# A Registration-Based Atlas Propagation Framework for Automatic Whole Heart Segmentation

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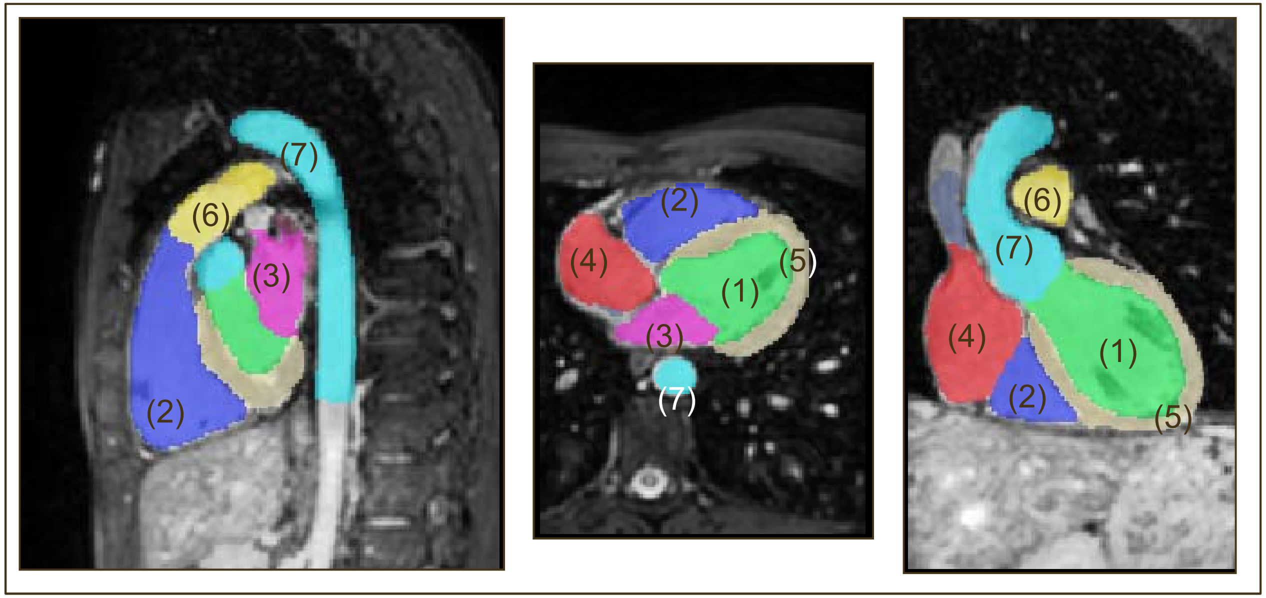
Fields-MITACS Conference on Mathematics of Medical Imaging: Cardiac image segmentation and registration

# Content

- Whole heart segmentation and challenges
- Whole heart segmentation framework
  - LARM: Locally Affine Registration Method
- Experiments and results
- Conclusion and extension works

# Whole heart segmentation and challenges

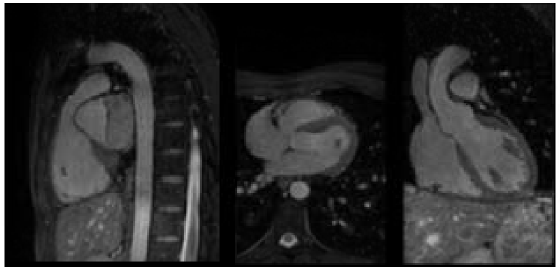
- Whole heart segmentation
  - Ventricle (myocardium)
  - Atria
  - And sometimes great vessels if needed



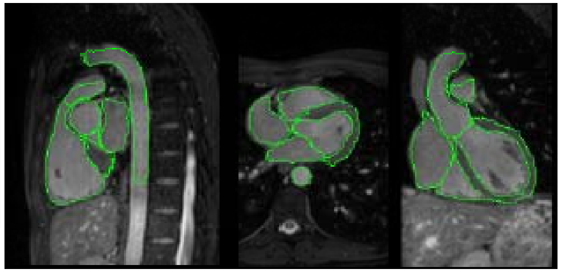

Left ventricle (1), right ventricle (2), left atrium (3), right atrium (4), myocardium (5), pulmonary artery (6), and aorta (7).

# Whole heart segmentation and challenges

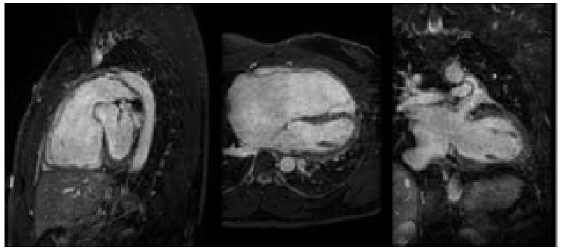
- Challenges of automation:
  - **Large shape variability**
  - Indistinct boundaries
  - Noise, artefacts, intensity inhomogeneity



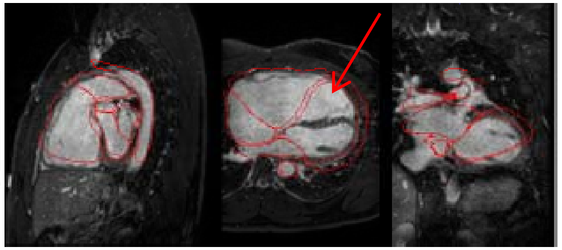
(a)



(b)



(c)



(d)

(a) MR image from a healthy volunteer; (b) a successful segmentation of (a) using a model based segmentation ;
(c) MR image from a patient with right ventricle hypertrophy; (d) an erroneous segmentation of (c).

# Whole heart segmentation framework

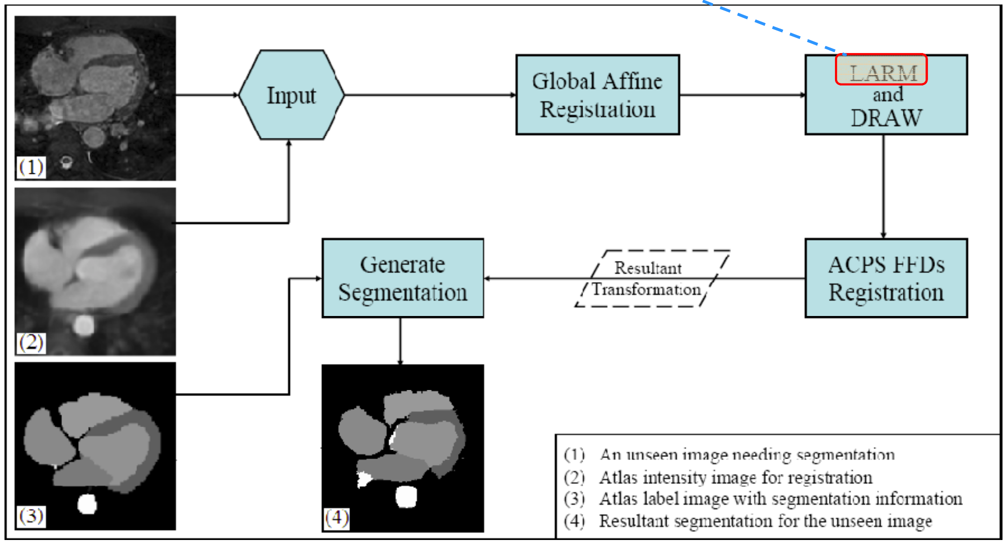
- Atlas propagation using image registration

Zhuang, X., *et al.*: An atlas-based segmentation propagation framework using locally affine registration -Application to automatic whole heart segmentation. *MICCAI* 2008

Zhuang, X., *et al.*: Free-Form Deformations Using Adaptive Control Point Status for Whole Heart MR Segmentation. Functional Imaging and Modelling of the Heart 2009

Zhuang, X., *et al.*: A Registration-Based Propagation Framework for Automatic Whole Heart Segmentation of Cardiac MRI. *IEEE Trans. Med. Imag.* 29 (9), 1612-1625, 2010.

LARM: locally affine registration method

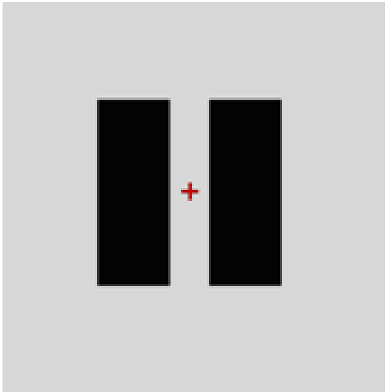



Shape from **an** atlas + LARM = model the variations for all cardiac images with different shapes

# LARM: Locally Affine Registration Method

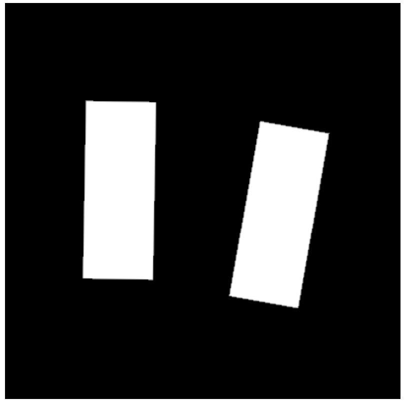
1. Difference intensity distribution (modality)

Test image



(a)

Ref image 1



(b)

Ref image 2

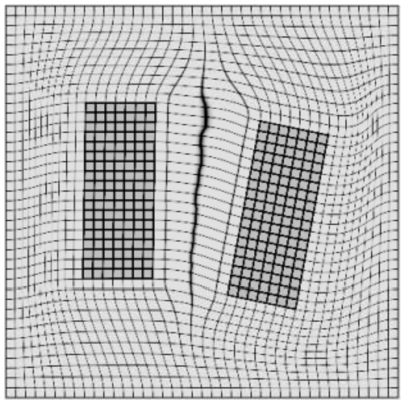
(c)

Locally affine transformation model:

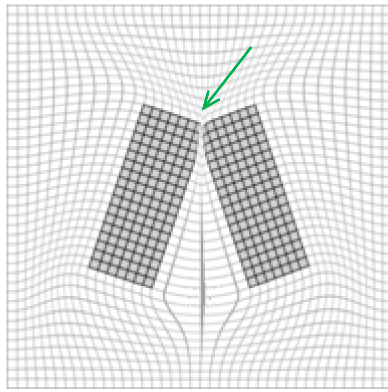
1) Pre-defined local regions

2) Assign an affine for each local region

Registration result: transformation field



(d)



(e)

2. Locally: preserve the affinity or maximally preserve the affinity

3. Globally: maintain diffeomorphic mapping

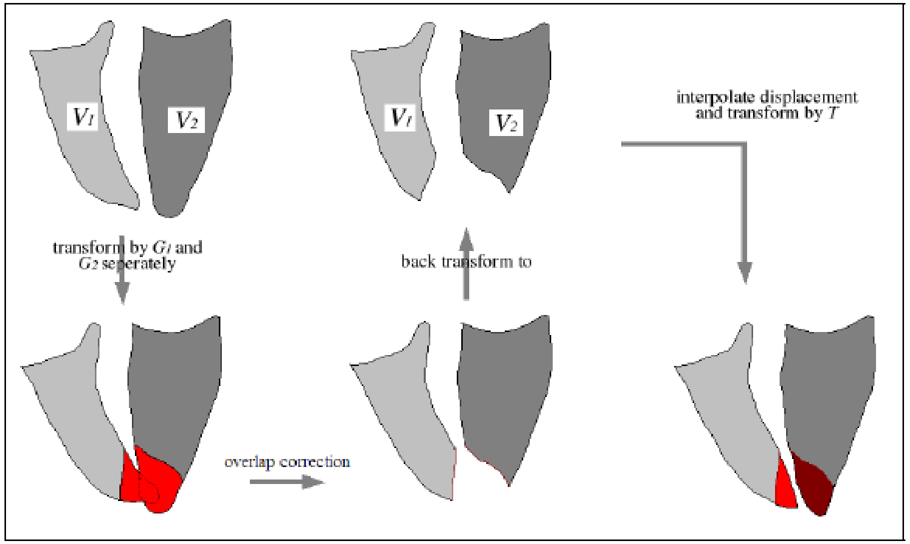
# LARM: Locally Affine Registration Method

- Locally affine transformation model

$$T(X)=\begin{cases} G_i(X), & X\in U_i,\ i=1\ldots n \\ \sum_{i=1}^{n} w_i(X)G_i(X_i), & X\notin \bigcup_{i=1}^{n} U_i \end{cases} \qquad w_i(X)=\left(1/d_i(X)^e\right)\Big/\left(\sum_{i=1}^{n} 1/d_i(X)^e\right)$$

Where $\{U_i\}$ and $\{G_i\}$ are local regions and assigned affine transformations and $\{w_i\}$ are normalized weighting functions, $d_i(X)$ is distance between $X$ and $U_i$.

1. **Region overlap** -> correction $V_i = G_i^{-1}(G_i(V_i) - \mathbf{DI}_L(R_{ij}))$



# LARM: Locally Affine Registration Method

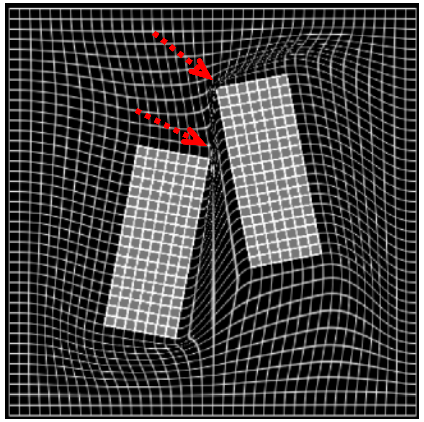
- Locally affine transformation model
  1. Region overlap
  2. **Folding caused by large displacements**

     -> Monitor Jacobian matrix

     and concatenation

     - Jacobian matrix:

$$J_T = \sum_{i=1}^{n} \frac{\partial w_i}{\partial x} G_i + \sum_{i=1}^{n} w_i \frac{\partial G_i}{\partial x} = \nabla \mathbf{W} \cdot \mathbf{G}^{\mathrm{T}} + \nabla \mathbf{G} \cdot \mathbf{W}^{\mathrm{T}}$$



     - Monitor the determinant: $\|J(T_c)\| < 0.5$
     - Whenever the condition is met, we apply current locally affine transformation result $T_c$ to the source/target image to generate a new one, and then reset the registration
     - Final transformation is the concatenation of each locally affine transformations: $T = T_1 \circ T_2 \circ \ldots \circ T_m$

Tool download: http://www.cs.ucl.ac.uk/staff/X.Zhuang/zxhproj.html
zxhlarm : locally affine registration method

# LARM: Locally Affine Registration Method

- Similarity measure
  - Mutual information

$$\mathrm{MI}(I_r, I_f) = H(I_r) + H(I_f) - H(I_r, I_f)$$
$$H(I_r, I_f) = -\sum_{r,f} p(r,f)\log p(r,f) \qquad (1)$$
$$p(i) = \sum_{x\in\Omega} \omega(I(x))$$

*I*: image intensity; *H*: entropy;

*p*: probability function; $\omega$ is parzen window function.

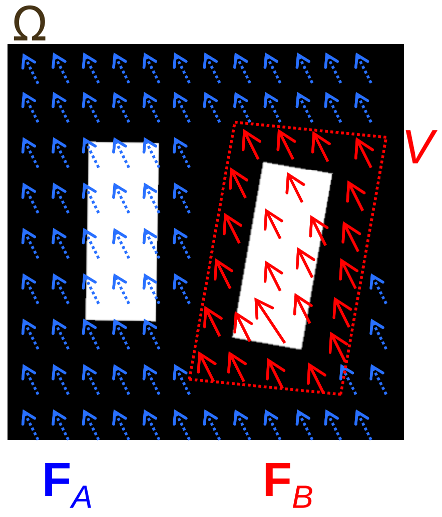
  - Computation of driving forces

$$\mathrm{F}_{\theta_i} := \frac{\partial H}{\partial \theta_i} = \left(-\sum_p (1+\log(p))\frac{\partial P_A}{\partial \theta_i}\right) + \left(-\sum_p (1+\log(p))\frac{\partial P_B}{\partial \theta_i}\right) = \mathrm{F}_A + \mathrm{F}_B \qquad (2)$$

$$p = P_A + P_B \qquad P_A = \sum_{x\in\bar{V}i}\omega(I(x)) \qquad P_B = \sum_{x\in Vi}\omega(I(x))$$

$$\longrightarrow \mathrm{F}_{\theta_i} := \mathrm{F}_B = -\sum_p (1+\log(p))\cdot\frac{\partial P_B}{\partial \theta_i} \qquad (3)$$

Save up to 100 times computation time in the 3D cardiac application without losing registration accuracy



# LARM: Locally Affine Registration Method

UCL

- Similarity measure
  - Mutual information

$$\mathrm{MI}(I_r, I_f) = H(I_r) + H(I_f) - H(I_r, I_f)$$
$$H(I_r, I_f) = -\sum_{r,f} p(r,f) \log p(r,f) \qquad (1)$$
$$\boxed{p(i) = \sum_{x \in \Omega} \omega(I(x))}$$

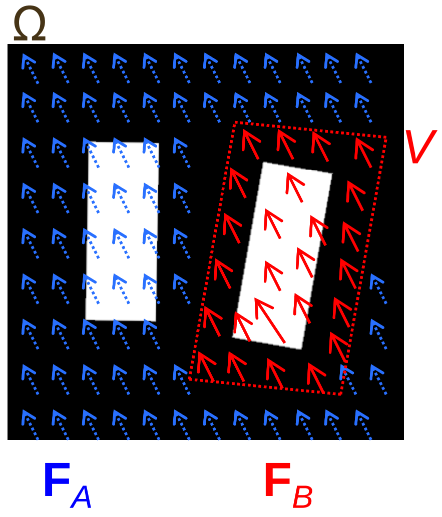
global intensity from Ω

  - Computation of driving forces

$$\mathrm{F}_{\theta_i} := \frac{\partial H}{\partial \theta_i} = \left( -\sum_p (1 + \log(p)) \frac{\partial P_A}{\partial \theta_i} \right) + \left( -\sum_p (1 + \log(p)) \frac{\partial P_B}{\partial \theta_i} \right) = \mathrm{F}_A + \mathrm{F}_B \qquad (2)$$

$$p = P_A + P_B \qquad P_A = \sum_{x \in \bar{V}i} \omega(I(x)) \qquad P_B = \sum_{x \in Vi} \omega(I(x))$$

$$\longrightarrow \mathrm{F}_{\theta_i} := \mathrm{F}_B = -\sum_p (1 + \log(\boxed{p})) \cdot \frac{\partial P_B}{\partial \theta_i} \qquad (3)$$




  - Different from region-based registration [Zhuang, et al. SPIE'08]
    - Each local region is extracted and registered to the target image separately

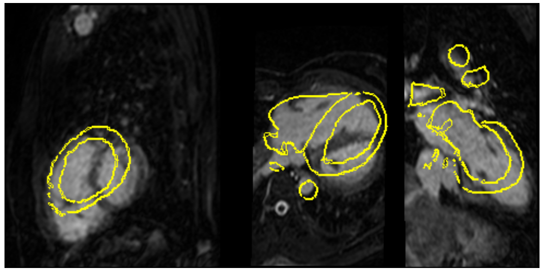
$$\mathrm{F}_{\theta_i} = -\sum_p (1 + \log(\boxed{P_B})) \cdot \frac{\partial P_B}{\partial \theta_i} \qquad (4)$$

local intensity from $V$

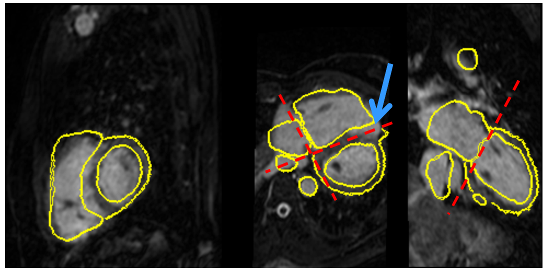
[Zhuang, et al.: In: SPIE Vol. 6914 Medical Imaging 2008: Image Processing, 6914, 07, 2008.]

# Application to whole heart segmentation

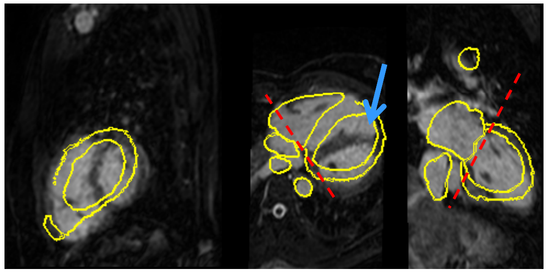
- Applied to whole heart segmentation for initialisation
  - Hierarchy scheme



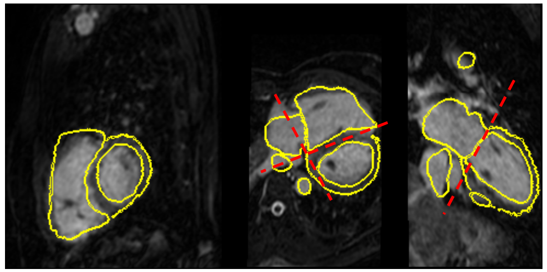
1) After global affine registration



3) After LARM of four regions



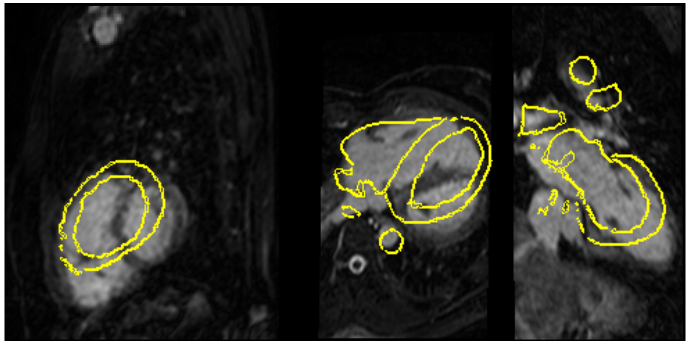
2) After LARM of two regions



4) After LARM of seven regions

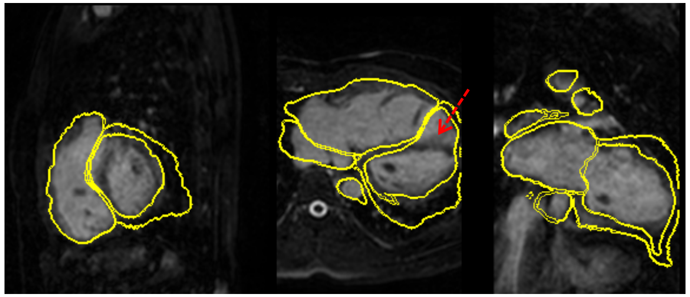
# Application to whole heart segmentation

Bad initialization by **global affine registration**



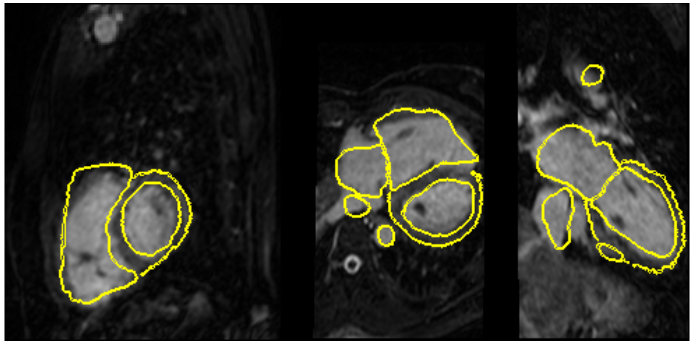
(a)

FFD nonrigid propagation result using
global affine registration for initialization



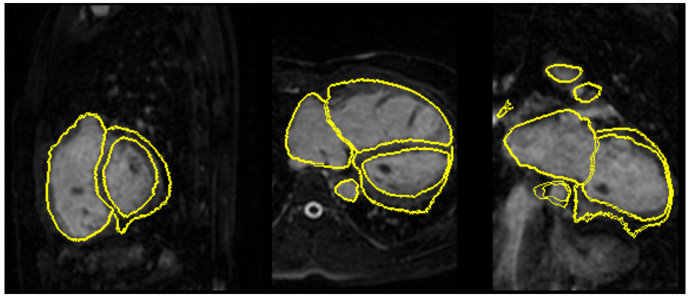
(c)

Good initialization by **locally affine registration method**



(b)

FFD nonrigid propagation result using
locally affine registration for initialization



(d)

# Whole heart segmentation framework

- Atlas propagation using image registration

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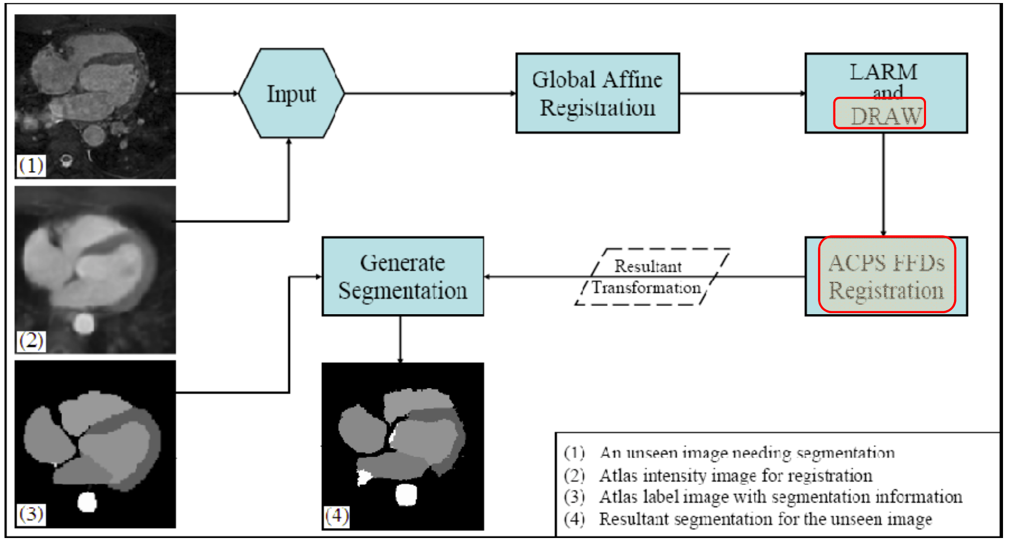
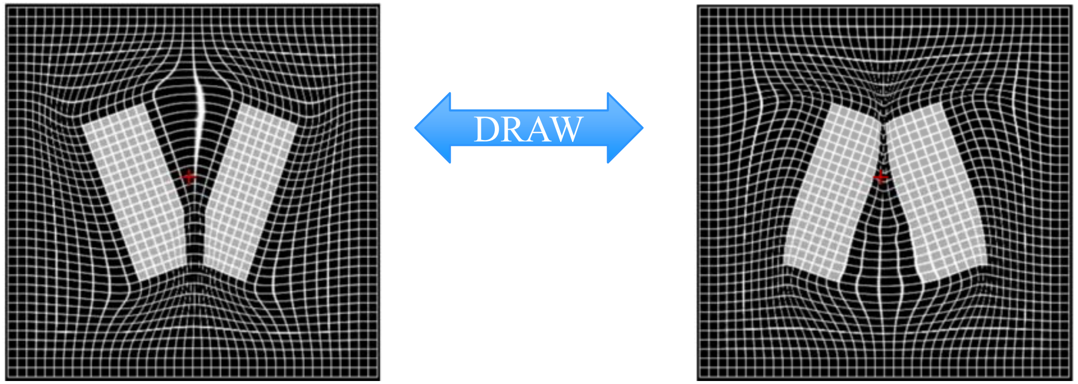



Shape from **an** atlas + LARM = model the variations for all cardiac images with different shapes

# Whole heart segmentation framework

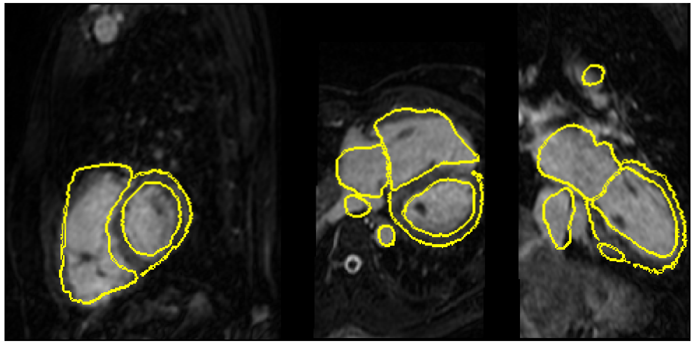
- **DRAW**: compute inverse transformation using Dynamic Resampling And distance Weighting interpolation
  - Maximal error is subvoxel for inverting dense displacements
  - Fast computation (~1minute for 3D cardiac application)



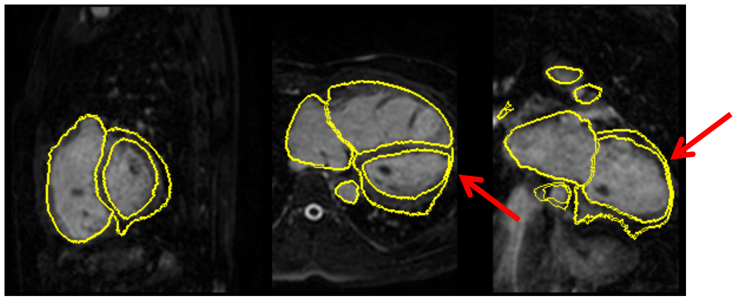
# Whole heart segmentation framework

- **ACPS FFDs**: free-form deformation registration with adaptive control point status
  - To incorporate prior knowledge for nonrigid registration

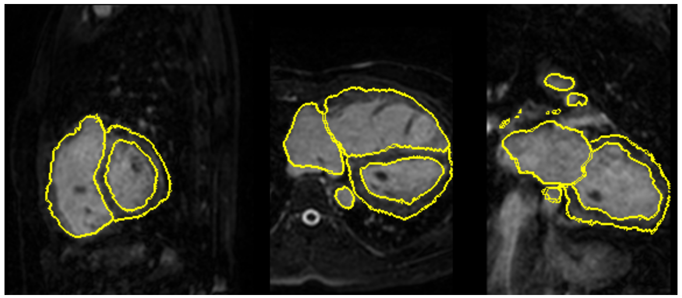
Good initialization by locally affine registration



FFD registration propagation result



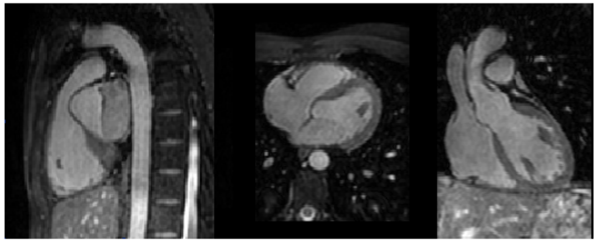
ACPS FFD registration propagation result

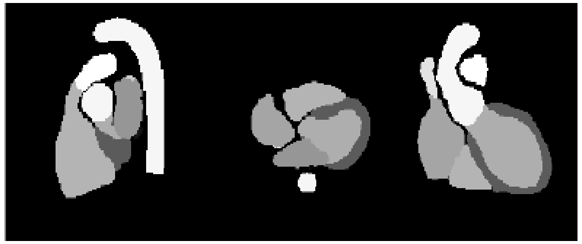


# Experiment&Result

- Data:
  - 3D cardiac MRI
  - A variety of pathologies and heart morphologies

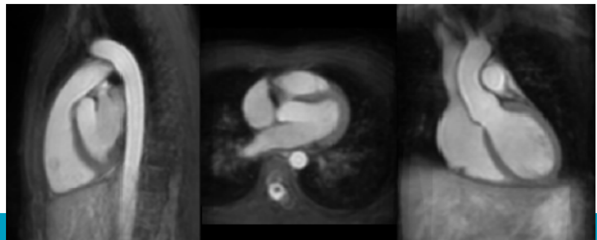
    19 of 37 with confirmed pathologies (from 9 different pathologies)
  - Manually segmentation for each case





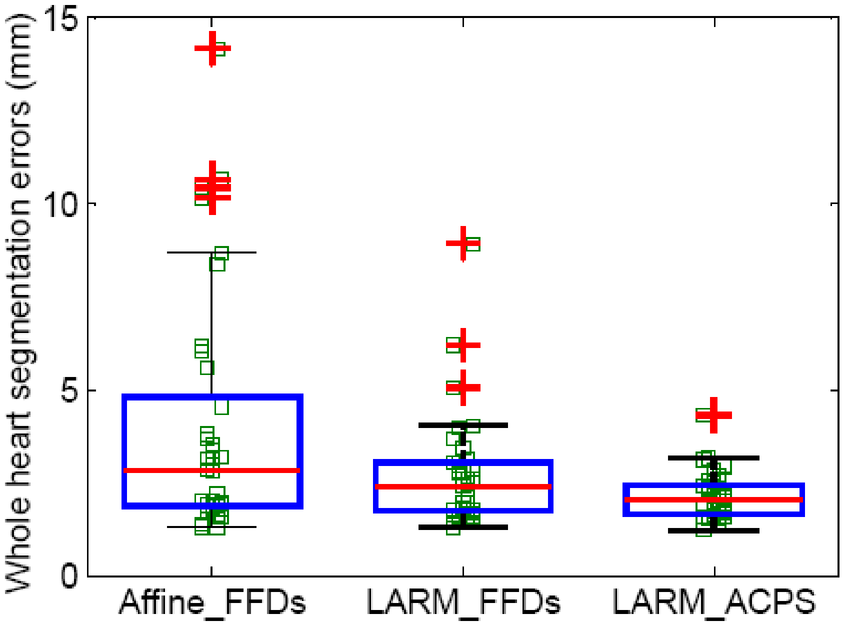
- Atlas:
  - One atlas intensity image and one label image
  - No statistical information for shapes, nor intensity distributions

Atlas intensity image

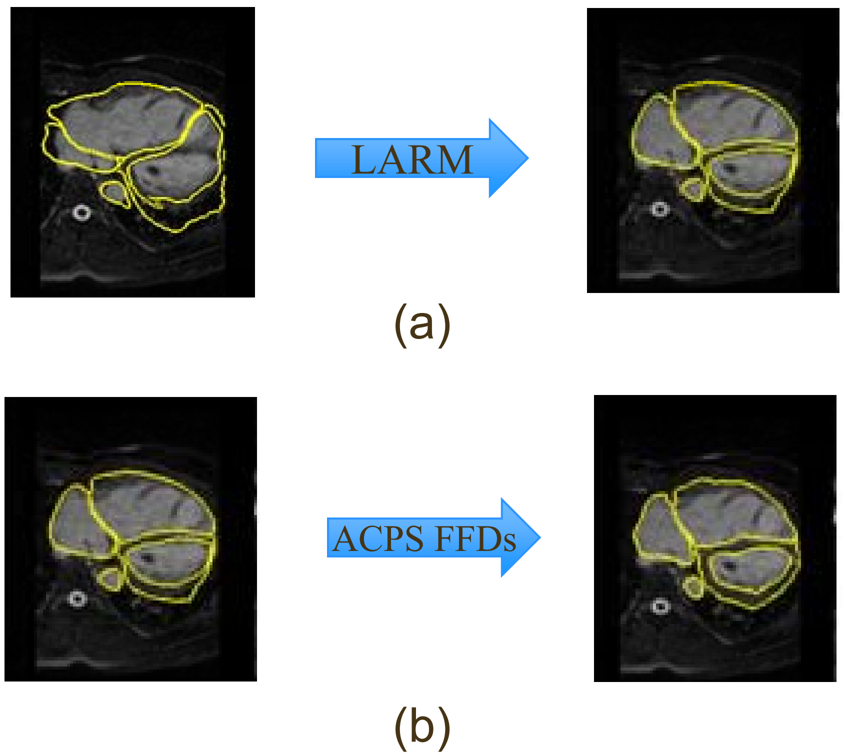


Atlas label image

- Propagation using alternative techniques
  - Affine_FFDs: global affine registration + traditional FFD registration
  - LARM_FFDs: global affine registration + LARM + traditional FFD registration
  - LARM_ACPS: global affine registration + LARM + ACPS FFD registration



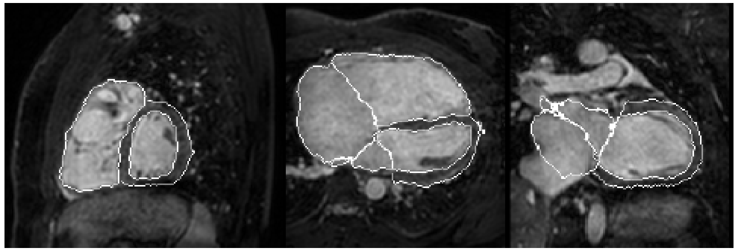

Box-and-Whisker diagrams of the whole heart segmentation errors using the RMS surface-to-surface error measure, the errors of the 37 cases using the three different segmentation frameworks.



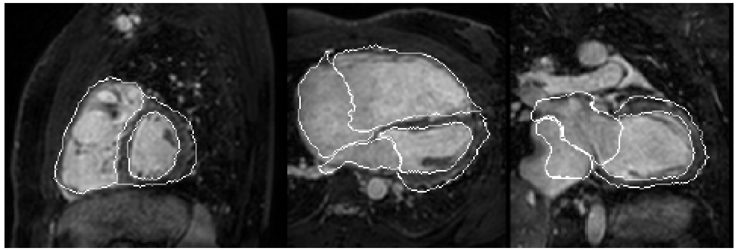

Zhuang, X., *et al.*: A Registration-Based Propagation Framework for Automatic Whole Heart Segmentation of Cardiac MRI. *IEEE Trans. Med. Imag.* 29 (9), 1612-1625, 2010.

# Experiment&Result

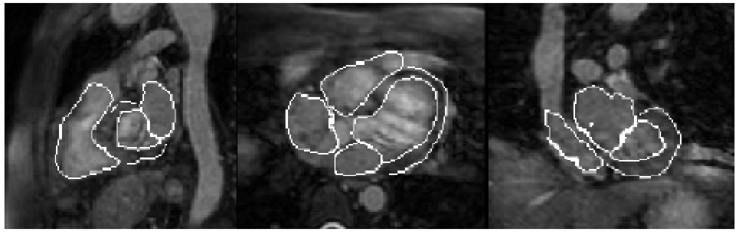
- Three worst cases



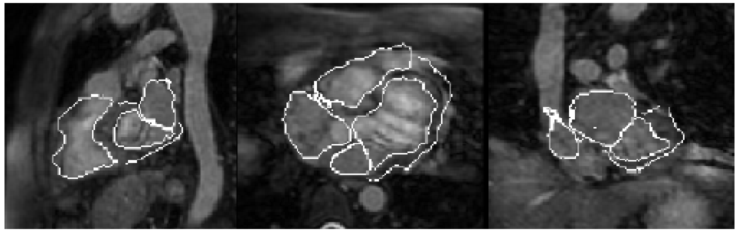
Subject-1, gold standard segmentation



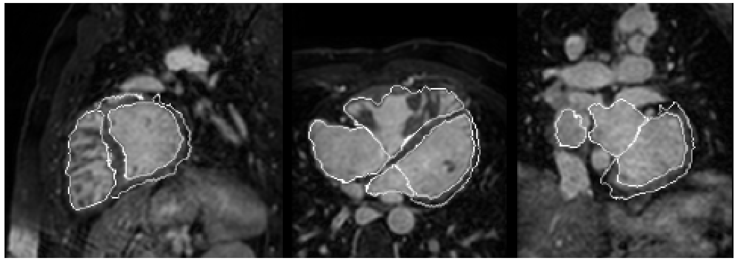
Subject-1, *LARM_ACPS* segmentation



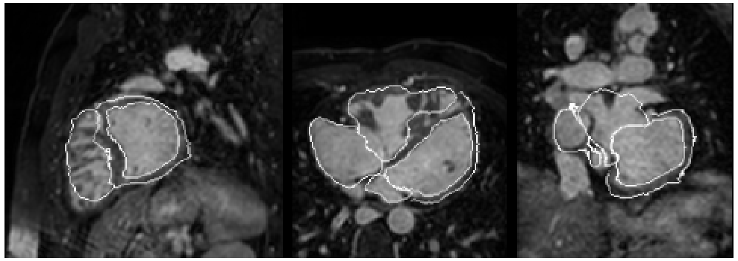
Subject-116, gold standard segmentation



Subject-116, *LARM_ACPS* segmentation



Subject-9, gold standard segmentation



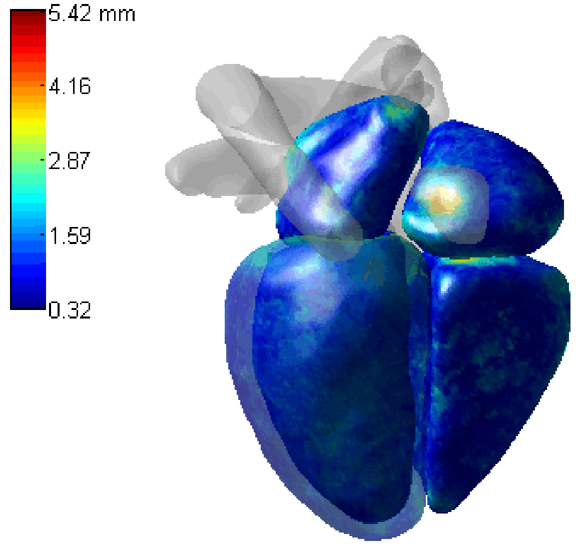
Subject-9, *LARM_ACPS* segmentation

The three worst cases by the three segmentation methods. Subject-1 is the worst case of the Affine FFDs, subject-116 is the worst case of LARM FFDs, and subject-9 is the worst case of LARM ACPS. Images are displayed with delineated contour superimposing on the MR images, in sagittal, transverse, andcoronary views. Subject-1 and subject-9 are pathological cases while subject-116 is a healthy case.

Zhuang, X., *et al.*: A Registration-Based Propagation Framework for Automatic Whole Heart Segmentation of Cardiac MRI. *IEEE Trans. Med. Imag.* 29 (9), 1612-1625, 2010.

# Experiment&Result

- Quantitative results
  - Color map of surface-to-surface errors of the whole heart segmentation
    (The 37 cases were mapped to a common space to compute the average error of them)




  - Visualize performance
    The big errors mainly distributed to the area of connections between substructures

Zhuang, X., *et al.*: A Registration-Based Propagation Framework for Automatic Whole Heart Segmentation of Cardiac MRI. *IEEE Trans. Med. Imag.* 29 (9), 1612-1625, 2010.

# Experiment&Result

- Quantitative results for all local region, using different error measures

| (error in mm) Structures | Affine_FFDs $\epsilon_{rms}$[max] | LARM_FFDs $\epsilon_{rms}$[max] | LARM_ACPS in different measures (ranges are of unit mm) $\epsilon_{rms}$[max] | $\epsilon_{mean}$ | $\epsilon_{std}$ | $0-2$ | $2-5$ | $>5$ |
|---|---|---|---|---|---|---|---|---|
| Left Ventricle | $3.79 \pm 4.38$[**19.6**] | $1.89 \pm 1.10$[**7.12**] | $1.47 \pm 0.32$ [**2.38**] | 1.06 | 1.02 | 82.9% | 16.5% | 0.6% |
| Left Atrium | $3.26 \pm 2.25$[**11.5**] | $2.81 \pm 1.65$[**9.28**] | $2.38 \pm 1.14$ [**7.33**] | 1.69 | 1.68 | 70.2% | 23.5% | 6.4% |
| Right Ventricle | $3.23 \pm 1.79$[**7.50**] | $2.75 \pm 1.51$[**8.57**] | $2.13 \pm 0.70$ [**4.05**] | 1.50 | 1.51 | 72.2% | 24.1% | 3.7% |
| Right Atrium | $3.06 \pm 1.74$[**9.44**] | $2.51 \pm 1.20$[**7.05**] | $2.22 \pm 0.75$ [**5.74**] | 1.51 | 1.62 | 73.0% | 22.5% | 4.5% |
| Epicardium | $4.78 \pm 4.88$[**20.4**] | $2.88 \pm 2.12$[**12.9**] | $2.32 \pm 0.82$ [**5.43**] | 1.69 | 1.60 | 68.6% | 25.7% | 5.6% |
| Whole Heart | $3.96 \pm 3.23$[**14.2**] | $2.71 \pm 1.50$[**8.93**] | $2.14 \pm 0.63$ [**4.31**] | 1.47 | 1.55 | 73.6% | 22.5% | 3.9% |

| Structures | Dice[min] | Overlap[min] | Diff(%)[max] | P-value (CI mL) | Pearson $R$ |
|---|---|---|---|---|---|
| Left Ventricle | $0.92 \pm 0.02$[**0.87**] | $0.85 \pm 0.04$[**0.78**] | $6.5 \pm 4.9$[**19.0**] | 0.028 (0.5,7.5) | 0.942 |
| Left Atrium | $0.81 \pm 0.10$[**0.47**] | $0.69 \pm 0.12$[**0.30**] | $14.1 \pm 12.0$[**48.4**] | 0.667 (-2.7,4.2) | 0.861 |
| Right Ventricle | $0.87 \pm 0.04$[**0.77**] | $0.77 \pm 0.06$[**0.63**] | $7.5 \pm 4.9$[**19.7**] | 0.048 (0.1,12.3) | 0.977 |
| Right Atrium | $0.84 \pm 0.05$[**0.71**] | $0.73 \pm 0.07$[**0.55**] | $9.0 \pm 7.2$[**28.7**] | 0.217 (-6.8,1.6) | 0.965 |
| Myocardium | $0.77 \pm 0.06$[**0.52**] | $0.63 \pm 0.07$[**0.35**] | $8.6 \pm 6.9$[**26.7**] | 0.940 (-4.7,5.1) | 0.892 |
| All substructures | $0.84 \pm 0.08$[**0.47**] | $0.73 \pm 0.10$[**0.30**] | $10.0 \pm 9.6$[**48.4**] | 0.097 (-0.3,3.7) | 0.974 |

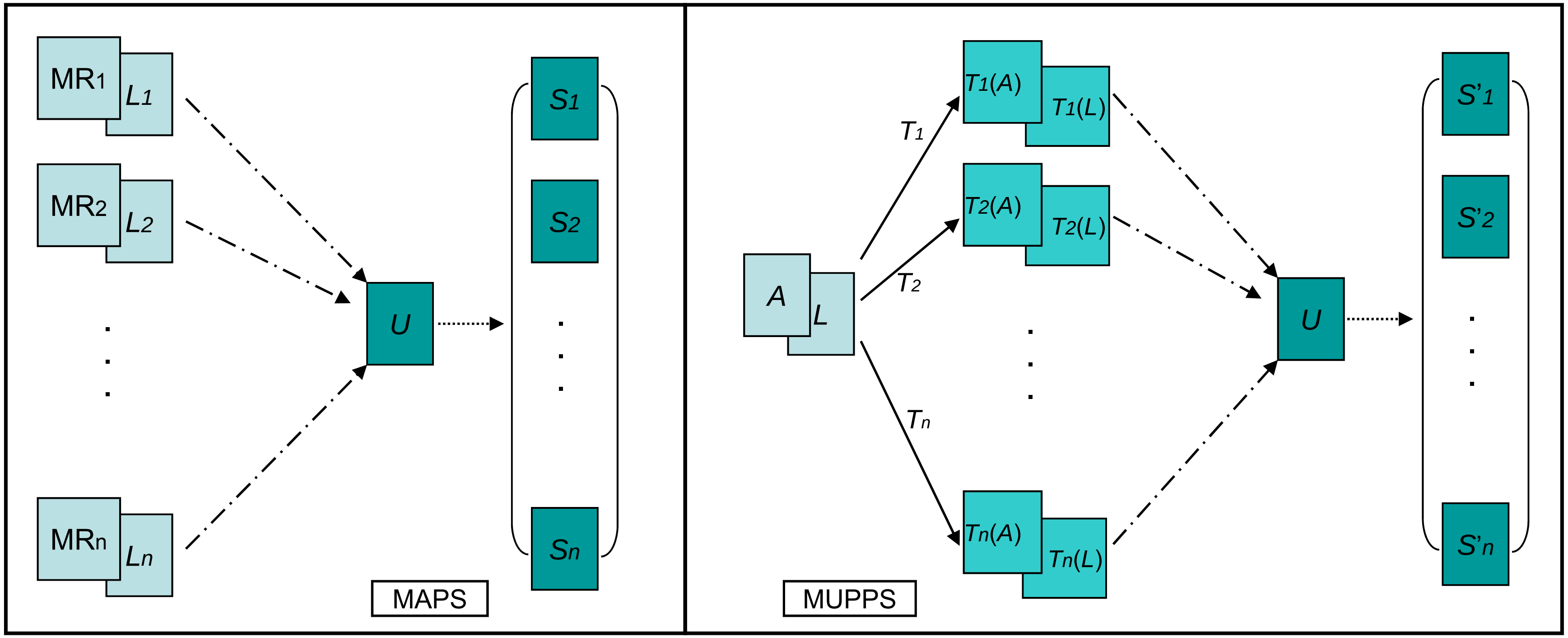
Zhuang, X., *et al.*: A Registration-Based Propagation Framework for Automatic Whole Heart Segmentation of Cardiac MRI. *IEEE Trans. Med. Imag.* 29 (9), 1612-1625, 2010.

# Conclusion &extension works

- Whole heart segmentation
  - Method
    - Localisation: global affine registration
    - **Initialisation**: Locally Affine Registration Method
      - Hierarchy scheme to increase the degree of freedom
      - Dynamic Resampling And distance Weighting interpolation
    - **Refine**: free form deformation registration with adaptive control point status
  - Validation: robust against a variety of pathologies

- Extension: to further improve accuracy
  - Multiple classification strategy
  - Refine with voxel-based classification techniques for accurate myocardium segmentation
  - Combining images from multiple MRI sequences for simultaneous segmentation

# Multiple-classifier scheme



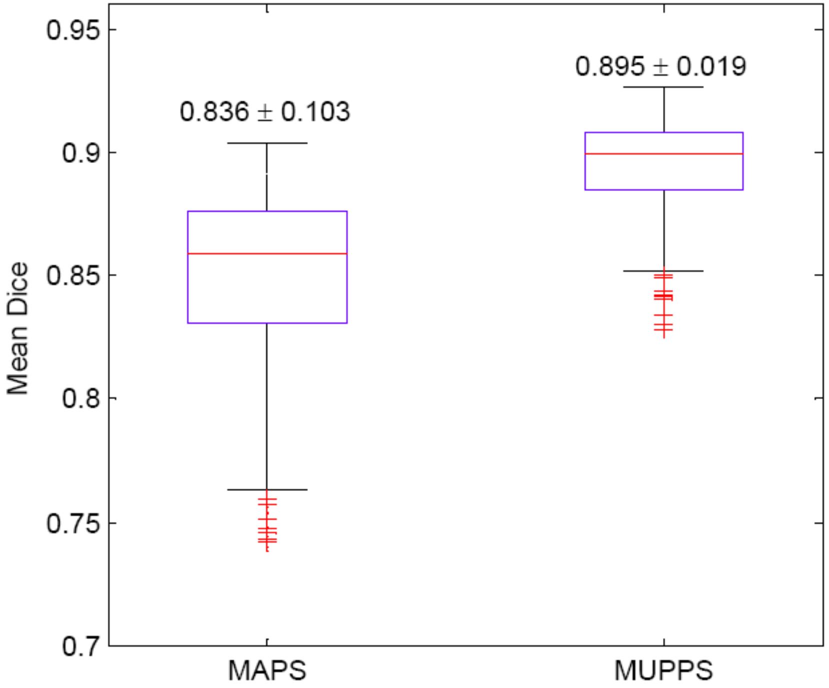

MAPS: multi-atlas propagation and segmentation

MUPPS: multiple path propagation and segmentation

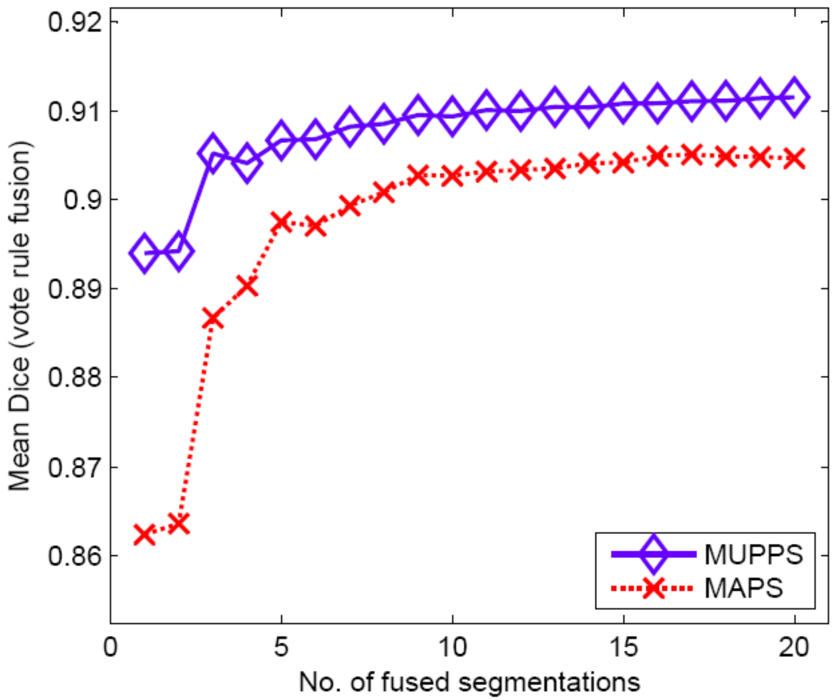
U: unseen images
A: atlas intensity image
{MR}: cardiac MR images
{L}: segmentation labels
{T}: deformation which initializes the propagation path
{S}: segmentation propagation results

[Zhuang, *et al.*: Whole Heart Segmentation of Cardiac MRI Using Multiple Path Propagation Strategy. MICCAI'10]

# Multiple-classifier scheme




Box-and-Whisker diagram of the Dice scores using MAPS and MUPPS.

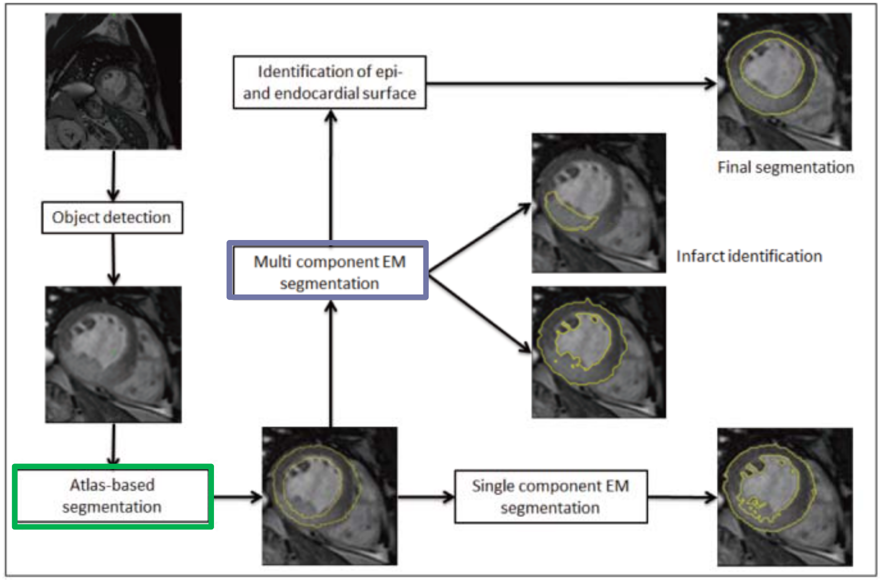


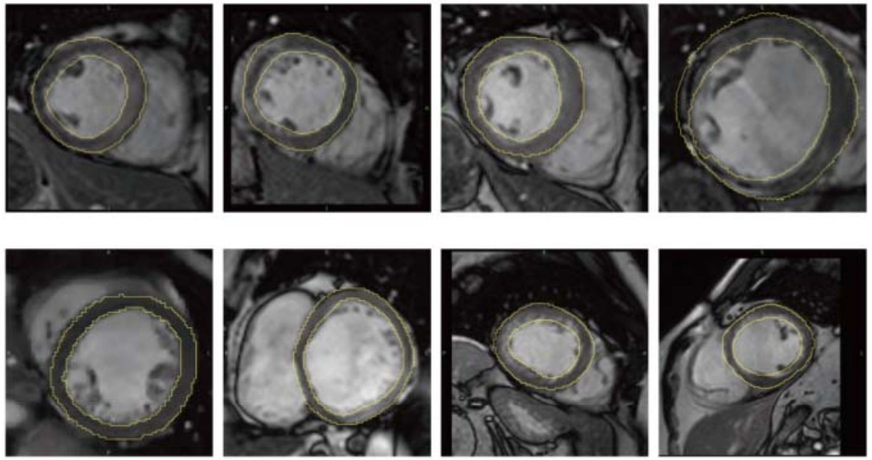

Dice scores from the VOTE fusion results of them

[Zhuang, *et al.*: Whole Heart Segmentation of Cardiac MRI Using Multiple Path Propagation Strategy. MICCAI'10]

# Myocardium segmentation

- Combine atlas propagation and voxel-based classification



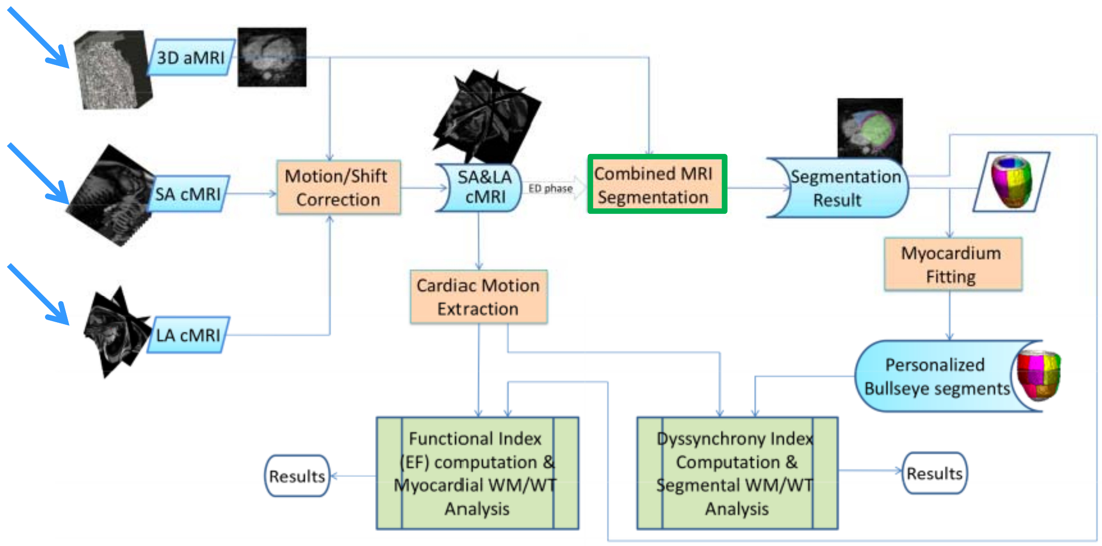



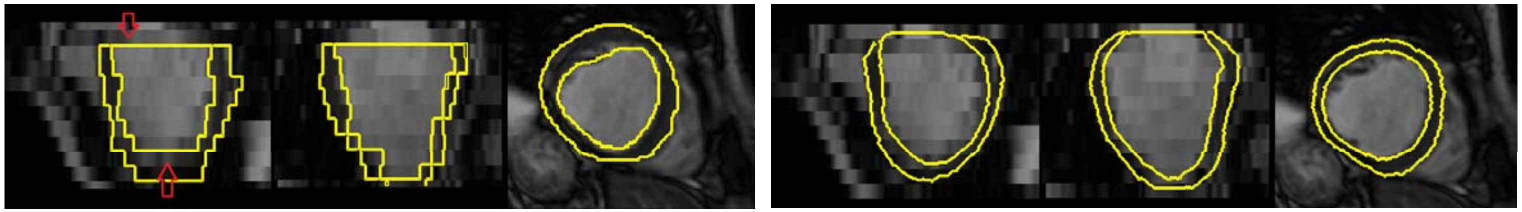
Randomly selected results of eight different patients
(from 90 subjects)

[Shi, Zhuang, et al. Automatic segmentation from cardiac cine MRI with different pathologies… FIMH'11]

# Combining multi-sequence

- Segmentation – extracting regions; Registration – motion tracking



Segmentation from single sequence (short-axis) Segmentation from multi-sequence MRIs
Red arrows point out the main difference by the two segmentation methods.