Good Morning!

Thank you for joining us

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

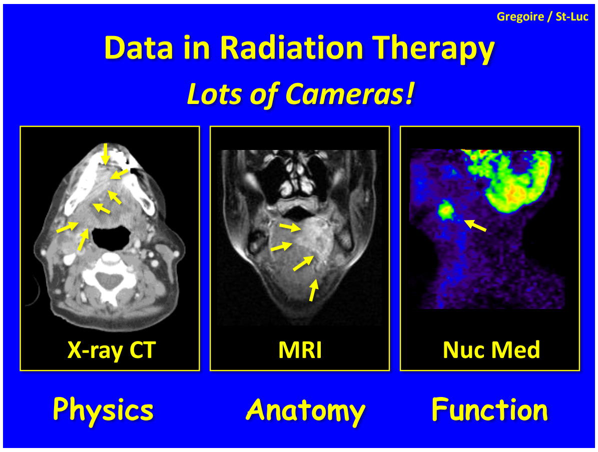
Marc Kessler, PhD, FAAPM
The University of Michigan

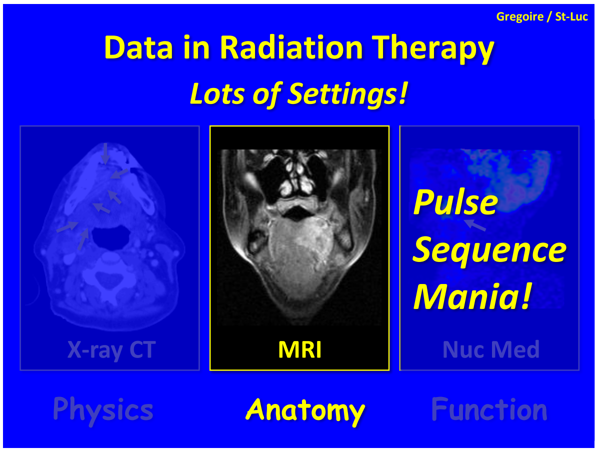
Conflict of Interest

I receive direct or indirect support from:

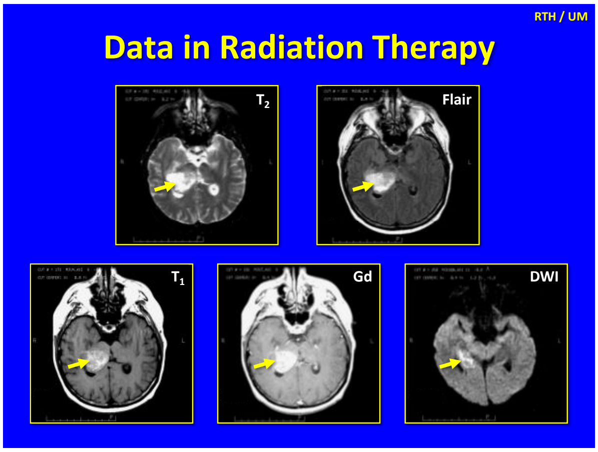
- University of Michigan
- National Institutes of Health
- Varian Medical Systems

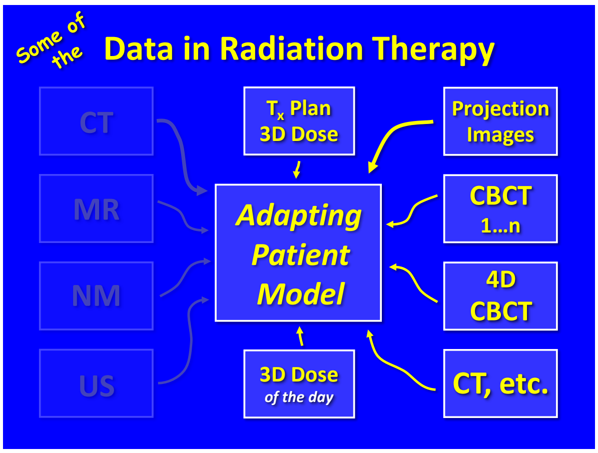
Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

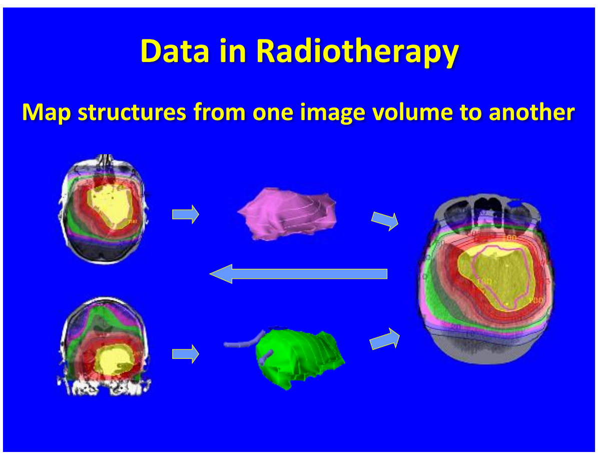




Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201







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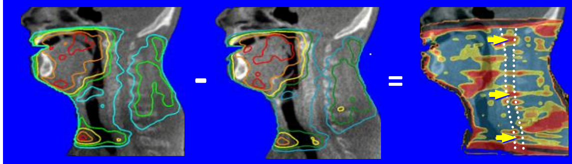
Pouliot / UCSF

Data in Radiotherapy

Map and *combine* doses from multiply Tx fractions

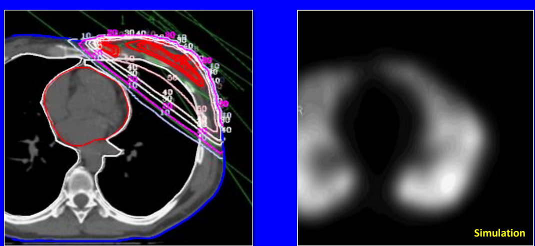
CBCT 1 CBCT 2



Fraction 1 Fraction 2 Δ Dose

Data in Radiotherapy

Map dose and correlate with functional changes



Planning CT SPECT Imaging

The Mechanics

- **Image registration**

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

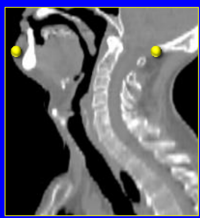
- **Data propagation and fusion**

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

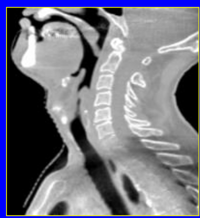
Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

The Mechanics

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



Planning CT



CBCT

The Mechanics

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

$$X_{CBCT} = F(X_{CT}, \{\beta\})$$

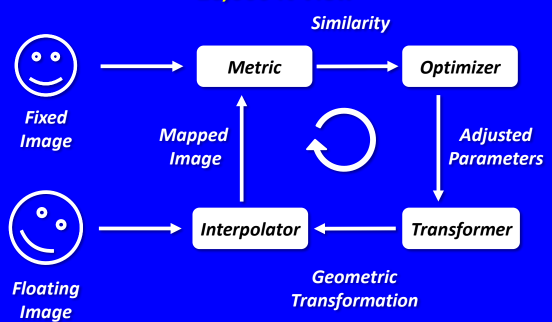
$$X_{CBCT} = F(X_{CT}, \{\beta(X_{CT})\})$$

$$X_{CBCT} = F(X_{CT}, \{\beta(X_{CT}, \varphi)\})$$

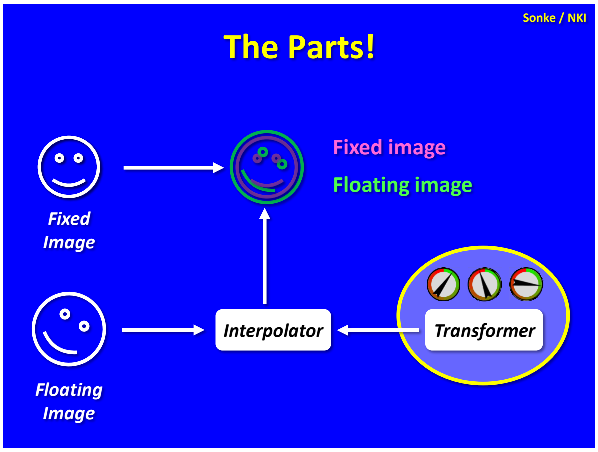
Sonke / Kessler

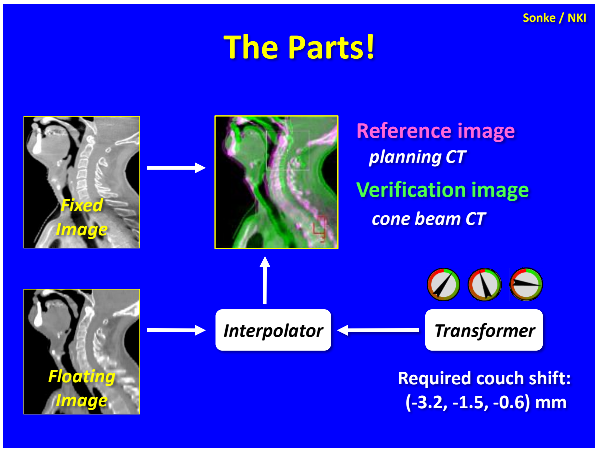
The Parts!

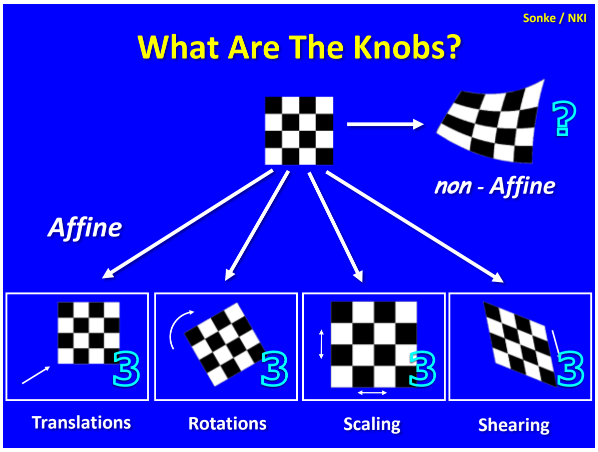
20,000 ft View

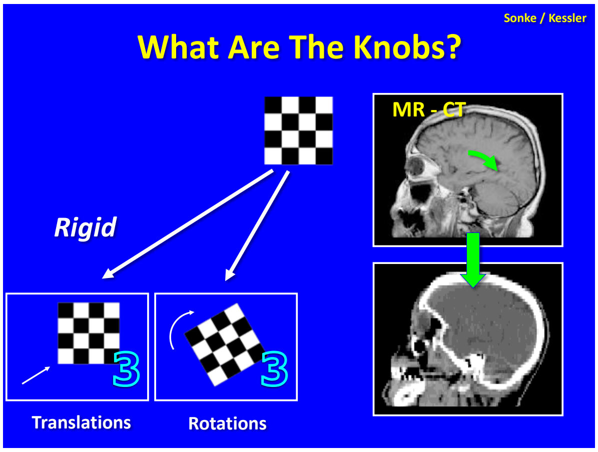


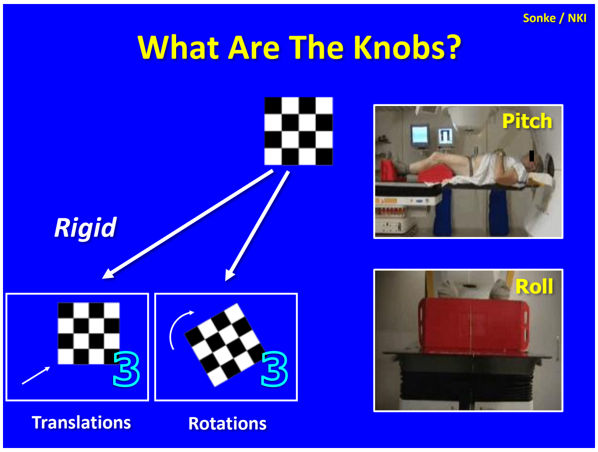
Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

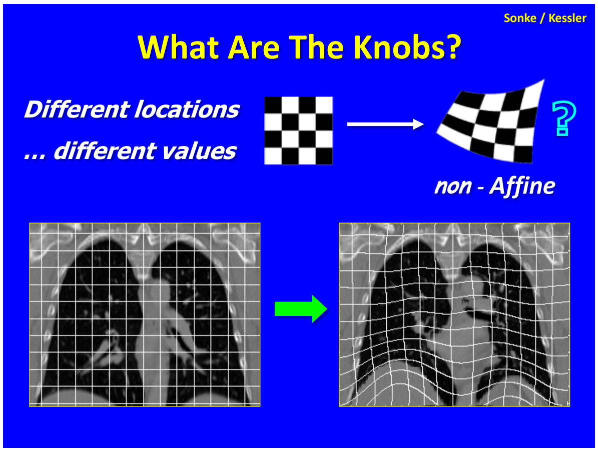


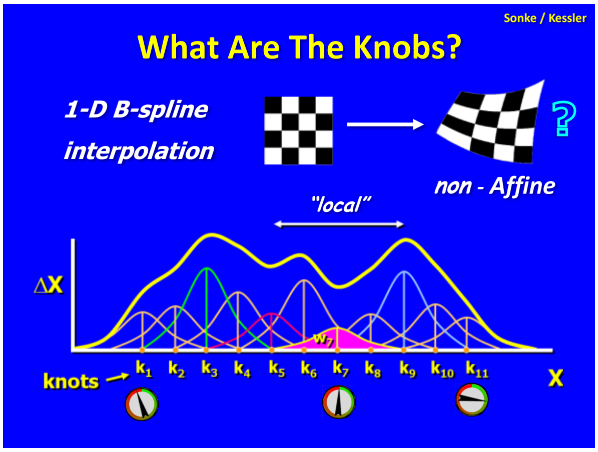


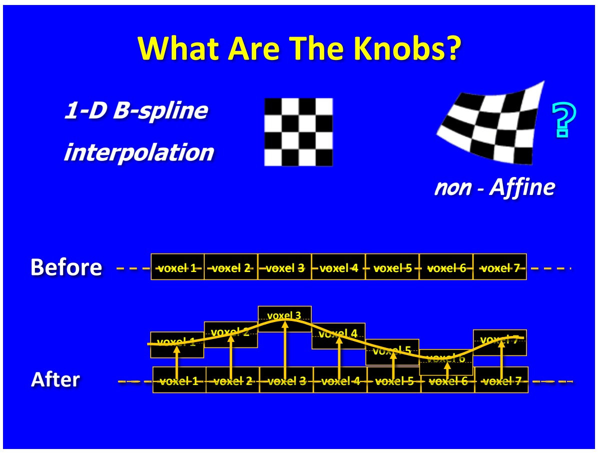


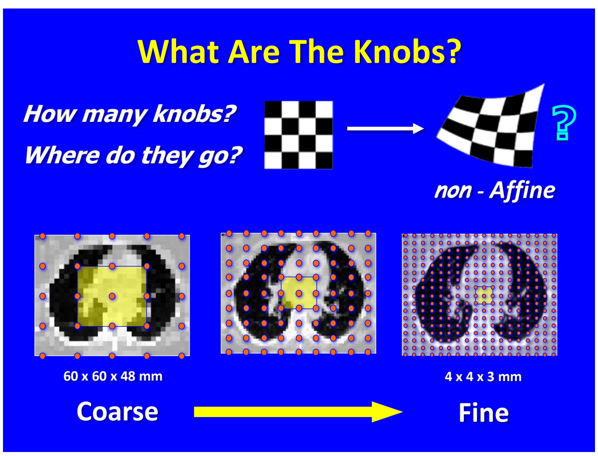

Sonke / Kessler
What Are The Knobs?
Rigid
MR - CT
3
3
Translations
Rotations

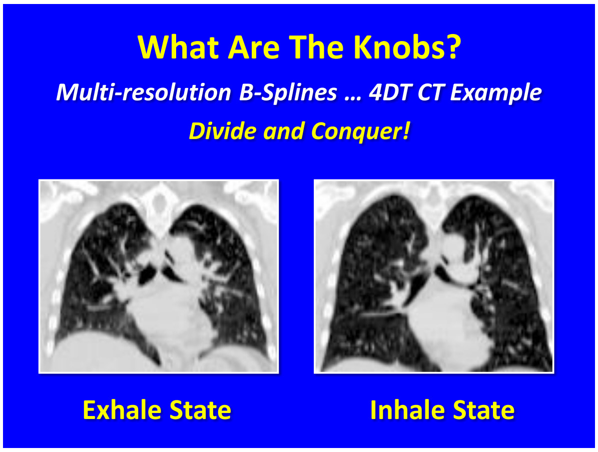

Sonke / NKI
What Are The Knobs?
Rigid
Pitch
Roll
3
3
Translations
Rotations

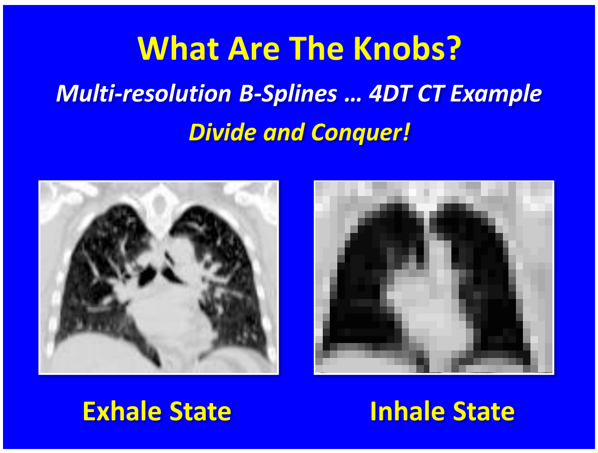

Sonke / Kessler
What Are The Knobs?
Different locations
… different values
?
non - Affine


Sonke / Kessler
What Are The Knobs?
1-D B-spline
interpolation
non - Affine
"local"
ΔX
knots
k1 k2 k3 k4 k5 k6 k7 k8 k9 k10 k11
X


What Are The Knobs?
1-D B-spline
interpolation
non - Affine
Before
voxel 1 voxel 2 voxel 3 voxel 4 voxel 5 voxel 6 voxel 7
After


What Are The Knobs?
How many knobs?
Where do they go?
non - Affine
60 x 60 x 48 mm
4 x 4 x 3 mm
Coarse
Fine


What Are The Knobs?
Multi-resolution B-Splines … 4DT CT Example
Divide and Conquer!
Exhale State
Inhale State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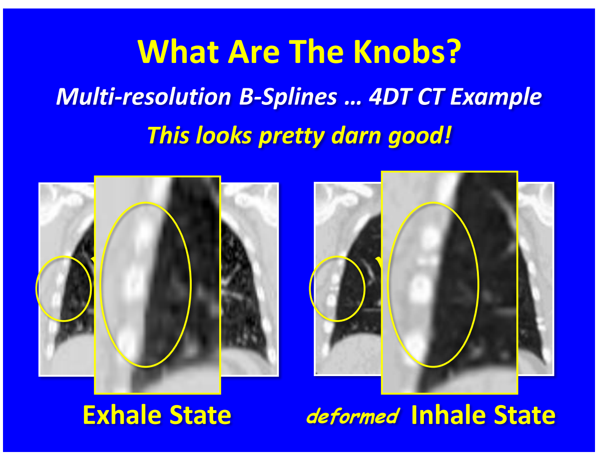
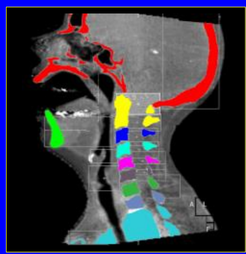
Exhale State
Inhale State


What Are The Knobs?
Multi-resolution B-Splines … 4DT CT Example
This looks pretty darn good!
Exhale State
deformed Inhale State

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

What Are The Knobs?

Different knobs for different locations?

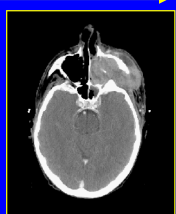


This requires a segmentation!

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

fewer knobs

Spatially variant ... *local*

B-splines, Cubic, Thin-plate

Finite element models

Dense deformation fields

... dx, dy, dz for every voxel!

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

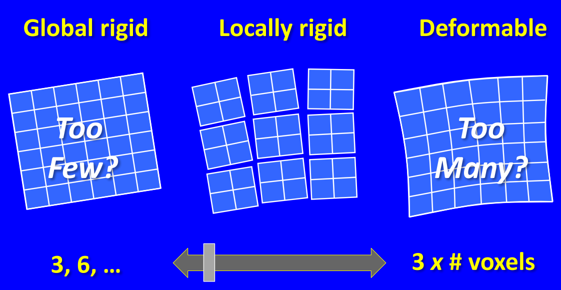
Dense deformation fields

... demons, other free form

fewer knobs

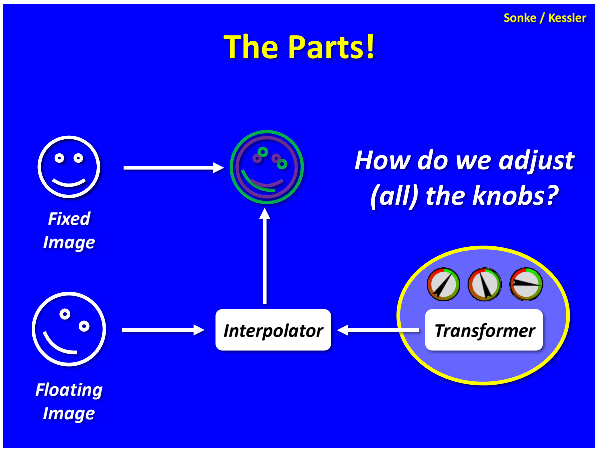
more knobs

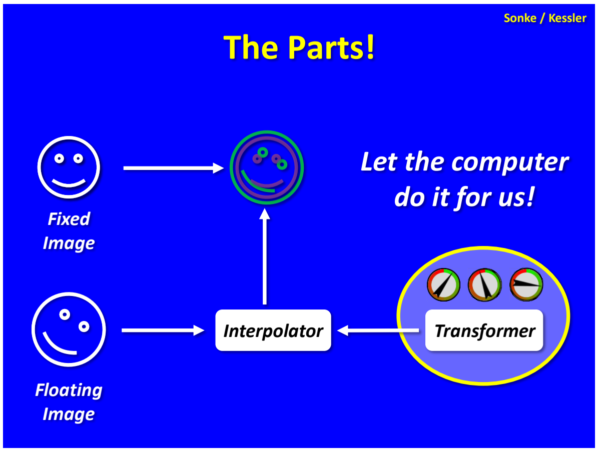
How Many Knobs?

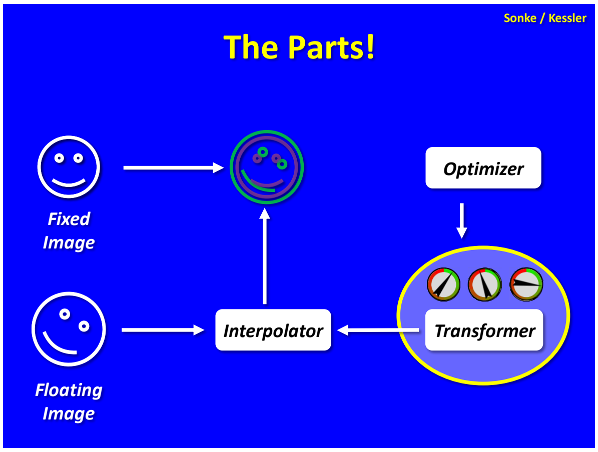


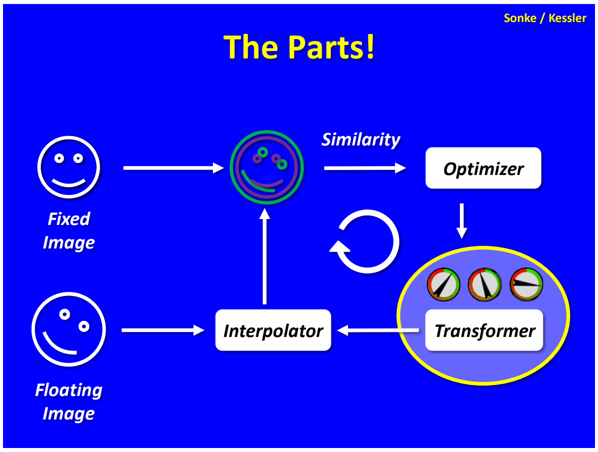
How many knobs (degrees of freedom) are needed to carry out (accurate) deformable image registration?

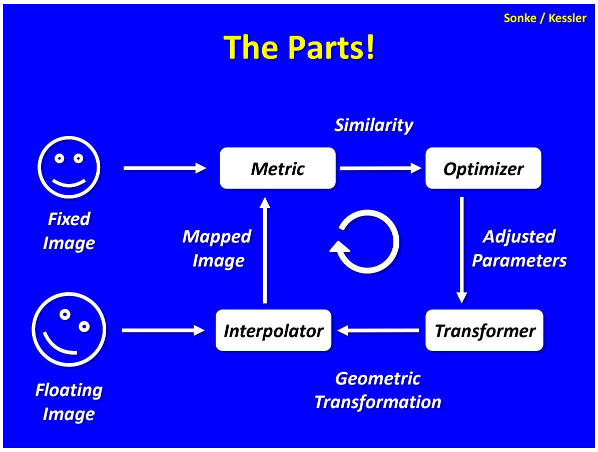
20%	1. 6
20%	2. 12
20%	3. 42
20%	4. 3 x number of voxels
20%	✓ 5. More than 12 and less than 3 x # voxels


Sonke / Kessler
The Parts!
How do we adjust (all) the knobs?
Fixed Image
Floating Image
Interpolator
Transformer


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





Similarity Metrics

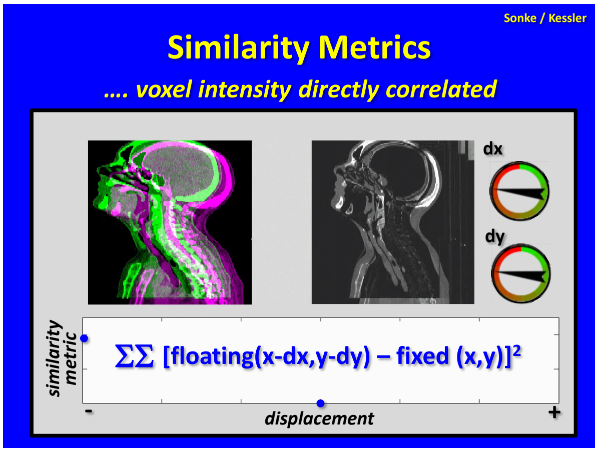
Image intensity based

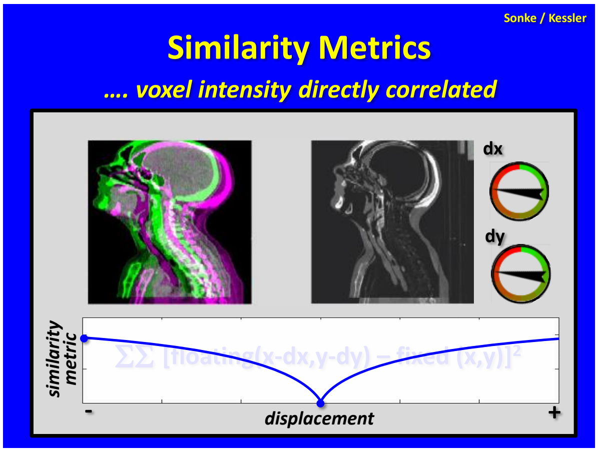
- Sum of the differences
- Cross correlation
- Mutual information (multimodality)

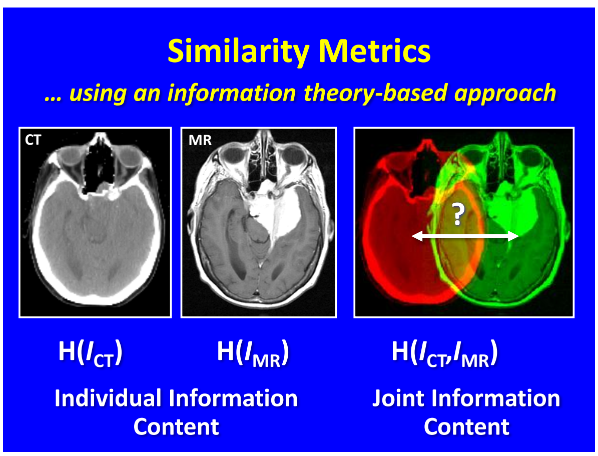
Geometry based

- Point matching (LMSE)
- Line / edge matching
- Surface / chamfer matching

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







Information Theory

$$H(I_A,I_B) = H(I_A) + H(I_B) - MI(I_A,I_B)$$

Joint Entropy | Individual Entropies | Mutual Information

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

These are just intensity histograms!

Information Theory

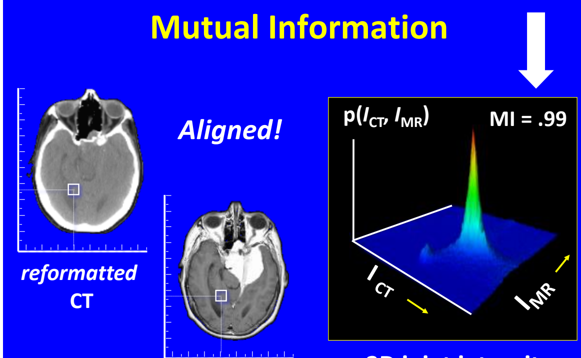
$$H(I_A,I_B) = H(I_A) + H(I_B) - MI(I_A,I_B)$$

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

... MI can be used as a metric

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

Mutual Information

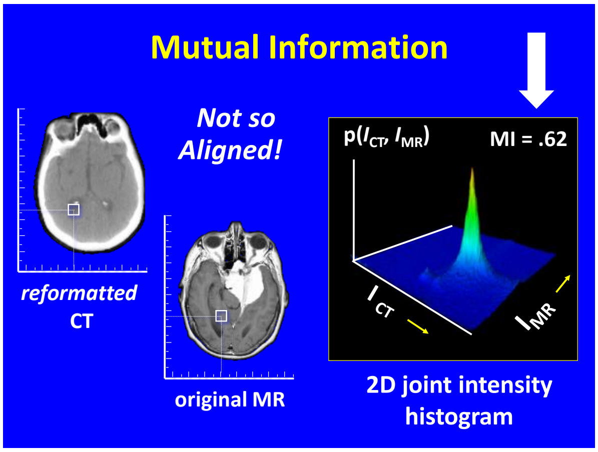


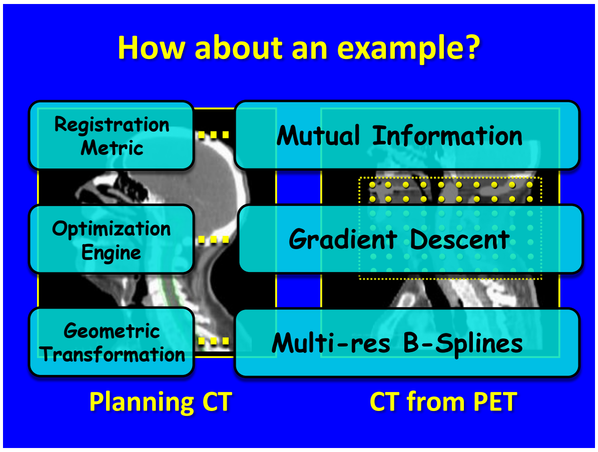
reformatted CT

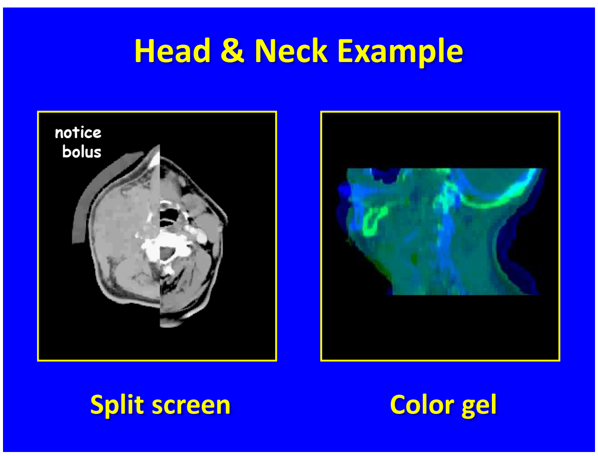
original MR

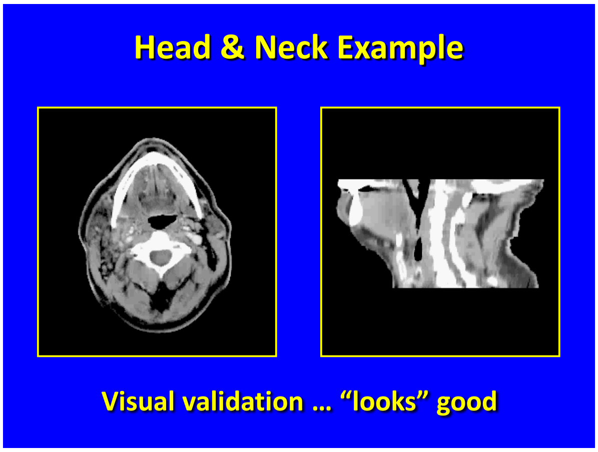
2D joint intensity histogram

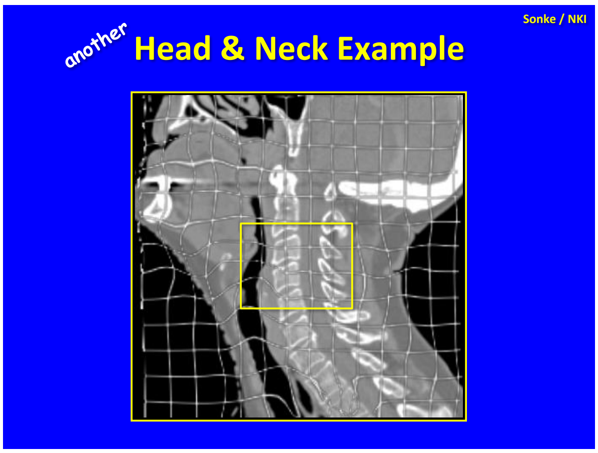
Deformable Image Registration, Contour Propagation and Dose Mapping: 101 and 201

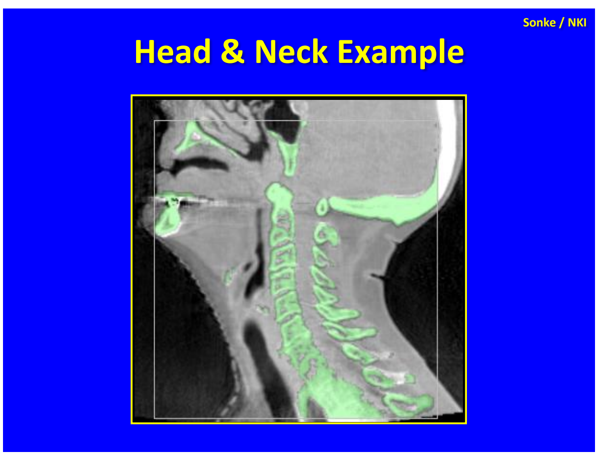






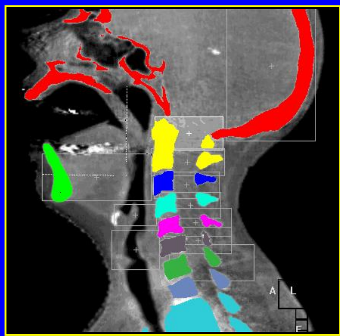

Head & Neck Example
Visual validation … "looks" good


Sonke / NKI
another
Head & Neck Example


Sonke / NKI
Head & Neck Example

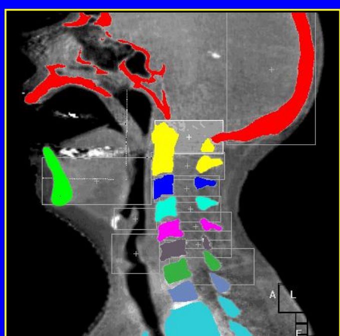
Head & Neck Example

Sonke / NKI



Head & Neck Example

Sonke / NKI



Constrained Optimization

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

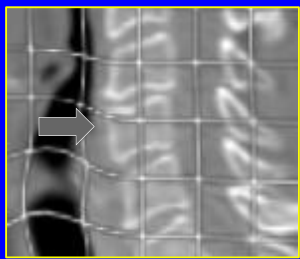
intensity similarity metric

tissue-dependent regularization

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

Constrained Optimization

Sonke / NKI



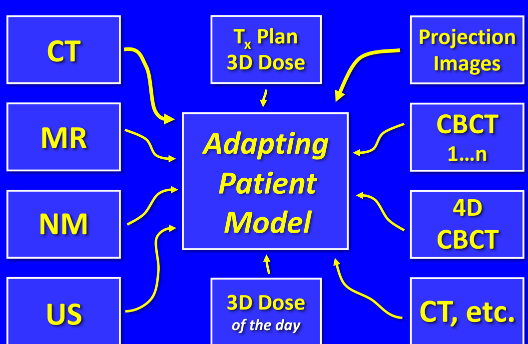
CBCT deformed w/ and w/o constaint

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



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**

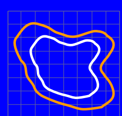
  Mapping data such as anatomic contours, regions of interest and doses between image data sets

Data Propagation

- **Outlines**

  contours

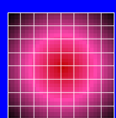
  … data *just* at boundaries



- **Voxel data**

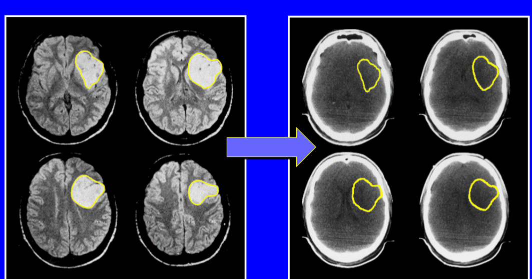
  dose & image values

  … data at *every* point



Contour Propagation

Circa 1985



Drawn Contours *Derived Contours*

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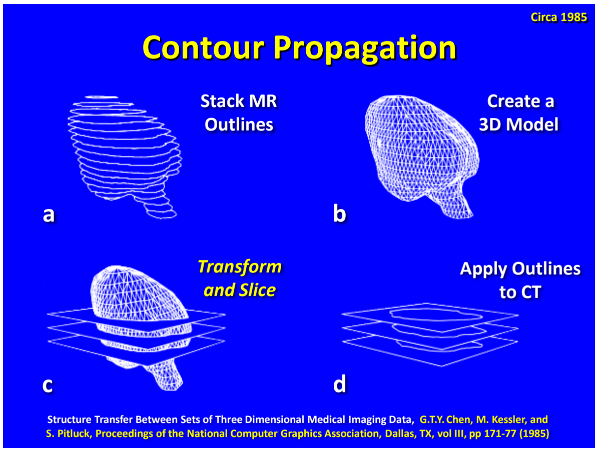

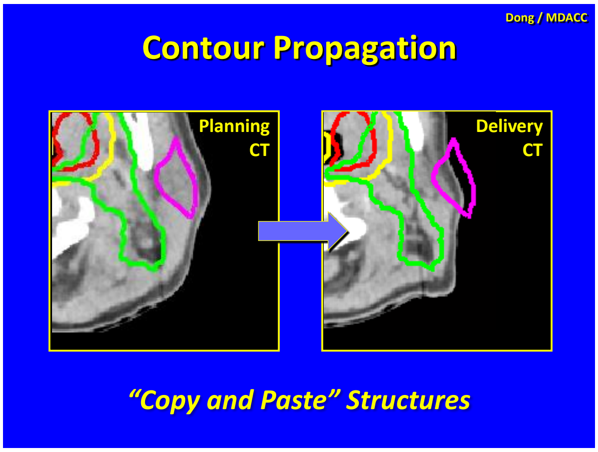

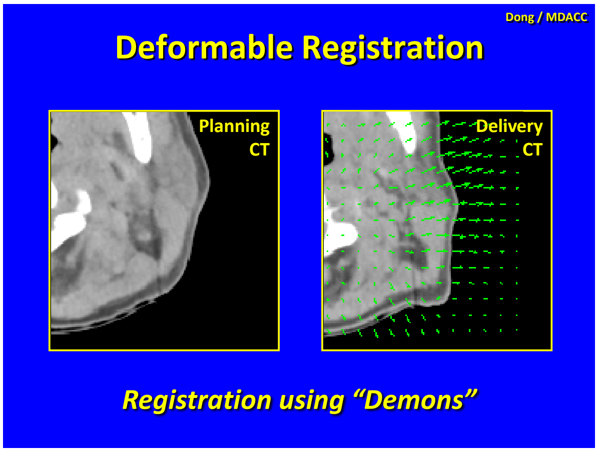

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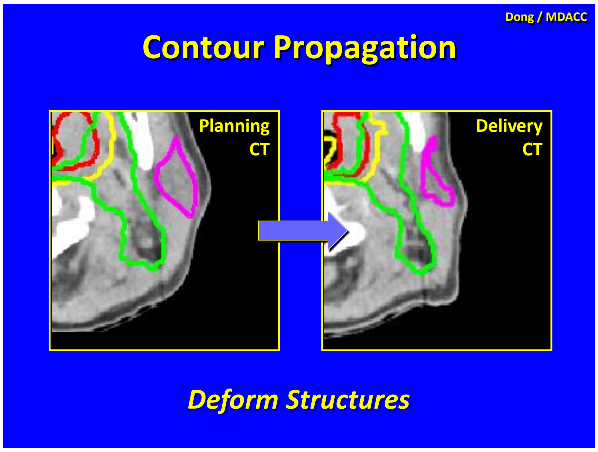
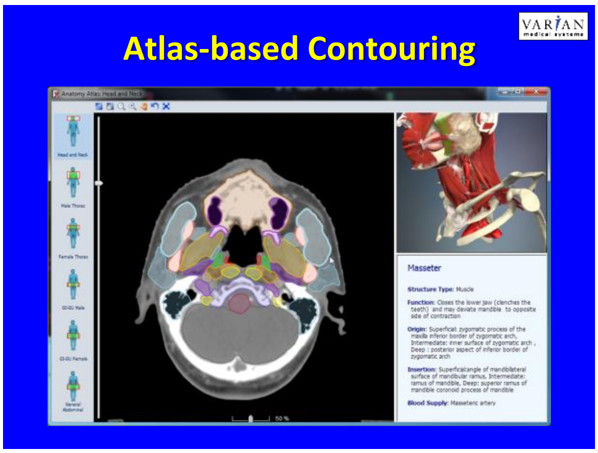
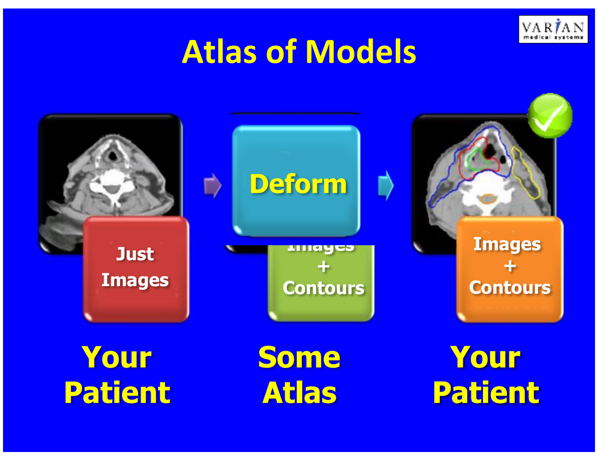

Dong / MDACC
Contour Propagation
Planning CT
Delivery CT
Deform Structures


Atlas-based Contouring
Masseter


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

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

Contours defined on one DICOM image study can be transferred to another DICOM image study by:

21% 1. using simple "cut and paste"

32% 2. registering the imaging studies then mapping the structures using the resulting transformation

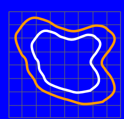
11% 3. using IHE-RO to transferring the contours and images between two DICOM servers

16% 4. scaling the contours by the ratio of the different pixel sizes

21% 5. It is not possible to transfer contours between studies

Data Propagation

- **Outlines**
  contours
  ... data *just* at boundaries



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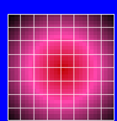
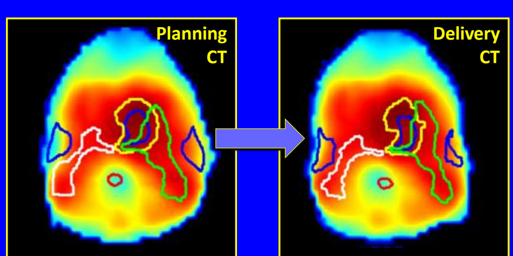
  dose & image values
  ... data at *every* point



Dong / MDACC

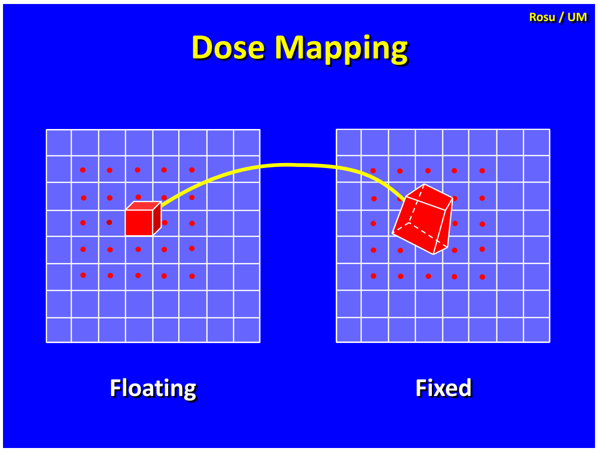
Dose Mapping

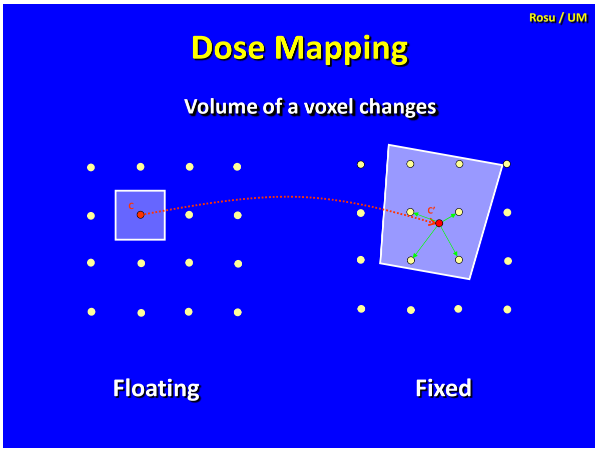


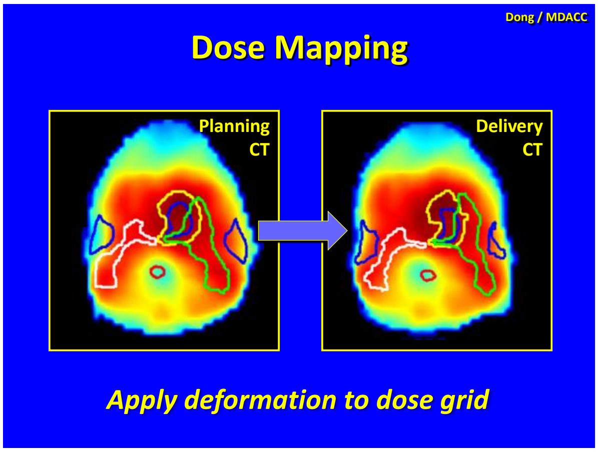
Apply deformation to dose grid

Marc L Kessler, PhD

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







Marc L Kessler, PhD

Pouliot / UCSF

Dose Mapping

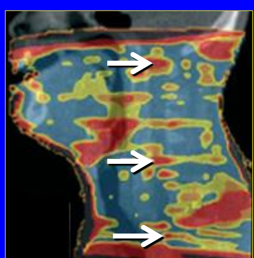
CBCT day n

CBCT day m

Pouliot / UCSF

Dose Mapping

Subtraction of two mapped doses



- *Change in shape*
- *Increased cord dose*

Dose Difference (%)
>5%
>10%

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

44%	1. Doses depend on tissue density and contours do not
11%	2. Doses do not change once a fraction is delivered, contours do
0%	3. Transferring doses is more time consuming than transferring contours
22% ✓	4. XF doses requires accurate registration at every voxel, XF contours requires this only at boundaries
22%	5. Transferring doses requires knowledge of the alpha-beta ratio, transferring contour does not

some of the Commercial Products

Independent of a Treatment Planning System

MIM Software · 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.

Other Questions to Asks

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 dose 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 overall *mechanical* objective of deformable image registration is to:

43% 1. maximize the similarity between two image datasets

21% 2. Register just non-rigid features

0% ✔ 3. Transfer and merge information from different imaging and dose datasets

21% 4. Handle CT-MR registration

14% 5. Account for changes between fractions

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

Adapt-a-thon

Texas Hold 'em Invitational

Promote a more open dialog about the theory and implementation of commercially available tools for adaptive radiotherapy.

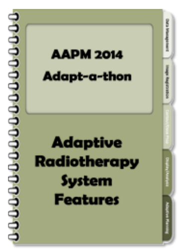
Develop a set of RFP-like questions to help guide this dialog.

It is important for the physicist to understand the assumptions and limits of these tools!

The Goals

Adapt-a-thon

Texas Hold 'em Invitational



- Data Management
- Image Registration
- Contours and Dose
- Display and Analysis
- Adaptive Planning

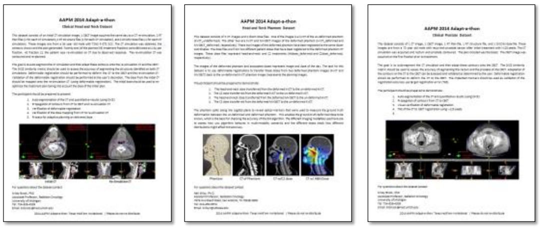
Adapt-a-thon

Texas Hold 'em Invitational

Data Management	Image Registration	Contours and Dose	Display and Analysis	Adaptive Planning
DICOM Import	Rigid Registration	Manual Contouring	Evaluate Transform	Dose on any Dataset
DICOM Export	Deformable Registration	Automated Contouring	Display ROI changes	Planning on any dataset
"Unlimited" Datasets	Multimodality Data	Contour Propagation	Display Dose / DVH changes	Optimize over other dose
Manage 4-D Data	Limited FOV	Dose Mapping	Display Image Differences	Response Assessment
Manage 5-D Data	Constraints and Penalities	Dose Accumulation	4D / 5D Display	Decision Support
Manage Approvals	Calculate "Inverse"	Biological Dose Summing	Quantitative Metrics	Workflow Automation
Remote Access	Missing / New "Objects"	Dose Metrics	Reporting Tools	Integration w/ Delivery

Adapt-a-thon

Three *common* cases for demonstrations!



Head & Neck Clinical data | **Head & Neck** Phantom data | **Prostate** Clinical data

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


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

Immediately after this session, in this Room (TU-B-19A-1)