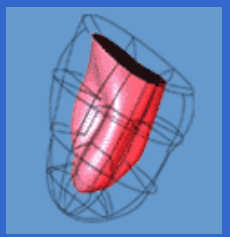
Dynamic Cardiac Information From Optical Flow Using Four-Dimensional Ultrasound Data



Qi Duan[1], Elsa D. Angelini[2], Susan L. Herz[1], Christopher M. Ingrassia[1], Olivier Gerard[3], Kevin D. Costa[1], Jeffrey W. Holmes[1], Shunichi Homma[4], Andrew F. Laine[1]

[1]Department of Biomedical Engineering, Columbia University, New York, NY, USA;

[2]Ecole Nationale Supérieure des Télécommunications, Département Traitement du Signal et des Images (TSI), Paris, France;

[3]Philips France, Suresnes, France;

[4]Department of Medicine, Columbia University, New York, NY, USA.

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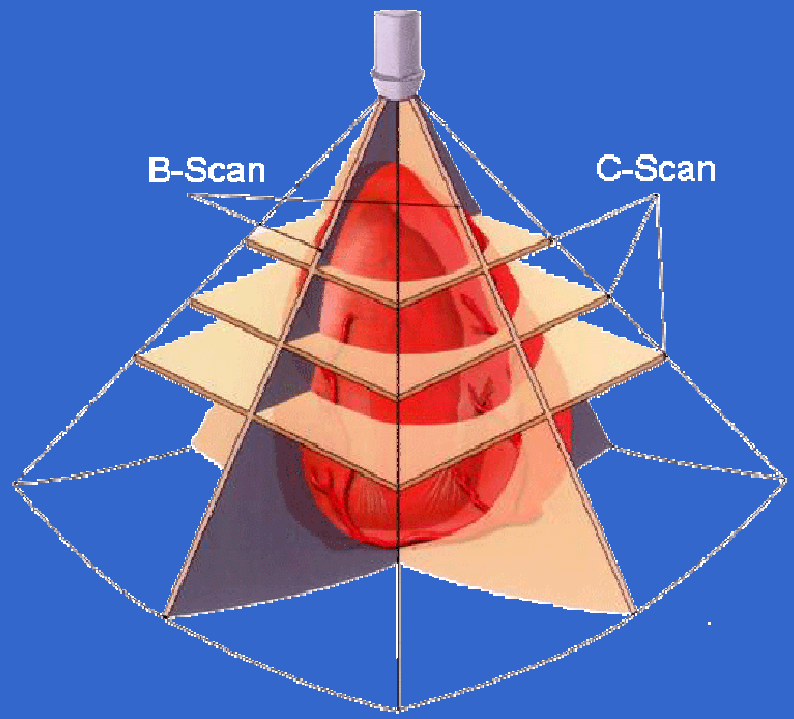
Outline

- Introduction to the clinical problem
- Method: Correlation-based optical flow
- Data: Real-time 3D ultrasound
- Results: Myocardium motion analysis
- Conclusion & Future work

Introduction

- 3D ultrasound based on matrix phased array transducer provides valuable and unique information.
- Abnormal ventricular wall motion can be detected via quantitative 4D analysis.
- Such analysis needs tracking and segmentation of ventricular surfaces



Data Rates:
~250MB/s for raw data

Introduction

- Manual segmentation is tedious, time-consuming, and impractical.
- Previous research from our group showed that optical flow can effectively track endocardial and epicardial surfaces.
- Optical flow provides a displacement field from which we derive several dynamic cardiac measurements.

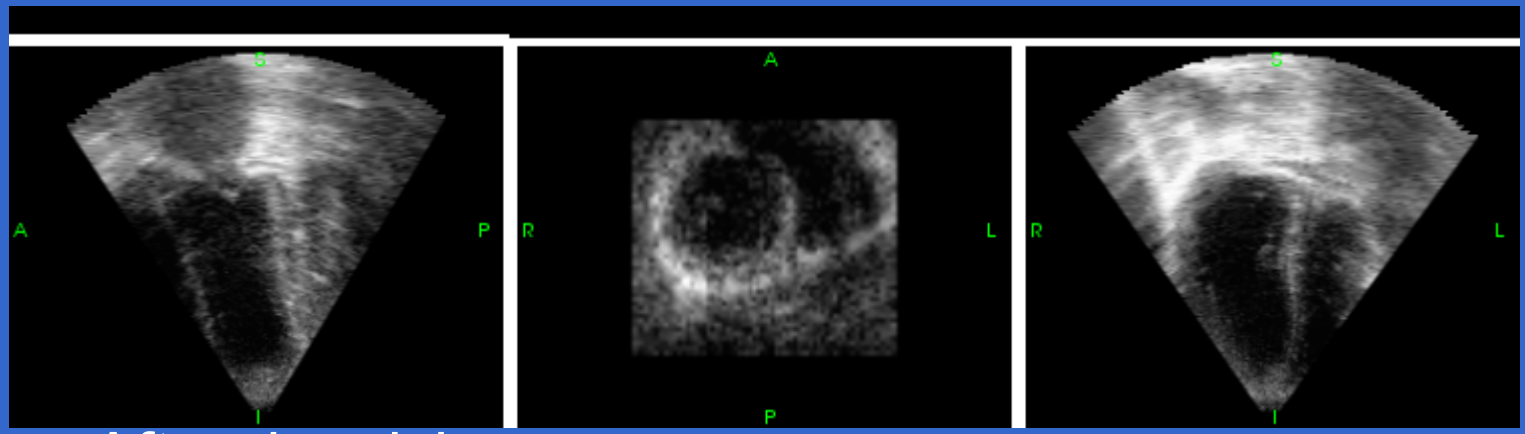
Pre-processing

- Presence of speckle noise complicates the interpretation of ultrasound images.

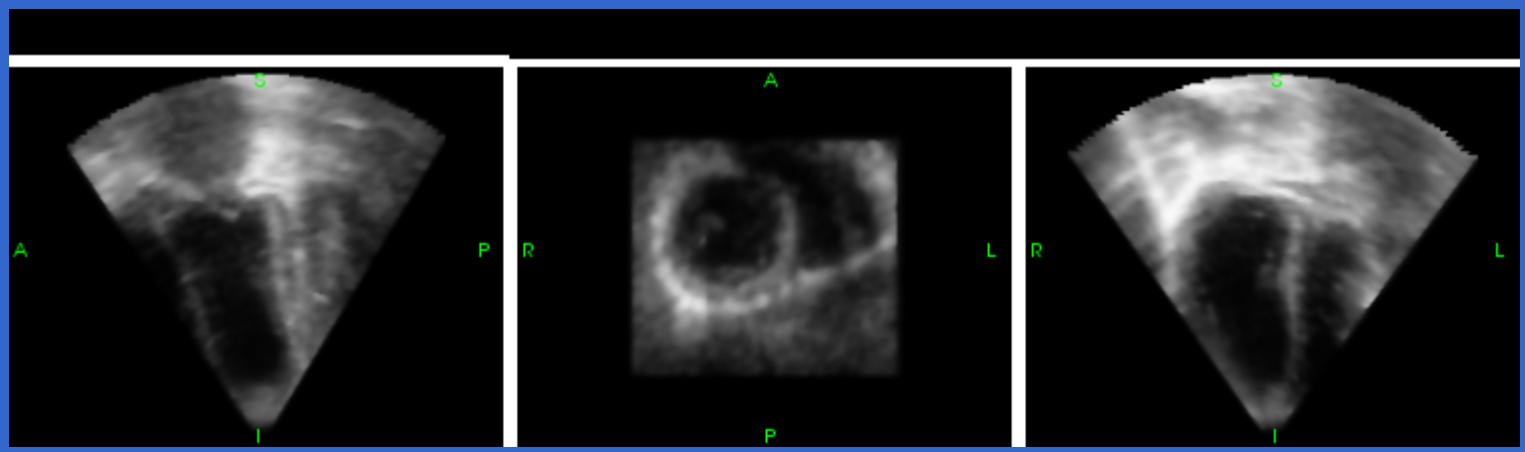
⇨ Pre-developed anisotropic diffusion filters with time-varying threshold was applied.

Pre-processing

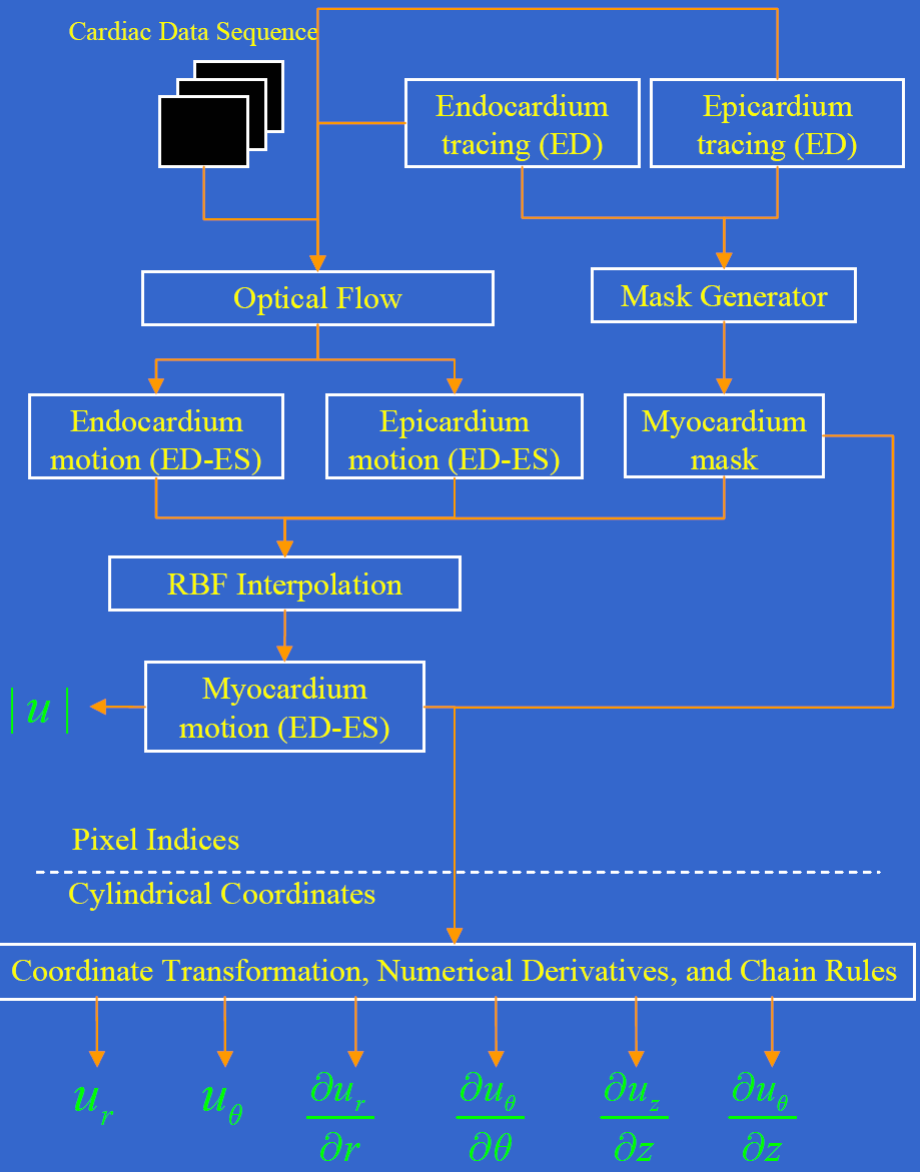
Before denoising



After denoising



Processing Flowchart



Initial Segmentation

- An expert performs manual tracing of endocardial and epicardial surfaces at end-diastole (1 frame) on :
  - rotating B-scan views (long-axis views)
  - parallel C-scan views (short-axis views).

Optical Flow

- Optical flow is defined as “displacement of apparent pixel intensity pattern”.
  ⇨ 3D correlation-based method.

- “Regularizing” parameters were added:
  - Variance threshold to avoid “aperture problem”.
  - Average threshold to avoid tracking dark regions.
  - Displacement vector field for each point on the surface is averaged within a 6-connected neighborhood to enhance robustness of the estimation.

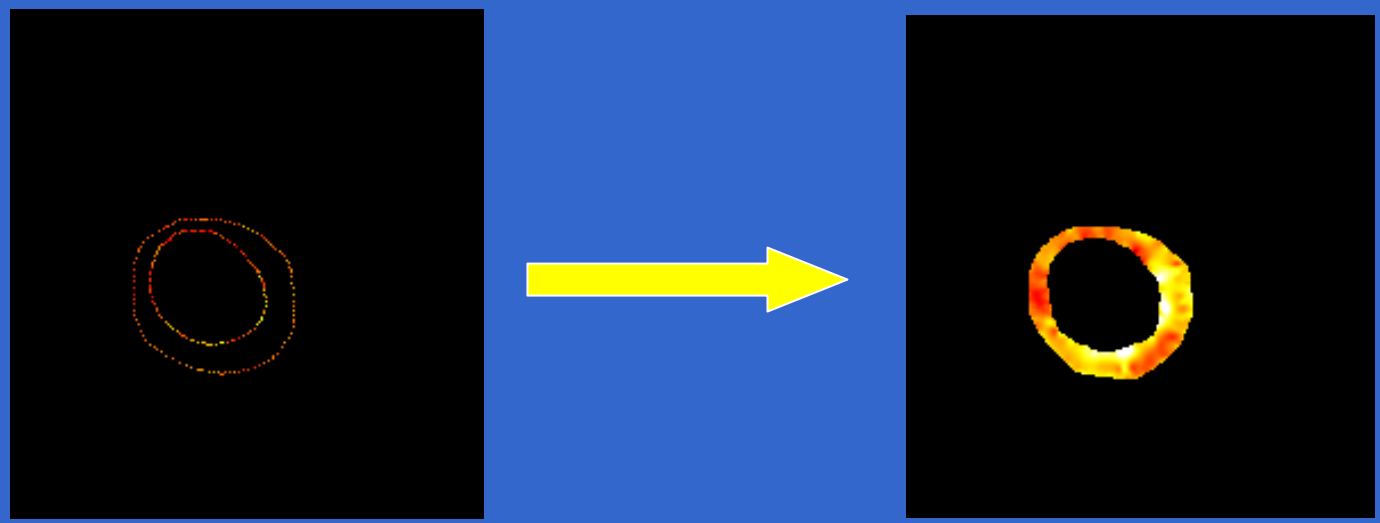
Surface Tracking

- Tracking was initialized at end-diastole (ED) with the manually traced surfaces.
- The endocardial and epicardial surface points were automatically tracked by optical flow through the systolic phase.

Motion Field Interpolation

Goal: Reconstruction of a continuous motion field based on scattered points.

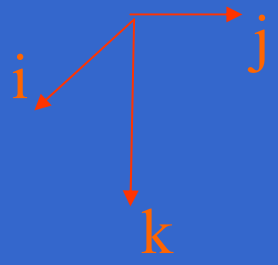
Method: Spatial interpolation with radial basis functions (thin-plate splines).

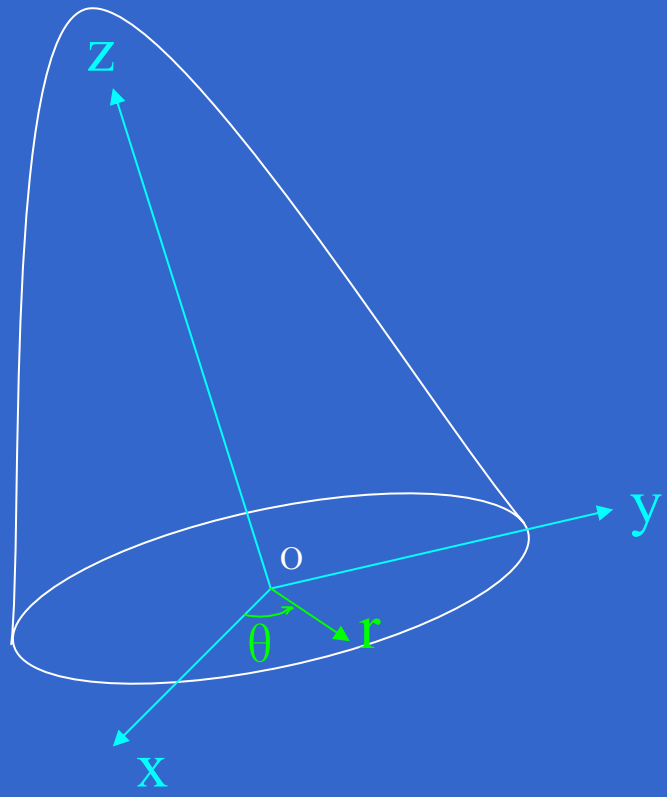


Motion field after myocardial surfaces tracking

Motion field interpolated inside the myocardium

Coordinates Systems





Pixel coordinates

Cartesian coordinates

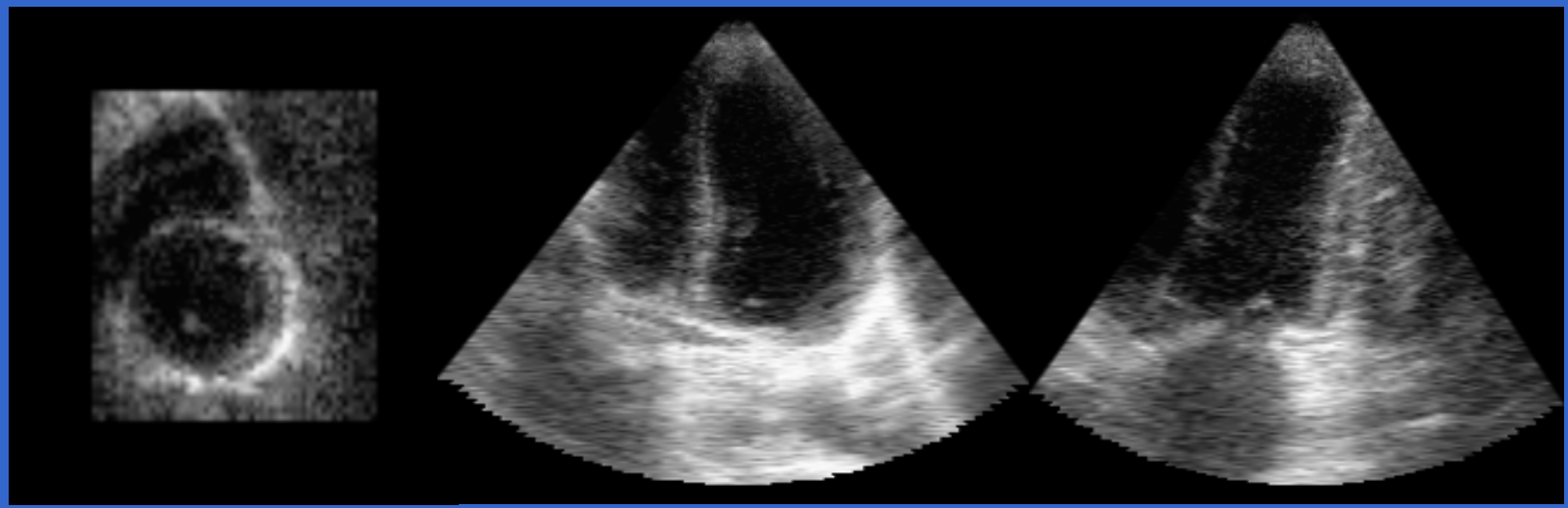
Cylindrical coordinates

Dynamic Cardiac Information

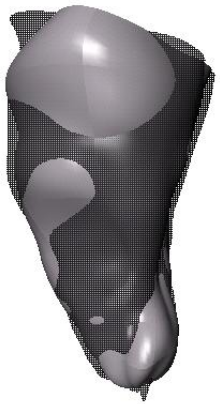
- Flow magnitude $|u|$ (mm)
- Radial displacement u_r (mm)
- Circumferential displacement u_θ (mm)
- Thickening $\frac{\partial u_r}{\partial r}$
- Circumferential stretch $\frac{\partial u_\theta}{\partial \theta}$
- Longitudinal stretch $\frac{\partial u_z}{\partial z}$
- Twist $\frac{\partial u_\theta}{\partial z}$

Experimental Data

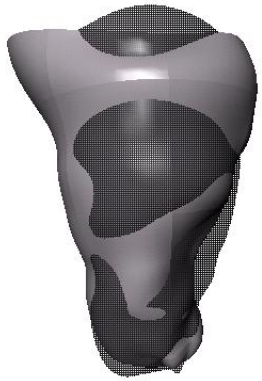
- Data acquired with a Philips SONOS 7500 3D ultrasound machine.
- Heart-transplant patient data set: $(0.8mm)^3$ and 16 frames per cycle.
- Data acquisition was triggered with EKG initialized at ED.
- Due to the limits of field of view, the epicardial surface was not visible at the apex.



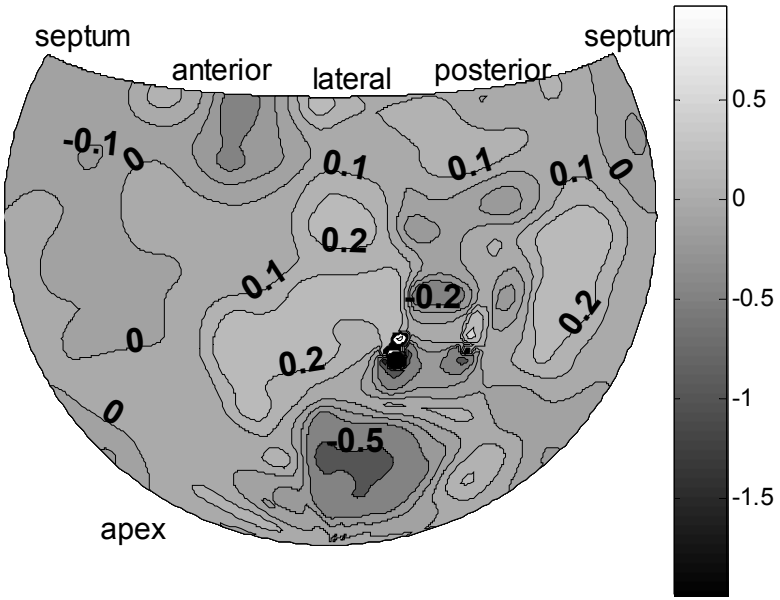
Experimental Results: Surface Tracking



Lateral view



Anterior view

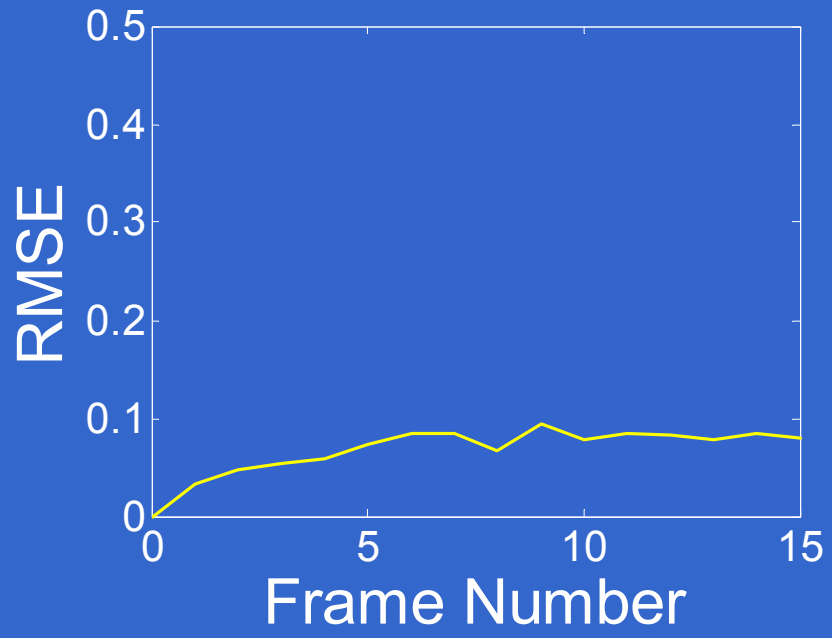


Results at end-systole:

- Volume:
  - Difference = + 2.51%
- Ejection Fraction:
  - EF_{manual} = 46%
  - Difference = -1.4%
- Surface agreement:
  - 47% with <5% difference
  - 73% with <10% difference
  - Average intra-user manual tracing difference: 17.43%.

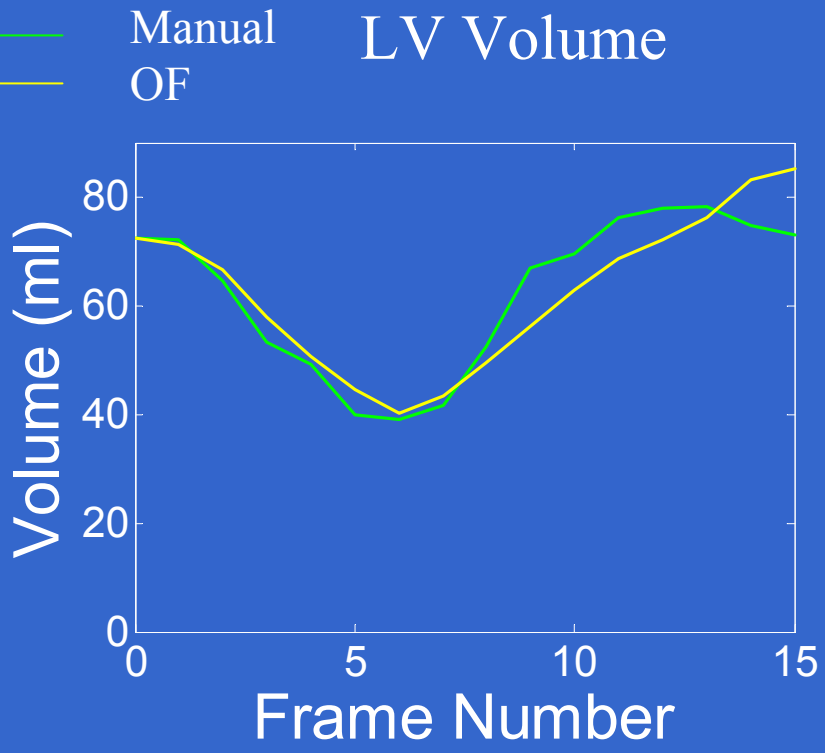
Experimental Results: Surface Error Comparison

RMSE



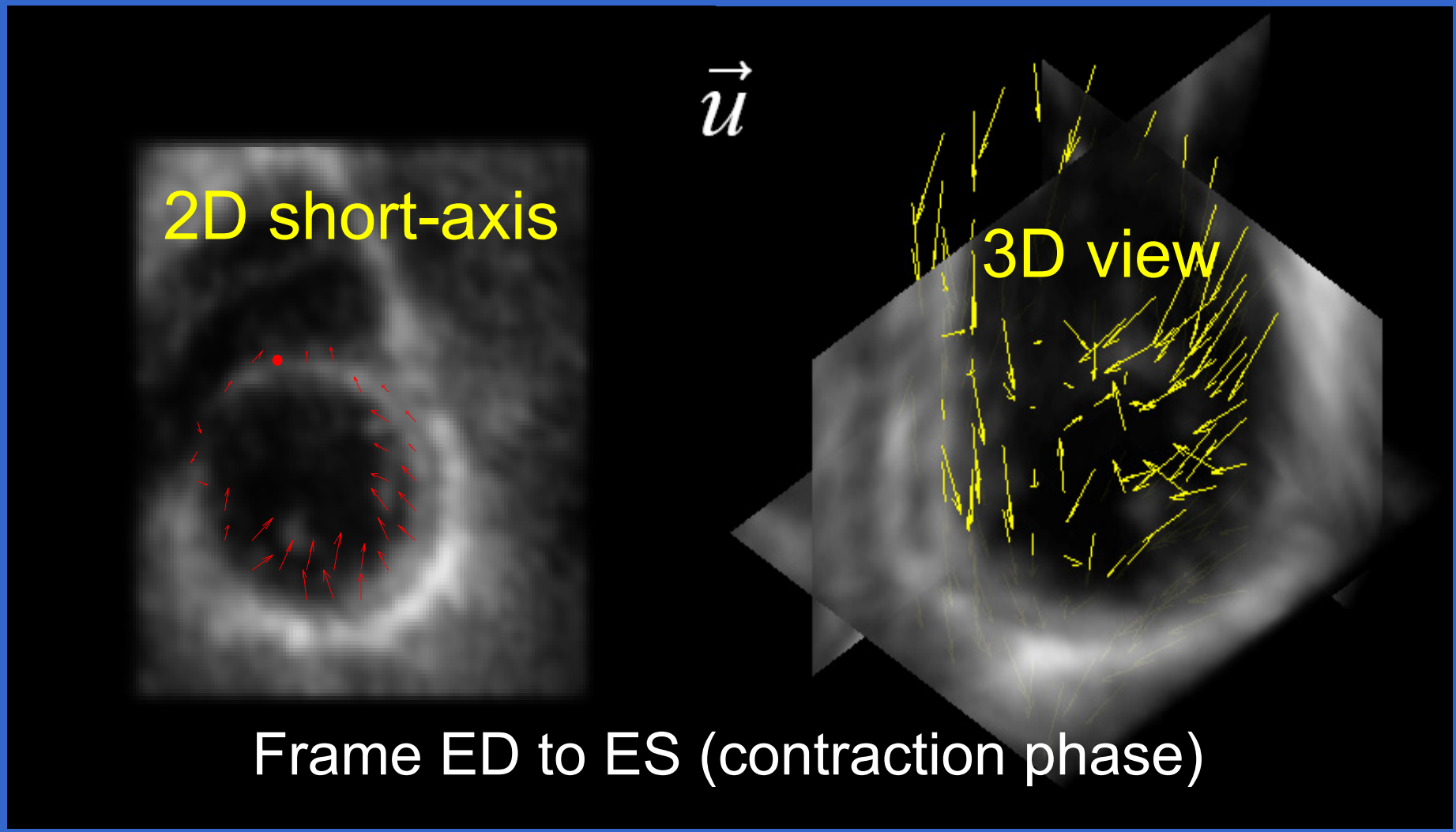
Maximum RMSE:
0.09 (frame 9)
(λ =0.6$\pm$0.2 at ED
λ = 0.5$\pm$0.2 at ES)

LV Volume

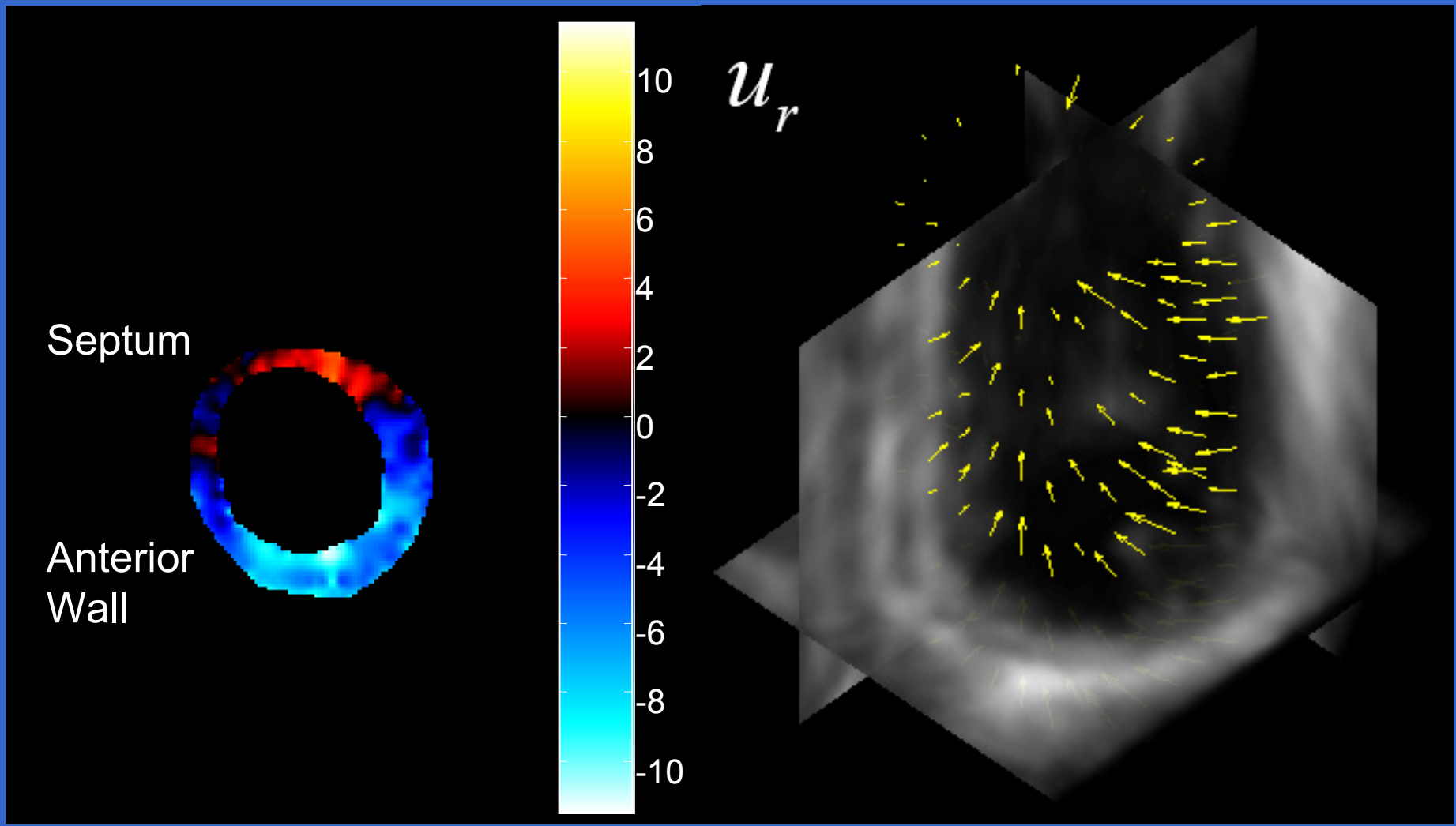


Maximum error:
10ml

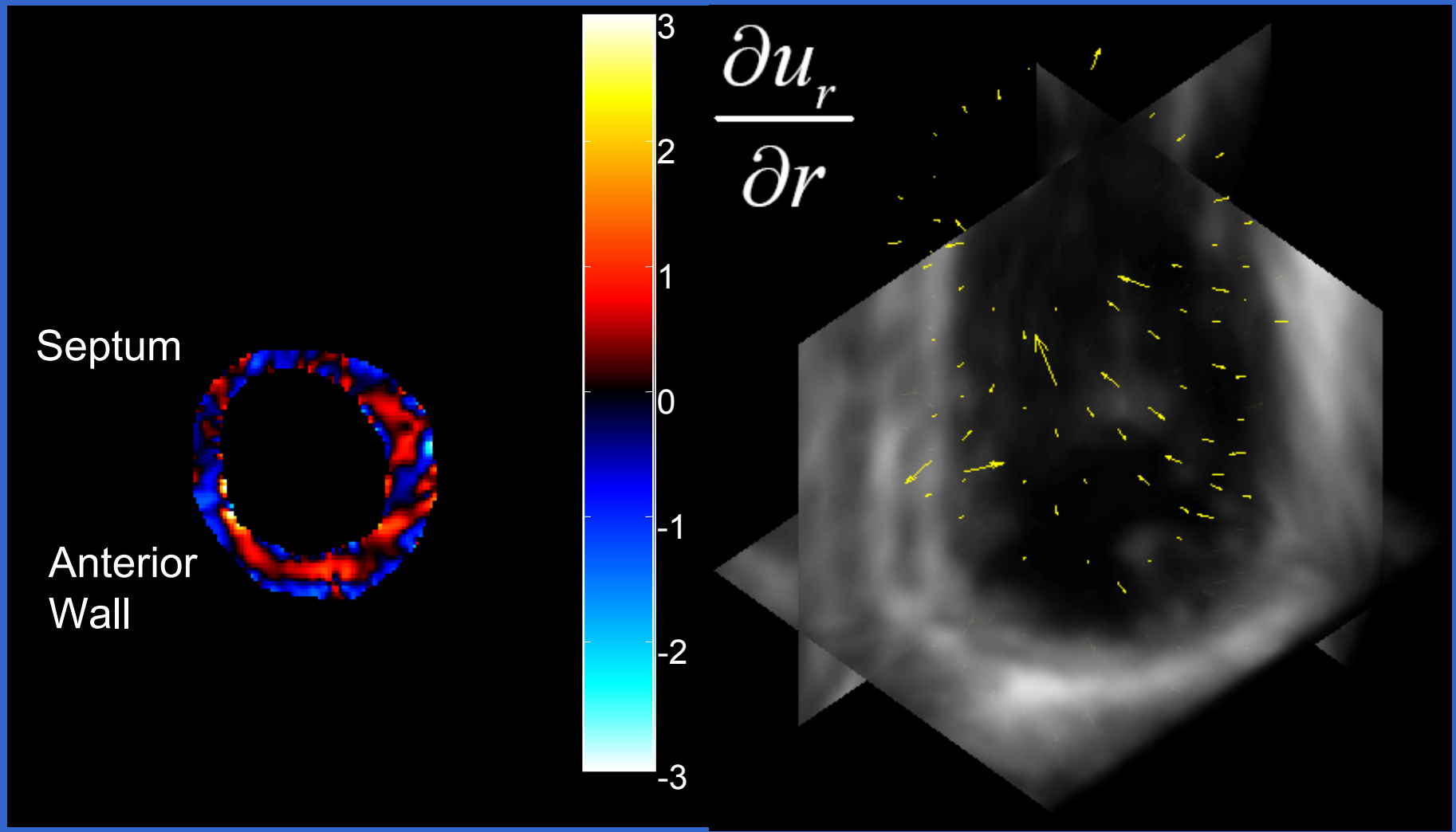
Experimental Results: Motion Field



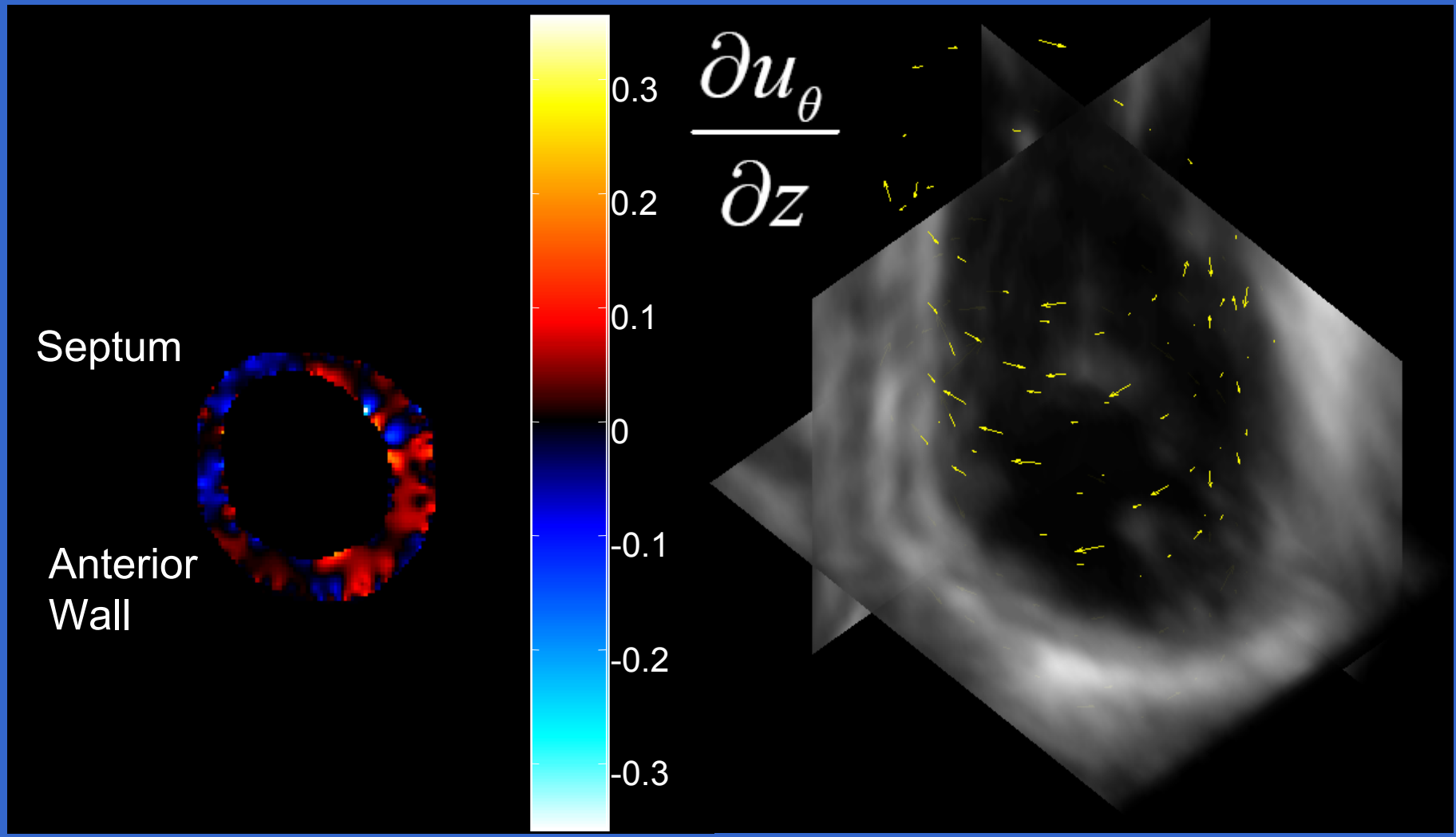
Experimental Results: Radial Displacement



Experimental Results: Wall Thickening



Experimental Results: Twist



Conclusions

- A 4D optical flow algorithm was applied to RT3D ultrasound data for tracking endocardial and epicardial surfaces.
- Dense myocardium motion fields were recovered via radial basis function interpolation.
- Dynamic cardiac parameters were computed (can provide new diagnostic information).
- On one experiment, preliminary results agreed with clinical anatomical facts for the normal part of the heart as well as showed characteristic patterns of decreased motion on the "immobile" septum due to the heart-transplant procedure ("Pure Septal Defect").

Future Work

- Comparison of wall motion analysis with tagged MRI.
- Multi-resolution implementation for real-time computation.
- Full-field optical flow computation.
- Clinical evaluation of abnormal wall motion.

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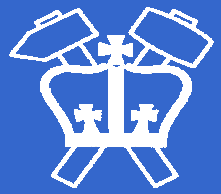
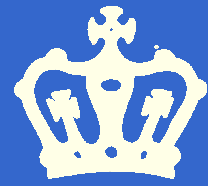
- Dr. Todd Pulerwitz (Department of Medicine, Columbia University).

Thank you!

For additional information please see:

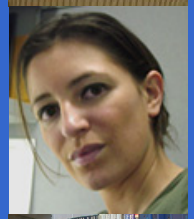
http://hbil.bme.columbia.edu





Personnel

Qi Duan
Graduate Research Assistant
Heffner Biomedical Imaging Lab
Dept. of Biomedical Engineering
Columbia University



Dr. Elsa Angelini
Assistant Professor
Ecole Nationale Supérieure des Télécommunications

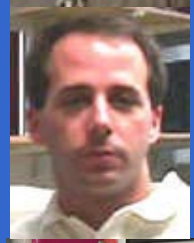
Susan Herz
Graduate Research Assistant
Cardiac Biomechanics Lab
Dept. of Biomedical Engineering
Columbia University

Christopher Ingrassia
Graduate Research Assistant
Cardiac Biomechanics Lab
Dept. of Biomedical Engineering
Columbia University

Dr. Pascal Allain
Senior Research Scientist
Medical Imaging Systems Group
Philips Research France

Dr. Olivier Gerard
Senior Research Scientist
Medical Imaging Systems Group
Philips Research France

Dr. Kevin Costa
Assistant Professor
PI of cardiac Biomechanics Lab
Dept. of Biomedical Engineering
Columbia University



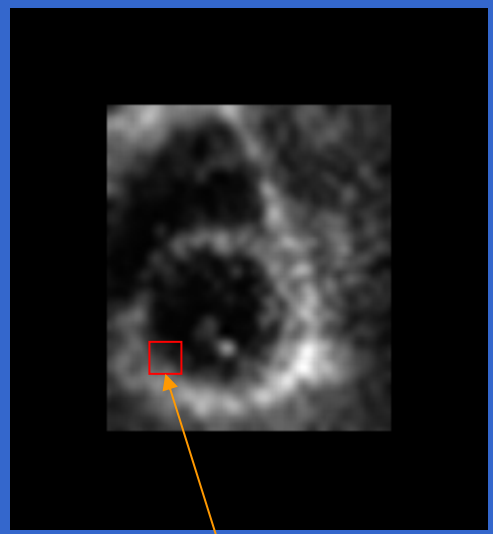
Dr. Jeffrey Holmes
Assistant Professor
PI of cardiac Biomechanics Lab
Dept. of Biomedical Engineering
Columbia University

Dr. Andrew Laine
Associate Professor
Director of HBIL
Dept. of Biomedical Engineering
Columbia University

Dr. Shunichi Homma, M.D.
Associate Professor of Medicine and
Director, Lab. of Echocardiography Service.
Dept. of Medicine
Columbia University

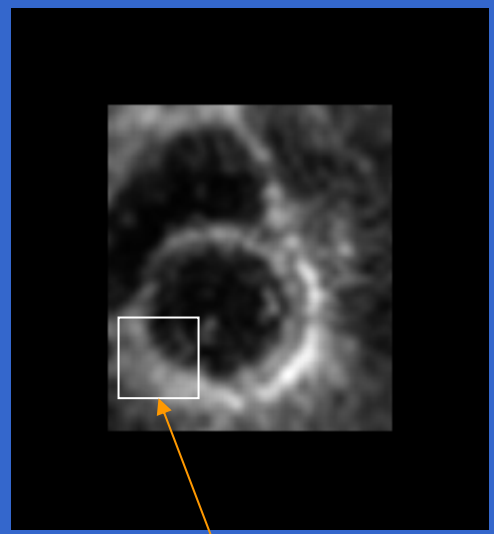
Correlation Method

Frame 1



Small neighborhood
(5x5x5)

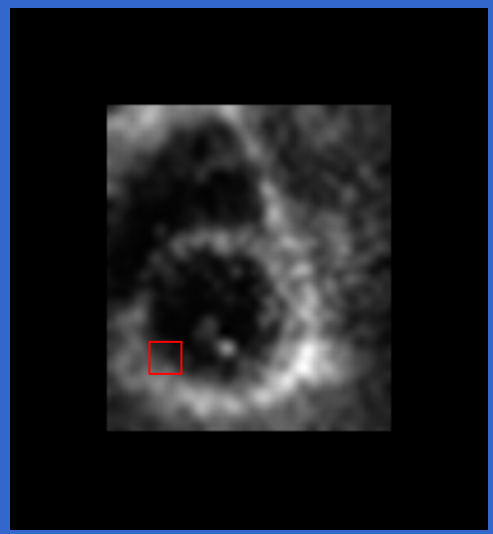
Frame 2



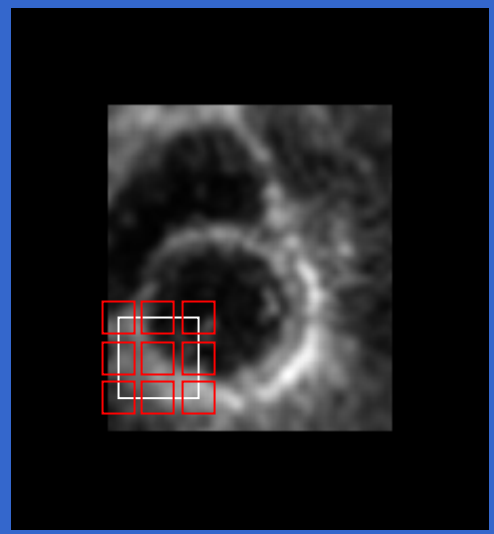
Search range
(7x7x7)

Correlation Method

Frame 1



Frame 2

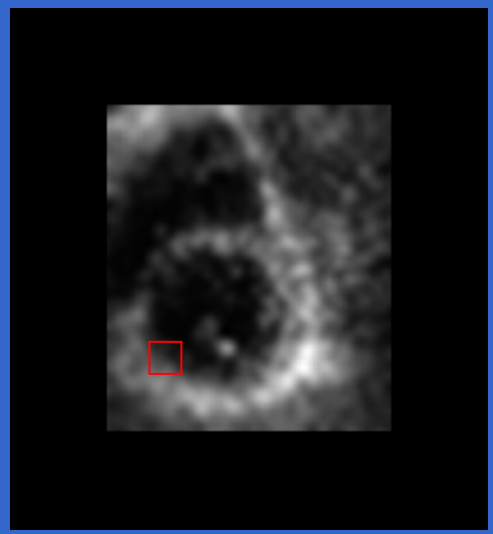


Correlation Coefficient

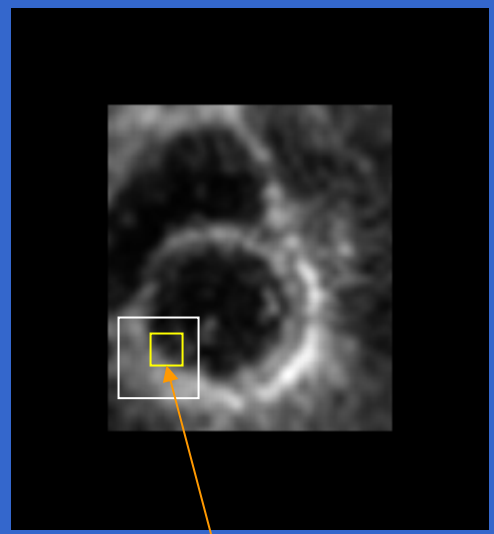
$$r = \frac{\sum_{\mathbf{x}\in\Omega}\left(I(\mathbf{x},t) * I(\mathbf{x}+\Delta\mathbf{x},t+\Delta t)\right)}{\sqrt{\sum_{\mathbf{x}\in\Omega} I^2(\mathbf{x},t)\sum_{\mathbf{x}\in\Omega} I^2(\mathbf{x}+\Delta\mathbf{x},t+\Delta t)}}$$

Correlation Method

Frame 1



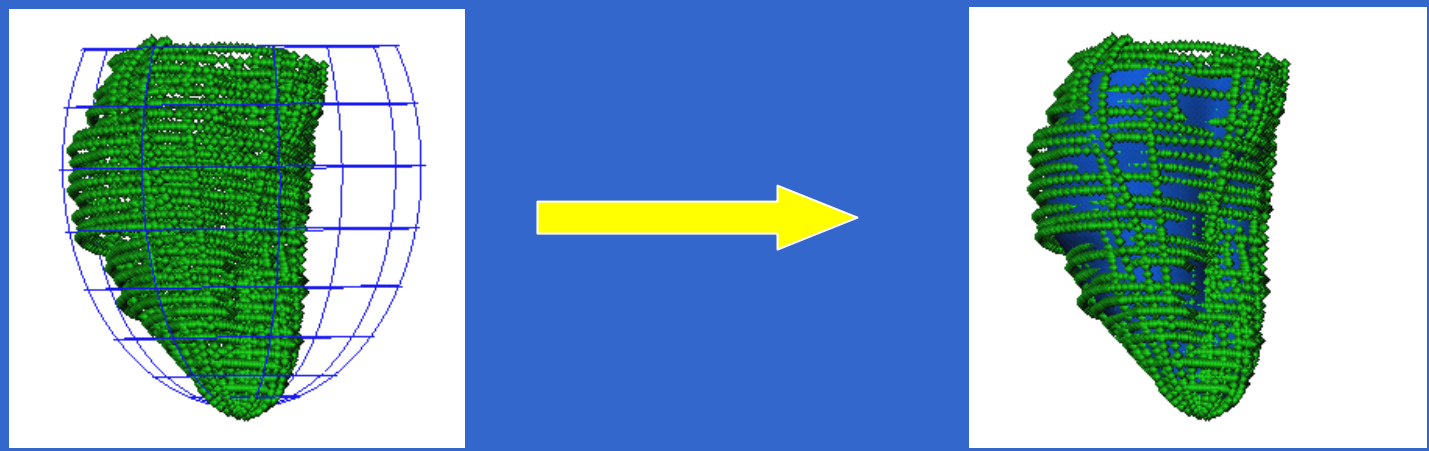
Frame 2



Most similar position

Surface Reconstruction

- Surface reconstruction is based on FEM
- Each surface was registered with anatomical landmarks.
- Each surface was fitted into a 64-element mesh in prolate spheroidal coordinates.
- Bicubic Hermite interpolation was used to yield a realistic 3D endocardial surface.



Surface Reconstruction

- Quantitative measurements:
  - Root mean squared errors (RMSE) of the difference of the radial coordinates λ at node points for OF and manual tracing result.
  - Ventricular volume and ejection fraction
  - Relative error was used to generate local relative error map as a Hammer map.

$$\varepsilon = (\lambda_{\text{manual}} - \lambda_{\text{optical}}) / \lambda_{\text{manual}}$$