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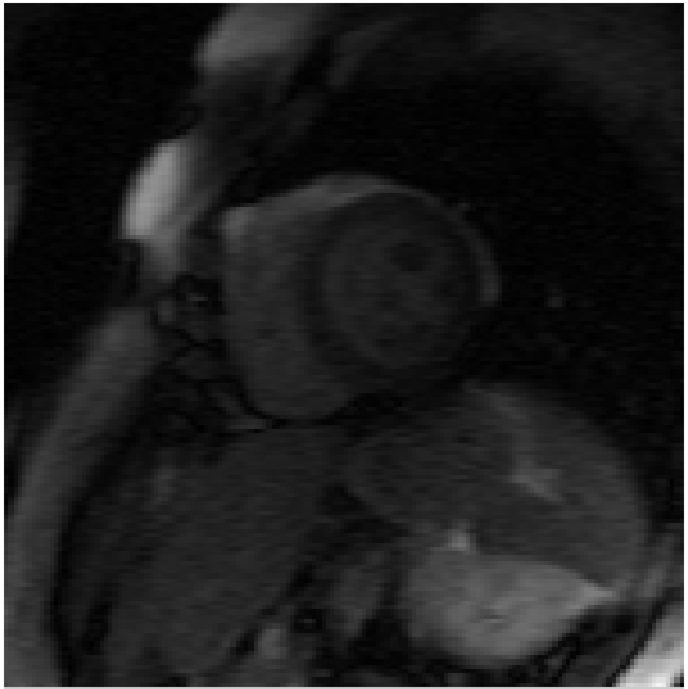
Stabilization of the Heart in Cardiac Perfusion MRI

Introduction

- A patient's heart moves and changes shape during cardiac perfusion MR imaging.
- To study the function of the heart in perfusion MRI, it is necessary to digitally stabilize the heart.



Introduction (cont'd)

- Challenge:
  - The intensity of the heart chamber changes as the blood with contrast agent flows into and out of the heart chamber.
- Requirement:
  - Develop an algorithm to stabilize the heart in a perfusion MRI so that it does not appear to move or change shape over time.
  - Visualize the stabilization results in video.

Method

- Automatically solve the problem in 3 steps:
  - Select reference frame and ROI
  - Initial alignment (global translation)
  - Nonrigid Registration

Select Reference Frame and ROI

- Find frames having good contrast;
- Thresholding & labeling;
- Look for the one that is least eccentric, most circular, and most convex – LV cavity;
- Define bounding box. [1]

Global Translation

- Challenge
  - Intensity/contrast change over time.
- Motivation
  - The orientation of the edges along tissue boundaries do not change much.
- Method
  - Contrast invariant similarity measure [2]
  - Obtain θ (direction) and M (magnitude) using a Sobel edge detector :

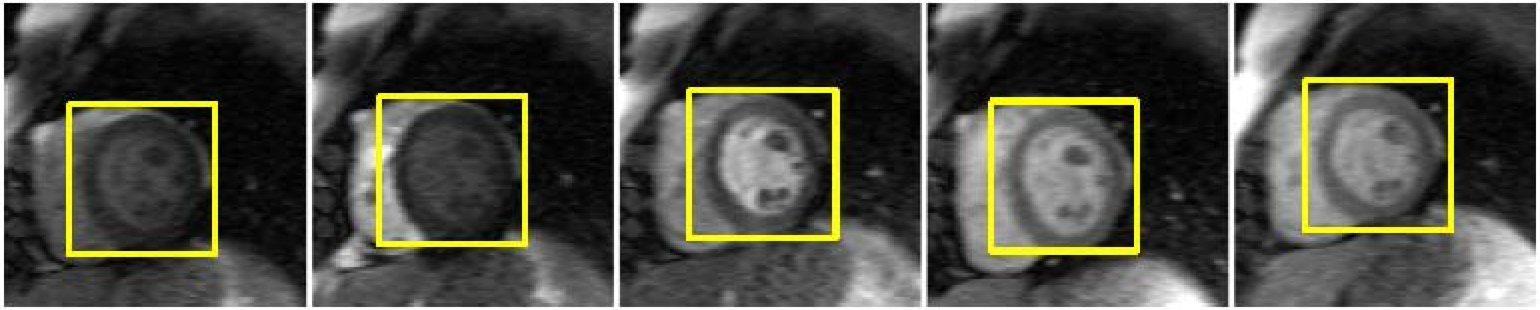
$$\Delta\theta(x,y;dx,dy) = \theta_c(x+dx,y+dy) - \theta_r(x,y),$$

$$w(x,y;dx,dy) = \frac{M_c(x+dx,y+dy)M_r(x,y)}{\sum_{(x,y)\in\mathcal{R}} M_c(x+dx,y+dy)M_r(x,y)}$$

$$S\,(dx,dy) = \sum_{(x,y)\in\mathcal{R}} w(x,y;dx,dy)\cos\left(2\Delta\theta(x,y;dx,dy)\right)$$

Global Translation (cont'd)

- Results of global translation.
  - Rigid motion has been compensated.
  - Still contains residue motion incurred by the local elastic deformation of LV. (See last 3 frames.)



Nonrigid Registration

- Challenge
  - Intensity/contrast change over time.
- Motivation
  - Instead of using one frame within the sequence as target, we generate a target sequence to match the intensity variation.
- Method
  - Use spatiotemporal constraints to estimate Pseudo Ground Truth.
  - Use demons [3] to register corresponding frames.

Energy Function

- Let ***H*** denote the deformation function, ***g*** denote the observed sequence, and ***f*** the pseudo ground truth. Then the Energy function is given by:

$$E(H(g), f) = E_d(H(g), f) + \alpha E_s(f) + \beta E_t(f)$$

  - $E_d(H(g), f)$ is the data fidelity term measuring the difference between ***H(g)*** and ***f***.
  - $E_s(f)$ is the spatial smoothness constraint for Pseudo Ground Truth ***f***.
  - $E_t(f)$ is the temporal smoothness constraint for ***f***.
  - α and β are positive scalars that control the weights of different terms.

Data Fidelity Term

- Let $\tilde{g}$ = *H(g)* denote the image sequence obtained by deforming ***g*** with ***H***, then the data fidelity term is:

$$E_d(H(g), f) = E_d(\tilde{\mathrm{g}}, \mathrm{f}) = (\tilde{\mathrm{g}} - \mathrm{f})^{\mathrm{T}}(\tilde{\mathrm{g}} - \mathrm{f})$$

Where

$$\tilde{\mathrm{g}} = \mathrm{vec}(\tilde{g}) = \mathrm{vec}(H(g))$$

is the column vector form of image sequence $\tilde{g}$.

Spatial Smoothness Constraint

- Pixels of the same tissue type have similar intensities in each frame of the sequence.
- We penalize the intensity difference of neighboring pixels:

$$E_s(f) = E_s(\mathbf{f}) = \sum_{k=1}^{K} (\mathbf{D}_k^s \mathbf{f})^{\mathrm{T}} \mathbf{W}_k (\mathbf{D}_k^s \mathbf{f})$$

- K=4 is the number of neighboring pixels being considered.
- $\mathbf{D}_k^s$ is the first order spatial derivative operator.
- W_k is the corresponding weight matrix to make sure intensity differences between neighboring pixels of different tissue types are not penalized.

Temporal Smoothness Constraint

- The intensity increase/decrease step-size does not vary much during the same perfusion phase.
  Therefore, the second order time derivative of the pseudo ground truth is penalized:

$$E_t(f) = E_t(\mathbf{f}) = (\mathbf{D}_2^t \mathbf{f})^{\mathrm{T}} (\mathbf{D}_2^t \mathbf{f})$$

where $\mathbf{D}_2^t$ is the second order time derivative operator.

Energy Minimization

- Find *H* and *f* that minimize:

$$E(H(g), f) = E_d(H(g), f) + \alpha E_s(f) + \beta E_t(f)$$

- Expectation-Maximization.
  - 1) Fix *H*, optimize *f*.
  - 2) Fix *f*, optimize *H*.
  - 3) Repeat 1) and 2) until converge.

Energy Minimization (cont'd)

- Fix *H* , optimize *f*:
  - Let $\tilde{\mathbf{g}} = \mathrm{vec}(\tilde{g}) = \mathrm{vec}(H(g))$, we have

$$E = (\tilde{\mathbf{g}} - \mathbf{f})^{\mathrm{T}}(\tilde{\mathbf{g}} - \mathbf{f}) + \alpha \sum_{k=1}^{K} (\mathbf{D}_k^s \mathbf{f})^{\mathrm{T}} \mathbf{W}_k (\mathbf{D}_k^s \mathbf{f}) + \beta (\mathbf{D}_2^t \mathbf{f})^{\mathrm{T}} (\mathbf{D}_2^t \mathbf{f})$$

Then, let $\partial E / \partial f = 0$, we have

$$\left[\mathbf{I} + \alpha \sum_{k=1}^{K} \left({\mathbf{D}_k^s}^{\mathrm{T}} \mathbf{W}_k \mathbf{D}_k^s \right) + \beta {\mathbf{D}_2^t}^{\mathrm{T}} \mathbf{D}_2^t \right] \mathbf{f} = \tilde{\mathbf{g}}$$

which can be solved by using Gaussian elimination.

Energy Minimization (cont'd)

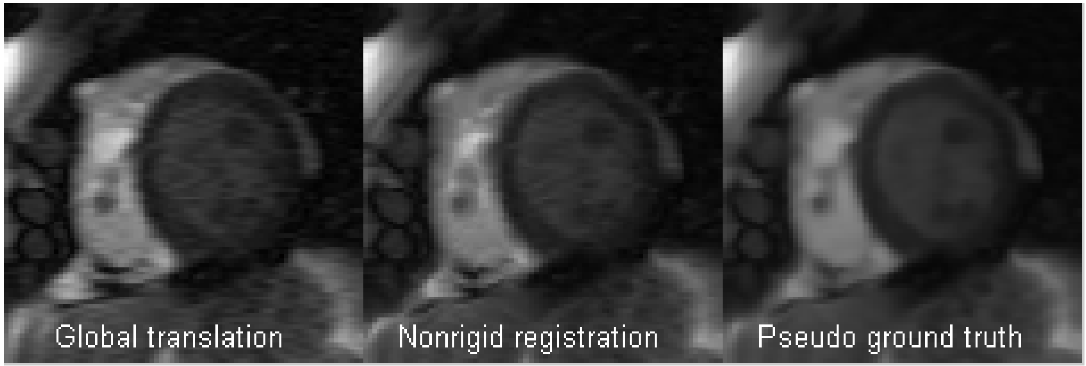
- Fix *f*, optimize *H*:
  - We use *demons* nonrigid registration algorithm [3] to find the deformation *H* from observed sequence *g* to the estimated Pseudo Ground Truth *f*.
  - *Demons* nonrigid registration algorithm estimates the deformation using a coarse-to-fine fashion.

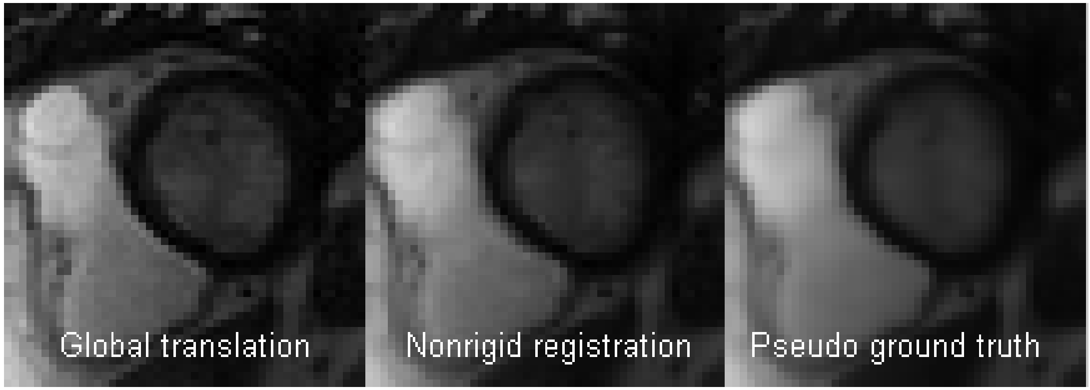
$$\vec{u} = \frac{(m-s)\vec{\nabla} s}{|\vec{\nabla} s|^2 + (m-s)^2}$$

  - In our implementation, *m* is the image sequence after global translation, *s* is the Pseudo Ground Truth (f).

Experimental Results

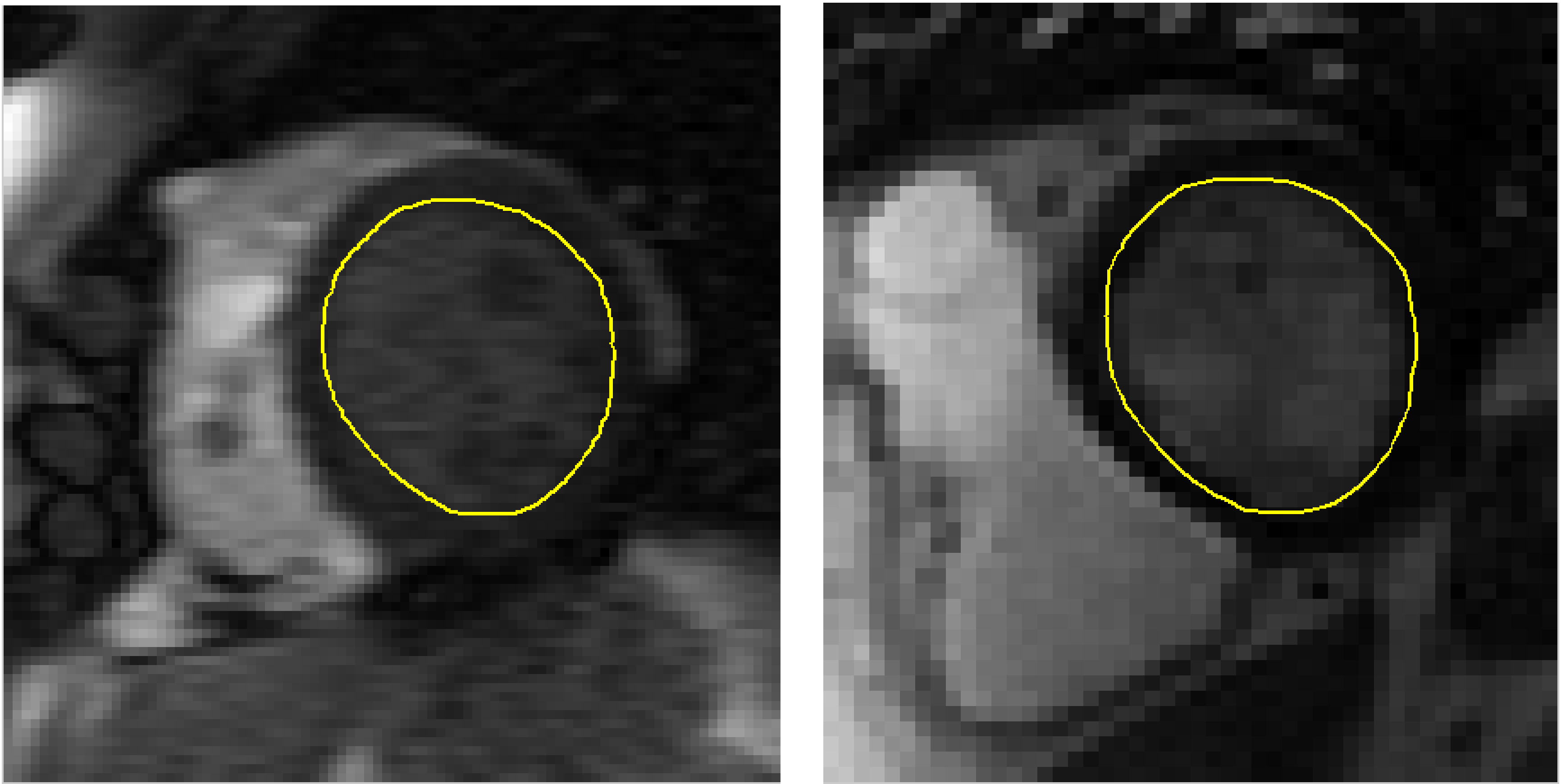
- Visualize the stabilization results in videos





Experimental Results (cont'd)

- Visualize the propagated contours.

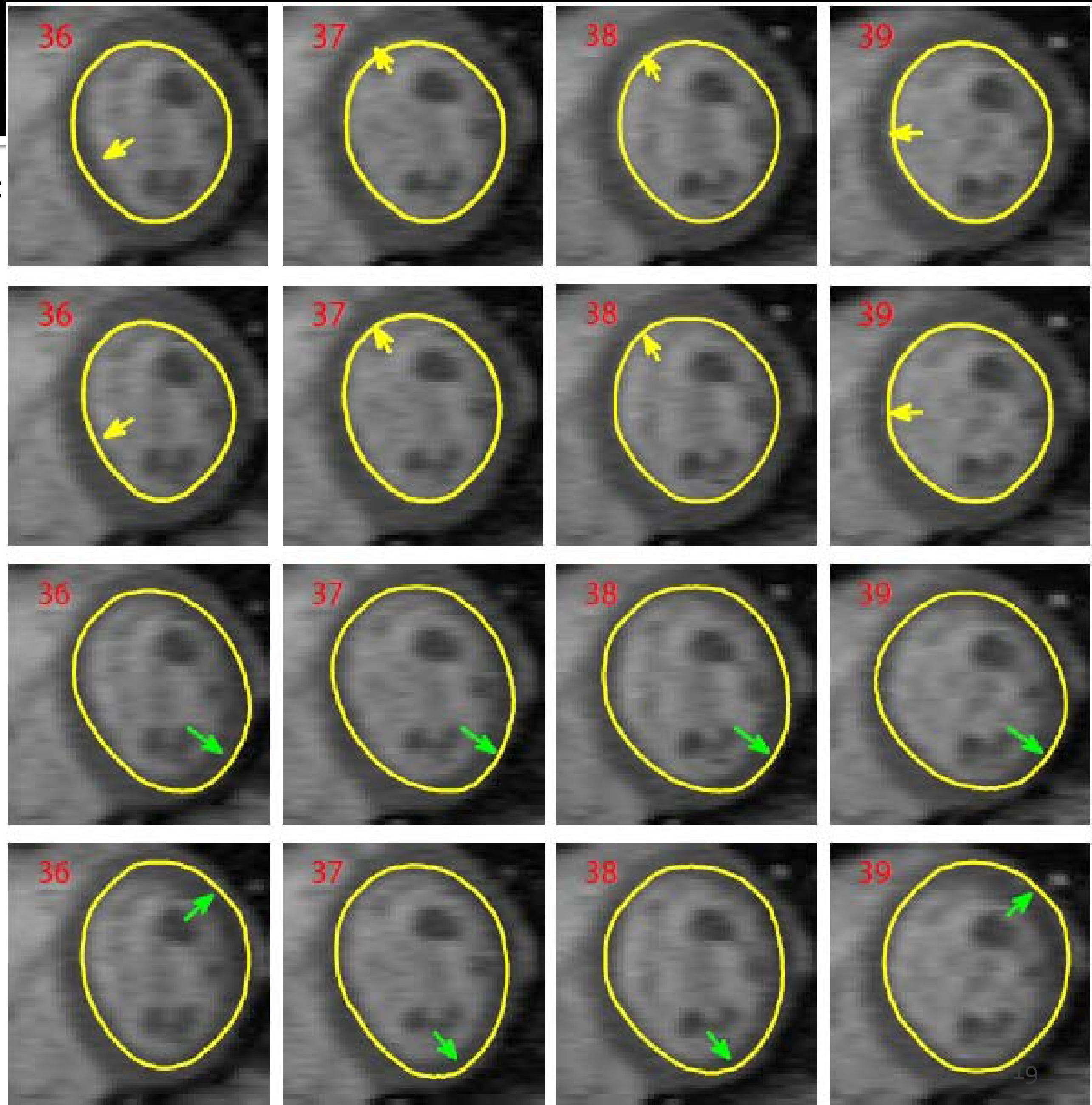


Conclusion

- Achievement
  - Stabilize both the heart's motion and shape;
  - Over the whole sequence;
  - Overcome the intensity change.
- Method
  - Nonrigid registration with pseudo ground truth.

Other Methods I have tried:

- Before nonrigid Reg.:
- Use Pseudo Ground Truth:
- Serial demons:
- FFD with Mutual Info.:



Reference

- [1]. Lorenz, C.H., Sun, Y., et al.Generation of MR myocardial perfusion maps without user interaction. ISMRM-ESMRMB '07
- [2]. Sun, Y., Jolly, M.P., Moura, J.M.F., Contrast-Invariant Registration of Cardiac and Renal MR Perfusion Images, MICCAI '04
- [3]. Thirion, J.P., Non-rigid matching using demons. CVPR '96