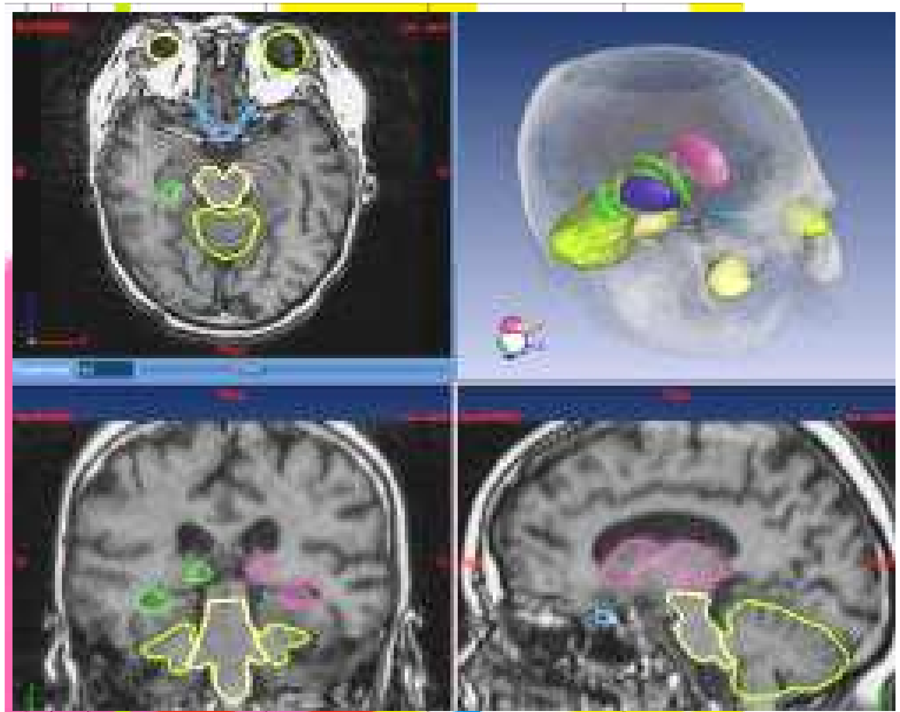


# Design and Use of Anatomical Atlases for Radiotherapy

**Olivier COMMOWICK**

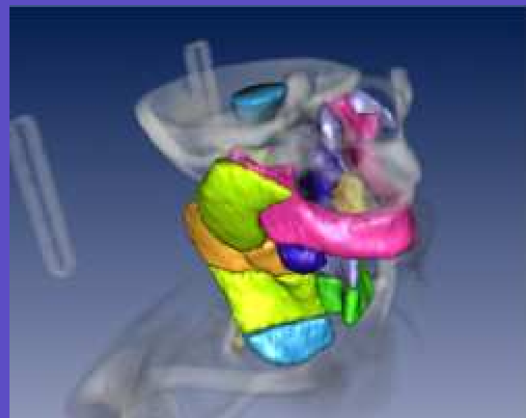
February 14, 2007

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

INRIA SOPHIA ANTIPOLIS

**Jury:**

- Patrick Clarysse (reviewer) – CNRS
- Grégoire Malandain (advisor) – INRIA
- Nicholas Ayache – INRIA
- Pierre-Yves Bondiau – Centre Antoine Lacassagne
- Guido Gerig – University of North Carolina
- Vincent Grégoire – Université Catholique de Louvain
- Hanna Kafrouni (invited) – DOSIsoft S.A



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# Road Map

- Introduction
- Incorporating Priors in Non Linear Registration
- Atlas-Based Brain Segmentation
- Head and Neck Atlas-Based Segmentation
- Conclusion and Perspectives

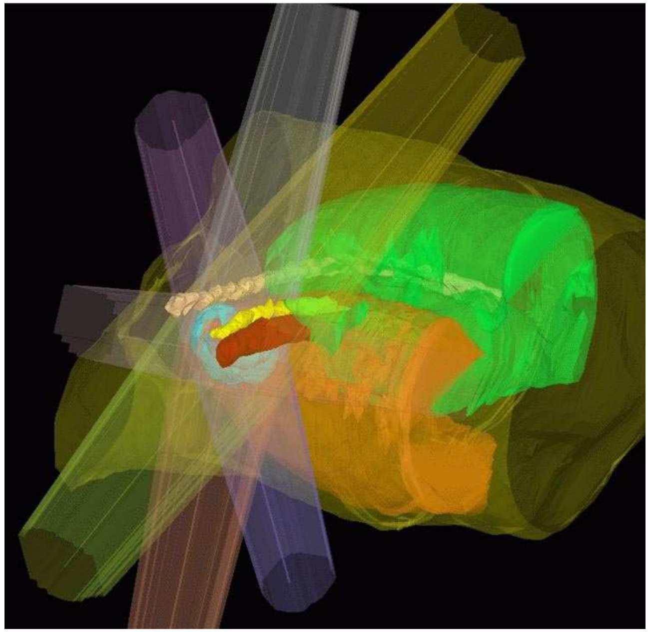
# Medical Context

- Different cancer treatments
  - Chemotherapy
    - Drugs killing cells in division
  - Surgery
    - Remove physically the tumor
  - Radiotherapy
    - High irradiation killing cells in division

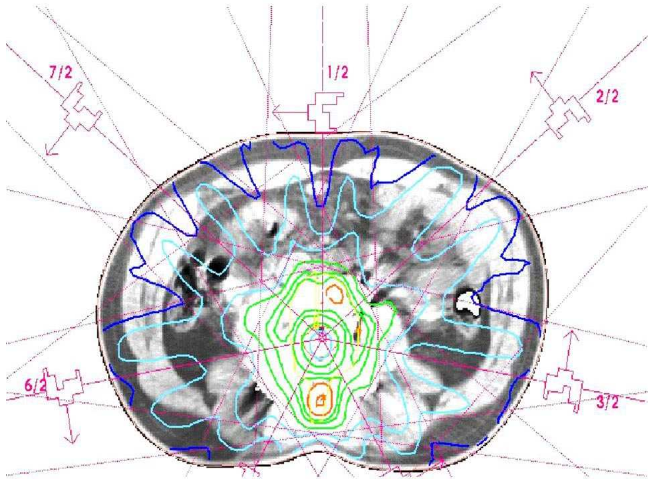
- Treatment of tumors on two regions
  - Brain
  - Head and Neck

# Radiotherapy

- Radiotherapy principle:
  - Use of high energy irradiation beams
  - Optimize dose on the tumor
  - Control irradiation of critical structures (OAR)



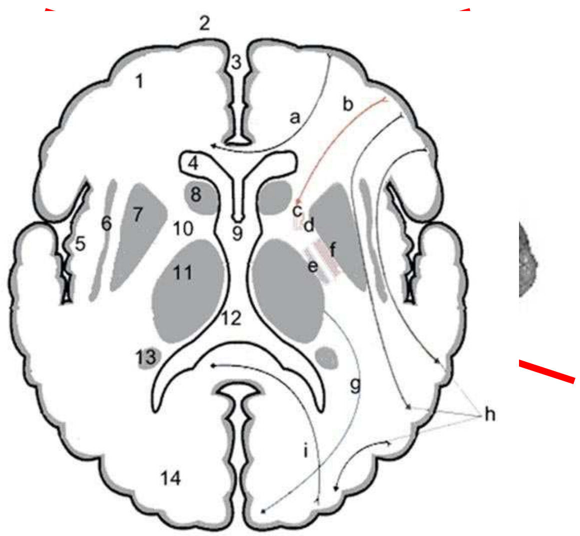
➔ Need for high precision planning
  - Irradiation doses computed on each organ
  - Compare doses with expected levels
  - Requires delineation of structures

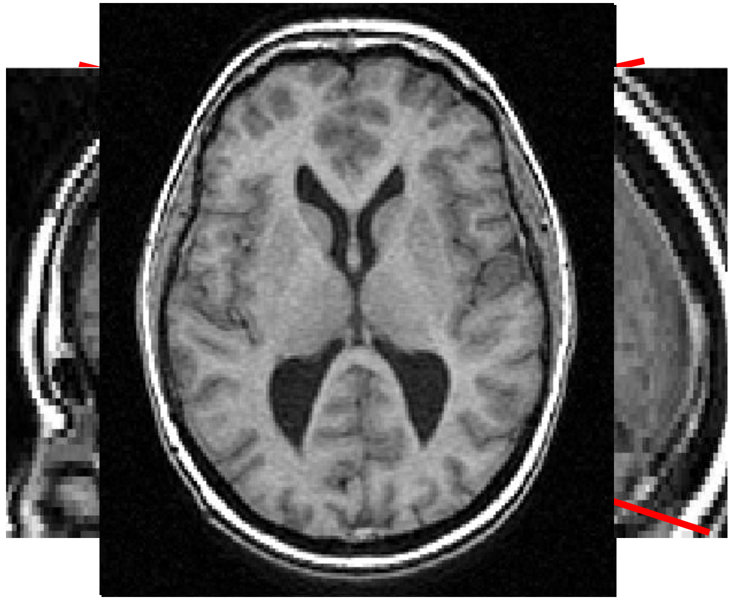


# Brain Anatomy

- Many organs at risk
  - Eyes, optic nerves, chiasma
  - Brainstem, cerebellum
  - Grey nuclei

- Different categories [Pontvert, 2004]
  - Very high risk (eyes)
  - High risk (optic nerves, brainstem)
  - Medium risk (grey nuclei)



**[Pontvert, 2004]: Radiothérapie des tumeurs cérébrales. 2004.**

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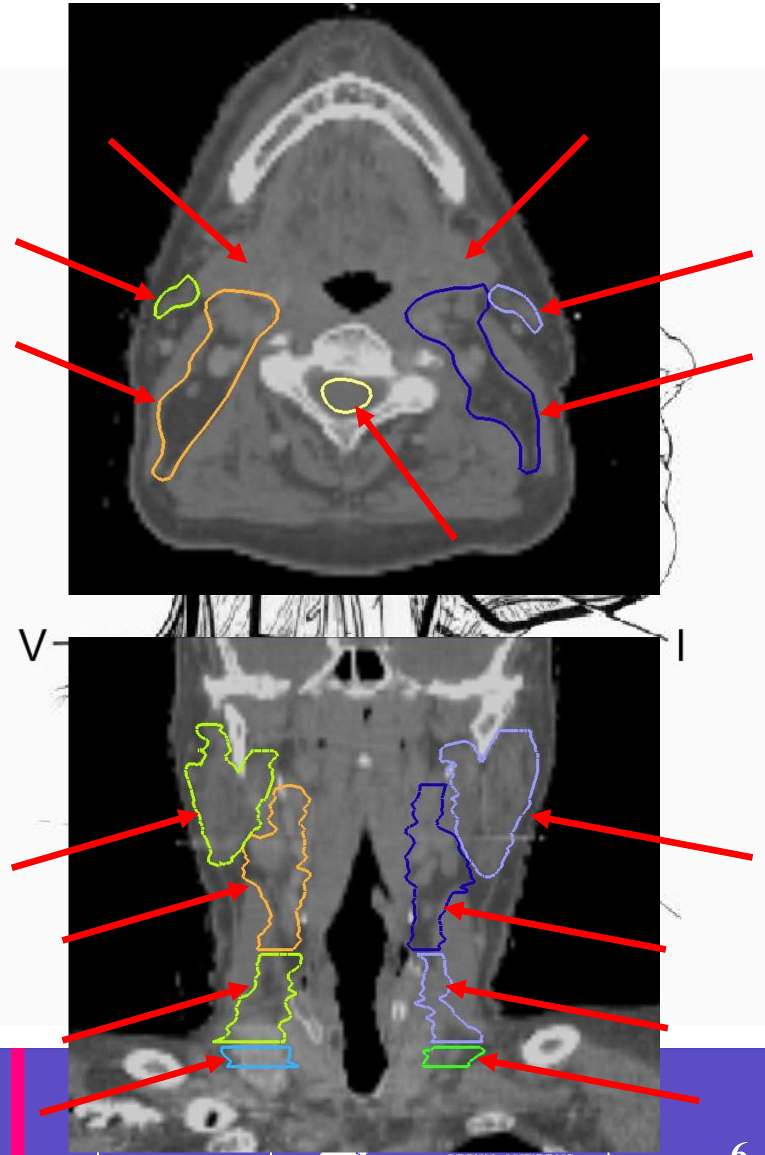
# Head and Neck Anatomy

- Structures of interest
  - Lymph nodes areas
    - Separated using visible landmarks
    - Tumor dissemination regions
  - Parotids
  - Spinal cord
  - Sub-mandibular glands




**[Grégoire et al., 2003] CT-based delineation of lymph node levels and related CTVs in the node-negative neck : DAHANCA, EORTC, GORTEC, NCIC, RTOG consensus guidelines. Radiotherapy Oncology, 2003.**

# Radiotherapy planning

- Requires an accurate delineation
  - Head and Neck radiotherapy
    - Only CT image acquired, necessary for dosimetry
  - Brain radiotherapy
    - MRI exam often added
    - Better differentiation of soft tissues

- Segmentation done manually
  - Time consuming (2 to 4 hours)
  - Not reproducible

- Objective: provide fast and automatic segmentation tools

# Automatic Segmentation for Radiotherapy

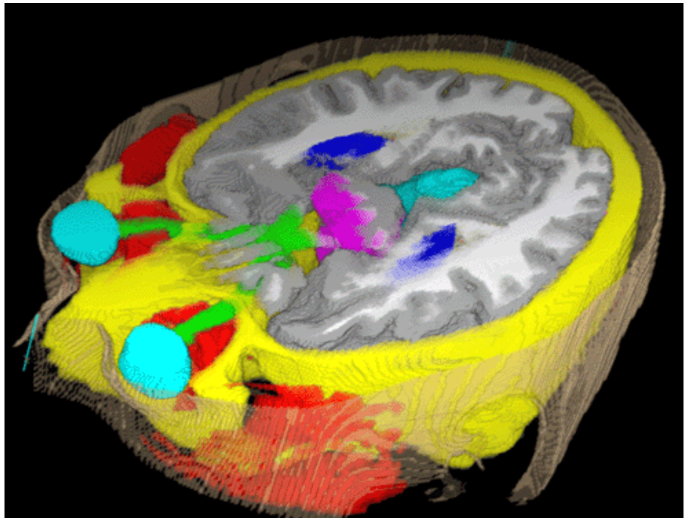
- Goal: automatic segmentation of organs at risk

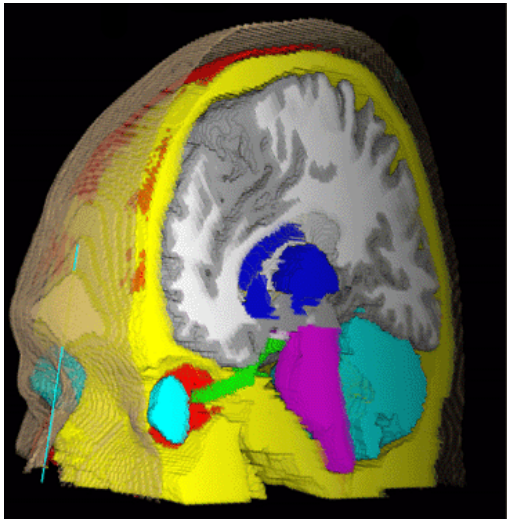
- Available segmentation methods
  - Intensity based (adaptive thresholding, EM)
    - No prior on shape or position
  - Deformable models, level-sets, active contours
    - Possible priors on structures
  - Atlas based segmentation
    - Atlas: image and its segmentation
    - A priori on respective positions and shapes

Increasing prior knowledge

# Atlas Construction

- First approach:
  - One image delineated by an expert
    - Brain atlas (from Dr. Pierre-Yves Bondiau [Bondiau, PhD, 2004])
    - must be representative (possible bias)

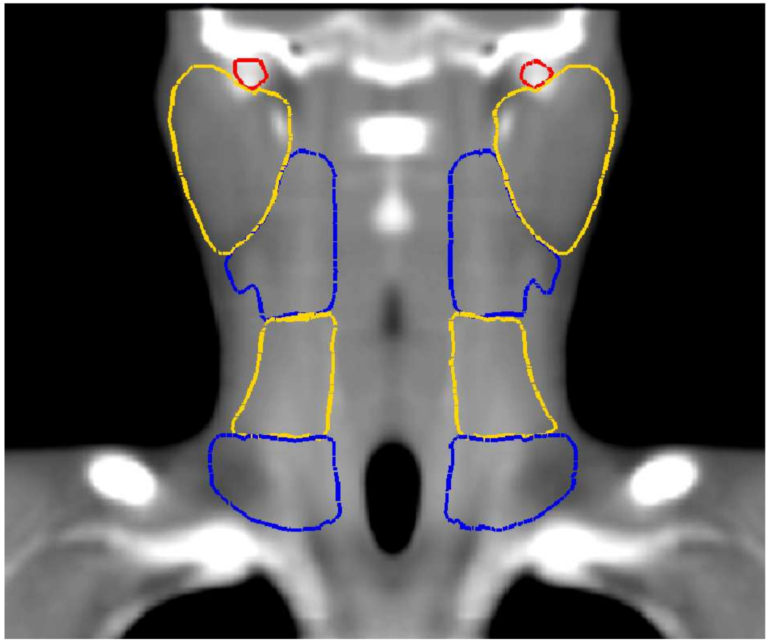


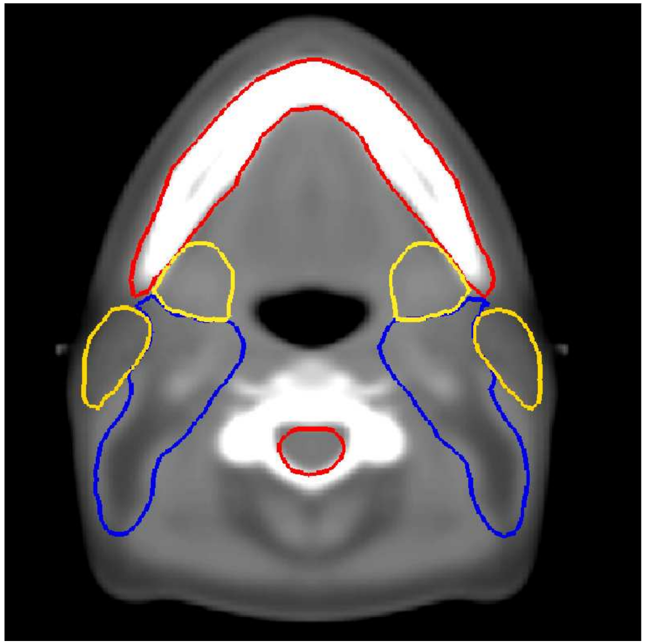


[Bondiau, PhD, 2004]: Mise en oeuvre et évaluation d'outils de fusion d'image en radiothérapie. November 2004.

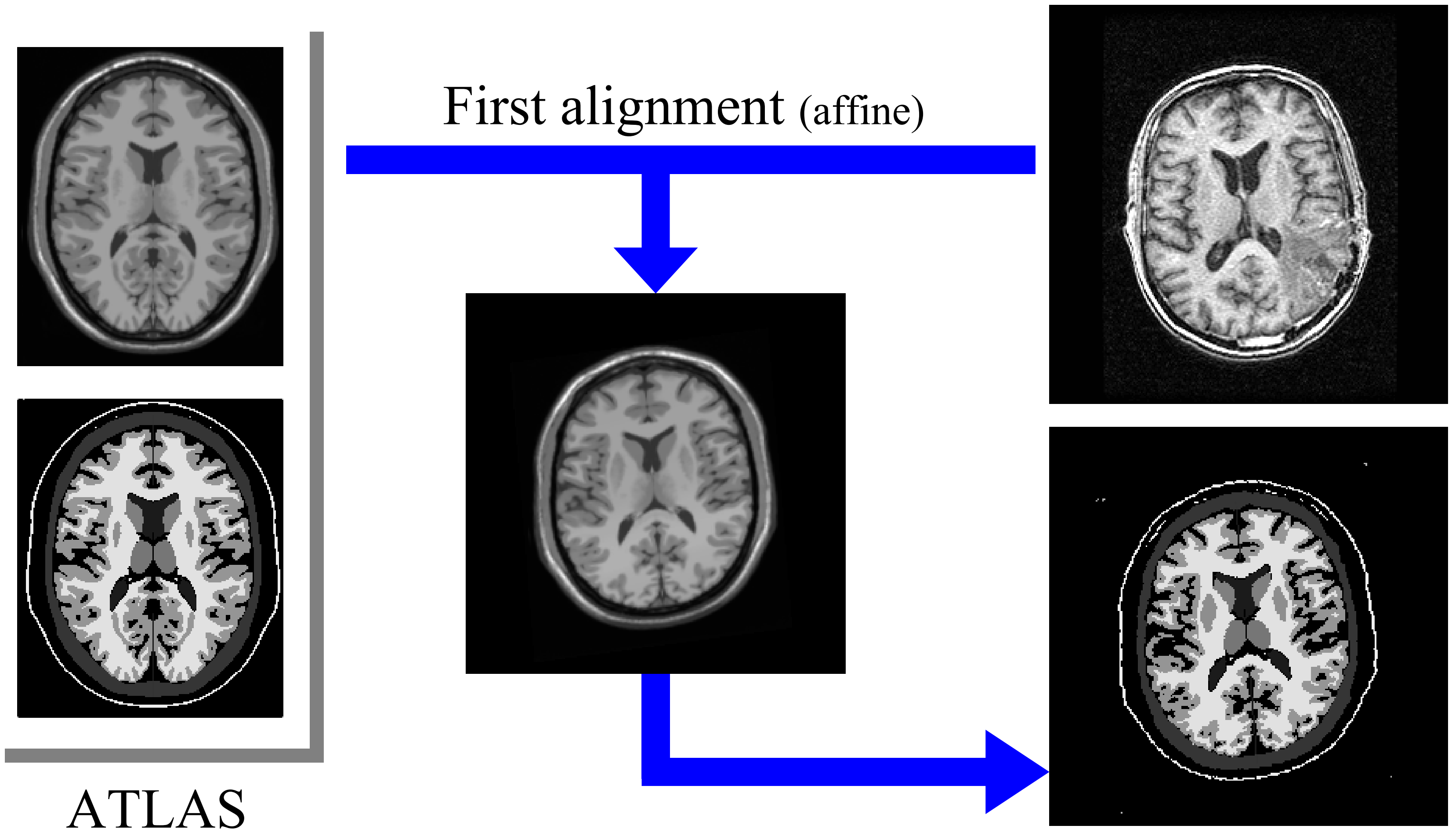
# Atlas Construction

- Second approach:
  - Average image from a dataset of images
  - Head and neck atlas
    - Images from Pr. Vincent Grégoire (UCL)

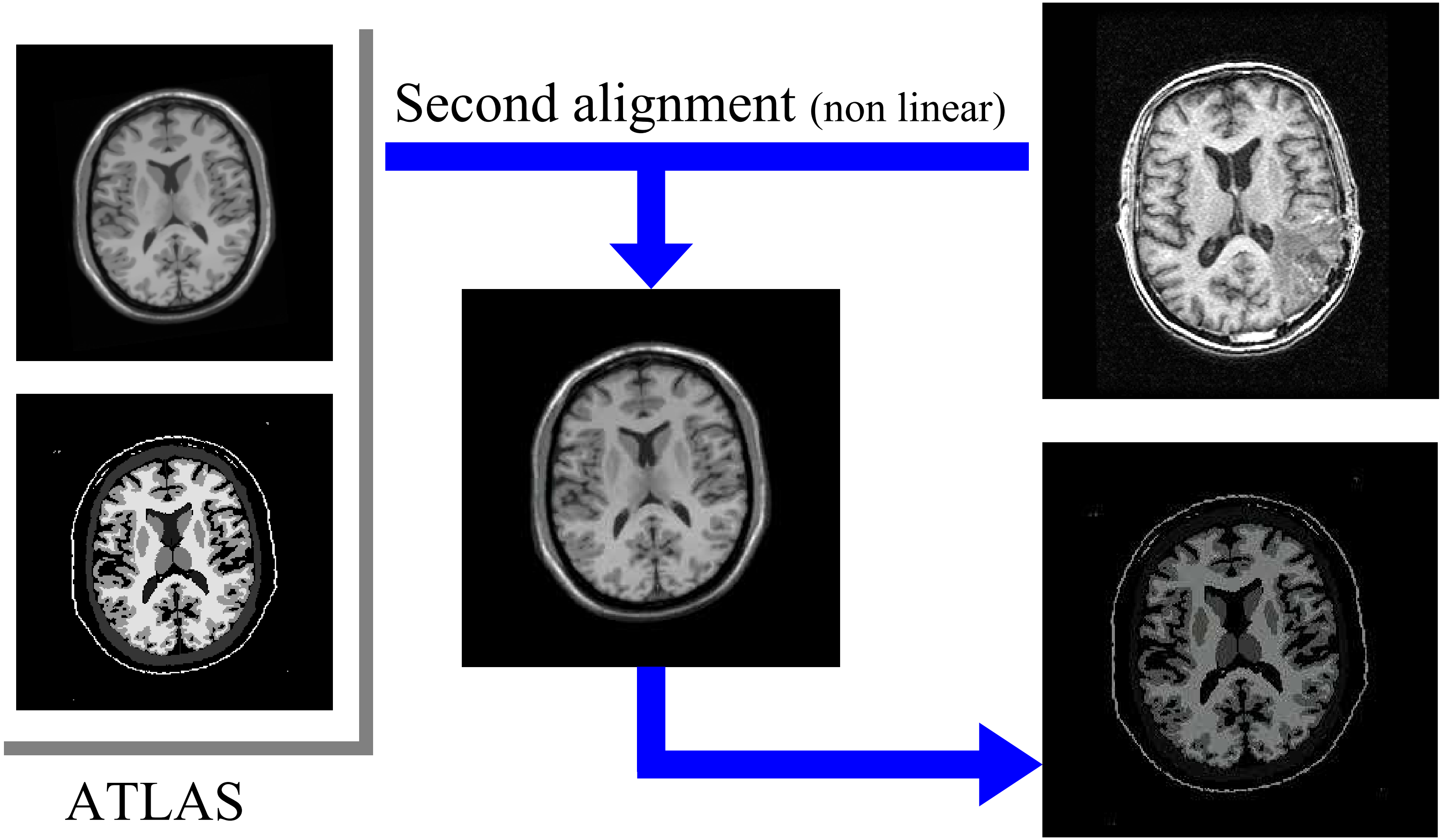




# Atlas-based Segmentation Principle



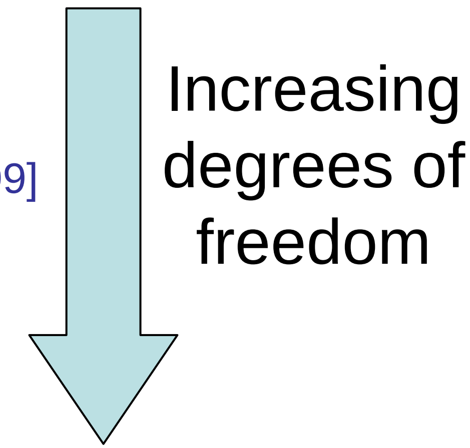
# Atlas-based Segmentation Principle



# Non linear transformations

- Tradeoff in non linear registration
  - Able to handle atlas/subject variability
  - Robust and smooth

- Transformations:
  - Parametric
    - Interpolated between control points
    - Arbitrary number of degrees of freedom
    - RBF [Rohde et al., 2003], FFD [Rueckert et al., 1999]
  - Dense
    - One displacement vector per voxel
    - Maximal number of degrees of freedom
    - Pasha [Cachier et al, 2003], …




[Rohde et al., 2003] The adaptive bases algorithm for intensity based nonrigid image registration.. IEEE TMI, 2003.

[Rueckert et al., 1999] Non Rigid Registration Using Free-Form Deformations: Application to Breast MR Images. TMI, 1999.

[Cachier et al., 2003] Iconic Feature Based Nonrigid Registration : The PASHA Algorithm. CVIU, 2003.

# Challenges in Atlas-Based Segmentation

- Goal: Automatic segmentation of critical structures for radiotherapy

- Requirements:
  - Minimal interaction from user
  - Robust to different acquisition protocols
  - Realistic contours in a minimal time

- Key point of the approach: non linear registration
  - Smooth transformation
  - Able to handle atlas/subject variability
  - Robust registration method
  - Method as fast as possible

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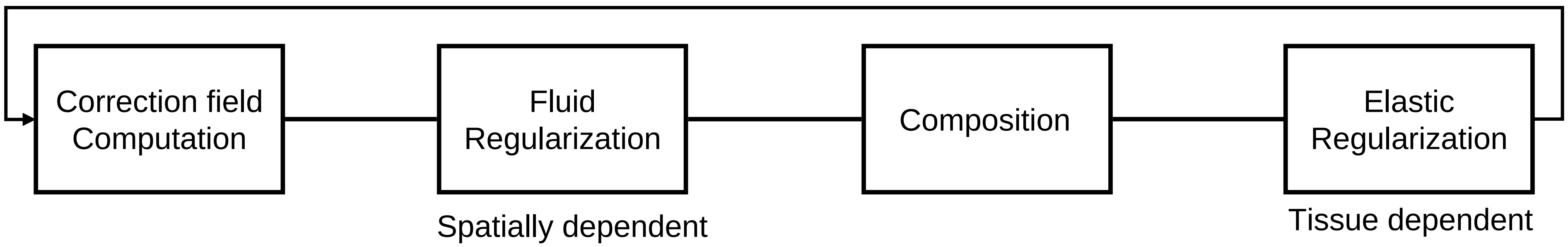
# Existing Dense Non Linear Registration

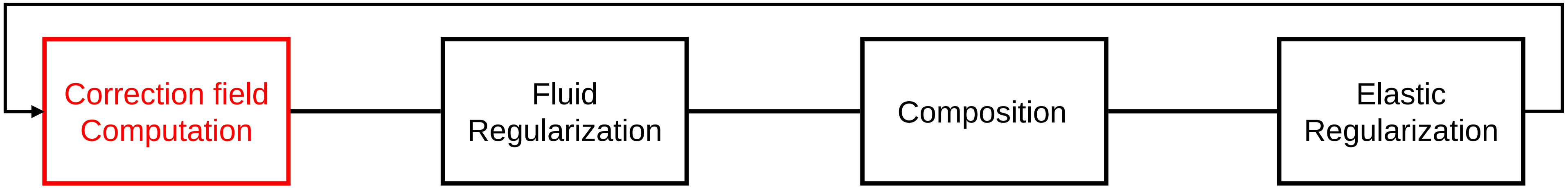
- Method of [Stefanescu et al., 2004]: Runa
    - Spatially inhomogeneous regularization
    - Fluid regularization on highly variable regions
    - More elastic regularization elsewhere

- Iterative process




**[Stefanescu et al., 2004]: Grid Powered Nonlinear Image Registration with Locally Adaptive Regularization, MedIA, 2004.**

# Runa: Correction Field Computation

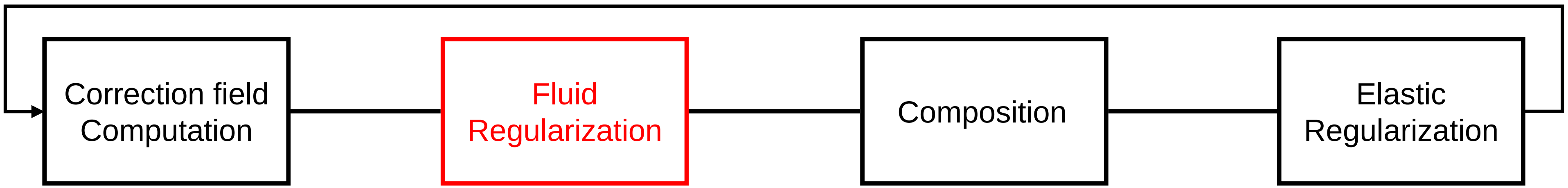



- Computation of correction $\delta T$
  - Gradient descent on a similarity measure:

$$\delta T = \nabla SSD(R, F \circ T^{l-1}) = (R - F \circ T^{l-1}).\nabla(F \circ T^{l-1})$$

  - SSD: Sum of Squared Differences
  - R : reference image
  - F : floating image
  - $T^{l-1}$ : transformation obtained at iteration $l-1$

# Runa: Fluid Regularization

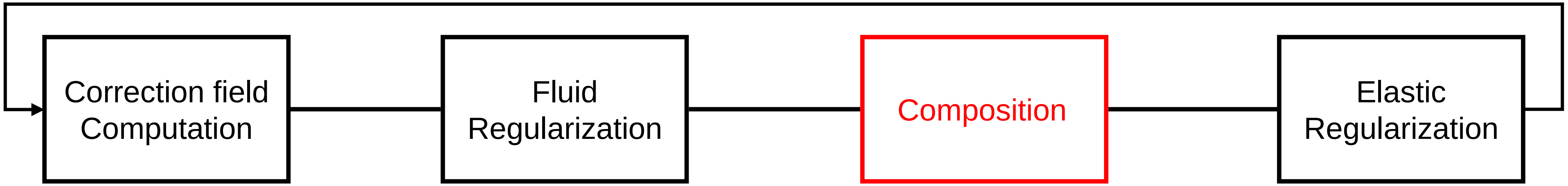



- Regularization of correction field

$$\frac{\partial \delta T}{\partial t}(x) = (1 - k(x))\Delta \delta T(x)$$

- Weighted by a factor $k(x) = f_1(\|\nabla R\|)$
  - Spatially dependent
  - Less confidence (more regularization) in homogeneous regions

# Runa: Composition of Correction

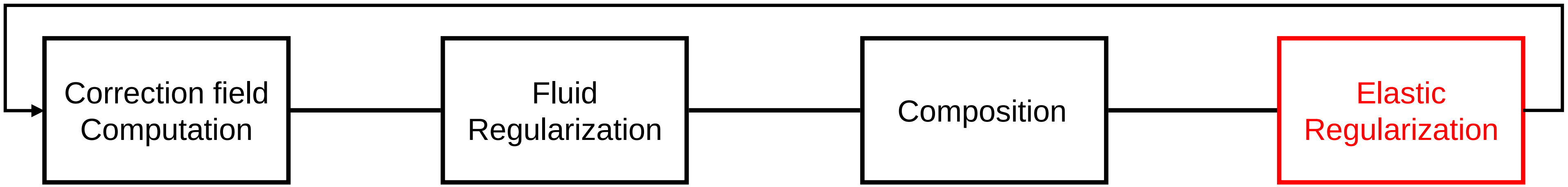



- Regularized correction field: $\delta\widetilde{T}$

- Composition with transformation at iteration $l-1$

$$T^{l} \leftarrow T^{l-1} \circ \delta\widetilde{T}$$

# Runa: Elastic Regularization

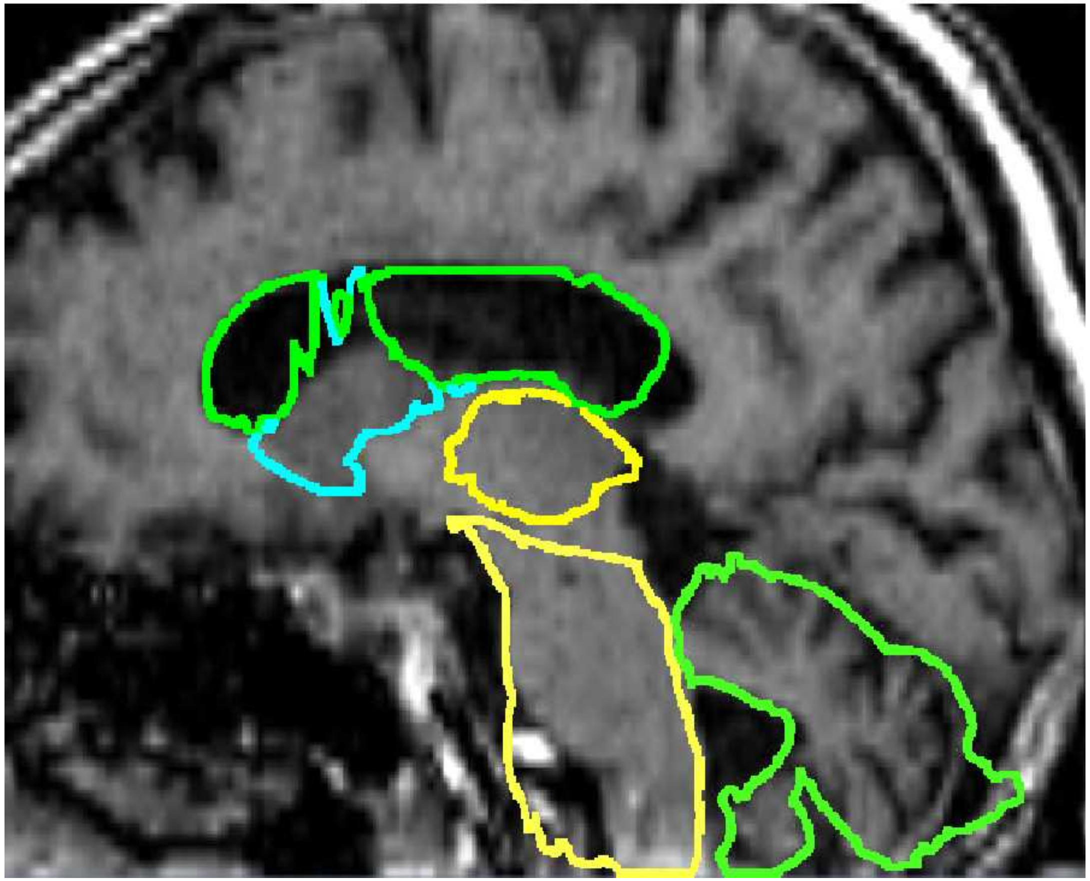


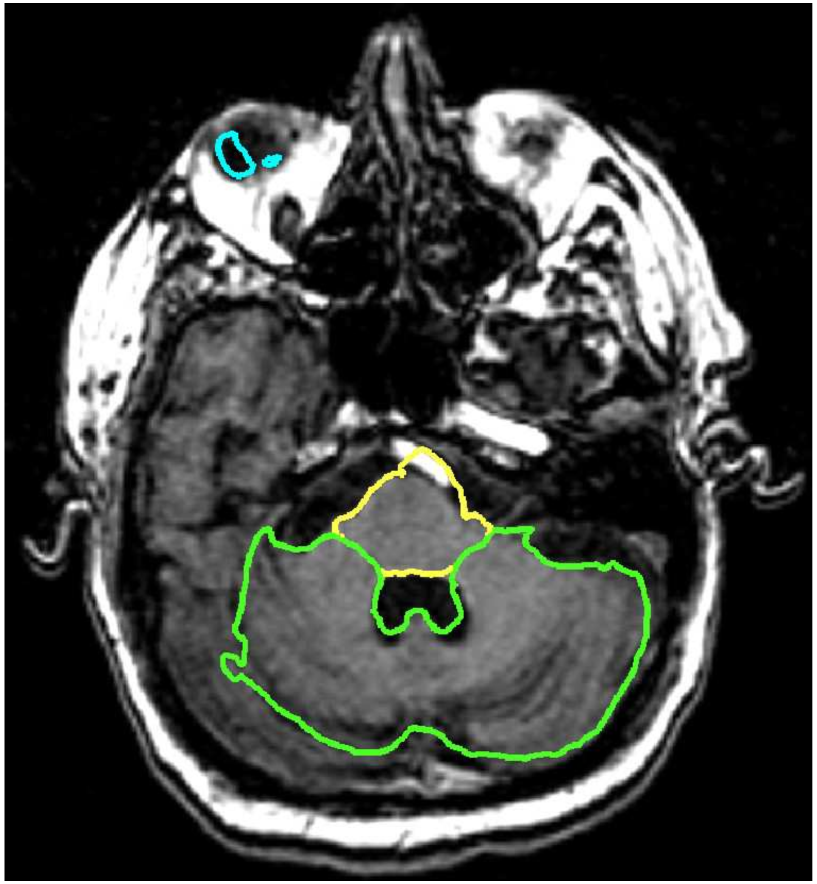

- Regularization of the transformation

$$\frac{\partial T^l}{\partial t} = \nabla.(D(x)\nabla T^l)$$

- Weighted by $D(x) = f_2(i(x))$
  - Scalar, tissue dependent $i(x)$ , heuristic model
  - White and grey matter: high regularization
  - CSF: low regularization

# Segmentation Result (Runa)





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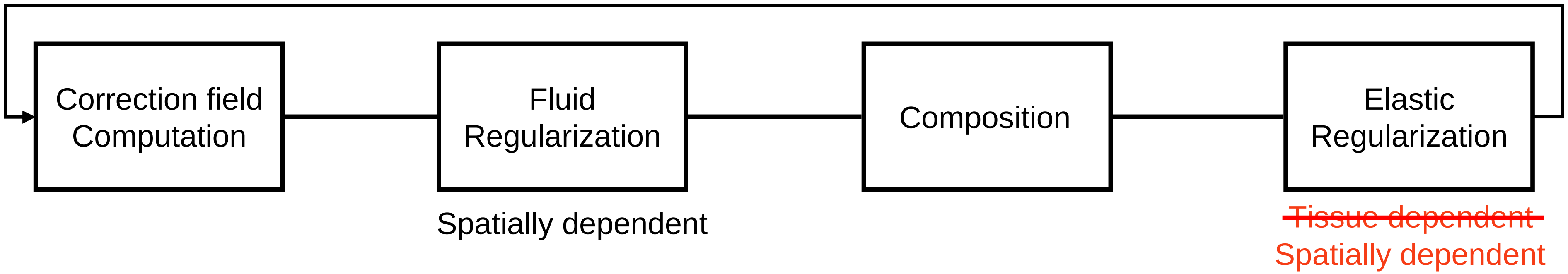
# Summary

- Advantages
  - Precise deformations
  - Inhomogeneous regularization

- Drawbacks
  - Noisy contours (not realistic)
  - Registration parameters
    - Need to be set for each patient
    - Need to be set for each acquisition protocol

- Solution



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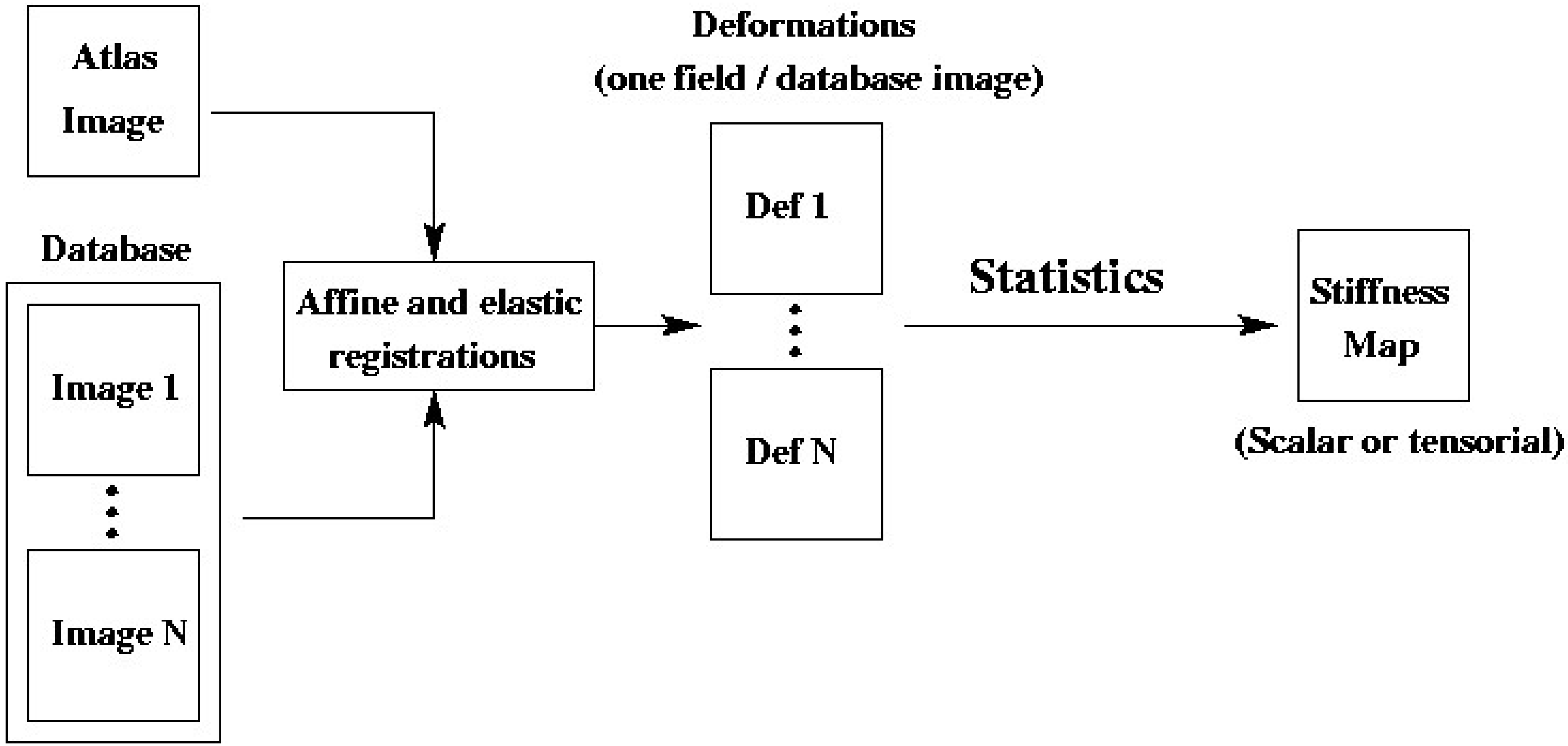
# Statistics Computation Pipeline




**[Rueckert et al., 2003]: Automatic Construction of 3D Statistical Deformation Models of the Brain using Non Rigid Registration. IEEE TMI, 2003.**

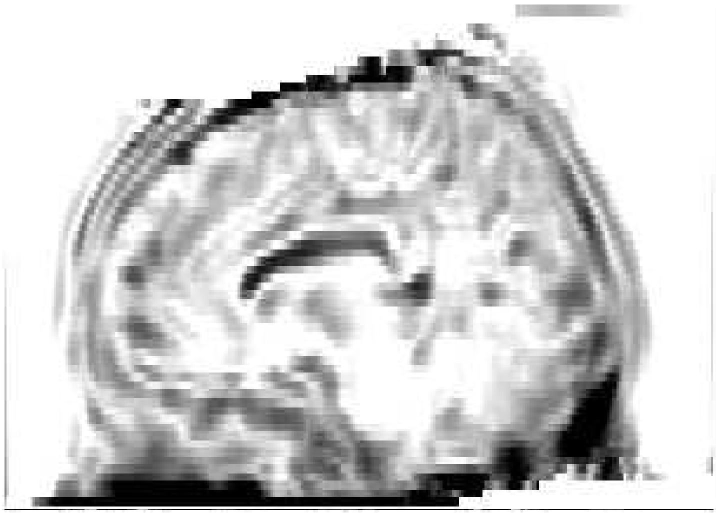
# Scalar Mean Deformability

- Isotropic measure of deformability

- Determinant of the Jacobian matrix $|J_i(x)|$
  - $|J_i(x)| > 1$ : local dilation
  - $|J_i(x)| < 1$ : local contraction

- Mean deformability:

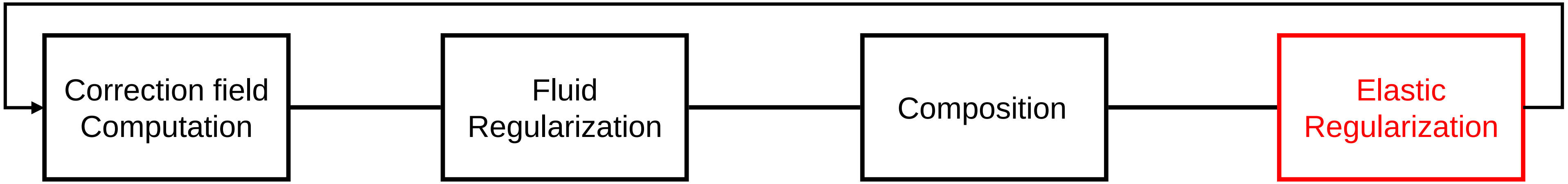
$$\overline{Def}(x) = \frac{1}{N} \sum_i \mathrm{abs}(\log(|J_i(x)|))$$



Heuristic Scalar Stiffness Map

Mean Scalar Stiffness Map

# Incorporating Statistics in Regularization



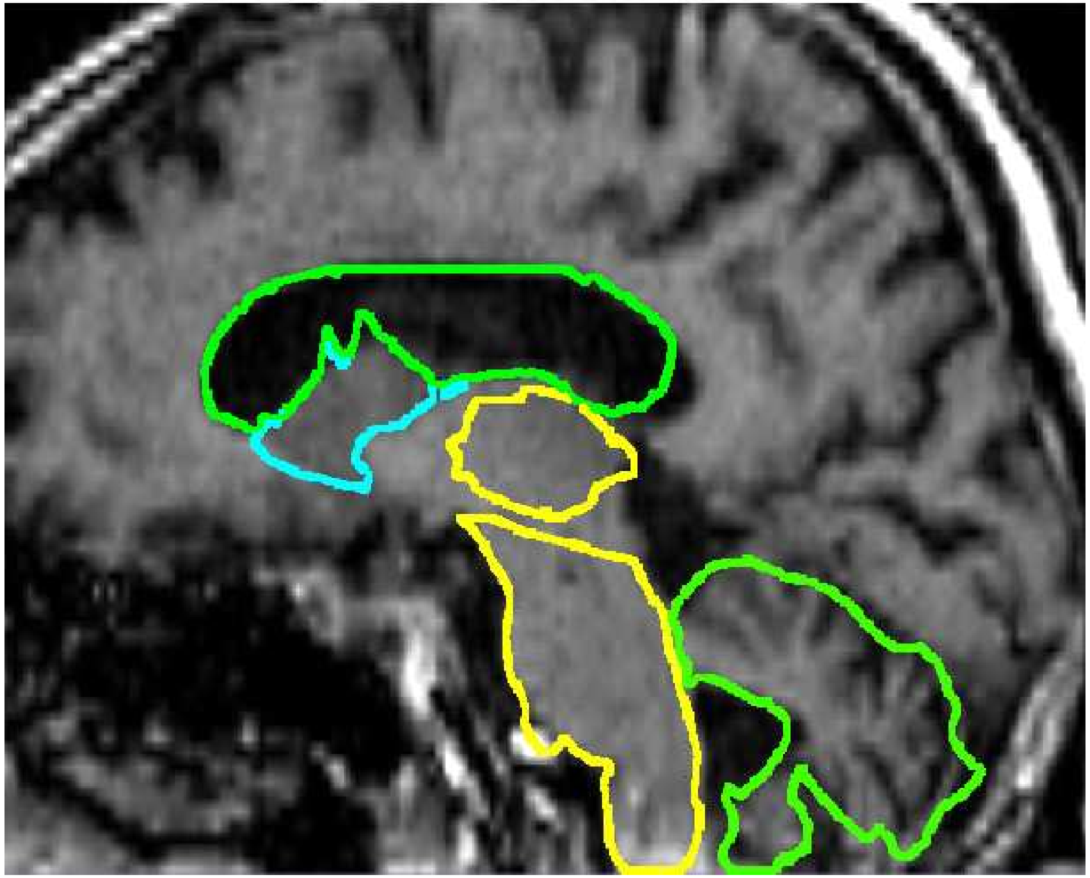

$$\frac{\partial T^l}{\partial t} = \nabla.(D(x)\nabla T^l)$$

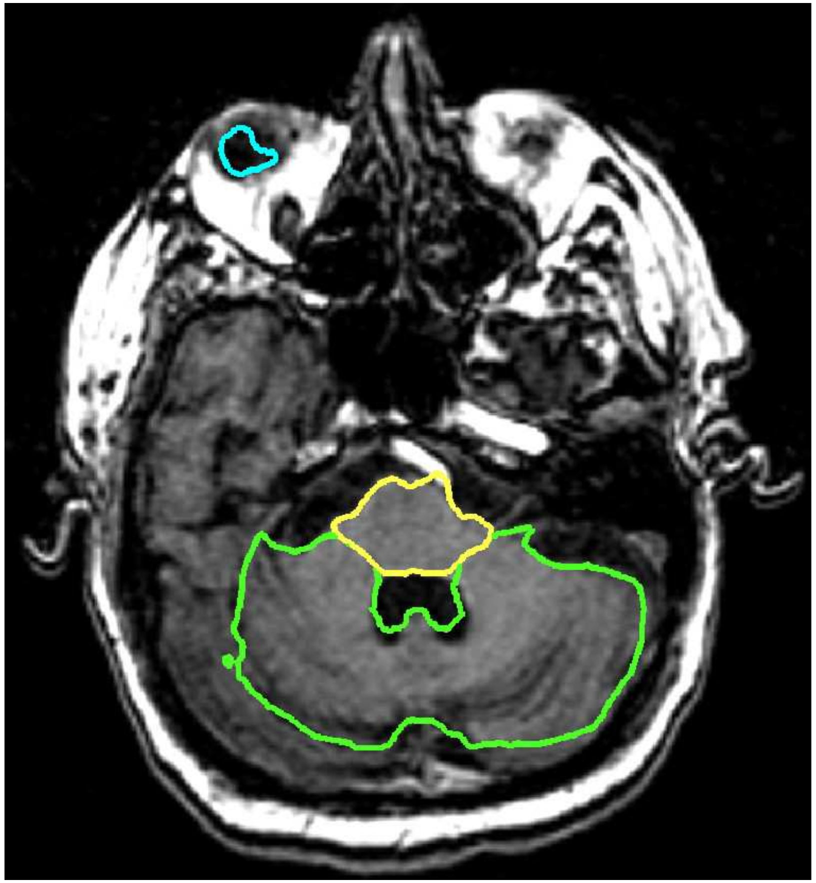
- Inverse mean scalar deformability measure

$$D(x) = \left(1 + \lambda \overline{Def}(x)\right)^{-1}$$

- Values of $D(x)$
  - Between 0 and 1
  - Close to 1: High regularization
  - Close to 0: Low regularization

# Segmentation Result (Runa, Scalar Statistics)





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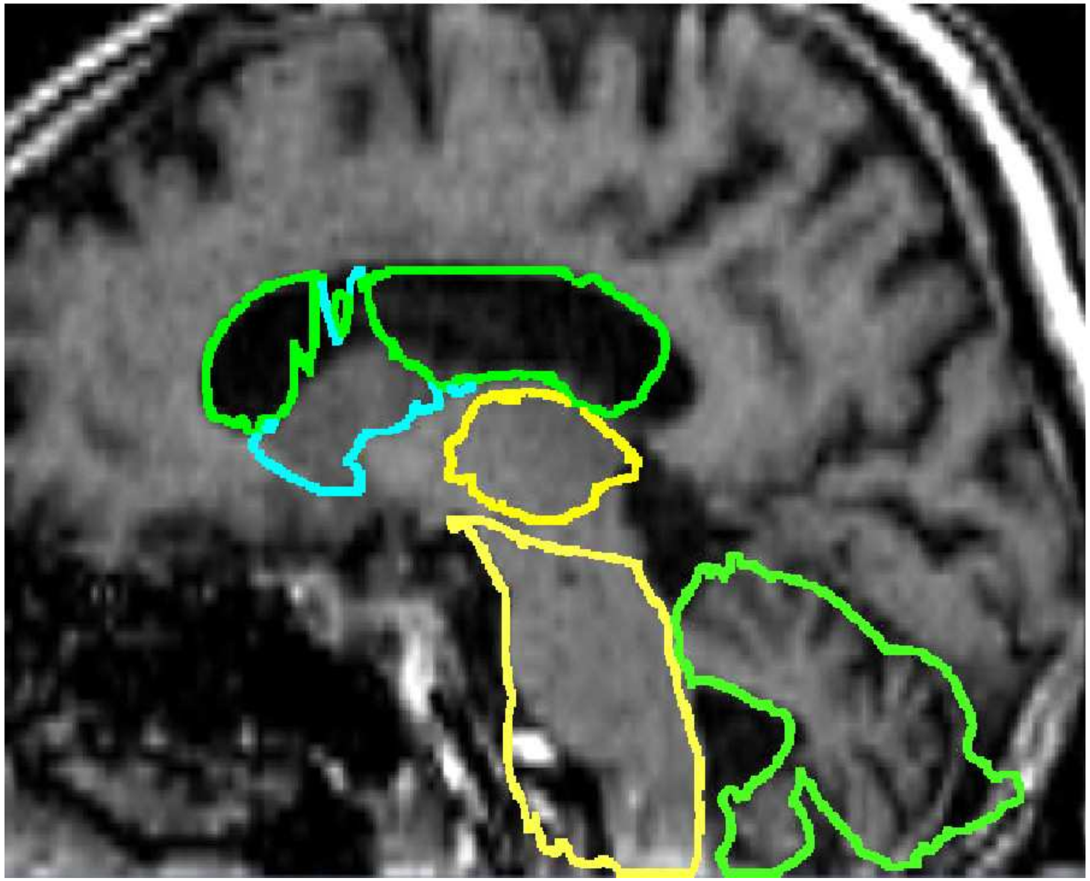
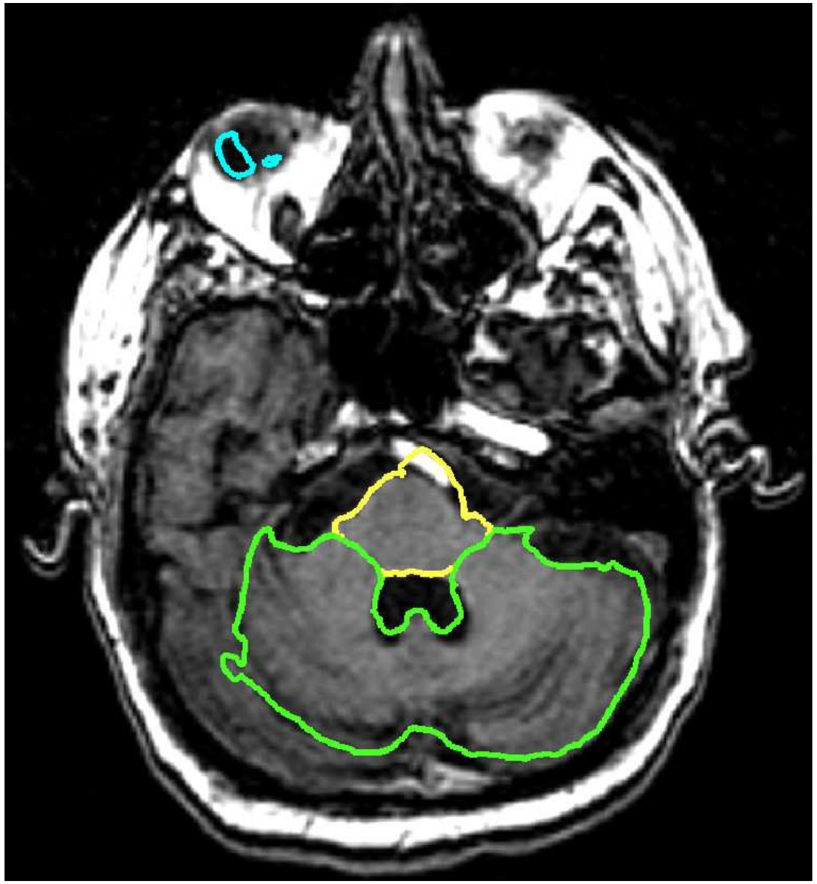




# Tensor-based Mean Deformability

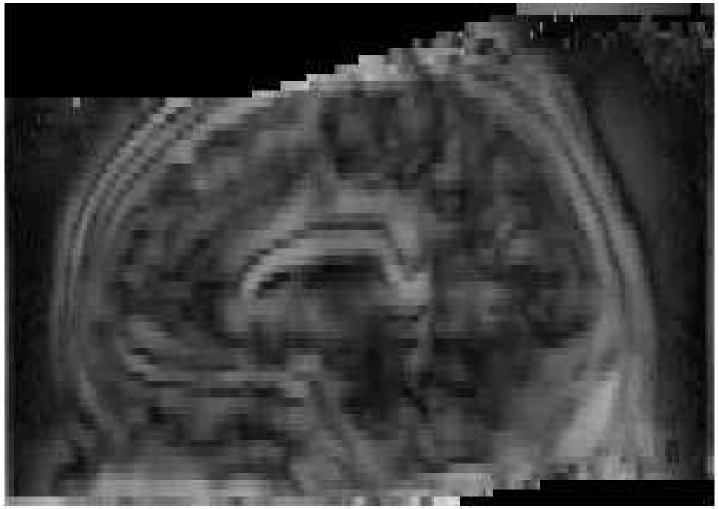
- Based on tensor derived from the Jacobian matrix

$$W_i(x) = J_i^T(x).J_i(x)$$

- Mean deformability

$$\overline{\Sigma}(x) = \frac{1}{N}\sum_i \text{abs}(\log(W_i(x)))$$

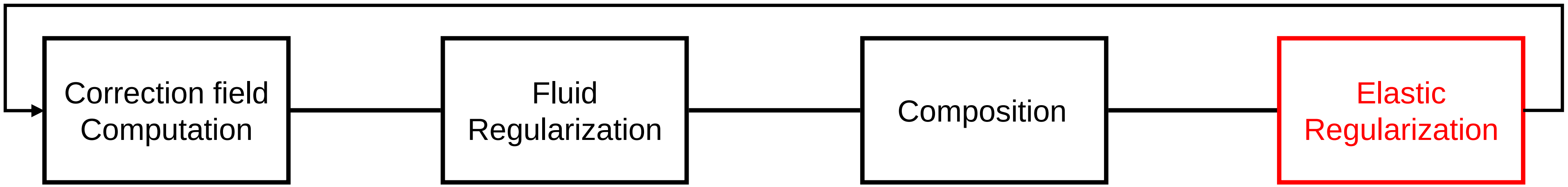
- Quantification of anisotropy in deformability



Mean Tensor-based Map

[Lepore et al., 2006]: Multivariate Statistics of the Jacobian Matrices in Tensor Based Morphometry and their Application to HIV / AIDS. MICCAI, 2006.

# Incorporating Statistics in Regularization

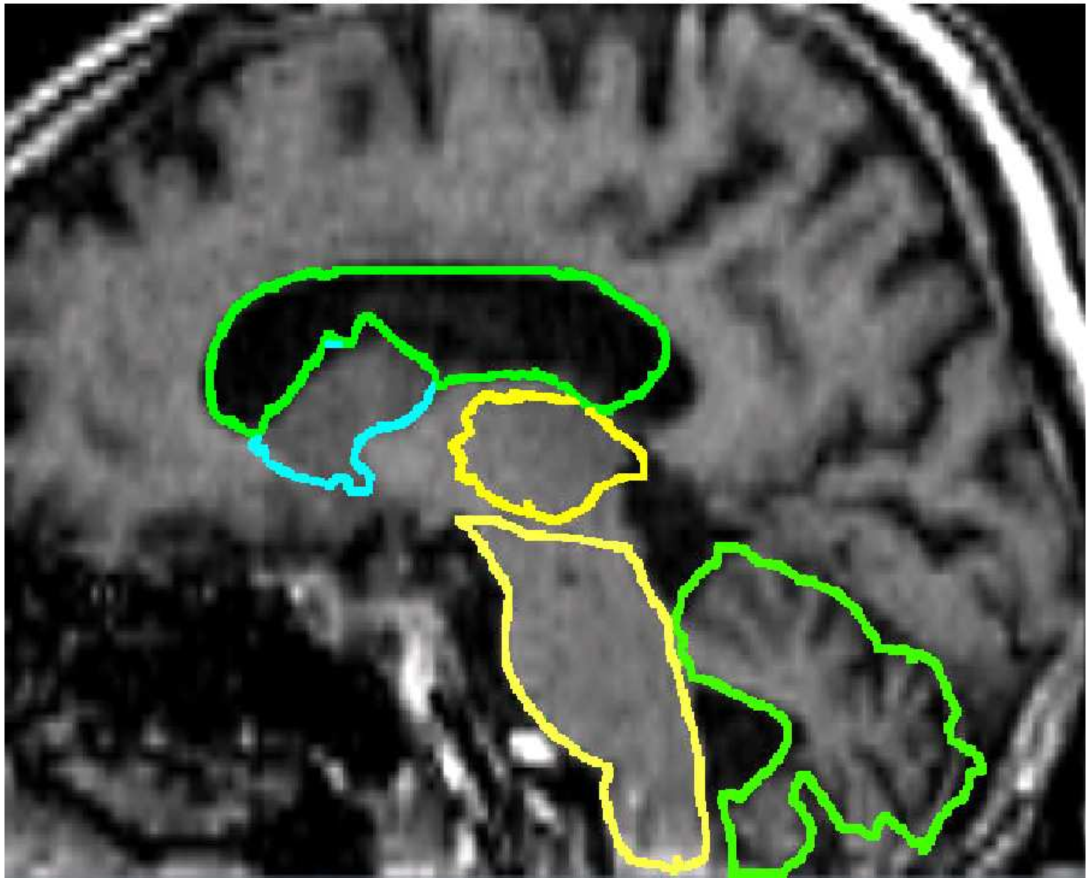


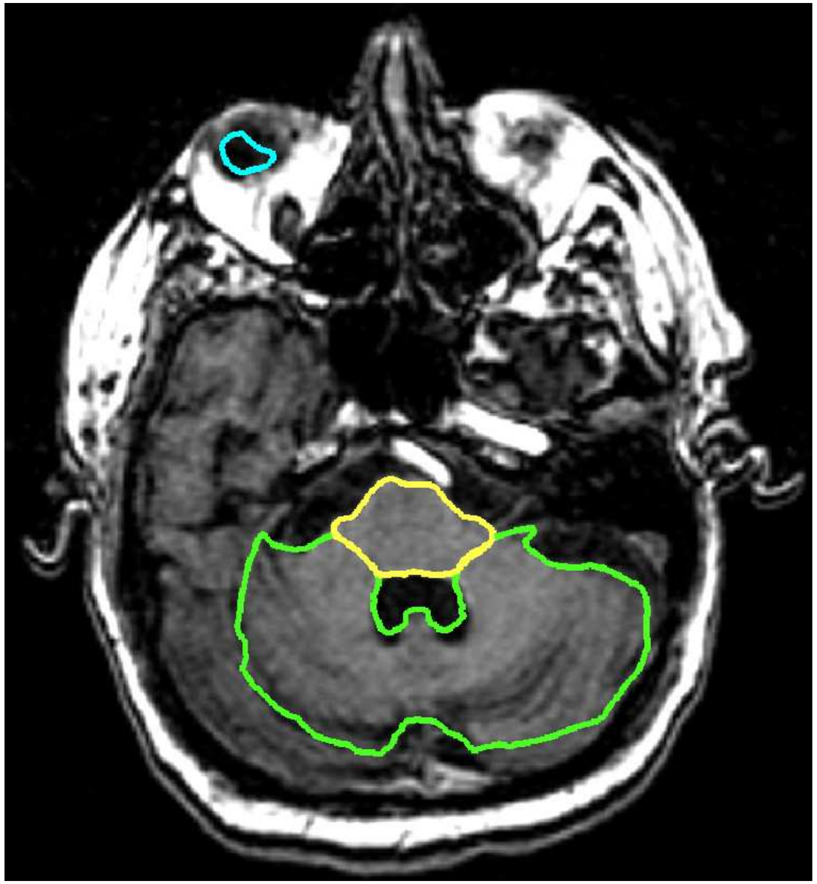

$$\frac{\partial T^l}{\partial t} = \nabla.(D(x)\nabla T^l)$$

- Inverse mean tensor-based deformability measure
  - Formula analogous to the scalar case

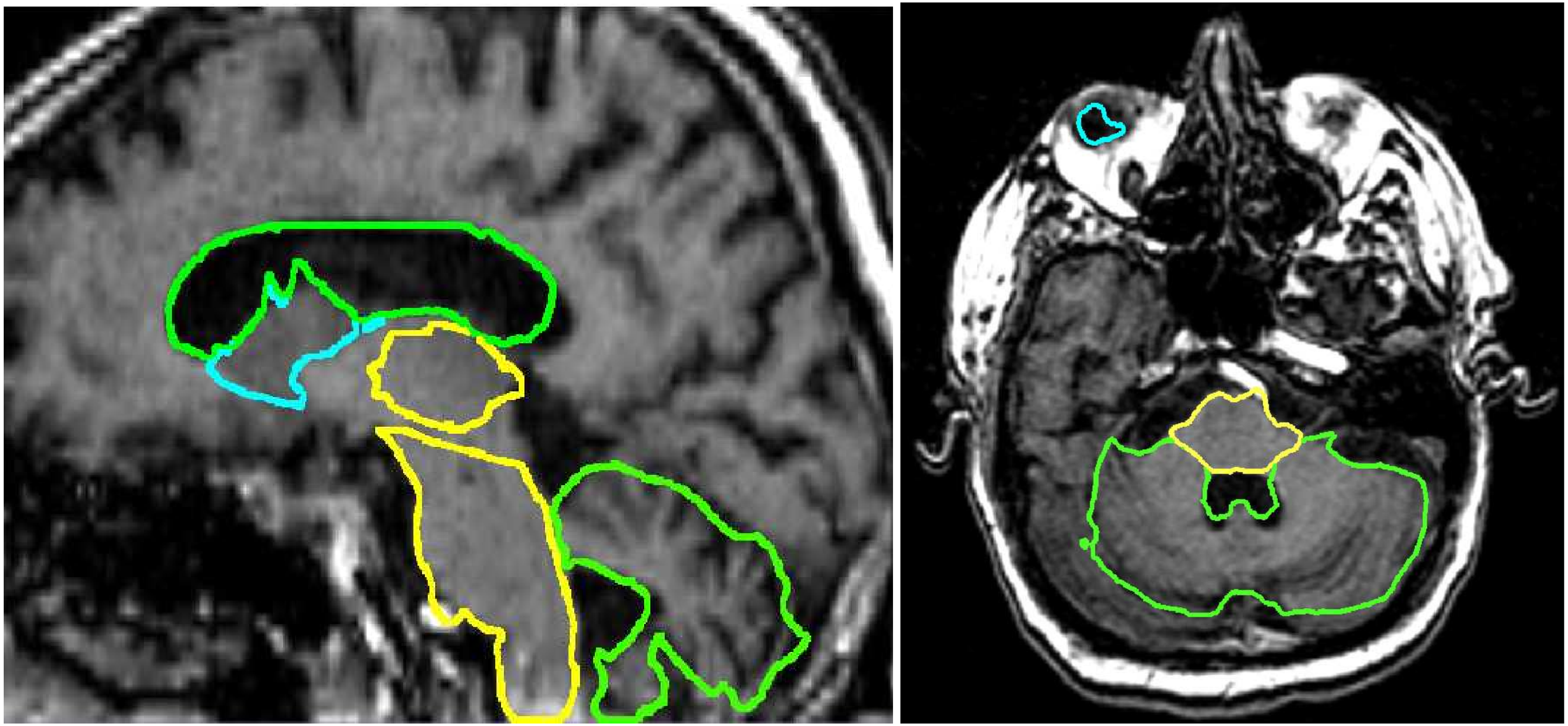
$$D(x) = (Id + \lambda \overline{\Sigma}(x))^{-1}$$

# Segmentation Result (Runa, Tensor Based Statistics)





# Segmentation Result (Runa, Scalar Statistics)



# Summary

- Introduction of deformability statistics [Commowick et al., 2005]
  - Reduced dependency to registration parameters
  - Smoother and more precise contours

- Problems:
  - Time consuming: around 40 minutes
  - Still regularity problems (eyes)
  - Parameters to set for each acquisition protocol

➔ Objective: Introduce more robustness and regularity

**[Commowick et al., 2005]: Incorporating Statistical Measures of Anatomical Variability in Atlas-to-Subject Registration for Conformal Brain Radiotherapy. MICCAI, October 2005.**

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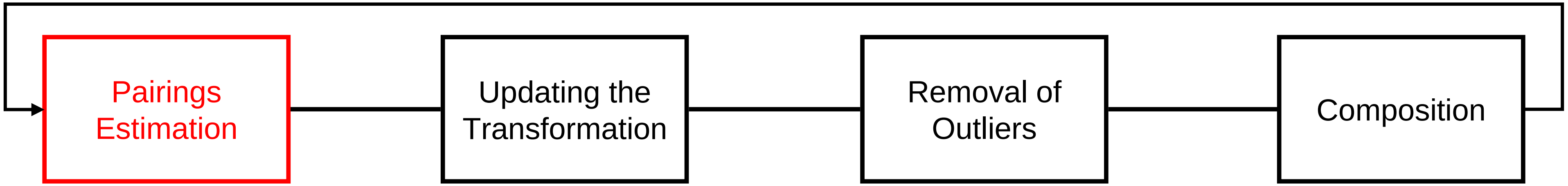
# Non Linear Registration with Outlier Rejection



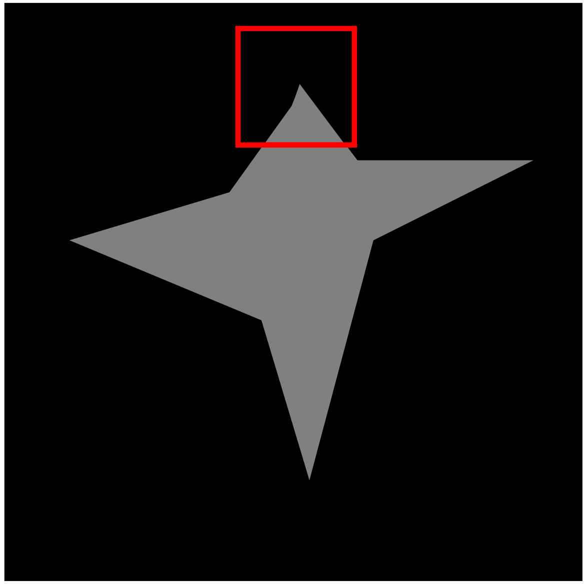

- Block-Matching method [Ourselin et al., 2000]
  - Move blocks in a neighborhood
  - Pairing: chosen according to a similarity value

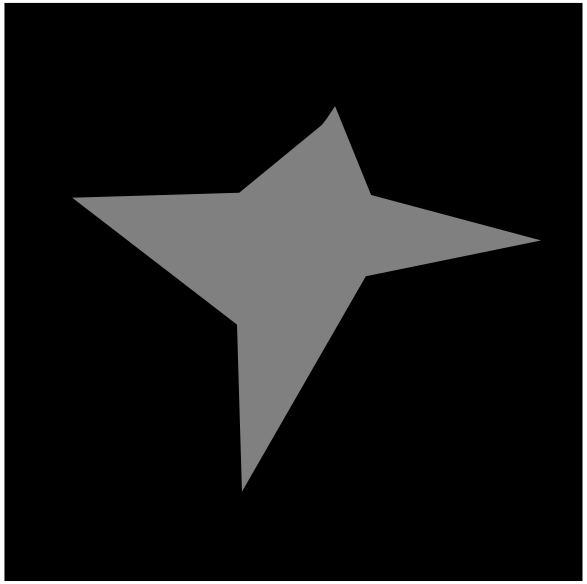
- Pairings Estimation (Block-Matching [Ourselin et al., 2000])
  - Sparse pairings field $C$
  - Associated to confidence field $k$: similarity value of each pairing

**[Ourselin et al., 2000]: A General Framework to Improve Robustness of Rigid Registration of Medical Images. MICCAI, 2000.**

# “Block Matching” Technique

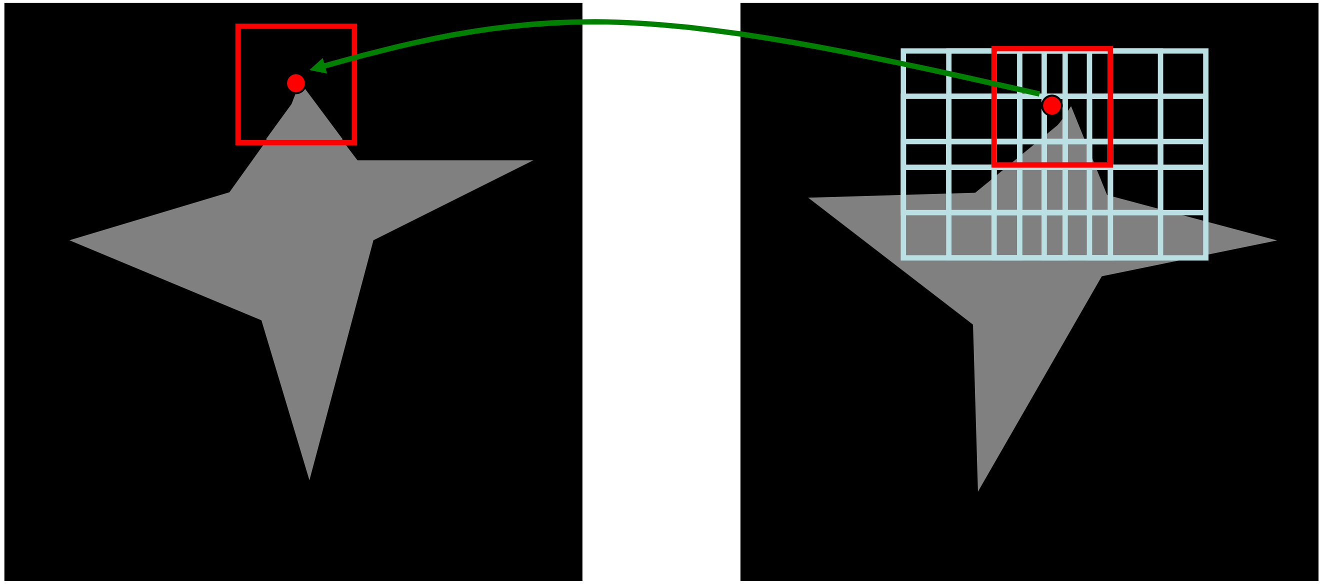
1. Consider regularly sampled sub-images (or “blocks”)





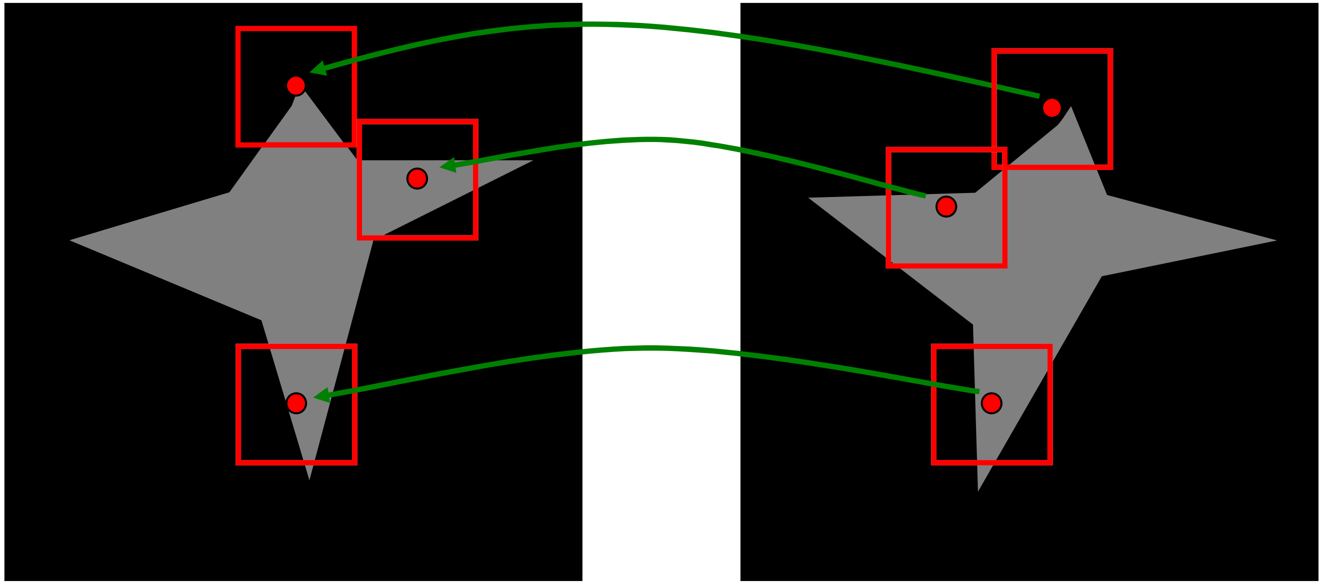
# “Block Matching” Technique

2. Search the “most similar” block: gives point to point correspondence

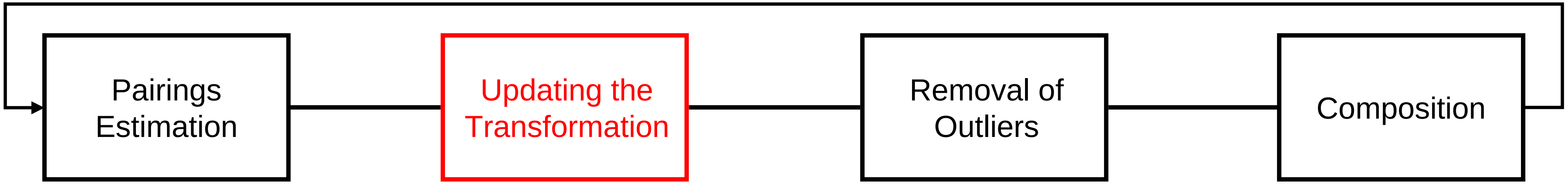


# "Block Matching" Technique

3. Obtain pairings sparse field from $(x_v, y_v), C(x_v) = y_v - x_v$



# Baloo: Updating the Transformation

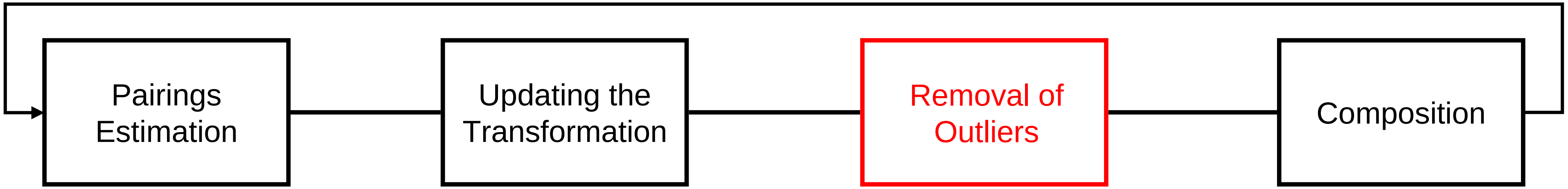



- Transformation correction $\delta T$ estimation
- Interpolated from pairings weighted by confidence field

$$\delta T = \frac{G_\sigma * kC}{G_\sigma * k}$$

- $G_\sigma$ : Gaussian kernel of variance $\sigma$

# Baloo: Removal of Outliers



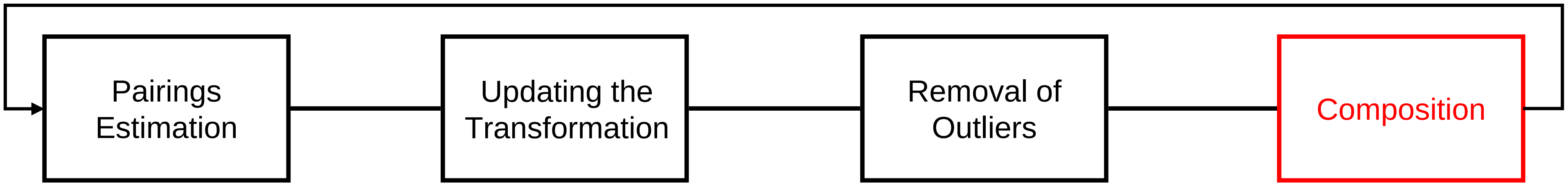

- Comparison between pairings and interpolated corrections

- Outlier criterion $\left\| C(x_v) - \delta T(x_v) \right\| > s$

- $s$ depends on mean $e$ and variance of errors $\sigma_e$

$$e = \frac{1}{N} \sum_v \left\| C(x_v) - \delta T^l(x_v) \right\| \qquad \sigma_e^2 = \frac{1}{N} \sum_v \left( e - \left\| C(x_v) - \delta T^l(x_v) \right\| \right)^2$$

# Baloo: Composition of Corrections

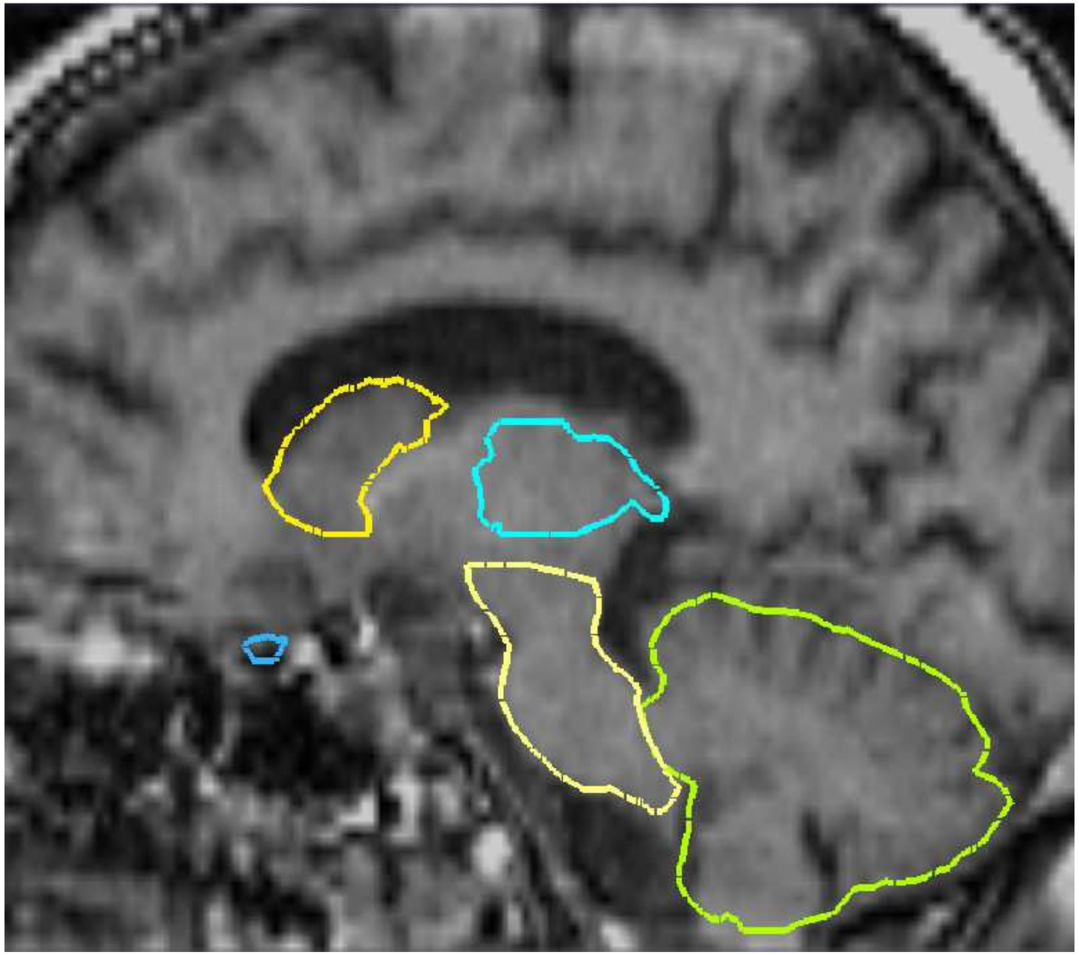


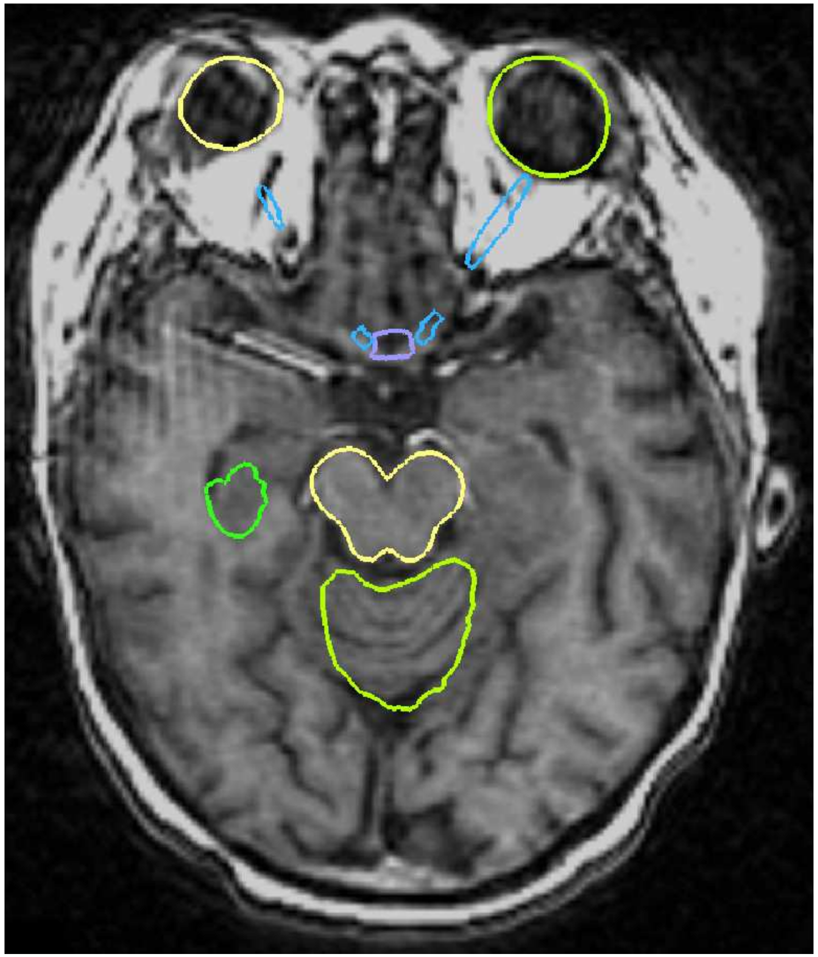

- $\delta\widetilde{T}$ : correction interpolated from pairings minus outliers

- Composition of current transformation $T^{l-1}$

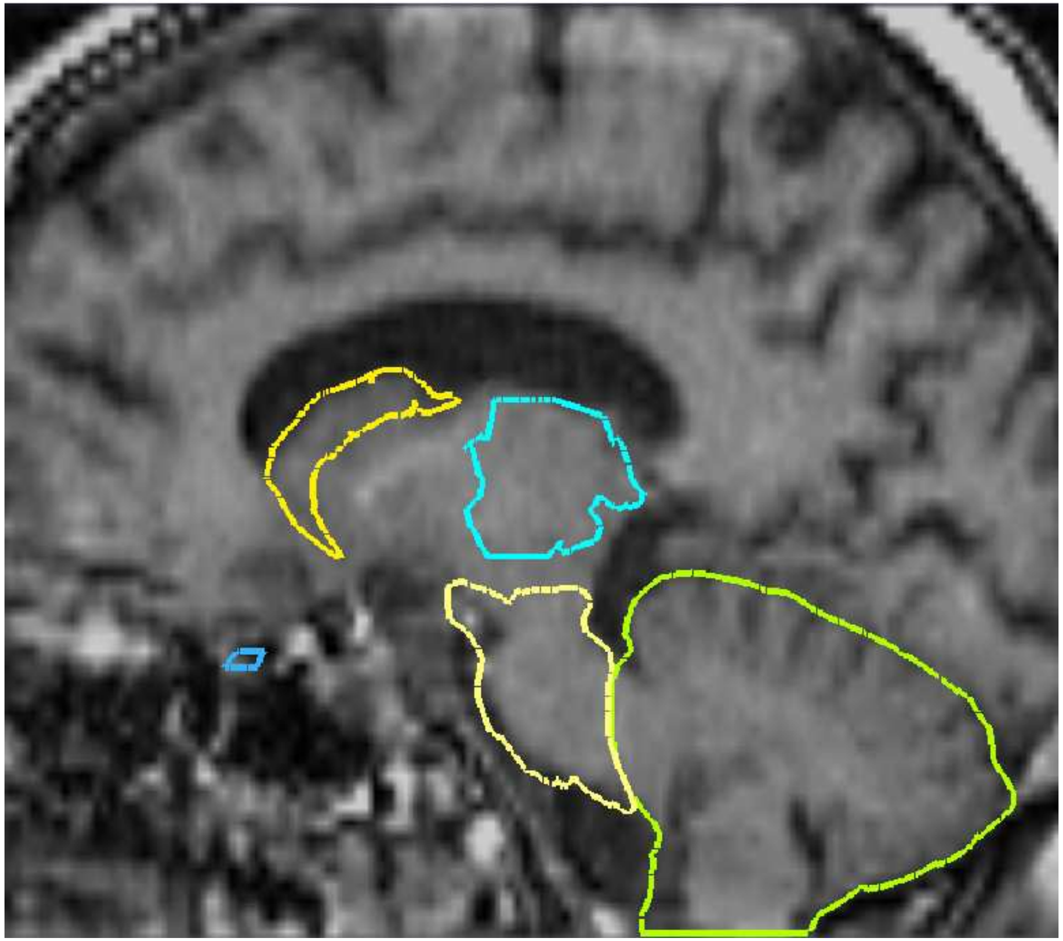
$$T^{l-1} : T^{l} \leftarrow T^{l-1} \circ \delta\widetilde{T}$$

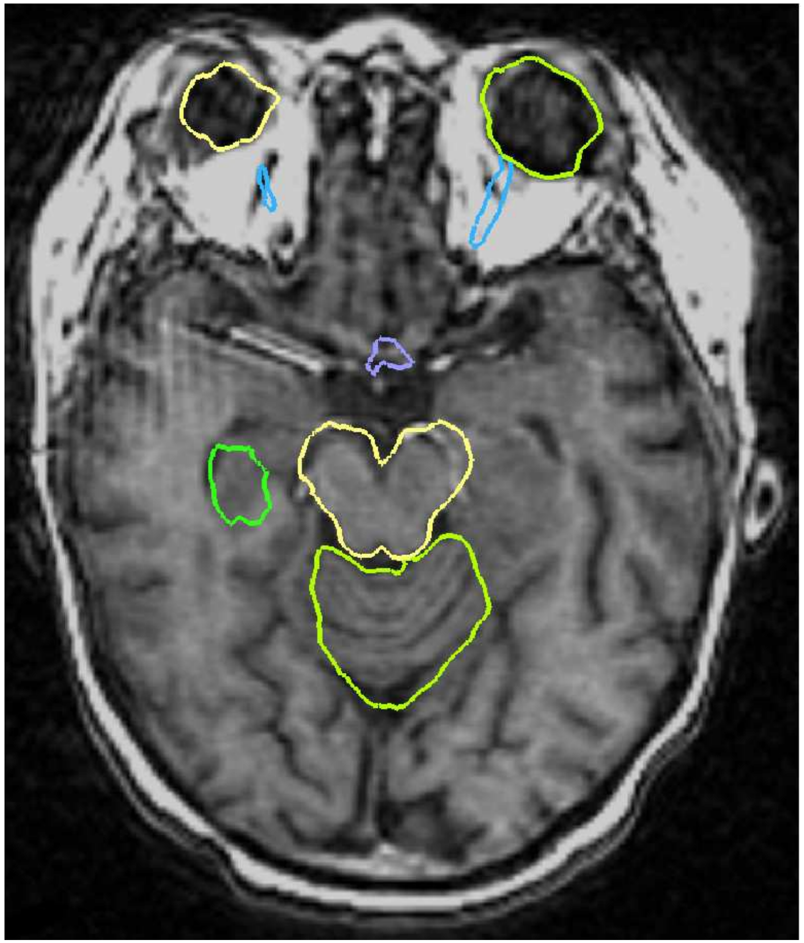
# Segmentation Result (Baloo)





# Segmentation Result (Runa)





# Summary

- Dense Registration with Outlier Rejection (Baloo)
    - Faster than classical dense registration (20 minutes)
    - Smooth transformation
    - Precise contours

- Problems left:
    - Still depends on images quality (eyes)
    - Larger slice thickness

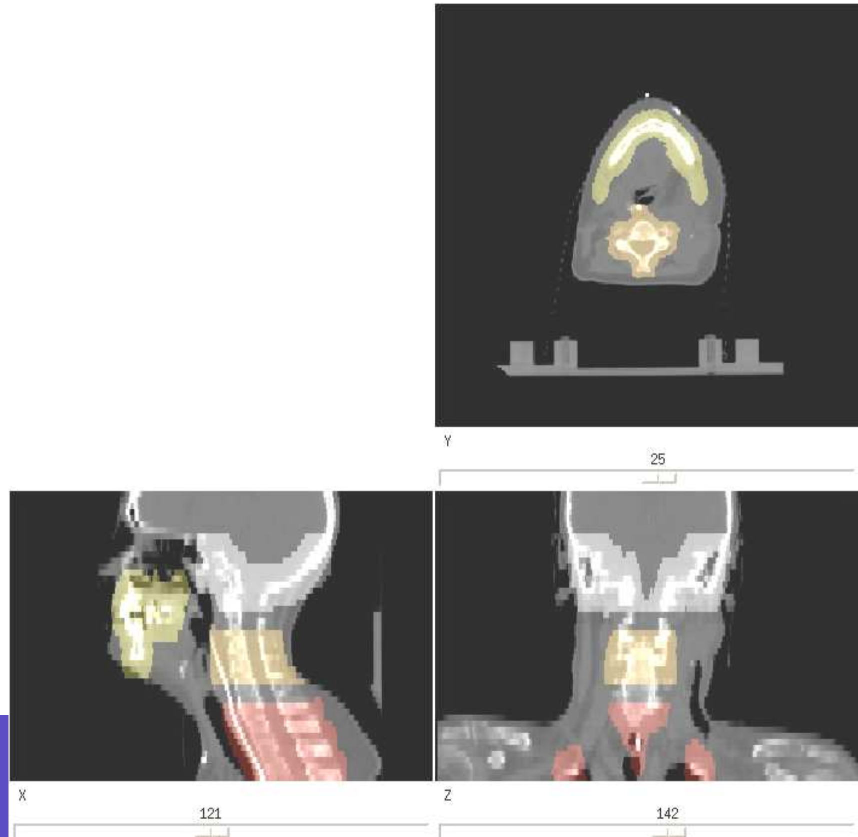
- Objectives
    - More robustness by constraining the transformation
    - Registration only on regions of interest

# Road Map

- Introduction
- Incorporating Priors in Non Linear Registration
    - Existing Registration Method
    - Incorporating Deformability Statistics in Registration
    - Non Linear Registration with Outlier Rejection
    - Locally Affine Registration Framework
- Atlas-Based Brain Segmentation
- Head and Neck Atlas-Based Segmentation
- Conclusion and Perspectives

# Locally Affine Framework

- Principle:
  - Register only anatomic areas of interest
  - Interpolate a global transformation from all local transformations



# Locally Affine Transformation

- Local transformation
  - Affine transformation $A_i$ associated to each region $R_i$
  - Weight function $w_i(x)$
    - Relative influence of each region at point x

$$w_i(x) = \frac{1}{1 + \lambda d(x, R_i)}$$

- Global transformation:
  - Solution 1: Weighted interpolation of affine components

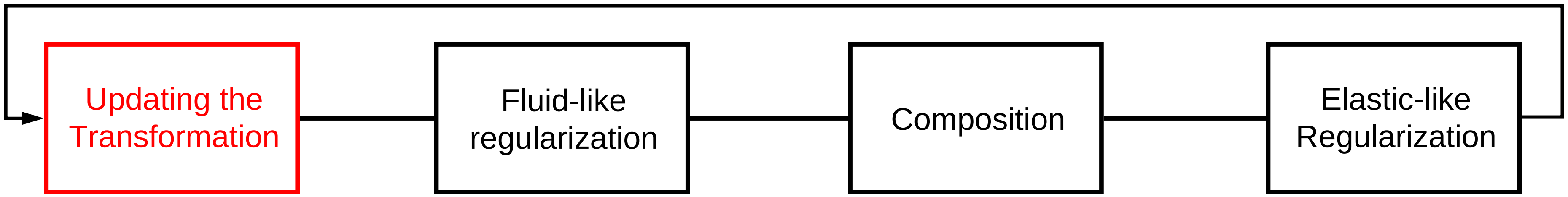
$$T(x) = \sum_{i=1}^{N} w_i(x) A_i(x)$$

  - Solution 2: Using an ordinary differential equation [Arsigny, PhD, 2006]

**[Little et al., 1997]: Deformations Incorporating Rigid Structures. CVIU, 1997.**

**[Arsigny, PhD, 2006]: Processing Data in Lie Groups: An Algebraic Approach. Application to Non-Linear Registration and Diffusion Tensor MRI. November 2006.**

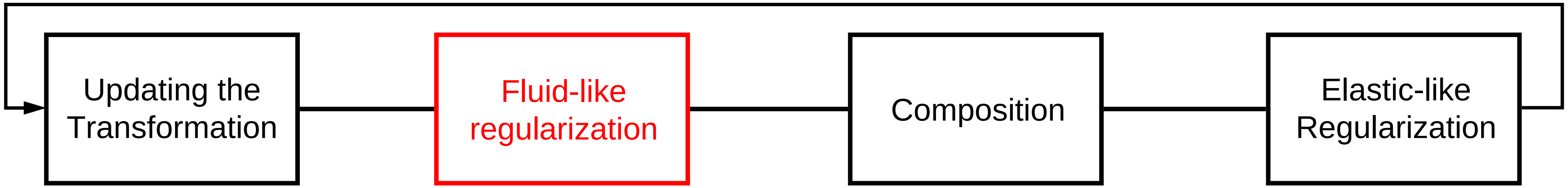
# LAF: Updating the Transformation




- Local affine correction $\delta A_i$ estimation

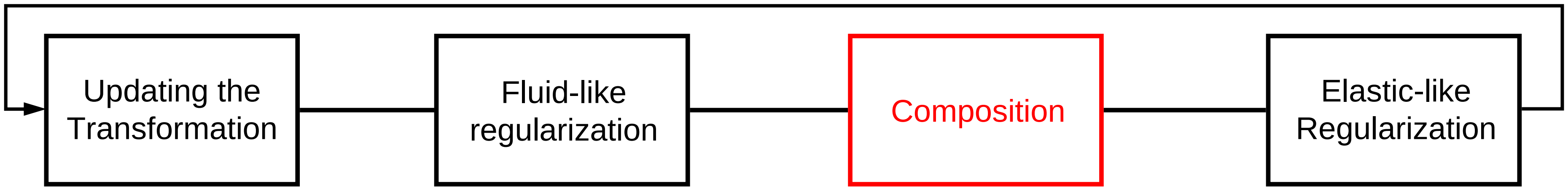
- Block-Matching algorithm
- Outlier rejection in the estimation process
- Least Trimmed Squares Weighted Estimation
  - Weighted by similarity measure values
  - Weighted by $w_i(x_v)$

# LAF: Fluid-like Regularization




- Fluid-like regularization of local transformation corrections
- Gradient descent on $\mathrm{Reg}(\delta A_i, w_i) = \sum_{i=1}^{N} \sum_{j \neq i} p_{i,j} \left\| \log(\delta A_i) - \log(\delta A_j) \right\|^2$
- Log-Euclidean polyaffine framework
  - $\log(A_i)$ belongs to a vector space
  - Generalization of usual regularization energies

# LAF: Composition of Corrections

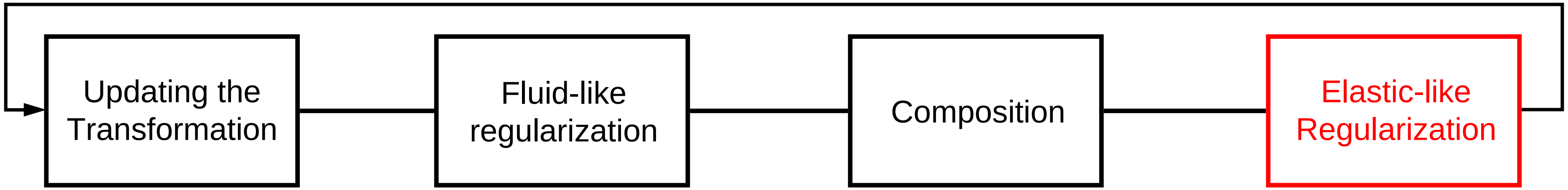



- Regularized corrections: $\delta\tilde{A}_i$

- Composition of corrections with the current transformation

$$A_i^l = A_i^{l-1} \circ \delta\tilde{A}_i$$

# LAF: Elastic-like Regularization



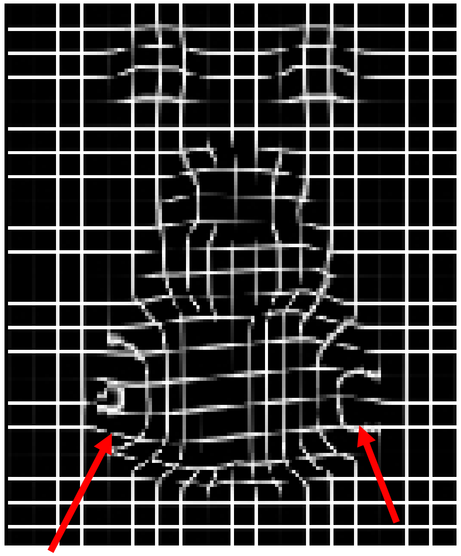

- Gradient descent on

$$\mathrm{Reg}(A_i^l, w_i) = \sum_{i=1}^{N} \sum_{j \neq i} p_{i,j} \left\| \log(A_i^l) - \log(A_j^l) \right\|^2$$

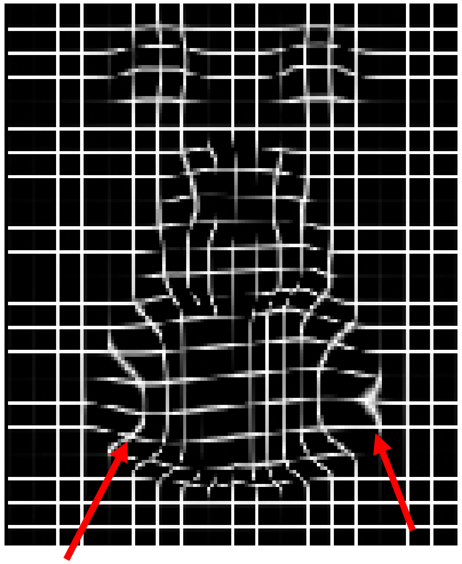
- Similar to fluid-like regularization
  - Regularization on transformations $A_i^l$

# Locally Affine Registration

- Final global transformation computation
  - Solution 1 (weighted interpolation): Fast but not always invertible
  - Solution 2 (polyaffine): Slower but always invertible

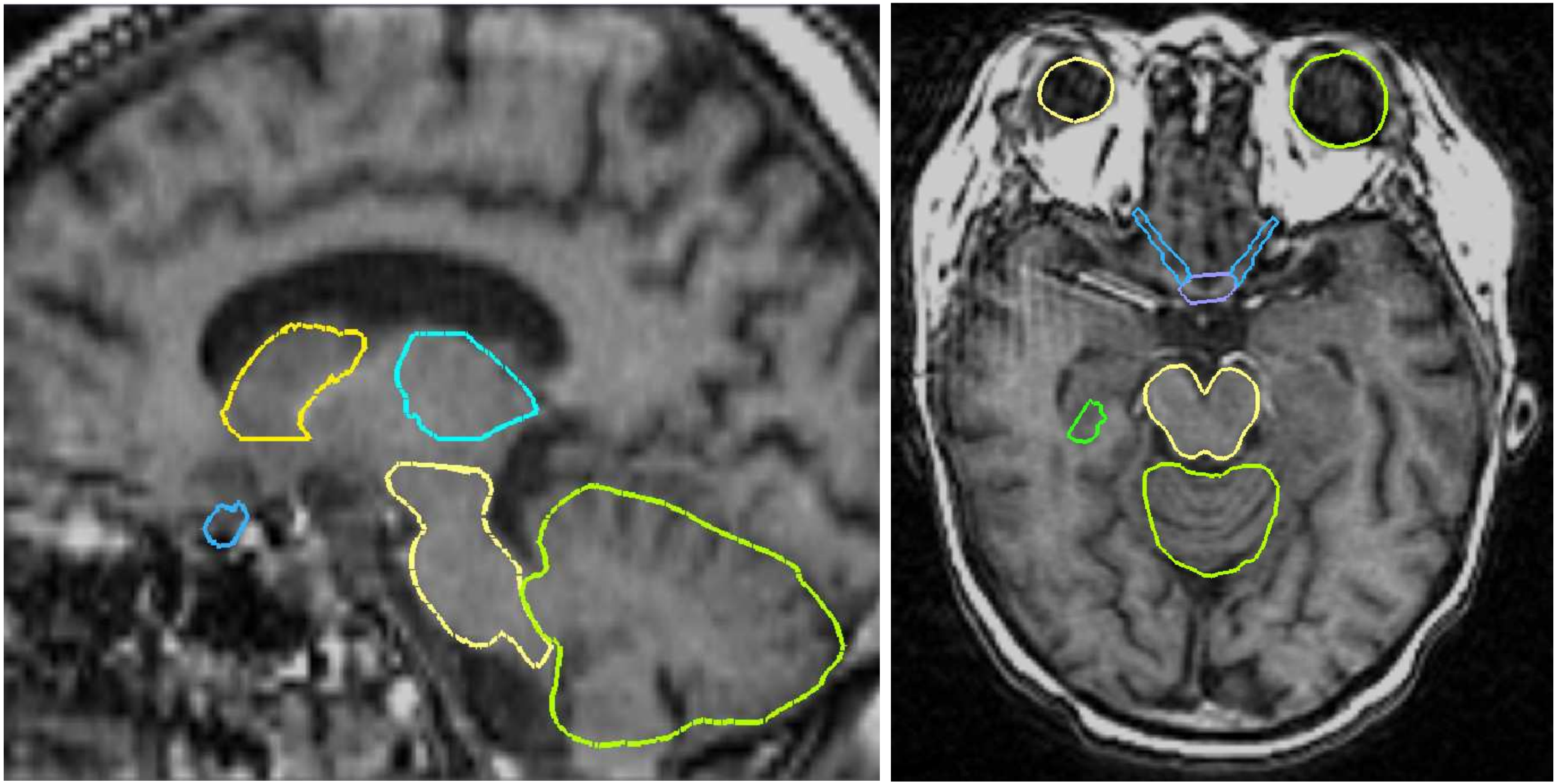


Transformation using solution 1

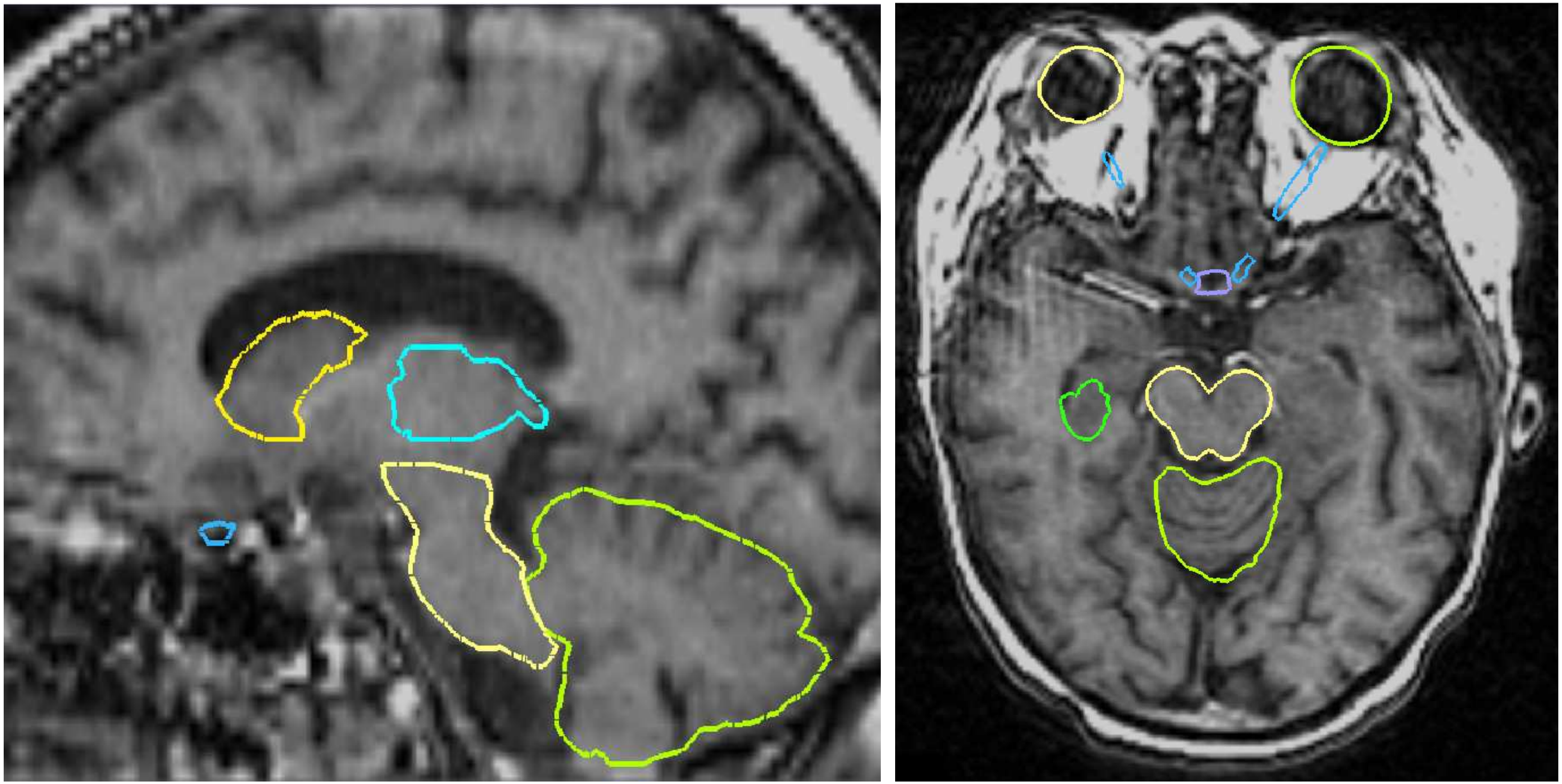


Transformation using solution 2

# Segmentation Result (Locally Affine)



# Segmentation Result (Baloo)



# Conclusion

- Locally Affine Registration [Commowick et al., 2006a], [Commowick et al., 2006b]
    - Smooth transformation
    - Robust registration
        - One parameter set for all tested acquisition protocols
    - Fast computation time (10 minutes)

- Registration method able to recover large displacements
    - Ideal for articulated structures (head and neck)

**[Commowick et al., 2006a]: An Efficient Locally Affine Framework for the Registration of Anatomical Structures. ISBI, 2006.**

**[Commowick et al., 2006b]: An Efficient Locally Affine Framework for the Smooth Registration of Anatomical Structures. Medical Image Analysis, 2006. *Submitted.***

# Road Map

- Introduction
- Incorporating Priors in Non Linear Registration
- Atlas-Based Brain Segmentation
- Head and Neck Atlas-Based Segmentation
- Conclusion and Perspectives

# Evaluation Methodology

- Three evaluation methods
  - Visual inspection
  - Semi-quantitative validation
    - Visual inspection by a clinician
    - Graduation between 0 and 5
  - Quantitative validation
    - Experts manual segmentations
    - Two steps:
      - Ground truth computation using STAPLE [Warfield et al., 2004]
      - A posteriori computation of sensitivity/specificity

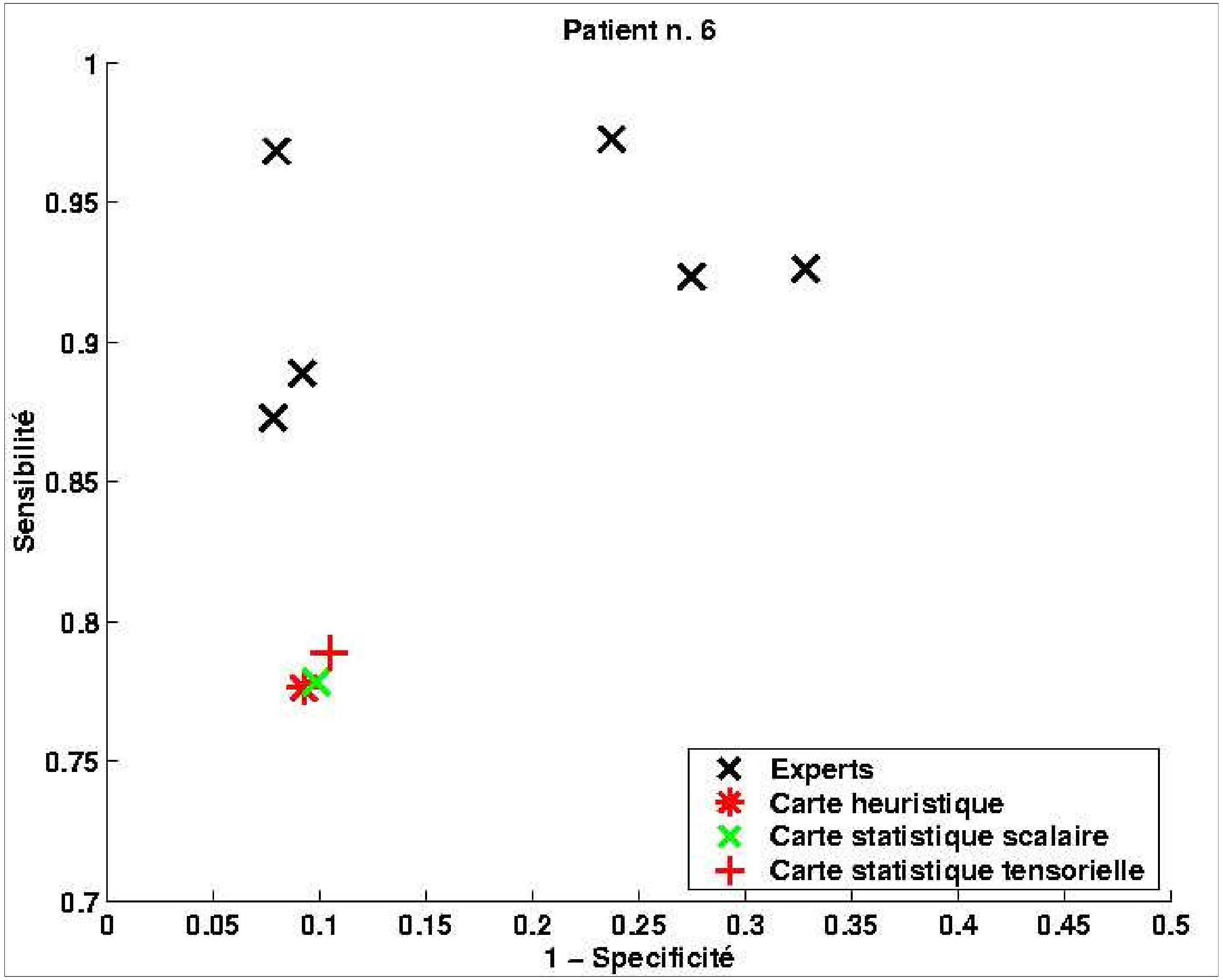
**[Warfield et al., 2004]: Simultaneous Truth and Performance Level Estimation (STAPLE): an Algorithm for the Validation of Image Segmentation, IEEE TMI, 2004.**

# Brain Evaluation

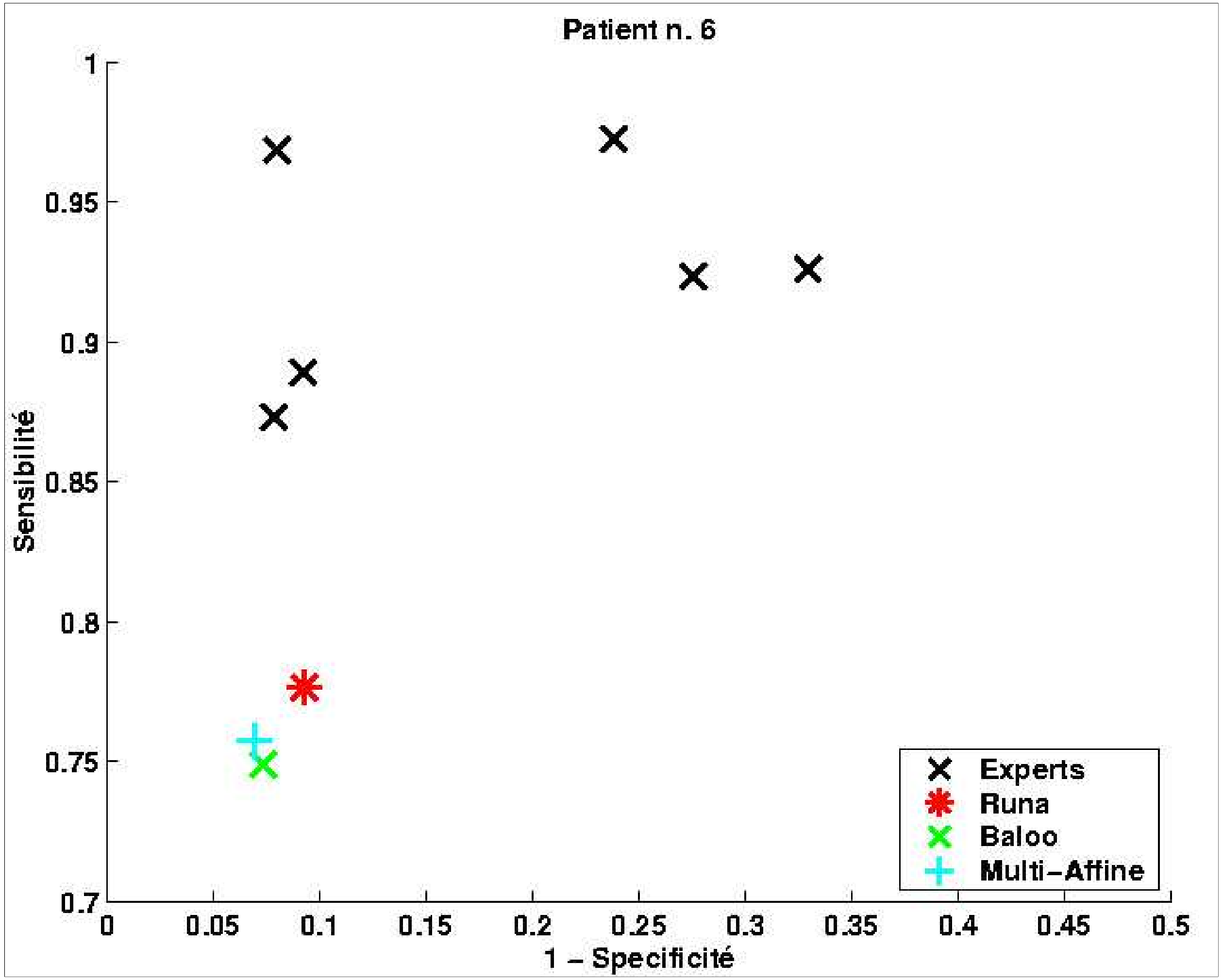
- Database of MRI from CAL Nice (Dr. P.-Y. Bondiau)
  - 2mm slice thickness

- Use of manual expert segmentations
  - Brainstem: 7 experts, 6 patients

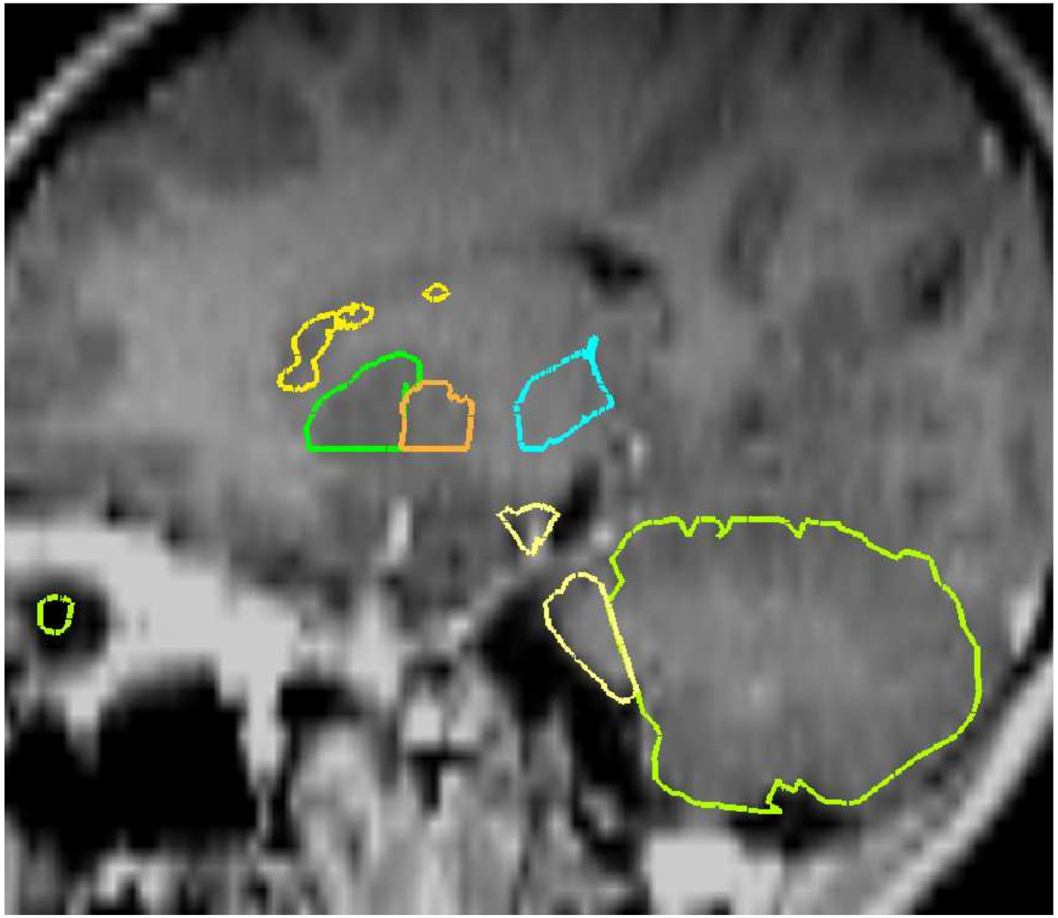
# Quantitative Evaluation (I): Introduction of Deformability Statistics

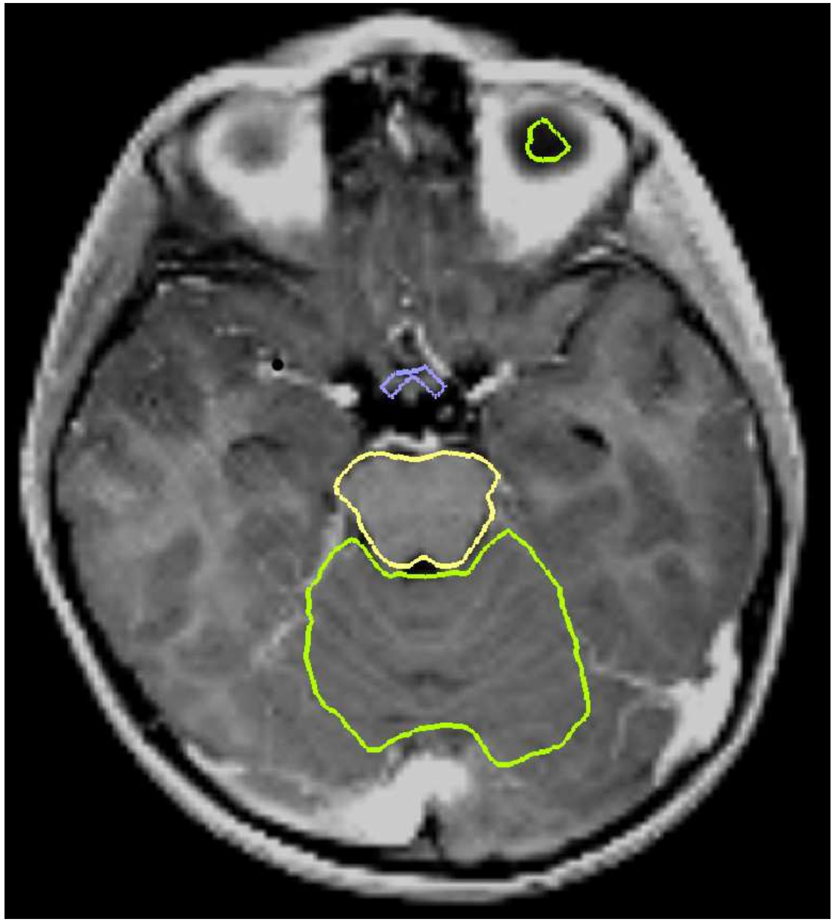


# Quantitative Evaluation (II): Runa, Baloo, LAF

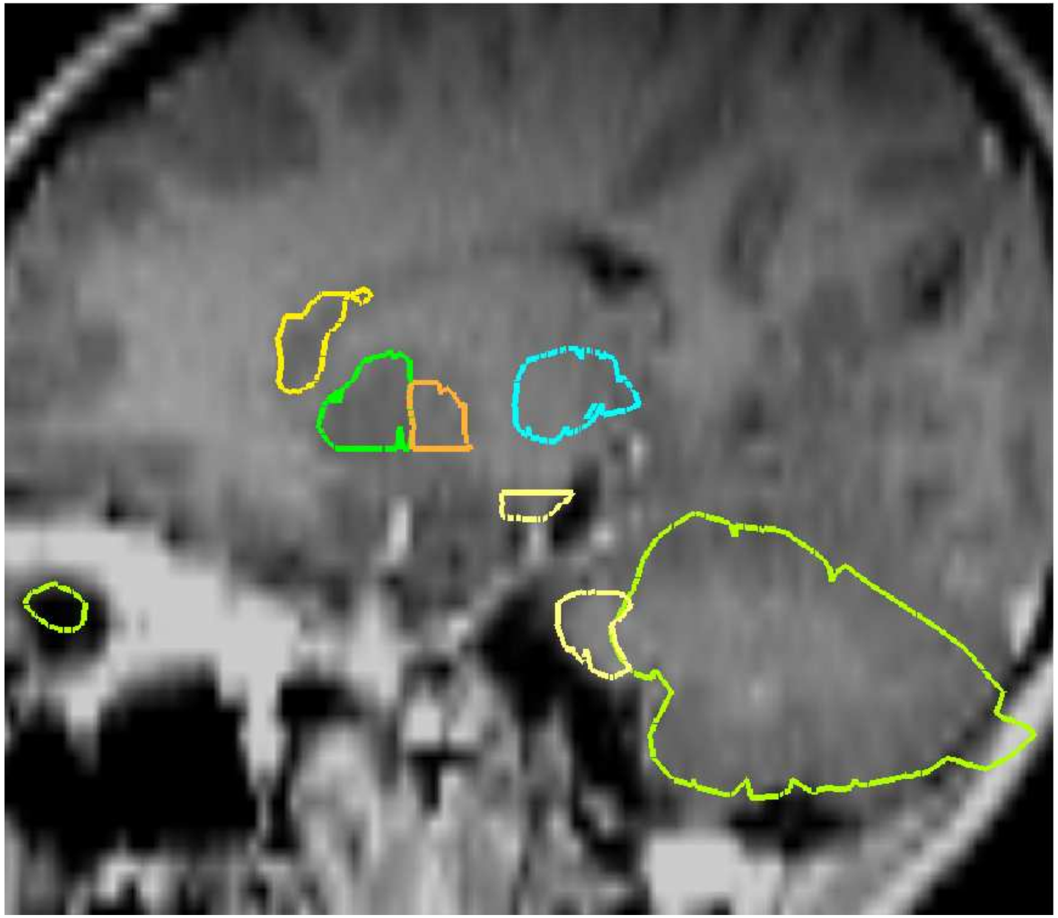


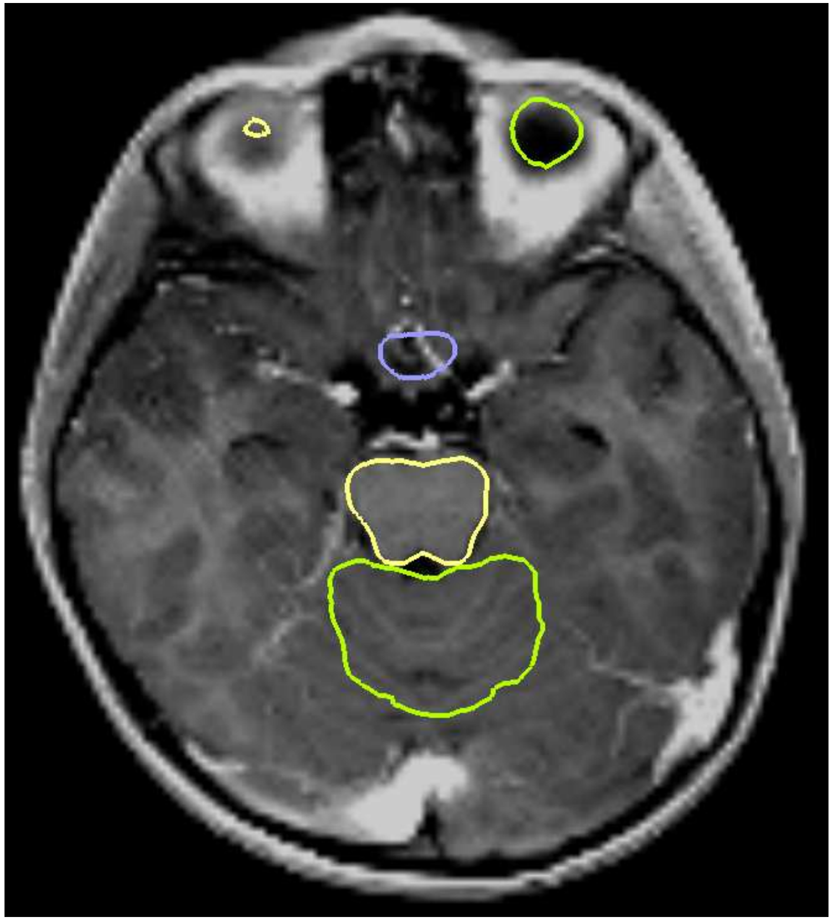
# Evaluation in Clinical Conditions (Runa)



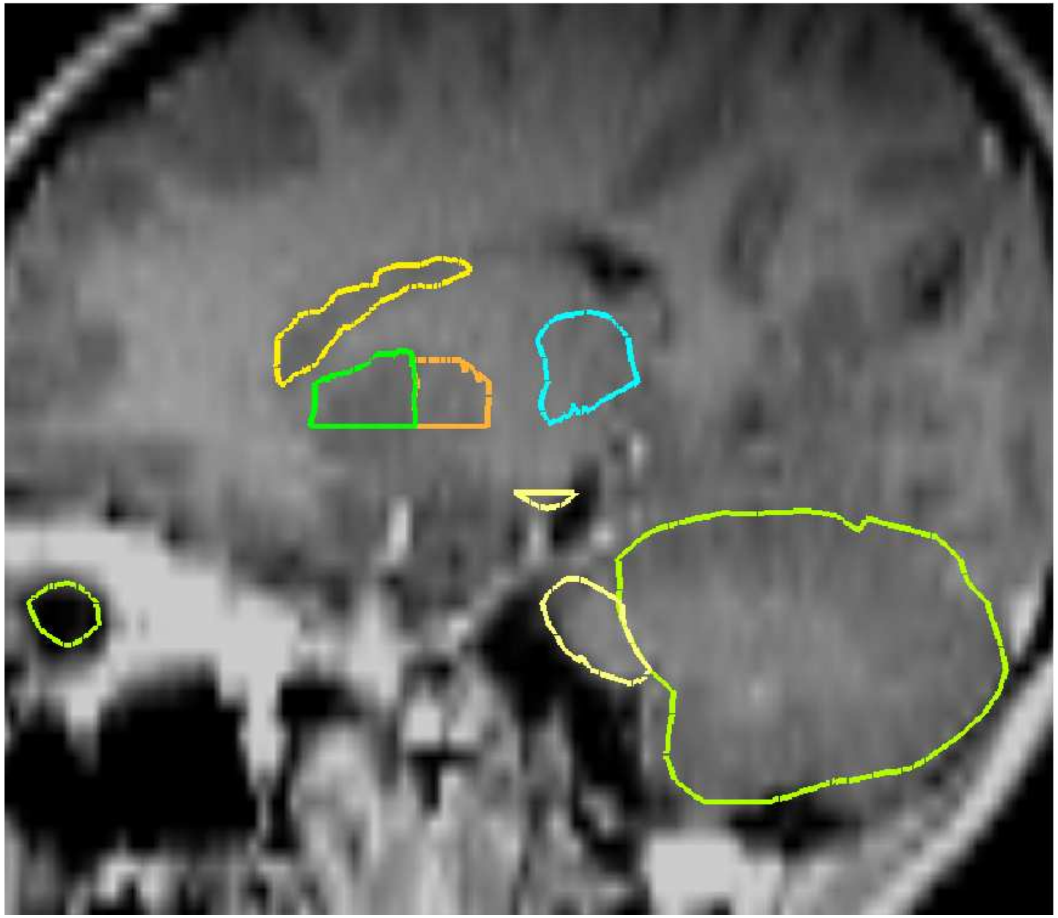


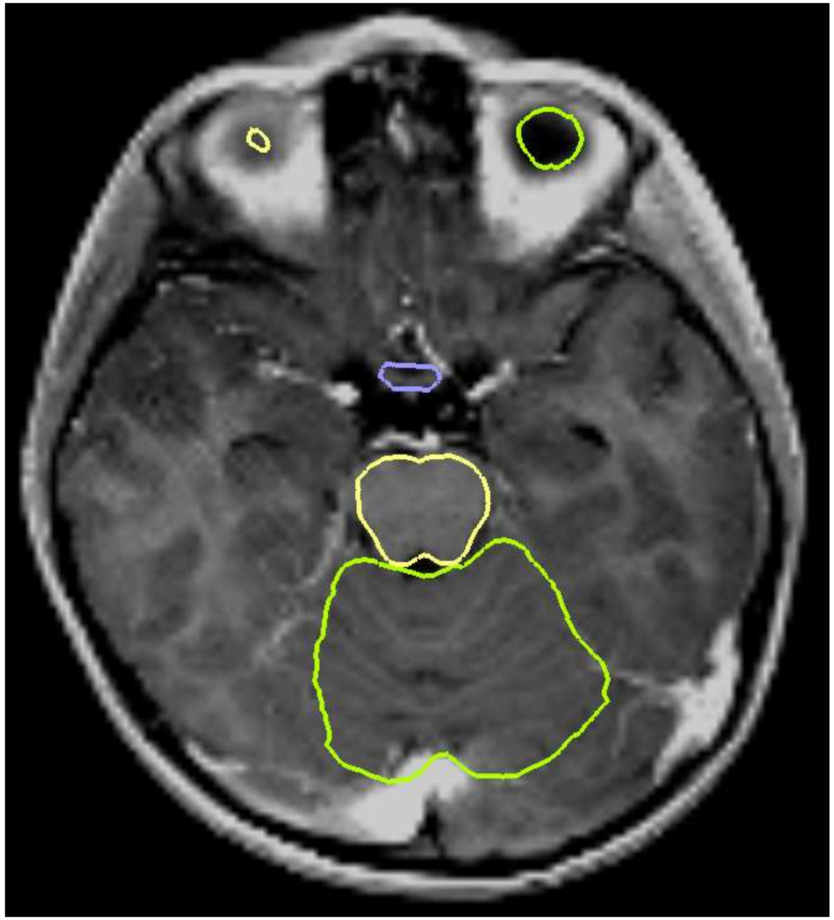
# Evaluation in Clinical Conditions (Baloo)





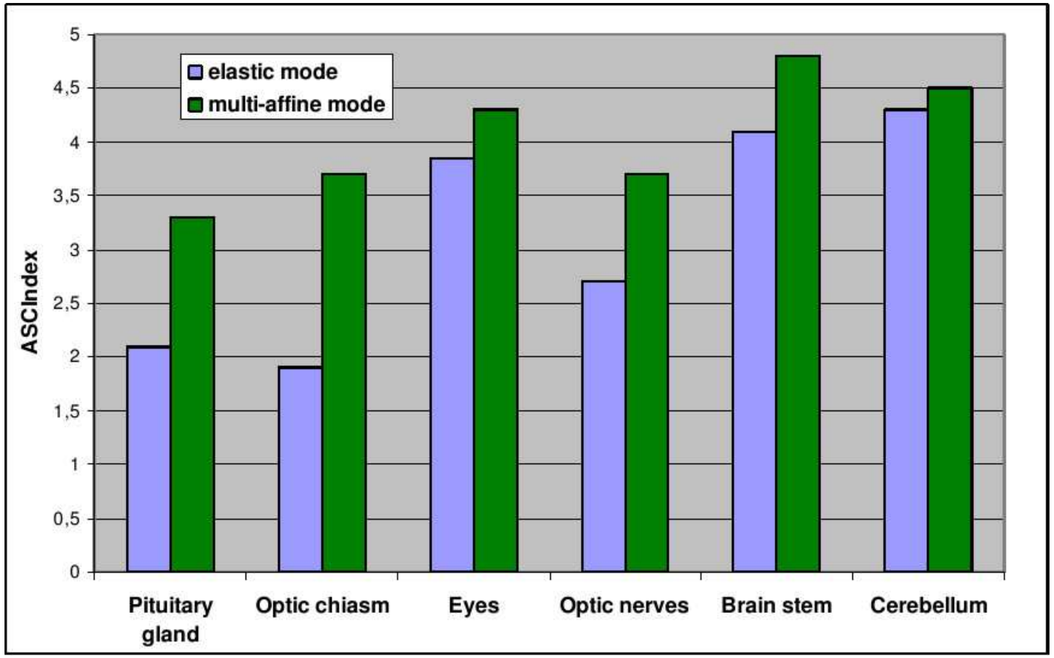
# Evaluation in Clinical Conditions (LAF)





# Semi-Quantitative Evaluation in Clinical Conditions

- Evaluation in clinical conditions [Isambert et al., 2005]
  - Done at Institut Gustave Roussy
  - In the frame of MAESTRO European project




**[Isambert et al., 2005]: Requirements for the use of an atlas-based automatic segmentation for delineation of Organs at Risk (OAR) in conformal radiotherapy (CRT): quality assurance (QA) and preliminary results for 22 adult patients with primary brain tumors. ESTRO, 2005.**

# Road Map

- Introduction
- Incorporating Priors in Non Linear Registration
- Atlas-Based Brain Segmentation
- Head and Neck Atlas-Based Segmentation
  - Atlas Construction Method
  - Atlas Evaluation
  - Results
- Conclusion and Perspectives

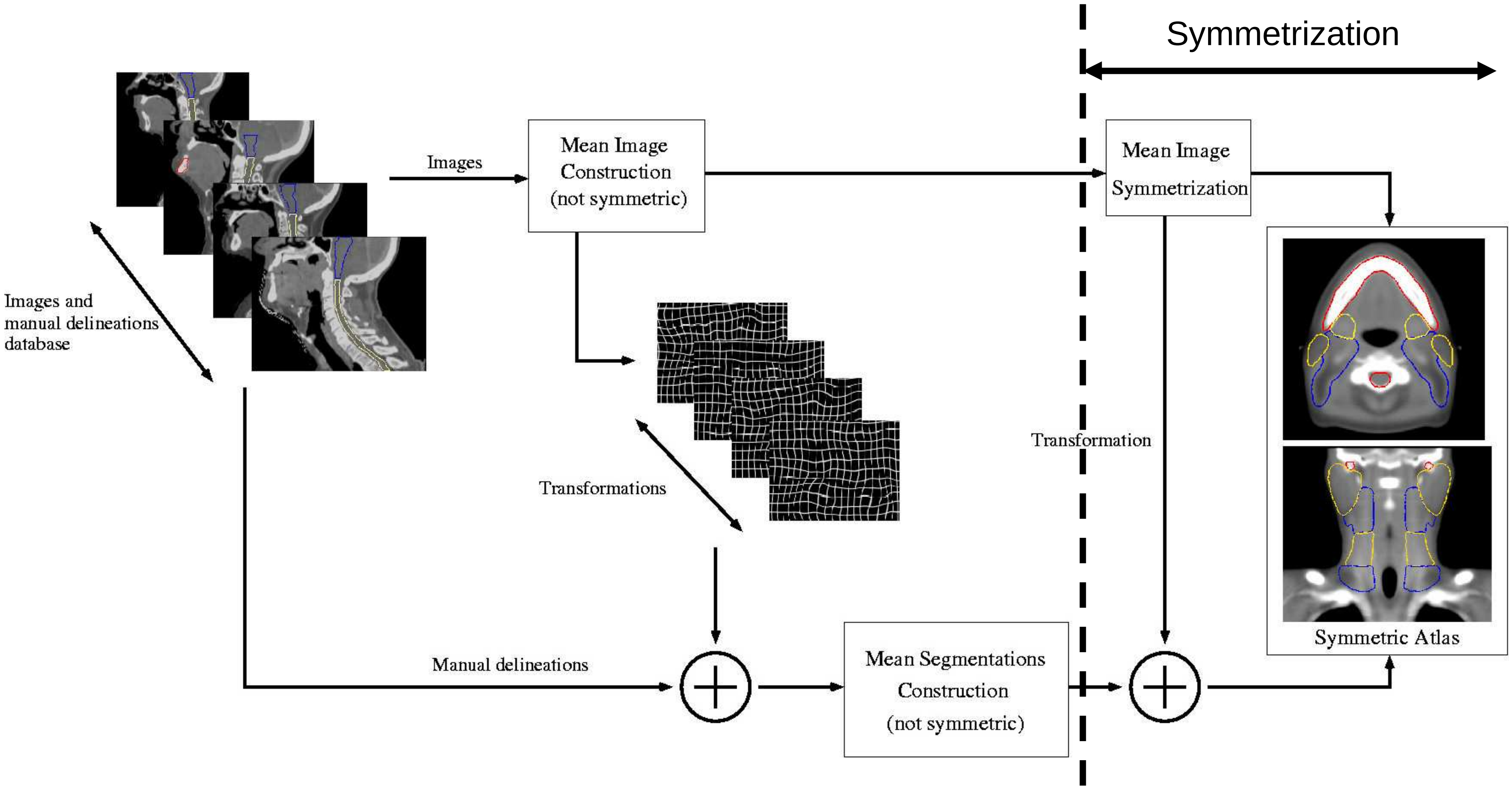
# Head and Neck Atlas Construction

- Atlas construction
  - From a dataset of delineated images
  - Needs to be representative of all patients
    - Symmetric atlas construction method
  - Other possible method: [Grabner et al., 2006]

- Three steps construction method
  - Mean image construction
  - Mean segmentations
  - Atlas symmetrization

**[Grabner et al., 2006]: Symmetric Atlasing and Model Based Segmentation: an Application to the Hippocampus in Older Adults. MICCAI, 2006.**

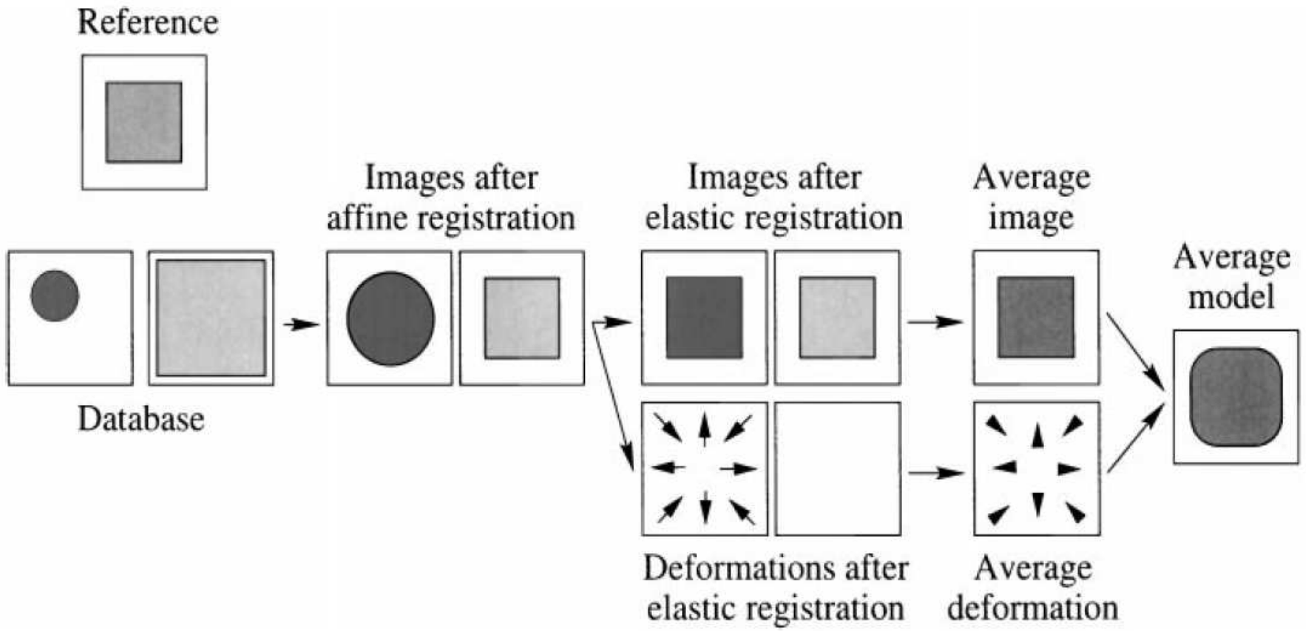
# Atlas Construction Method



# Mean Image Construction

• Unbiased atlas construction [Guimond et al., 2000]:

- Iterate the following process




- Take the average model as new reference image

**[Guimond et al., 2000]: Average Brain Models: A Convergence Study, CVIU, 2000.**

# Mean Segmentations

- One transformation for each patient
  - All segmentations in the mean image referential

- Mean segmentation using STAPLE [Warfield et al., 2004]:
  - Estimation of mean segmentations
  - Computation of performance parameters

- Probability maps for each class (including background)
  - A posteriori classification into structures

**[Warfield et al., 2004]: Simultaneous Truth and Performance Level Estimation (STAPLE): an Algorithm for the Validation of Image Segmentation, IEEE TMI, 2004**

# Atlas Symmetrization

- Method of [Prima et al., 2002]
  - Obtain transformation $R$ bringing $I$ on its mid-sagittal plane
  - Principle: registration between $I$ and the mirrored image $I \circ S$
  - $R$ satisfies the relation $I \circ R = I \circ R \circ S$

- Mean symmetric image obtained from $\widetilde{M}$

$$\widetilde{M}_S = \frac{\widetilde{M} \circ R + \widetilde{M} \circ R \circ S}{2}$$

- Mean symmetric segmentations obtained in two steps
  - Symmetrization of the probability maps from STAPLE
  - A posteriori classification into structures

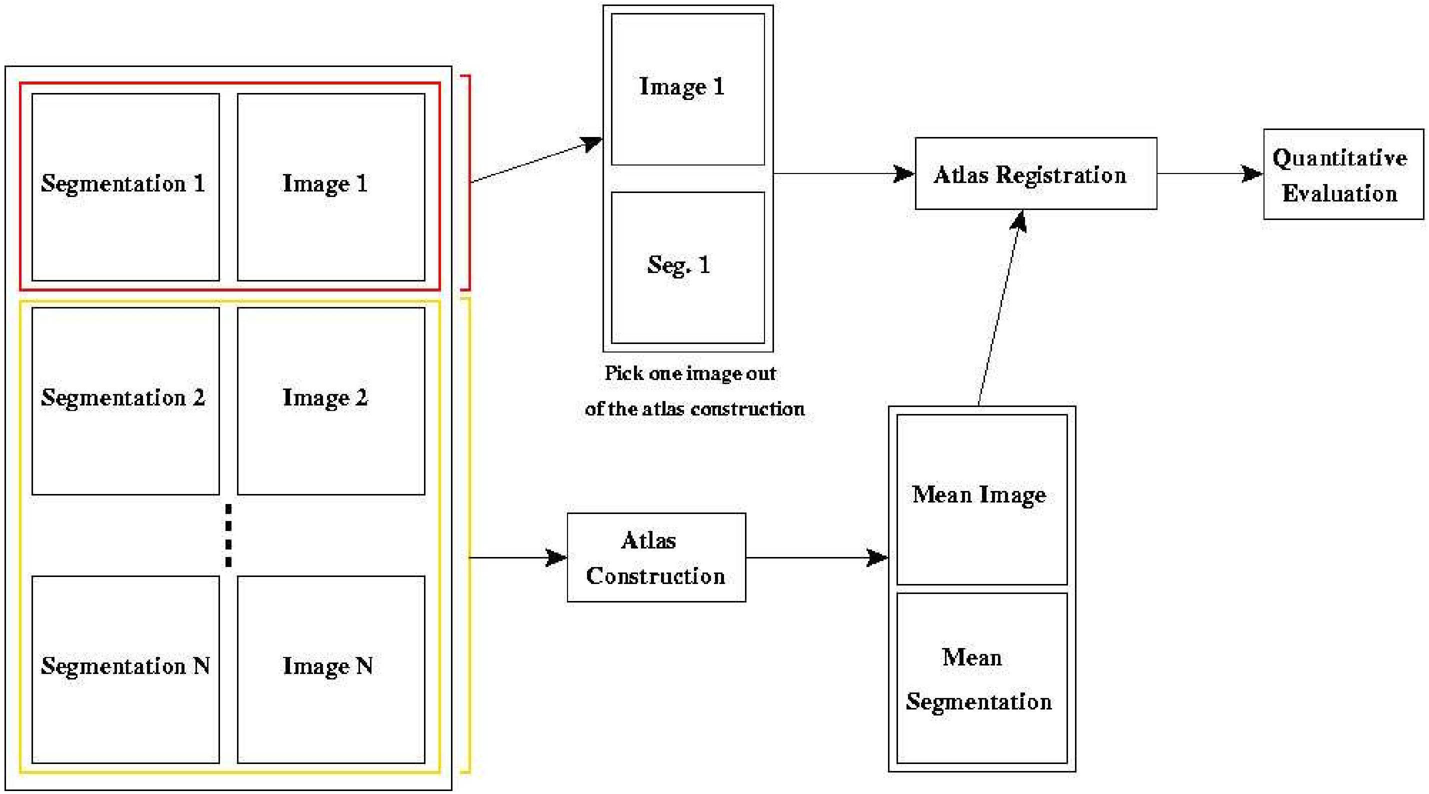
**[Prima et al., 2002]: Computation of the Mid-Sagittal Plane in 3D Brain Images. IEEE TMI, 2002.**

# Road Map

- Introduction
- Incorporating Priors in Non Linear Registration
- Atlas-Based Brain Segmentation
- Head and Neck Atlas-Based Segmentation
  - Atlas Construction Method
  - Atlas Evaluation Strategy
  - Results
- Conclusion and Perspectives

# Atlas Evaluation Strategy

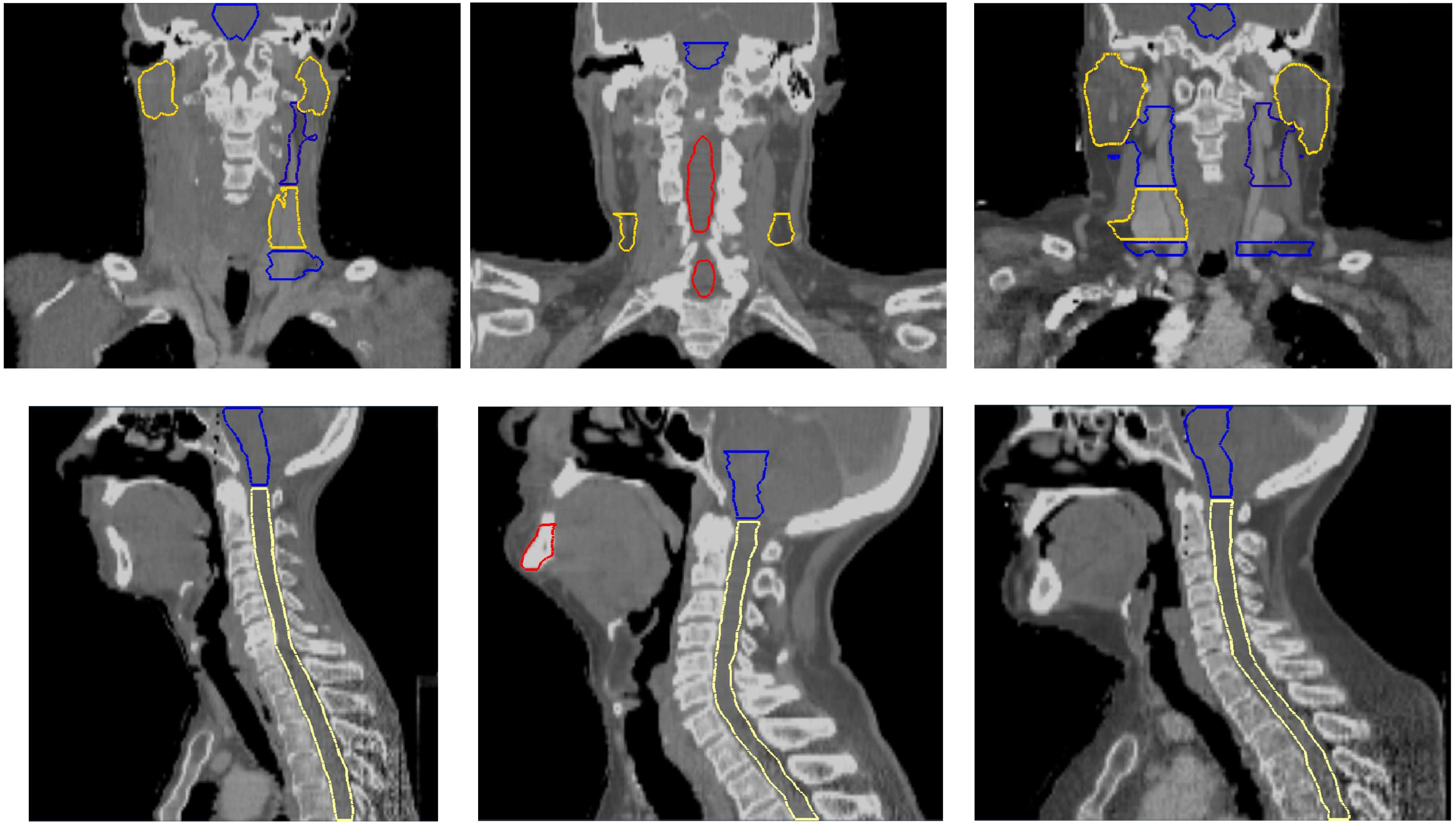
- Leave-One-Out method



# Evaluation protocol

- Image database:
  - 45 patient CT-scan images (Pr. V. Grégoire, MAESTRO)
  - Different tumors shapes at different localizations
  - Small tumors not deforming the surrounding anatomy (N0 grade)
  - Various patient position and anatomy
- Three registration methods compared:
  - $M_1$: Block-Matching based dense registration method
  - $M_2$: Locally-affine registration method
  - $M_3$: $M_2$ followed by $M_1$

# Image Database Examples

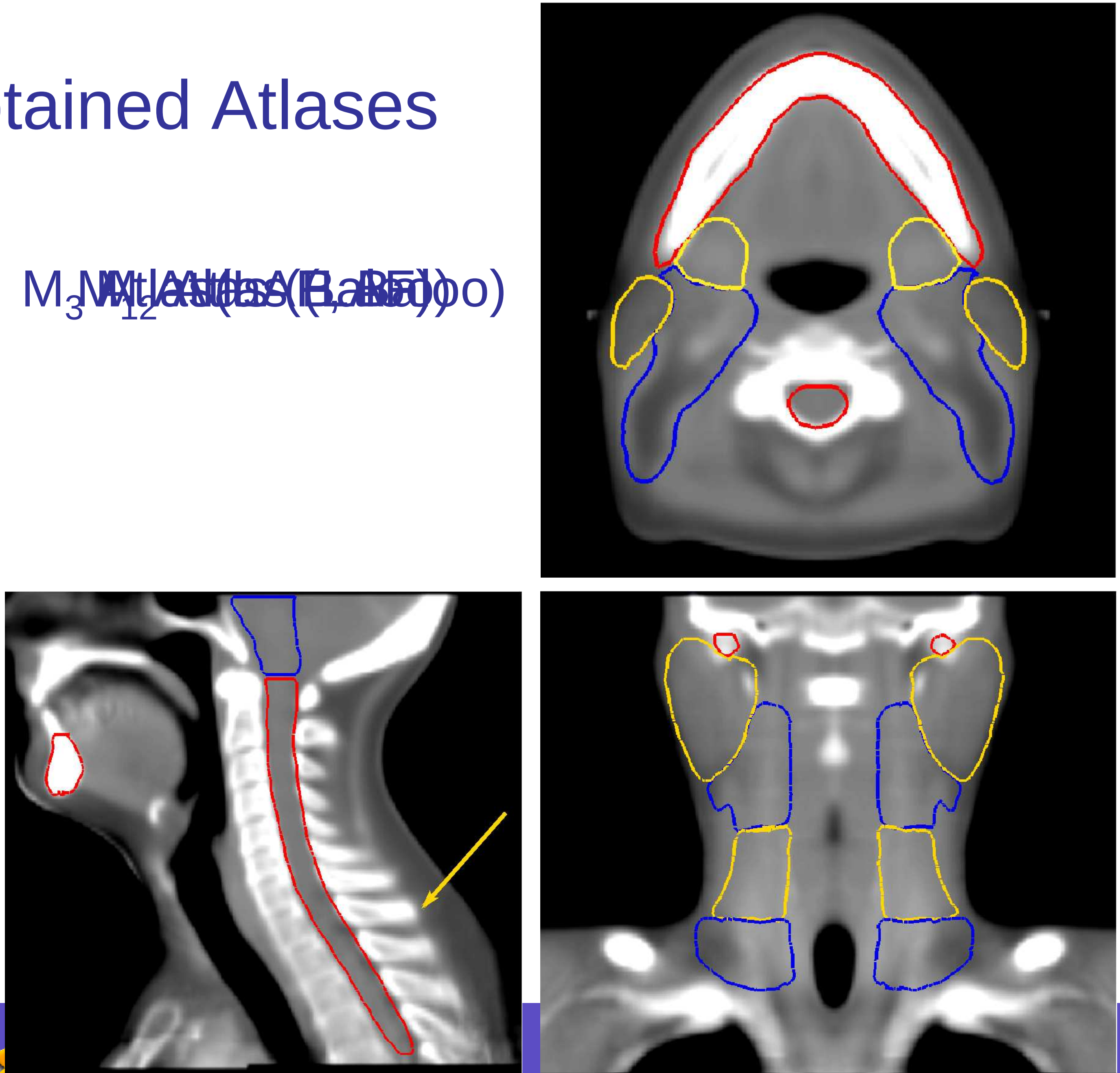


# Road Map

- Introduction
- Towards a Better Control of Registration Transformations
- Atlas-Based Brain Segmentation
- Head and Neck Atlas-Based Segmentation
    - Atlas Construction Method
    - Atlas Evaluation Strategy
    - Results
- Conclusion and Perspectives

# Obtained Atlases

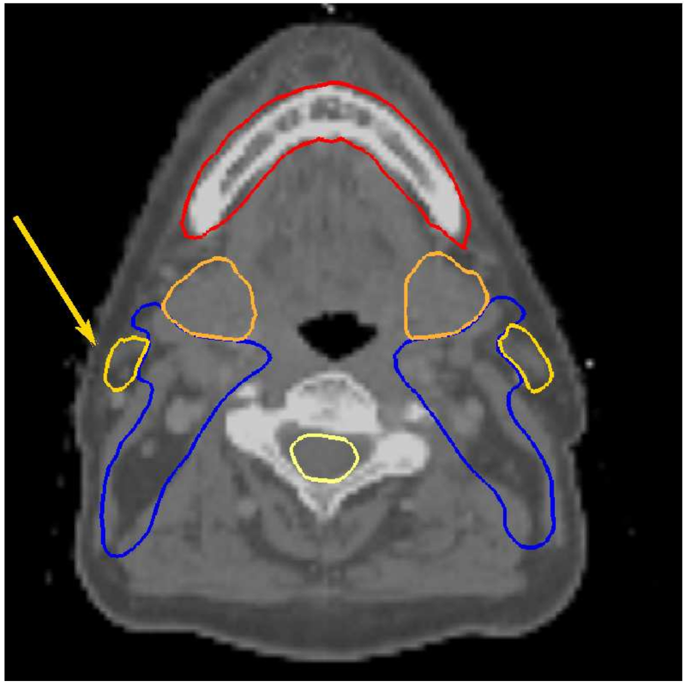
$M_3$ Atlas (B, R5)
$M_{12}$ Atlas (Baloo)

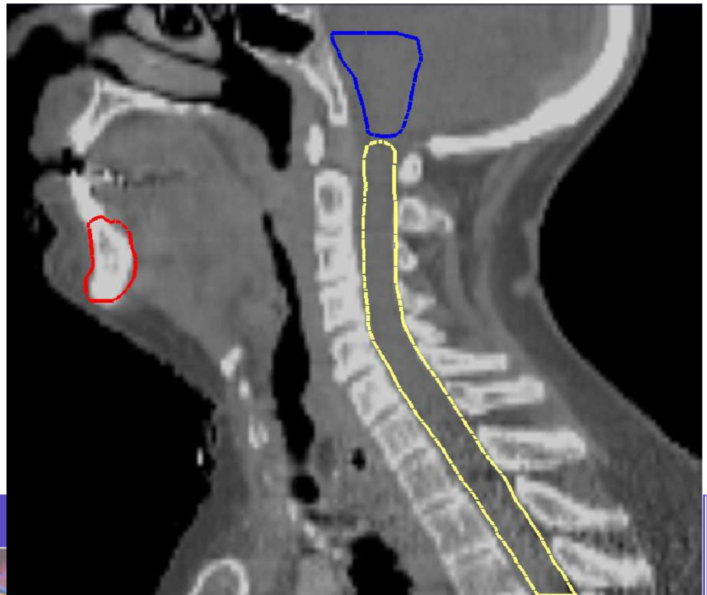


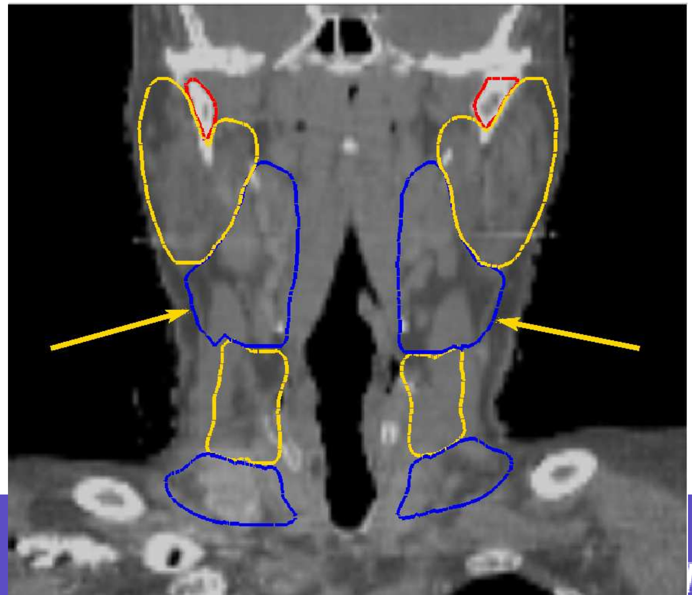
# Qualitative Results

Manual Segmentation

$M_2$ Atlas Segmentation

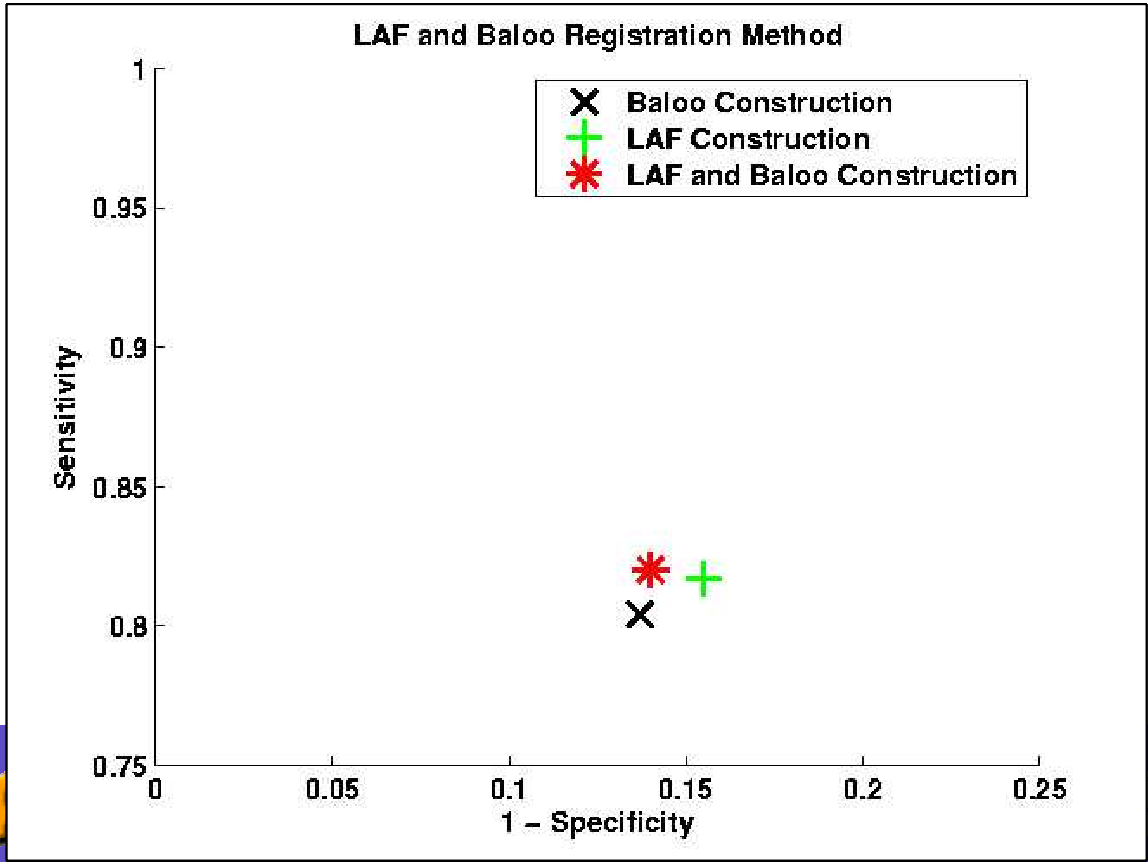






# Quantitative Atlas Evaluation

- Use of Leave-One-Out method:
  - Mean over 12 patients completely delineated (13 structures)
- $M_3$ Atlas performs better for atlas construction



# Conclusion

- Symmetric atlas construction method
  - From existing techniques
- Atlas Evaluation method [Commowick et al., 2006c]
  - Registration method to build the atlas
  - Registration method to register the atlas
- Application to Head and Neck
  - Hierarchical registration ($M_3$): well adapted in this context
  - Promising results
  - Many perspectives on atlas construction

**[Commowick et al., 2006c]: Evaluation of Atlas Construction Strategies in the Context of Radiotherapy Planning. SA2PM Workshop, held in conjunction with MICCAI. 2006.**

# Road Map

# Contributions

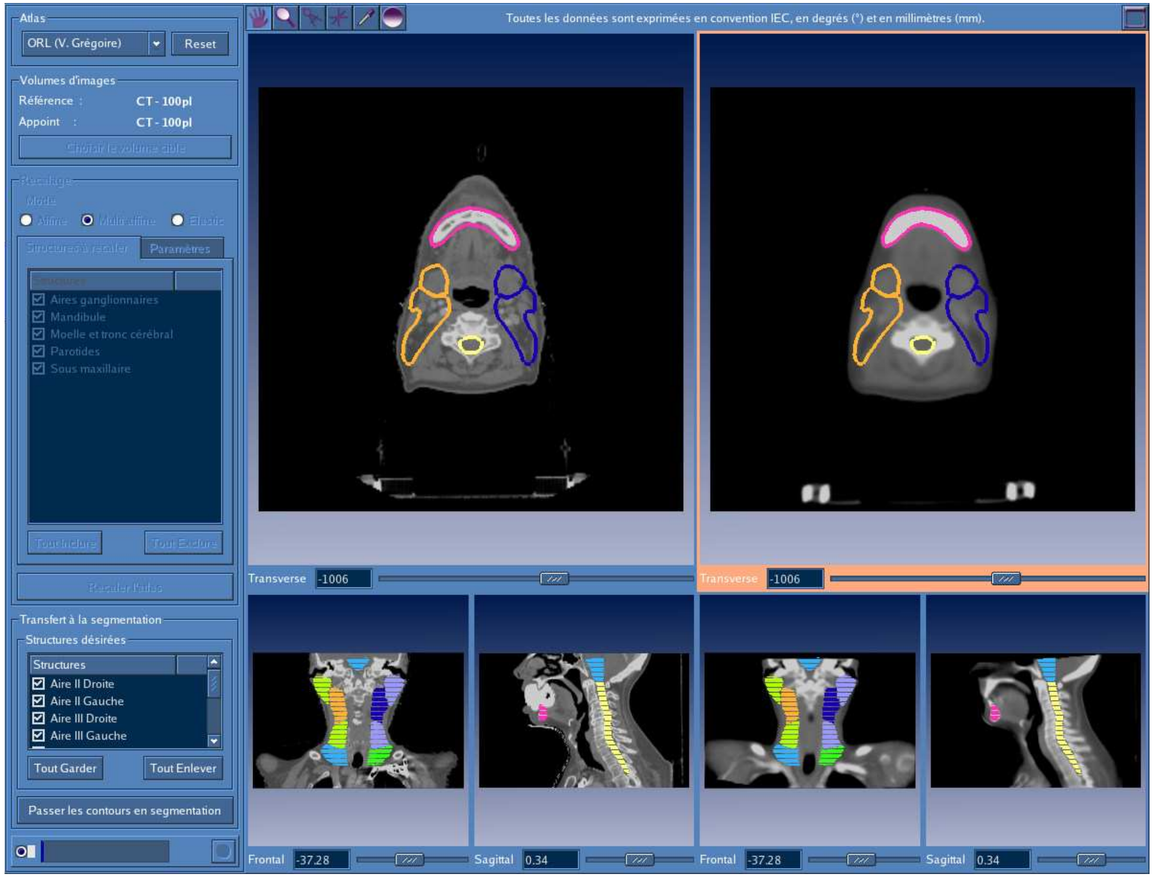
- Registration
  - Introduction of deformability statistics in registration
  - Dense registration with outlier rejection
  - Locally affine framework
    - Good results without changing parameters

- Head and neck atlas
  - Atlas construction method from a dataset of CT images
  - Evaluation via leave one out method

- Other contributions (not presented here)
  - Taking pathology into account in registration process
  - Ad-Hoc method for optic nerves segmentation

# Software Integration

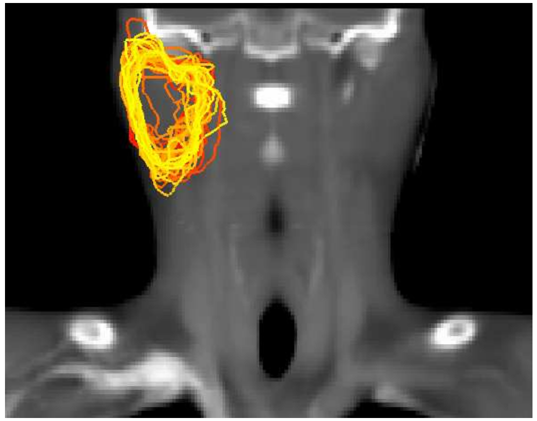
- Integration in DOSIsoft radiotherapy planning system
  - Atlas-based segmentation module
  - Both brain and head and neck atlases

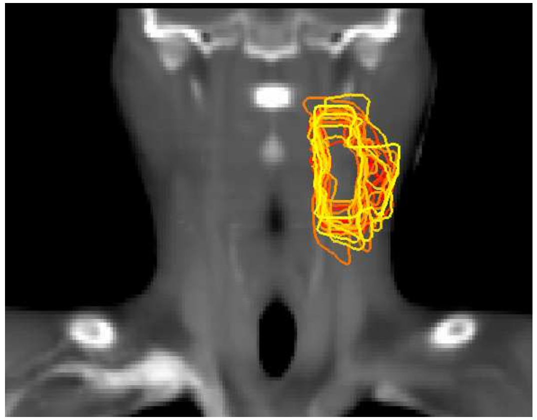


- Validation in clinical conditions at IGR
  - MAESTRO European project

# Discussion on Head and Neck Atlas

- Problem: Over-segmentation of the lymph nodes areas





- First reason: inside the atlas
  - Contours dispersion
    - Large inter-patient variation
  - STAPLE for generating mean segmentations
    - Influence of the background class

- Possible solutions
  - Cluster dataset in several groups
  - Use of new methods [Warfield et al., 2006]
    - No background class

**[Warfield et al., 2006]: Validation of Image Segmentation by Estimating Rater Bias and Variance. MICCAI 2006.**

# Discussion on Head and Neck Atlas

- Second reason: when registering the atlas
  - Large atlas/patient differences
    - Corpulence
    - Neck flexion

➔ Results in local discrepancies

- Possible solutions
  - Build several atlases from one database
    - Clustering of the dataset
  - Choose the closest image among the dataset images
    - Definition of distance

# Perspectives

- Registration methods
  - Computation of statistics of deformability
    - Several registration methods to build unbiased statistics
  - Locally affine framework
    - Refining local affine regions

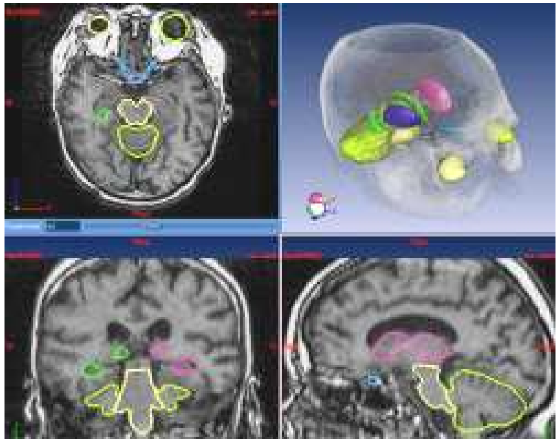
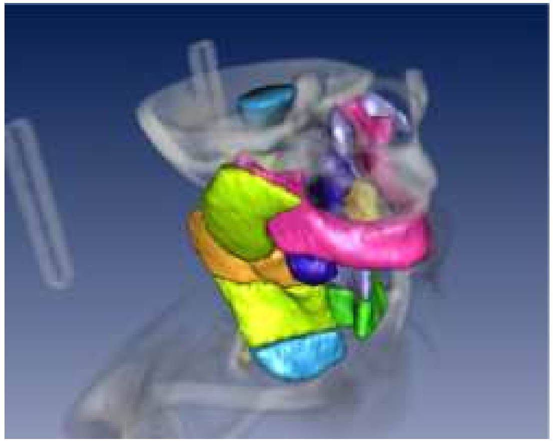
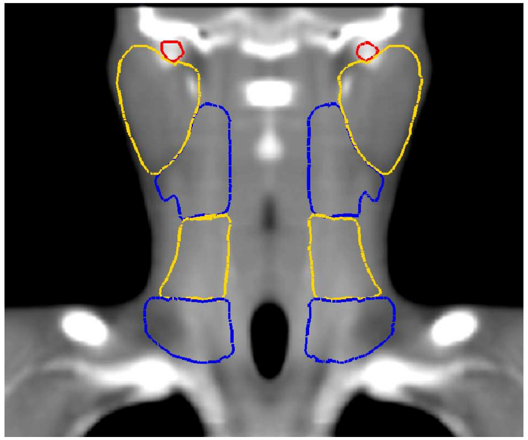
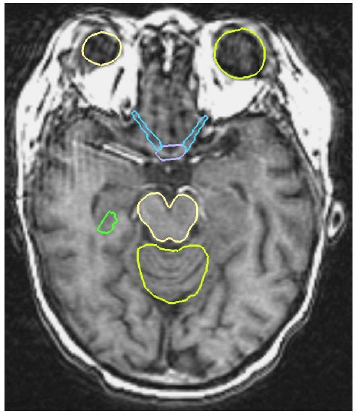
- Study of robustness of registration methods
  - With respect to registration parameters
  - Other type of validation

- Measure of quality of registration
  - Based only on images
  - Is a region well registered or not ?

# Perspectives

- Further validation
  - on more structures and more patients
  - Other quantitative measures
  - Fully quantitative validation in clinical conditions

- Taking into account pathology
  - Model the deformation caused by the tumor

# Questions