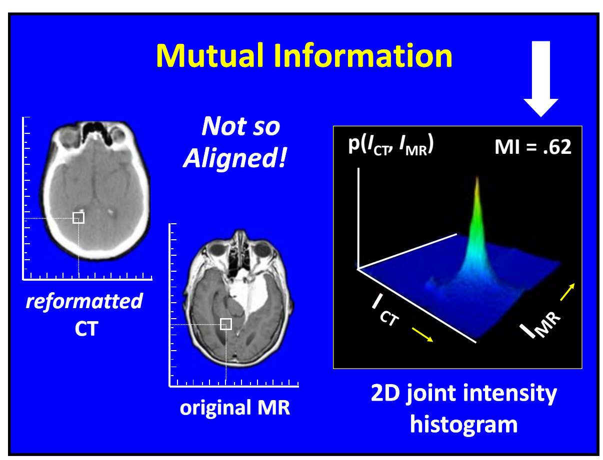


Please do not (re)redistribute

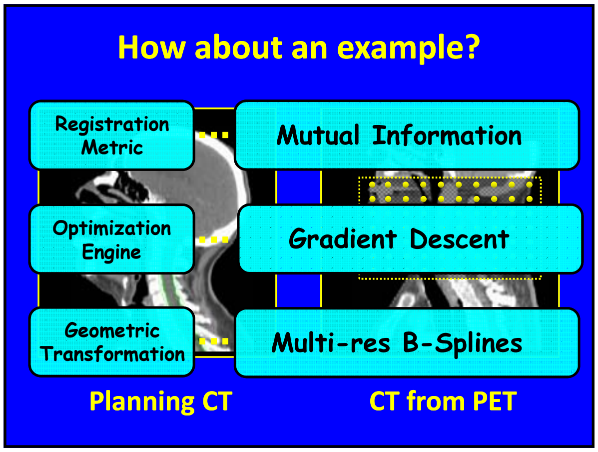


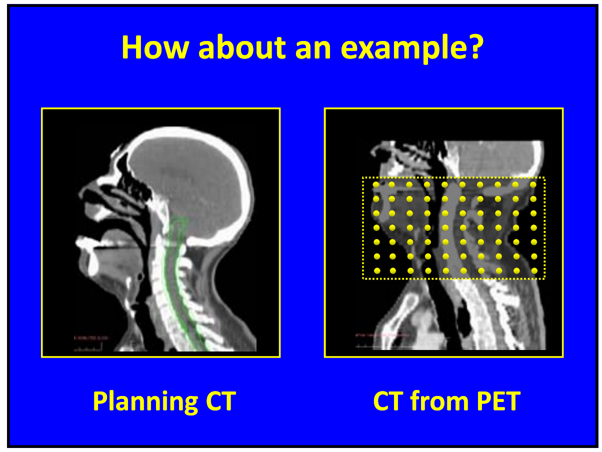




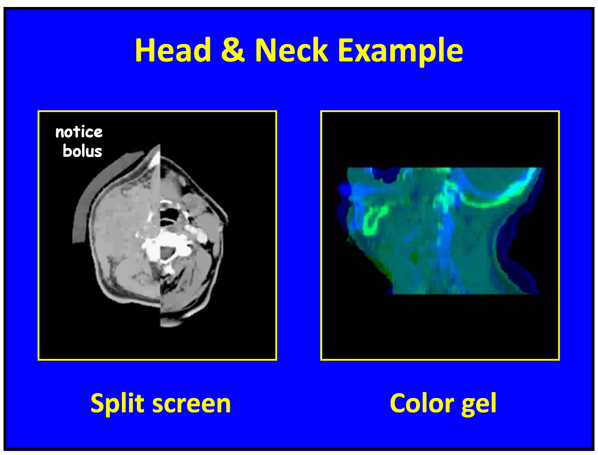


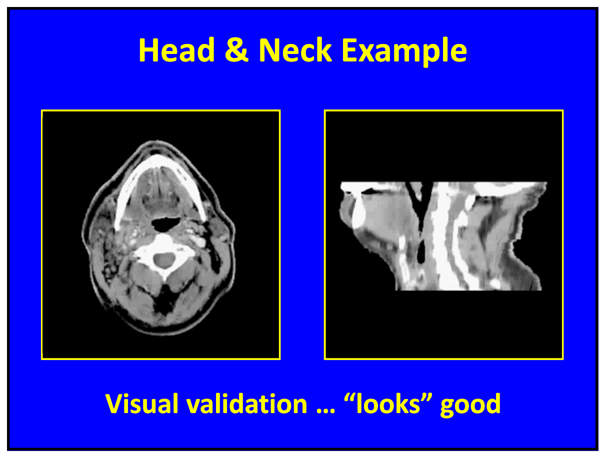
Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

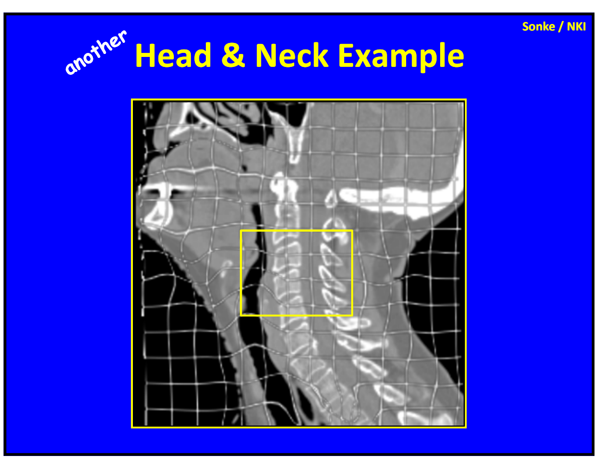


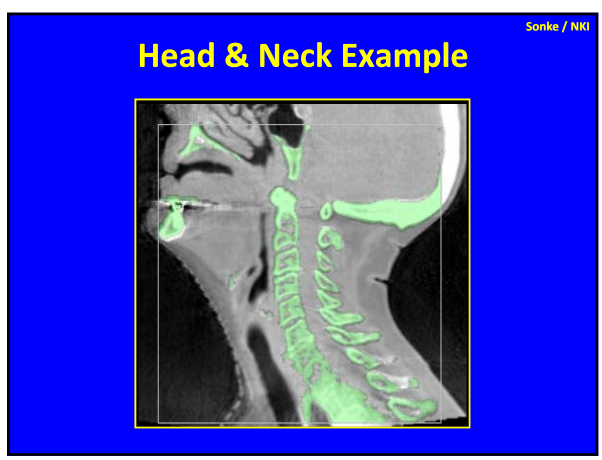


Please do not (re)redistribute



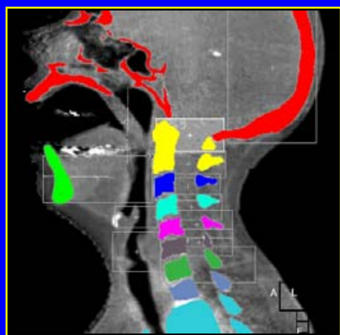






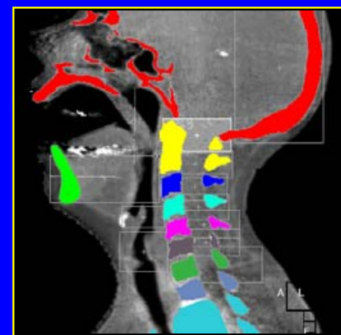
Sonke / NKI

Head & Neck Example



Sonke / NKI

Head & Neck Example



Constrained Optimization

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

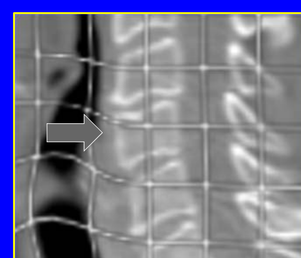
intensity similarity metric

tissue-dependent regularization

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

Sonke / NKI

Constrained Optimization



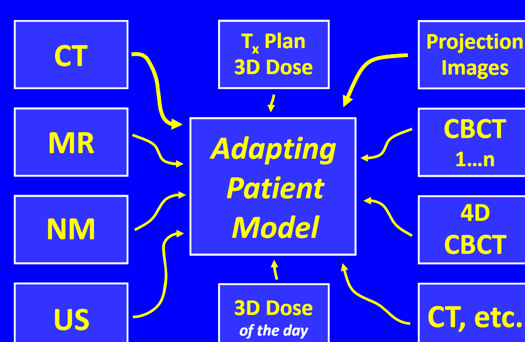
CBCT deformed w/ and w/o constaint

Regularization

… refers to a process of introducing additional information in order to solve an ill-posed problem or to prevent over-fitting.

This information is usually of the form of a penalty for complexity, such as restrictions for smoothness or bounds on the vector space norm.

Grand Unification



Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

Grand Unification

Essential Image Processing Tools

- **Image registration**

  Finding geometric correspondences between image data sets (2D/3D/4D) that differ in time, space, modality … and … maybe even subject

- **Data propagation and fusion**

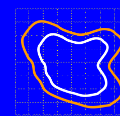
  Mapping data such as anatomic contours, regions of interest and doses between image data sets

Data Propagation

- **Outlines**

  contours

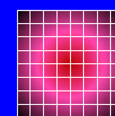
  … data *just* at boundaries



- **Voxel data**

  dose & image values

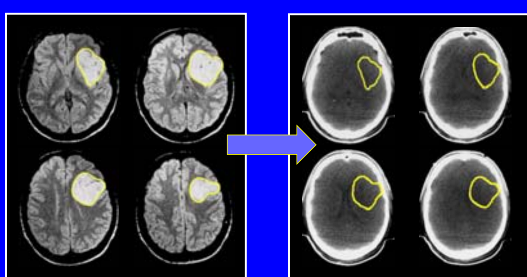
  … data at *every* point



Please do not (re)redistribute

Circa 1985

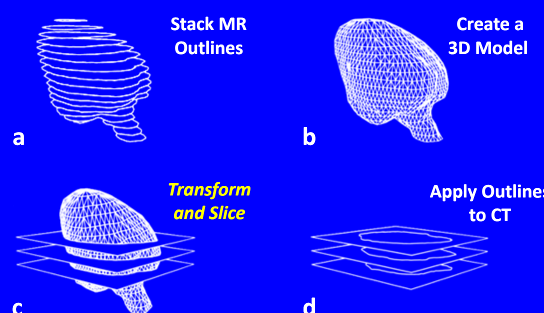
Contour Propagation



Drawn Contours ***Derived Contours***

Circa 1985

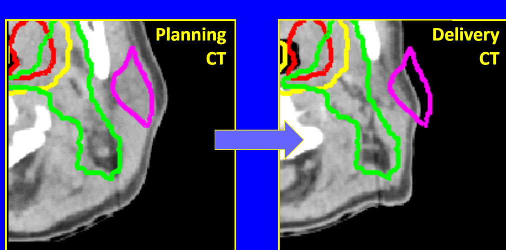
Contour Propagation



Structure Transfer Between Sets of Three Dimensional Medical Imaging Data, G.T.Y. Chen, M. Kessler, and S. Pitluck, Proceedings of the National Computer Graphics Association, Dallas, TX, vol III, pp 171-77 (1985)

Dong / MDACC

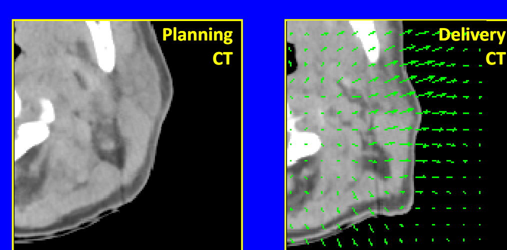
Contour Propagation



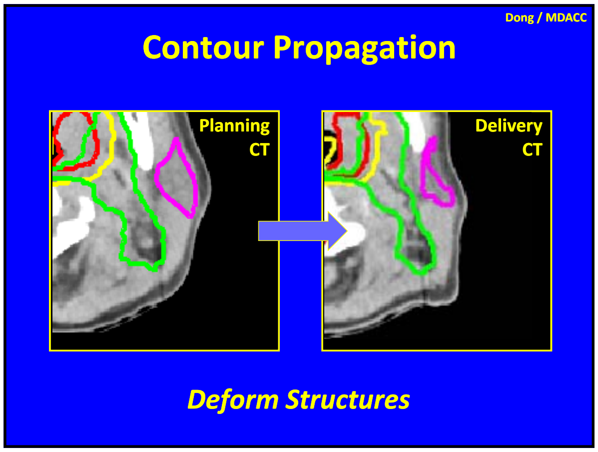
"Copy and Paste" Structures

Dong / MDACC

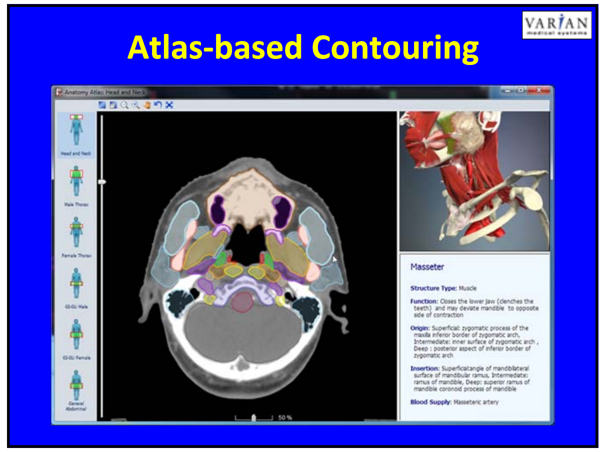
Deformable Registration



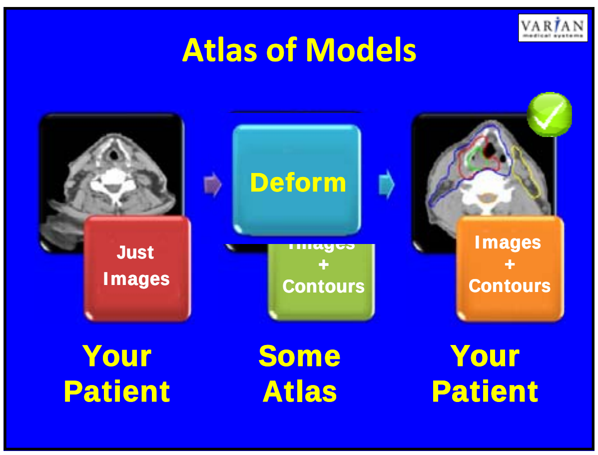
Registration using "Demons"



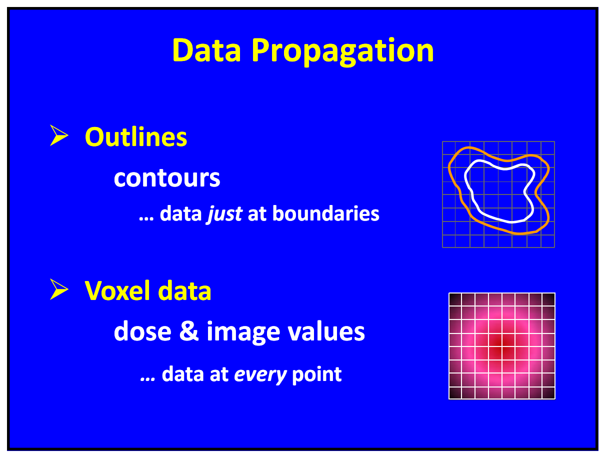
Dong / MDACC
Contour Propagation
Planning CT
Delivery CT
Deform Structures



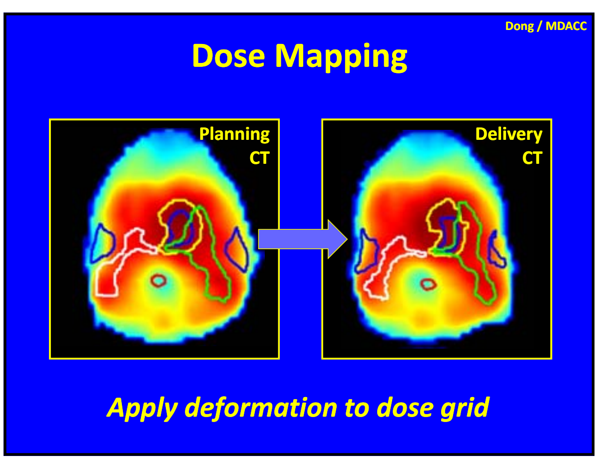
Atlas-based Contouring
VARIAN
Masseter



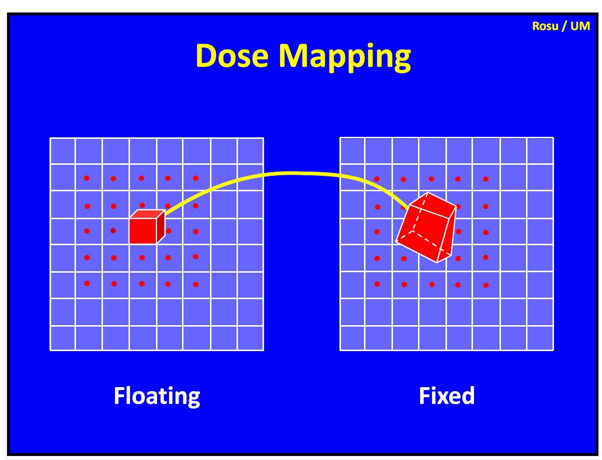
Atlas of Models
VARIAN
Just Images
Deform
Images + Contours
Images + Contours
Your Patient
Some Atlas
Your Patient



Data Propagation
Outlines
contours
... data just at boundaries
Voxel data
dose & image values
... data at every point

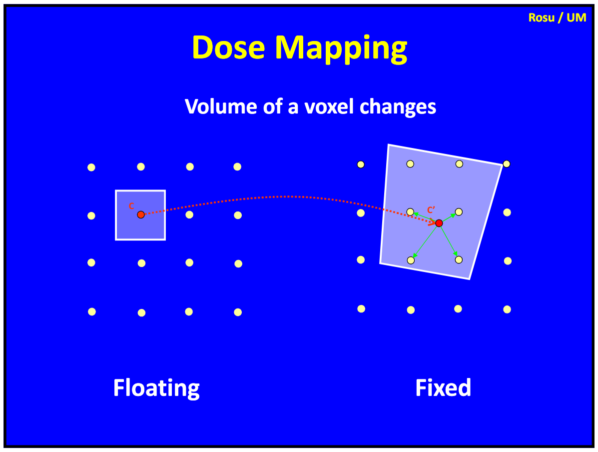


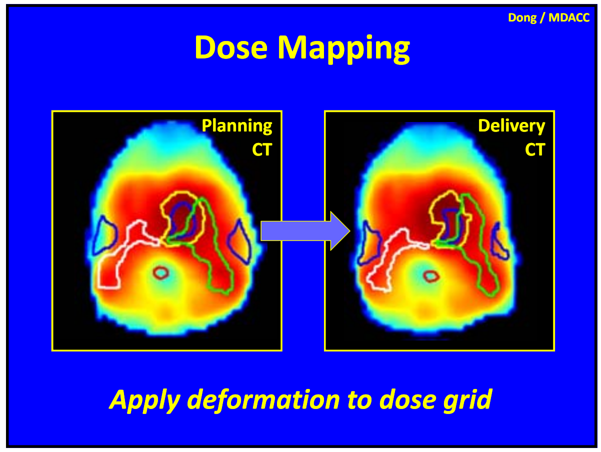
Dong / MDACC
Dose Mapping
Planning CT
Delivery CT
Apply deformation to dose grid



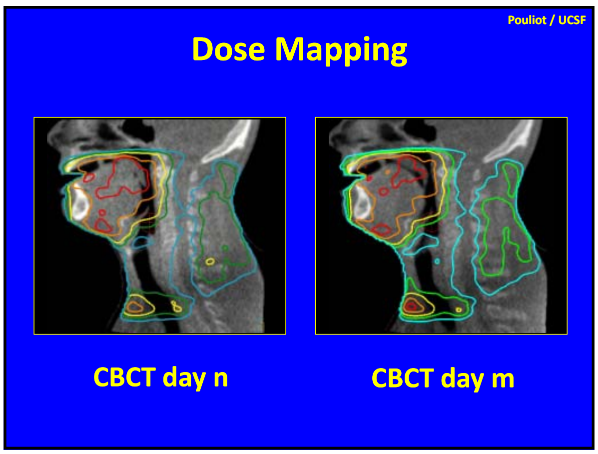
Rosu / UM
Dose Mapping
Floating
Fixed

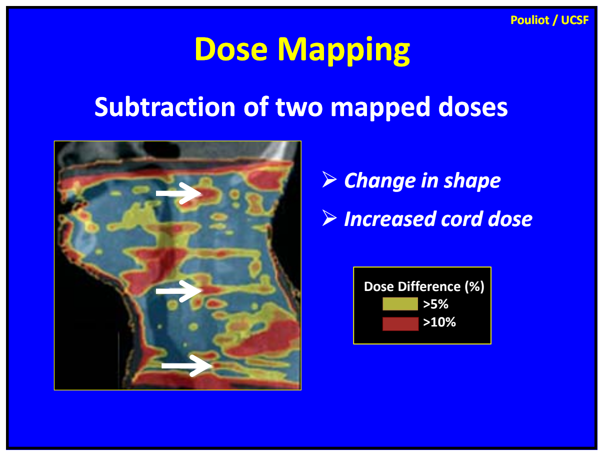
Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201





Please do not (re)redistribute





The major difference in the process of transferring doses and contours between two studies is ...

- 0% 1. Doses depend on tissue density and contours do not
- 0% 2. Doses do not change once a fraction is delivered, contours do
- 0% 3. Transferring doses is more time consuming than transferring contours
- ✔ 4. XF doses requires accurate registration at every voxel, XF contours requires this only at boundaries
- 0% 5. Transferring doses requires knowledge of the alpha beta ratio, transferring contour does not

10 Countdown

some of the Commercial Products

Independent of a Treatment Planning System

mim · MIRADA medical · Velocity

Part of a Treatment Planning System

ELEKTA · PHILIPS · RaySearch Laboratories · VARIAN medical systems

Vendor Questionnaire

1. What are the degrees of freedom of the approach (e.g., 3 x # of B-spline knots, DVF)?
2. What is the “goodness of match” metric that drives the registration?
3. What type of regularization do you use to keep the transformation “reasonable” and “useable”?
4. Any other “secret sauce” you want to explain or even allude to is great (and appreciated by everyone)?
5. Do you transfer / map structure outlines?
6. Do you transfer dose from one scan to another?

Vendor Answers - Raysearch

What are the degrees of freedom of the approach

The number of degrees of freedom equals 3 x # voxels in the deformation grid

What is the “goodness of match” metric that drives the registration?

An objective function consisting of 4 non-linear terms

Image similarity through correlation coefficient (CT/CBCT) or mutual information (MR)

Grid regularization (see below)

Shape based grid regularization when regions of interest are defined in the reference/floating image to ensure that the deformable registration is anatomically reasonable.

When controlling structures (regions or points of interest) are defined in both images, a penalty term is added which aims to deform the structures in the reference image to the corresponding structures in the target image.

Vendor Answers - Raysearch

What type of regularization do you use to keep the transformation “reasonable” and “useable”.

Regularization of the deformation field is obtained by computing how much the coordinate functions deviate from being harmonic functions.

Any other “secret sauce” you want to explain or even allude to is great (and appreciated by everyone).

The use of both image intensity and structural information to anatomically constrain the deformations and give more control to the user.

Do you transfer / map structure outlines

Yes, in either direction.

Do you transfer dose from one scan to another?

Yes, in either direction.

AAPM Task Group No. 132

Use of Image Registration and Fusion Algorithms and Techniques in Radiotherapy: Report of the AAPM Radiation Therapy Committee Task Group No. 132

Today!

Room 116

3:00PM - 3:50PM

TU-F-116-1

Deformable Image Registration, Contour Propagation and Dose Mapping

AAPM 2013 SAMS Course

General questions to ask the vendors …

1. Is your method freeform or based on a mathematical model (e.g, B-Splines)?
2. What are the degrees of freedom of the approach?

   (e.g., 3 x # of B-spline knots, DVF)?

2. What is the "goodness of match" metric that drives the registration?
3. What type of *regularization* do you use to keep the transformation "reasonable" and "useable"?
4. Any other "secret sauce" you want to explain or even allude to is great (and appreciated by everyone)?
5. Do you transfer / map structure outlines?
6. Do you transfer dose from one scan to another?

Specific questions to ask the vendors …

1. Do you support multiple registrations per pair of datasets? Rigid and Deformable?
2. Do you support "limited field of view" clip boxes? Can these be based on anatomic structures?
3. How do you map / interpolate doses between datasets?
4. Can you export the resulting transformation? What about the interpolated image data?
5. What tools to access the accuracy of registrations?
6. Do you provide tools to document the results? Can you "lock and sign" a registration?

The general questions were sent to the vendors below and their replies compiled on the pages that follow.

Part of a Treatment Planning System

Independent of a Treatment Planning System

ELEKTA

What are the degrees of freedom of the approach (e.g., 3 x # of b-spline knots) ?

3 x # of image voxels (dense deformation vector field)

What is the “goodness of match” metric that drives the registration?

We use a combination of metrics, mainly a combination of Mutual Information and Local Cross Correlation

What type of regularization do you use to keep the transformation “reasonable” and “useable”?

Regularization is mainly achieved through Gaussian smoothing of the deformation vector field and the update field during the optimization. We also use a compositive update scheme to ensure the deformation vector field is non-singular (positive Jacobians).

Any other “secret sauce” you want to explain or even allude to is great (and appreciated by everyone)?

We found it more robust and accurate to gradually increase the degrees of freedom. Instead of directly estimating a dense vector field over every voxel of the image, we apply a block-matching scheme to match image blocks first. The typical multi-resolution scheme is also used.

Do you transfer / map structure outlines?

Yes, we map structure outlines instead of label maps.

Do you transfer dose from one scan to another?

Yes, in the research version.

PHILIPS

What are the degrees of freedom of the approach (e.g., 3 x # of b-spline knots)

3 mm isotropic resampled images

What is the “goodness of match” metric that drives the registration?

Demons equation

What type of regularization do you use to keep the transformation “reasonable” and “useable”?

Diffusion like regularization. Apply Gaussian smoothing to the spatial transformation at the end of each iteration, where spatial transformation at the end of each iteration is C= S + U. Here S is the spatial transformation in the beginning of the iteration. U is the incremental update field computed from the current iteration. If you apply Gaussian smoothing to the incremental field U, then it is fluid like regularization.

Any other “secret sauce” you want to explain or even allude to is great (and appreciated by everyone)?

Image preprocessing to increase speed and help minimize false registration matches especially with CT to CBCT registration

I would rather not disclose the methods

Do you transfer / map structure outlines?

Yes

Do you transfer dose from one scan to another?

Not yet commercially

RaySearch Laboratories

What are the degrees of freedom of the approach (e.g., 3 x # of b-spline knots)

The number of degrees of freedom equals 3 times the number of voxels in the deformation grid.

What is the “goodness of match” metric that drives the registration

An objective function consisting of four non-linear terms is used (and minimized in the optimization process):

1. Image similarity through correlation coefficient (CT/CBCT) or mutual information (MR)
2. Grid regularization (see below).
3. Shape based grid regularization when regions of interest are defined in the reference/floating image to ensure that the deformable registration is anatomically reasonable.
4. When controlling structures (regions or points of interest) are defined in both images, a penalty term is added which aims to deform the structures in the reference image to the corresponding structures in the target image.

What type of regularization do you use to keep the transformation “reasonable” and “useable”?

Regularization of the deformation field is obtained by computing how much the coordinate functions deviate from being harmonic functions.

Any other “secret sauce” you want to explain or even allude to is great (and appreciated by everyone)?

- The use of both image intensity and structural information to anatomically constrain the deformations and give more control to the user.
- The possibility to focus on specific regions.
- Through scripting the possibility to modify the weights of the terms in the objective function.
- The near-future implementation of more biomechanical information into the deformations.
- Single platform for dose / deformation / dose accumulation / adaptive planning.

Do you transfer / map structure outlines

Yes, in either direction.

Do you transfer dose from one scan to another?

Yes, in either direction.

CT-CT Deformable image registration used in SmartAdapt is an implementation of accelerated demons.

What are the degrees of freedom of the approach (e.g., 3 x # of b-spline knots)?

The deformation force is calculated at each image voxel

What is the "goodness of match" metric that drives the registration?

The goodness of match is measured by intensity difference. The registration is driven by forces which are function of image gradients calculated in both images and intensity difference.

What type of regularization do you use to keep the transformation "reasonable" and "useable"?

Gaussian smoothing

Any other "secret sauce" you want to explain or even allude to is great (and appreciated by everyone).

There are no "secret sauces"

Do you transfer / map structure outlines?

Yes

Do you transfer dose from one scan to another?

No

What are the degrees of freedom of the approach (e.g., 3 x # of b-spline knots)?

>= 3x3x3 mm resolution. Free form transformation (multiresolutional)

What is the “goodness of match” metric that drives the registration?

~SSD

What type of regularization do you use to keep the transformation “reasonable” and “useable”?

Multiple methods. This is some of the secret sauce.

We don't explicitly ensure that the Jacobian is always positive. We do of course regularized the deformation. Again, we have a complex strategy here that we don't share details on.

Any other “secret sauce” you want to explain or even allude to is great (and appreciated by everyone)?

1. Attempt to minimize bone deformation.

2. Reg Reveal and Reg Refine for user guidance towards locally "good" registrations.

Do you transfer / map structure outlines?

Yes.

Do you transfer dose from one scan to another?

Yes.

MIRADA medical

Mirada multi-modal deformable optimizes Radial Basis Function based deformation field using a Mutual Information like similarity function.

What are the degrees of freedom of the approach (e.g., 3 x # of b-spline knots)?

Mirada uses an adaptive algorithm to select this.

What is the “goodness of match” metric that drives the registration?

It’s a variant of Mutual Information.

What type of regularization do you use to keep the transformation “reasonable” and “useable”?

Diffusion PDE to the deformation field.

Any other “secret sauce” you want to explain or even allude to is great (and appreciated by everyone)?

The algorithm has quite a lot of adaptive parts that adjust according to MR resolution, orientation and algorithms to adapt to contrast too. Handling off-axis MR and the typically highly anisotropic MR (e.g. 10:1 voxel dimensions) needs special care.

Mirada CT Deformable is based on the Lucas-Kanade-Tomasi optic flow algorithm but with many enhancements.

What are the degrees of freedom of the approach (e.g., 3 x # of b-spline knots)?

Mirada uses an adaptive algorithm to select this.

What is the “goodness of match” metric that drives the registration?

Robust least squares (robust to handle artifacts and differences in HU)

What type of regularization do you use to keep the transformation “reasonable” and “useable”?

Diffusion PDE to the deformation field.

Any other “secret sauce” you want to explain or even allude to is great (and appreciated by everyone)?

The most important secret-sauces are the use of robust statistical approaches internally. These are necessary to prevent the algorithm from making arbitrary deformations in areas which have low image structure (e.g. in the liver, you want the algorithm to rely more on the regularization). Also, we use robust kernel to handle image artifacts (e.g. streaking due to metal) and HU differences.

As with the Multi-modal, the algorithm has quite a lot of adaptive parts that adjust according to the images. Also, we have different settings according to the use-case. For large deformation use-cases, like atlas contouring, we tend to use lower regularization than in other problems like dose mapping between consecutive CTs of the same person. There is a huge amount of optimization to make it work (quick).

Velocity

Velocity's primary registration algorithm uses a Multi-Resolution approach whereby the metric is based on Mattes Mutual Information, the transform used is a cubic B-Spline, the interpolatorused is a bi-linear interpolation and the optimizer is based on the method of steepest gradient descent. Please note, this approach is valid for all Velocity versions up to and including version 3.0.1 (version 3.1.0 of VelocityAI will use additional technologies currently in development). We also include a secondary algorithm based on a tunable “demons” approach. (We provide a tunable demons algorithm for research and comparison purposes, but highly recommend the Multi-resolution B-Spline algorithm for clinical use.)

What are the degrees of freedom of the approach (e.g., 3 x # of b-spline knots)?

Velocity is using a B-Spline of order 3 (cubic) with a uniform knot vector. The number of control points (per-dimension) is configurable with a minimum of 5 control points per-axis (no other constraints are imposed onto this value; the user can freely increase this value). Please note, the multi-resolution approach increases the number of control points used by the B-Spline transform between successively resolution levels.

What is the “goodness of match” metric that drives the registration?

Mattes Mutual Information as employed as the metric for our primary (B-Spline based) approach and a modified normalized correlation metric is used for.

What type of regularization do you use to keep the transformation “reasonable” and “useable”?

The main explicit regularization of our B-Spline algorithm is to restrict the optimizer in not allowing for crossings of the Control Points. This prevents “unnatural” results helps the deformation field conform to physical movements.

Implicit regularization in employed in the form of limiting the number of control points during the Multi-Resolution approach. Additionally, users are able in enabling the registration algorithm tomake use of the currently defined Window/Level settings of the loaded volumes (for establishing normalized spaces). In the case of MR, specialized algorithms may be used to reduce or eliminate any intensity inhomogeneities in MR volumes. Currently, Adaptive Filtering approaches on the deformation map are avoided.

Any other “secret sauce” you want to explain or even allude to is great (and appreciated by everyone)?

Velocity supports the following features for all of our registrations (rigid and deformable) which are unique to Velocity.

- Active display of the registration results in the views as a registration is being created/optimized.

- User can create as many registrations between two volumes as they wish and quickly and efficiently switch between and compare these registrations (registration management). This is an important feature for registration QA.

- Registrations can be updated by re-running the registration on all or part of the previous result. The region of interested can change to “fine tune” areas of interest

• Mathematical inversion of all of our registrations (rigid and deformable). This is critical for structure and volume transfers and for registration QA. If a deformable registrations cannot be mathematically inverted (as many “generic” ones can’t), it has not been properly constrained (regularized) for clinical use.

• Image pre-filtering: Modality specific filters (linear and non-linear) are applied to image volumes prior to the application of the deformable registration process

• Export of the deformation fields matrix in DICOM format or simplified “flat” format for user analysis by other tools. This is an important feature for registration QA by outside tools.

• Complete set of visual QA tools permitting the user to assess the clinical appropriateness of the deformation field.

Do you transfer / map structure outlines?

Structure transfers are fully supported through rigid and deformable registrations in Velocity to move structure from one volume to the other through the selected registrations. Since Velocity fully supports the mathematical inverse of all our registrations (rigid and deformable), structures can be transferred in either direction through the registration.

Do you transfer dose from one scan to another?

Volume transfers (including dose) are fully supported through rigid and deformable registrations in Velocity. Since Velocity fully supports the mathematical inverse of all our registrations (rigid and deformable), Volume transfers can be transferred in either direction through the registration.