Automated Frame-by-Frame Segmentation and Non-Rigid Registration of MRI Myocardial Perfusion Data at Rest and Stress

G. Tarroni[1,2], A.R. Patel[2], P.F. Antkowiak[3], F.H. Epstein[3], C.M. Kramer[3], C. Lamberti[1], R.M. Lang[2], V. Mor-Avi[2], C. Corsi[1]

[1]University of Bologna, Bologna, Italy
[2]University of Chicago, Chicago, Illinois, USA
[3]University of Virginia, Charlottesville, Virginia, USA

Computer-Assisted Radiology and Surgery
Berlin (Germany), June 22-25, 2011

Background

- Quantification of first-pass myocardial perfusion from CMR images relies on the definition of myocardial regions of interest (ROIs)

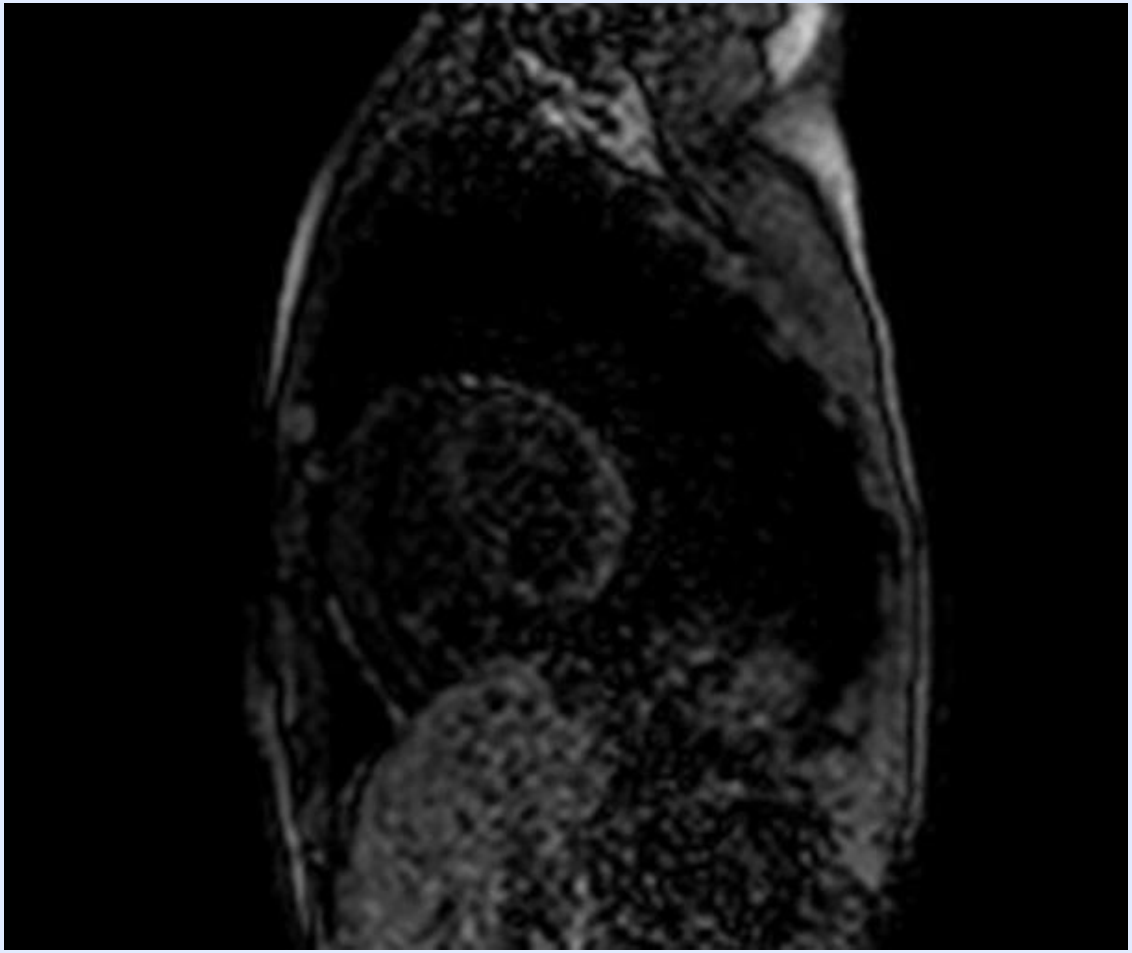
- This is usually achieved by manually drawing a ROI in one frame and then adjusting its position on subsequent frames

- In case of *out-of-plane* motion the ROIs need to be redrawn to match the changing shape of the myocardium

- This methodology is tedious, time-consuming and potentially inaccurate

Background

Example of MRI perfusion image sequence



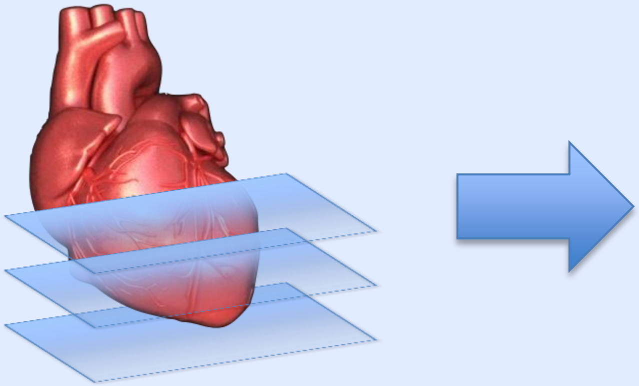
Aims

- Develop a technique for automated identification and non-rigid registration of myocardial ROIs as a basis for perfusion quantification

- Validate this technique against conventional manual analysis both at rest and during vasodilator stress, which is routinely used to induce perfusion defects in areas of the myocardium affected by coronary stenosis

Image Acquisition

- Siemens scanner (1.5T Avanto or Sonata)
- ECG-gated short -axis images at 3 levels of the left ventricle
- First pass of a Gd-DTPA bolus (0.075 mmol/kg, 4 ml/sec)



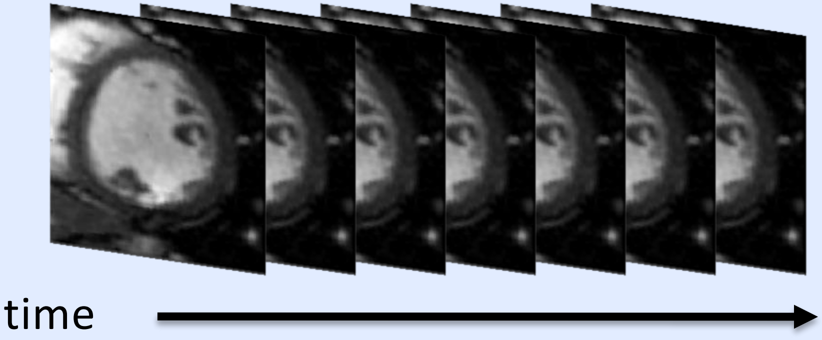


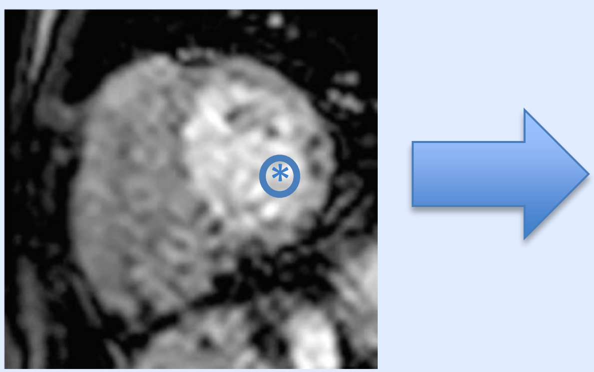
Image Acquisition Protocol

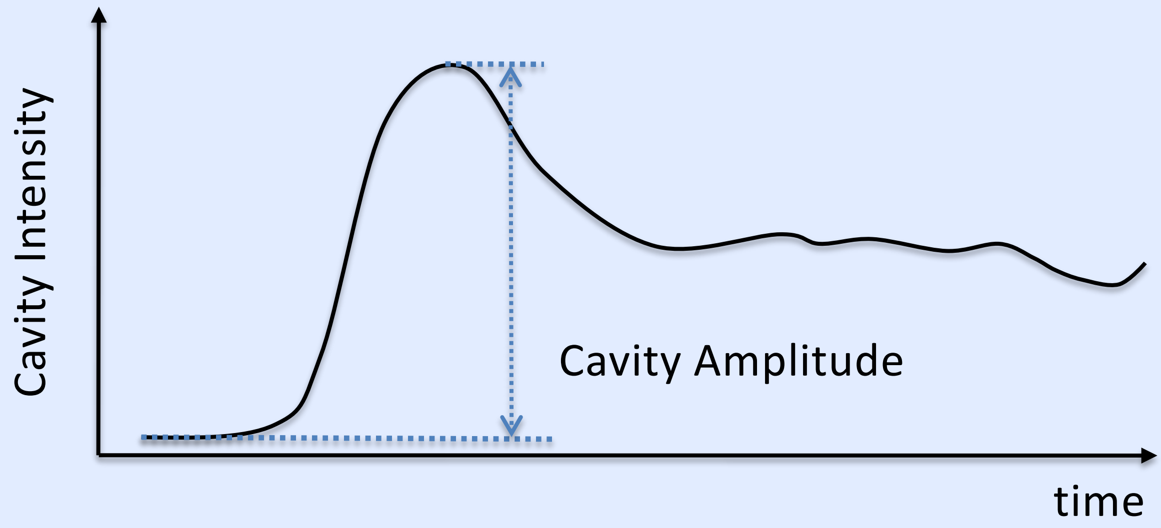
Hybrid gradient echo - echo planar imaging sequence

- a nonselective 90° saturation pulse + 80 ms delay
- voxel size ≈ 2.8 x 2.8 mm, slice thickness = 8 mm
- acquisition time ≈ 80 ms per slice, ≈ 1 min total; TR ≈ 5.9 ms, TE = 1.3 ms

Best Frame Selection for Myocardium Segmentation

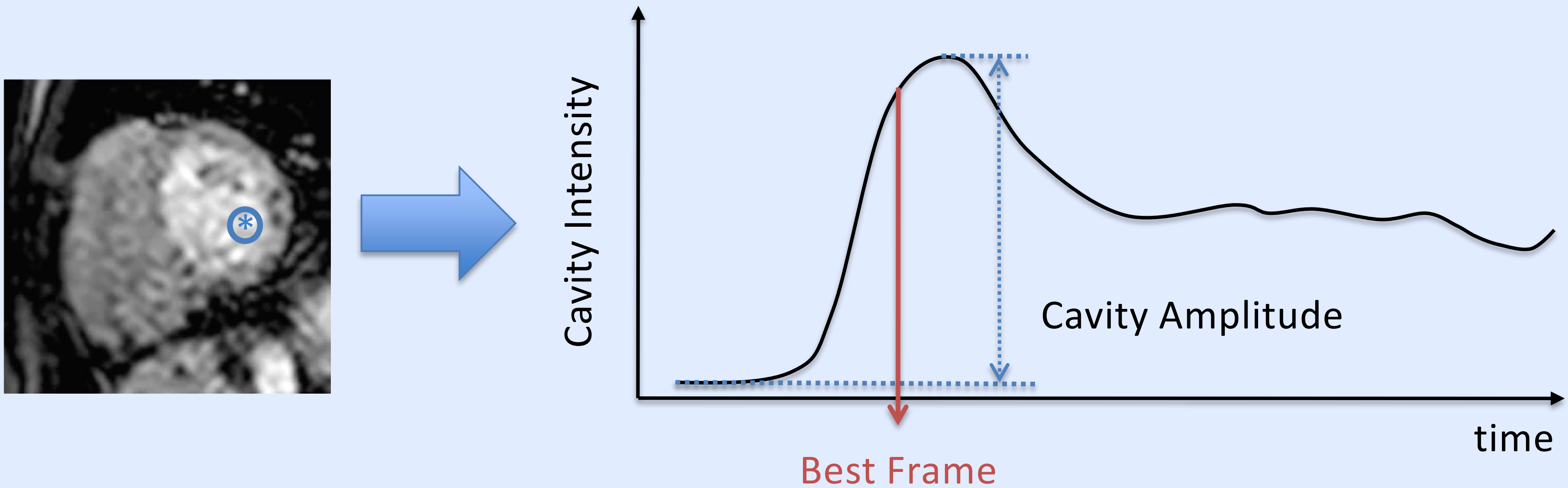
- Manual placement of a seed point in the LV cavity
- Automatic selection of the “best” frame for segmentation step in the perfusion data sequence





Best Frame Selection for Myocardium Segmentation

- Manual placement of a seed point in the LV cavity
- Automatic selection of the "best" frame for segmentation step in the perfusion data sequence

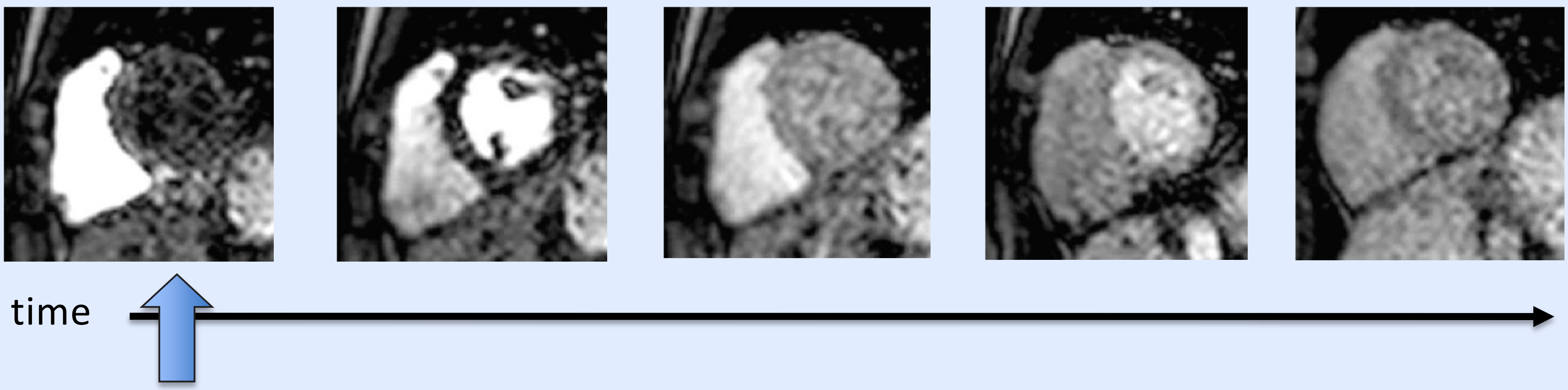


Best Frame

Frame at which Cavity Intensity reaches 95% of Cavity Amplitude

Best Frame Selection for Myocardium Segmentation

- Manual placement of a seed point in the LV cavity
- Automatic selection of the “best” frame for segmentation step in the perfusion data sequence



Best Frame

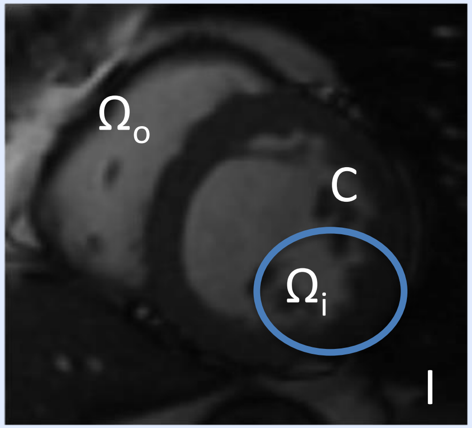
Frame at which Cavity Intensity reaches 95% of Cavity Amplitude

Endocardium Segmentation

Automated detection of the LV endocardial boundary:

- Statistical level-set algorithm based on the Gaussian noise distribution in MRI images applied to the reference frame

$$l(I,C) = \varepsilon \cdot lenght(C) + \int_{\Omega_i(C)} log\ p(I)dxdy\ + \int_{\Omega_o(C)} log\ p(I)dxdy$$



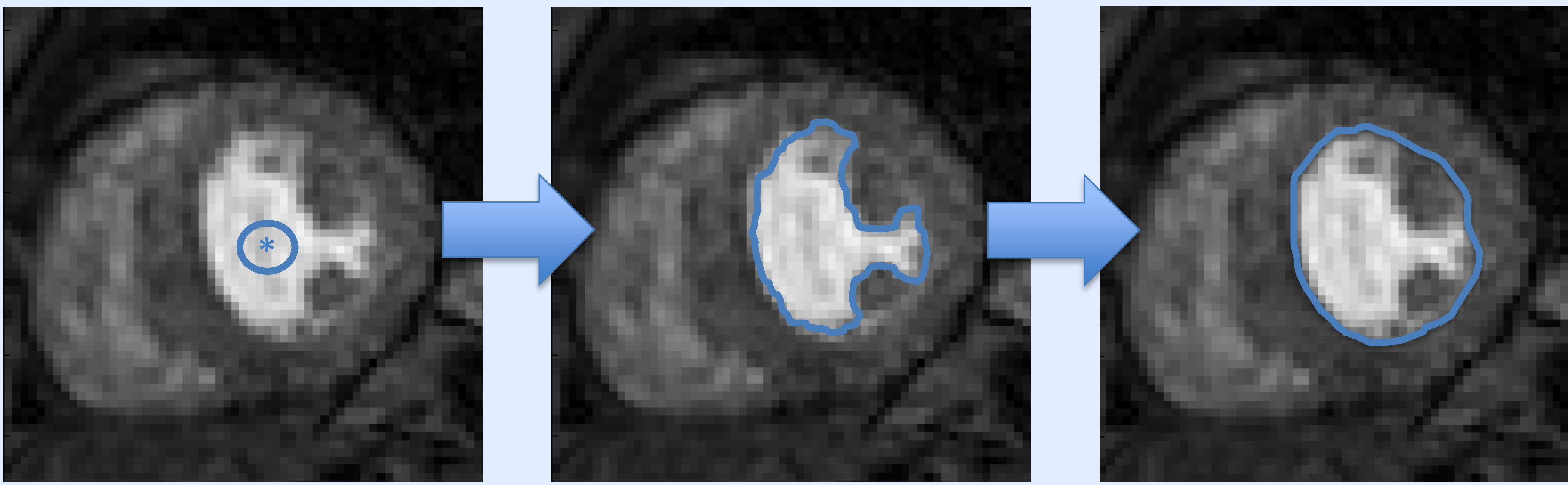
Variables Definition

- l = functional to be maximized
- C = contour during evolution
- $\Omega_{i/o}$ = in-out domains
- p(I) = Gaussian distribution
- I = gray level intensity image

- Selective Curvature-based regularization motion

Endocardium Segmentation

Initial Curve   Statistical Segmentation   Regularization



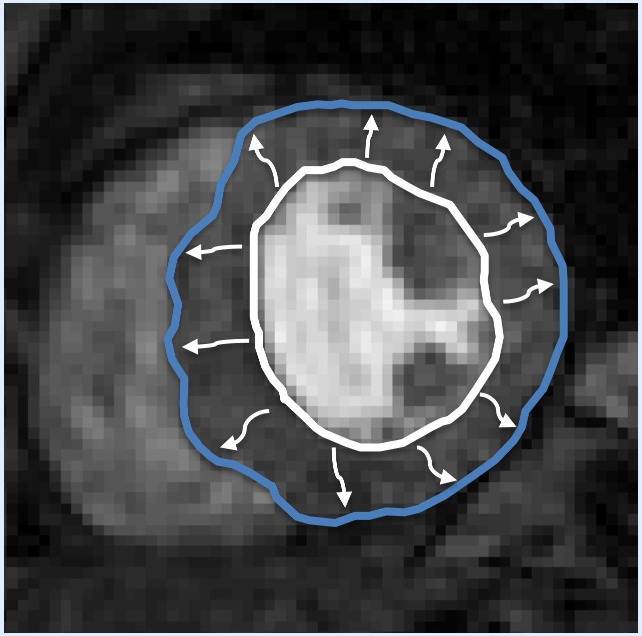
Epicardium Segmentation

Automated detection of the LV epicardial boundary:

- Edge-based Malladi-Sethian level-set algorithm applied to the reference frame that searches the image from the endocardium outwards

$$\frac{\partial \Phi}{\partial t} = g(\epsilon K - 1)|\nabla \Phi| + \nu \nabla g \cdot \nabla \Phi$$

with adequate boundary contidions and initial condition $\Phi_0(x,y) = \Phi_{endo}(x,y)$

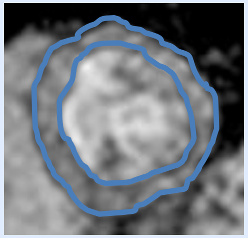


- Curvature-based regularization motion

Non-rigid Registration

Non-rigid registration is achieved by a multi-scale extension of 2D normalized cross-correlation to compensate for respiratory motion

Original Template



Frame t

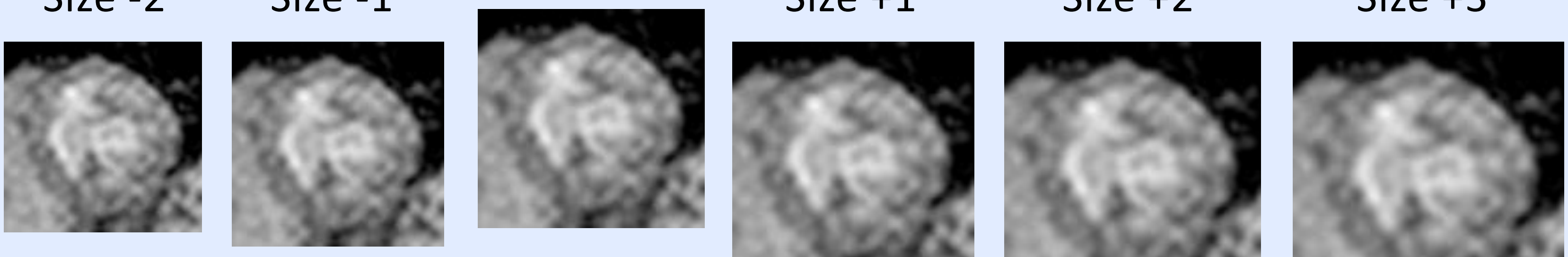
Registration Steps

1. Definition of Original Template

Non-rigid Registration

Non-rigid registration is achieved by a multi-scale extension of 2D normalized cross-correlation to compensate for respiratory motion

Size -2 | Size -1 | Original Template | Size +1 | Size +2 | Size +3



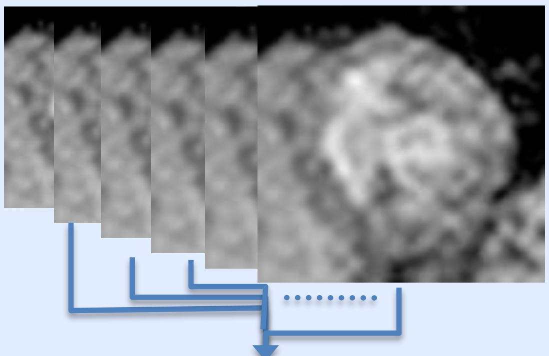
Frame t

Registration Steps

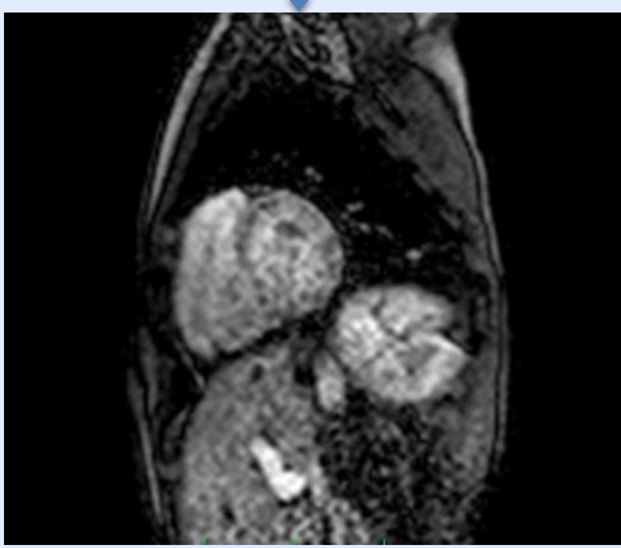
2. Definition of 5 Resized Templates

Non-rigid Registration

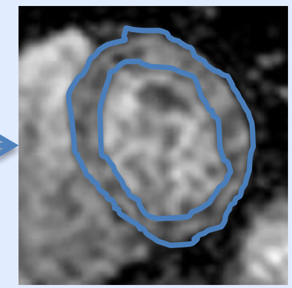
Non-rigid registration is achieved by a multi-scale extension of 2D normalized cross-correlation to compensate for respiratory motion



Frame t



Frame t+1



Highest Cross-Corr Peak

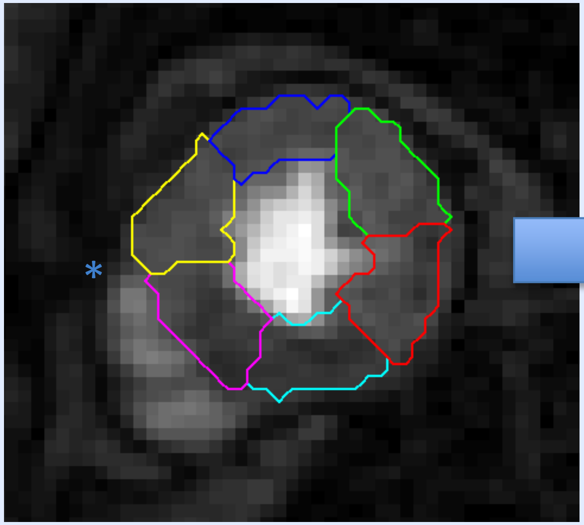
Registration Steps

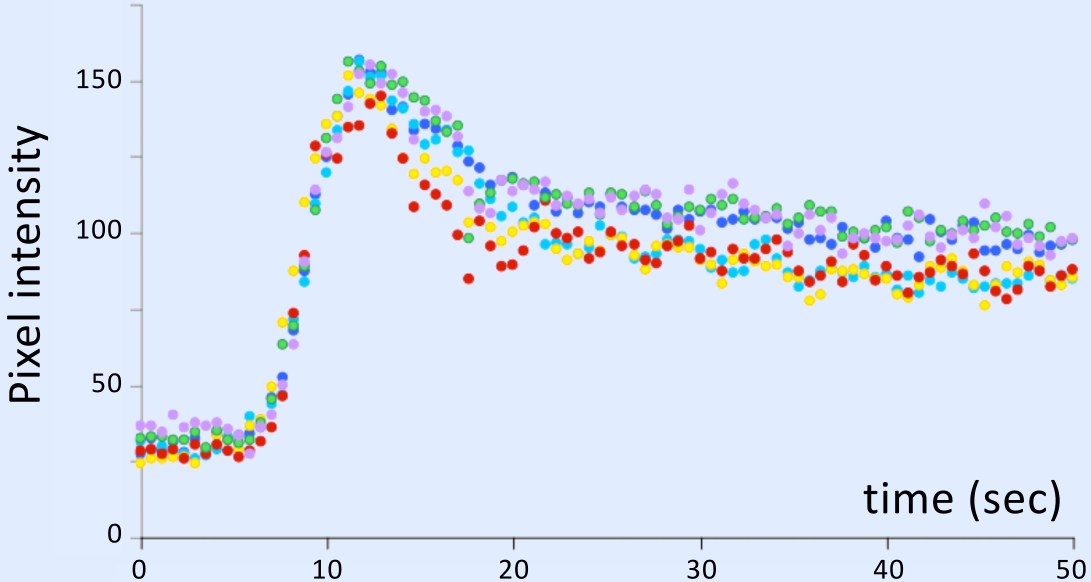
3. Norm Cross-Correlation (6 times)
4. Boundaries repositioning and resizing in highest cross-corr peak
5. Boundaries refinement with Malladi-Sethian algorithm

Quantification of contrast dynamics

The LV myocardium is divided into 16 wedge-shaped segments starting from a manually placed reference point

Pixel intensity is measured in each segment over time, resulting in contrast enhancement curves





Performance Evaluation

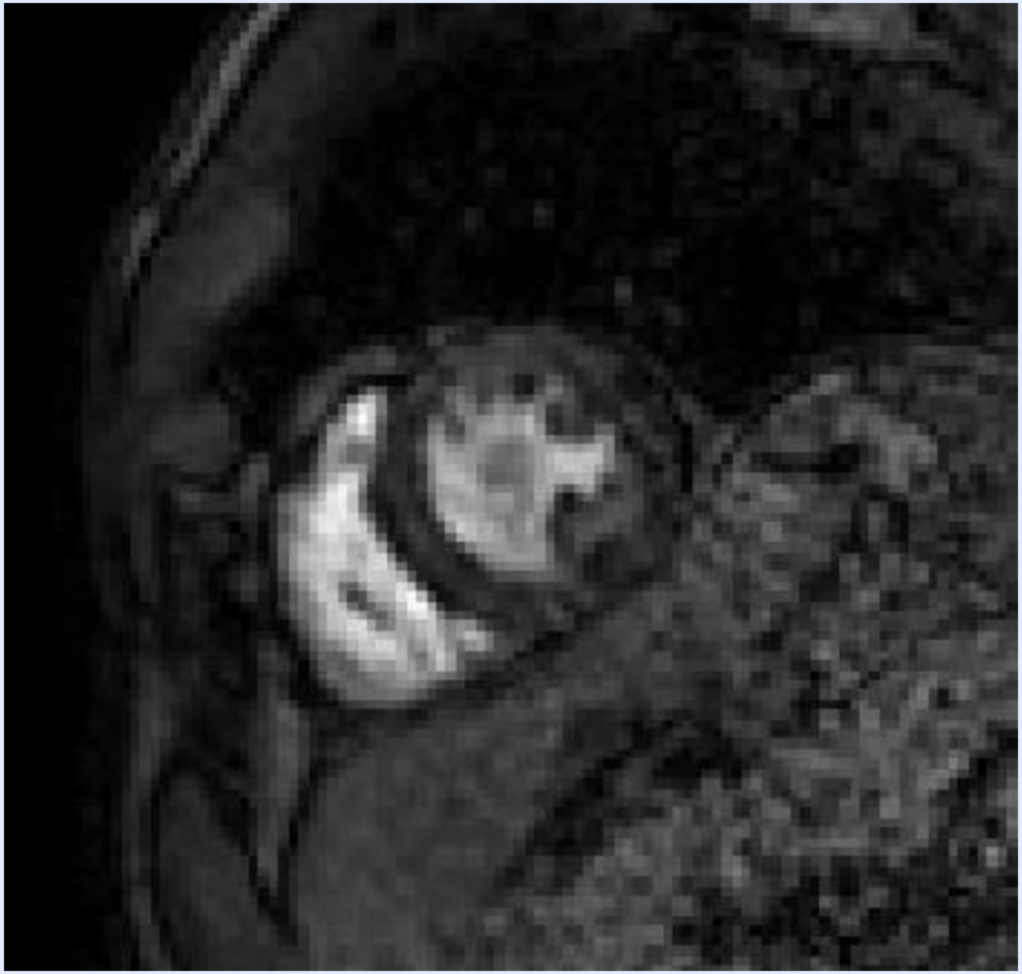
The technique was tested on 15 patients both at rest and during adenosine stress (*i.e.* 90 image sequences)

An experienced interpreter manually traced myocardial boundaries onto all image sequences, allowing the extraction of contrast enhancement curves used as reference

Validation

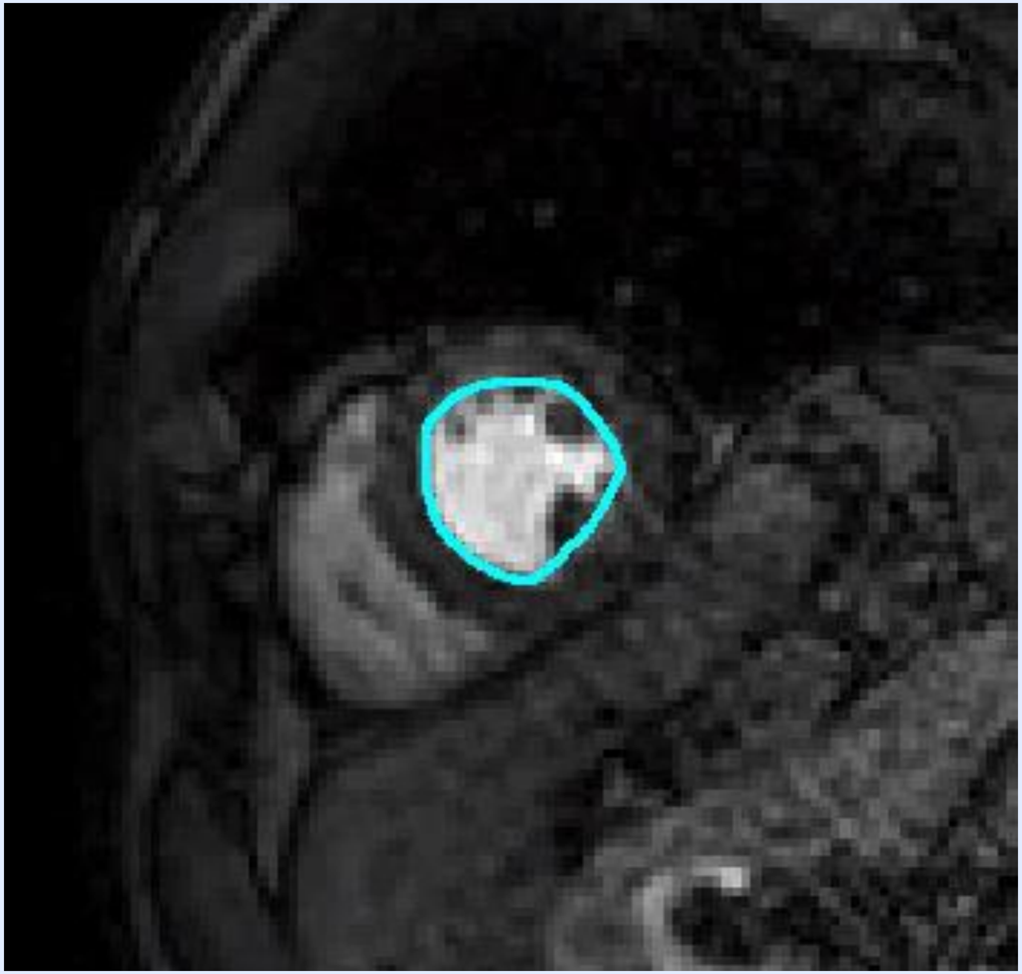
- Qualitative: visual assessment of boundaries position
- Quantitative: frame-by-frame comparison of mean pixel intensity in each segment between automated and manual analysis

Endocardial Detection



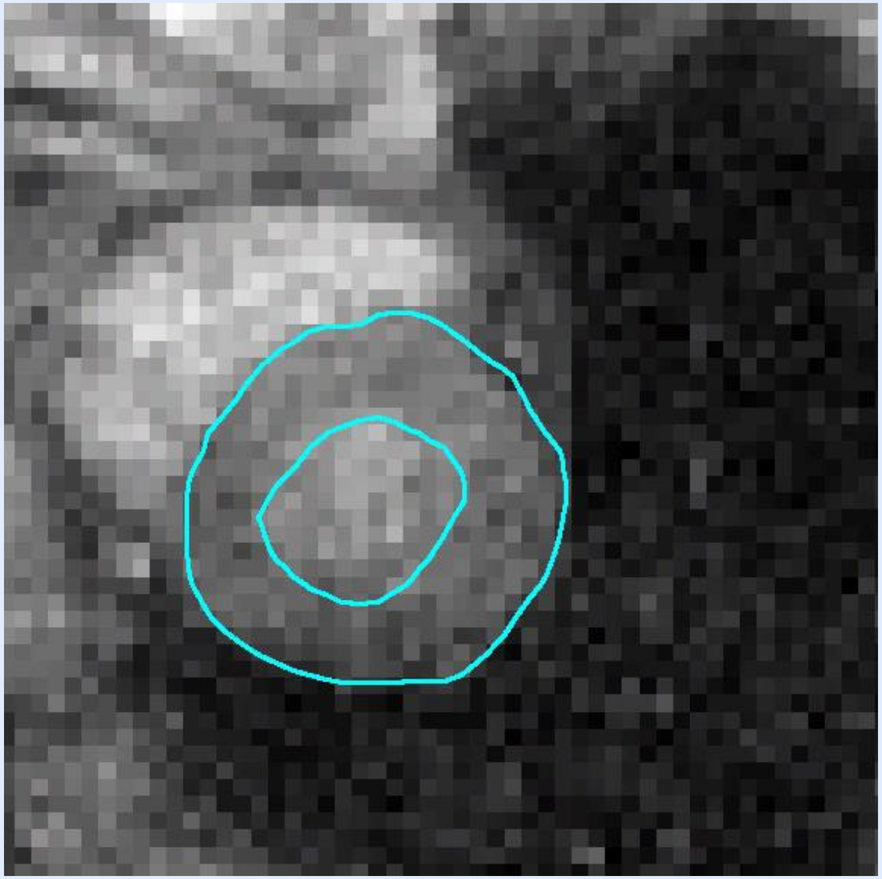
Required time ≈ 4 s

Epicardial Detection

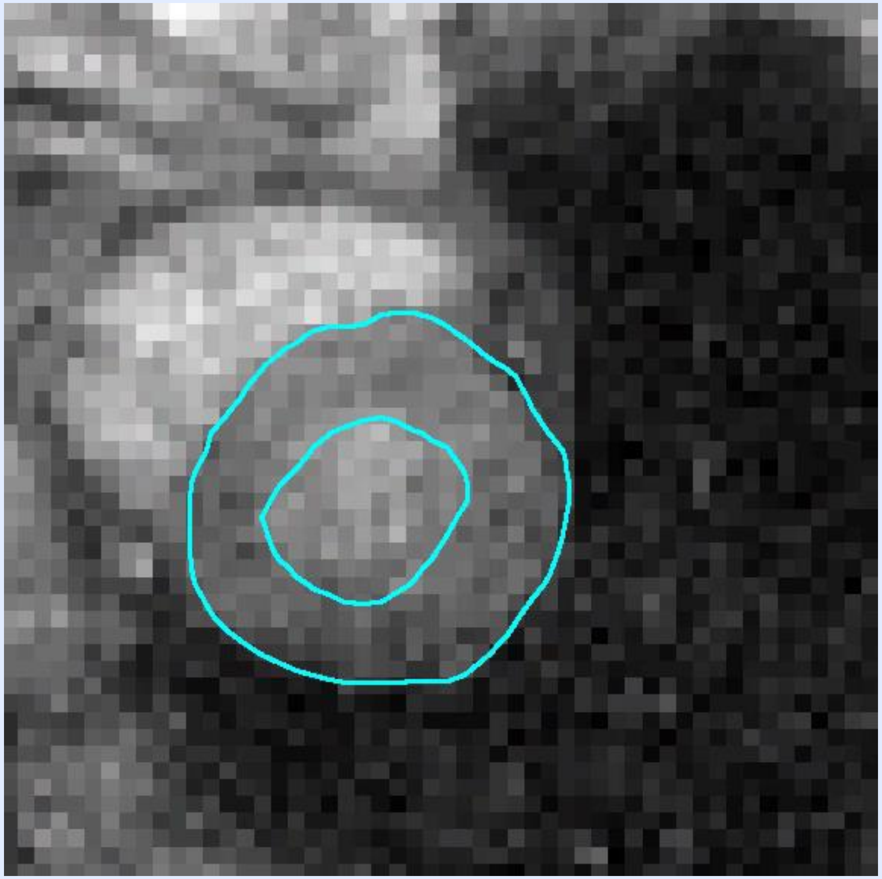


Required time ≈ 4 s

Non-rigid Registration



Without registration

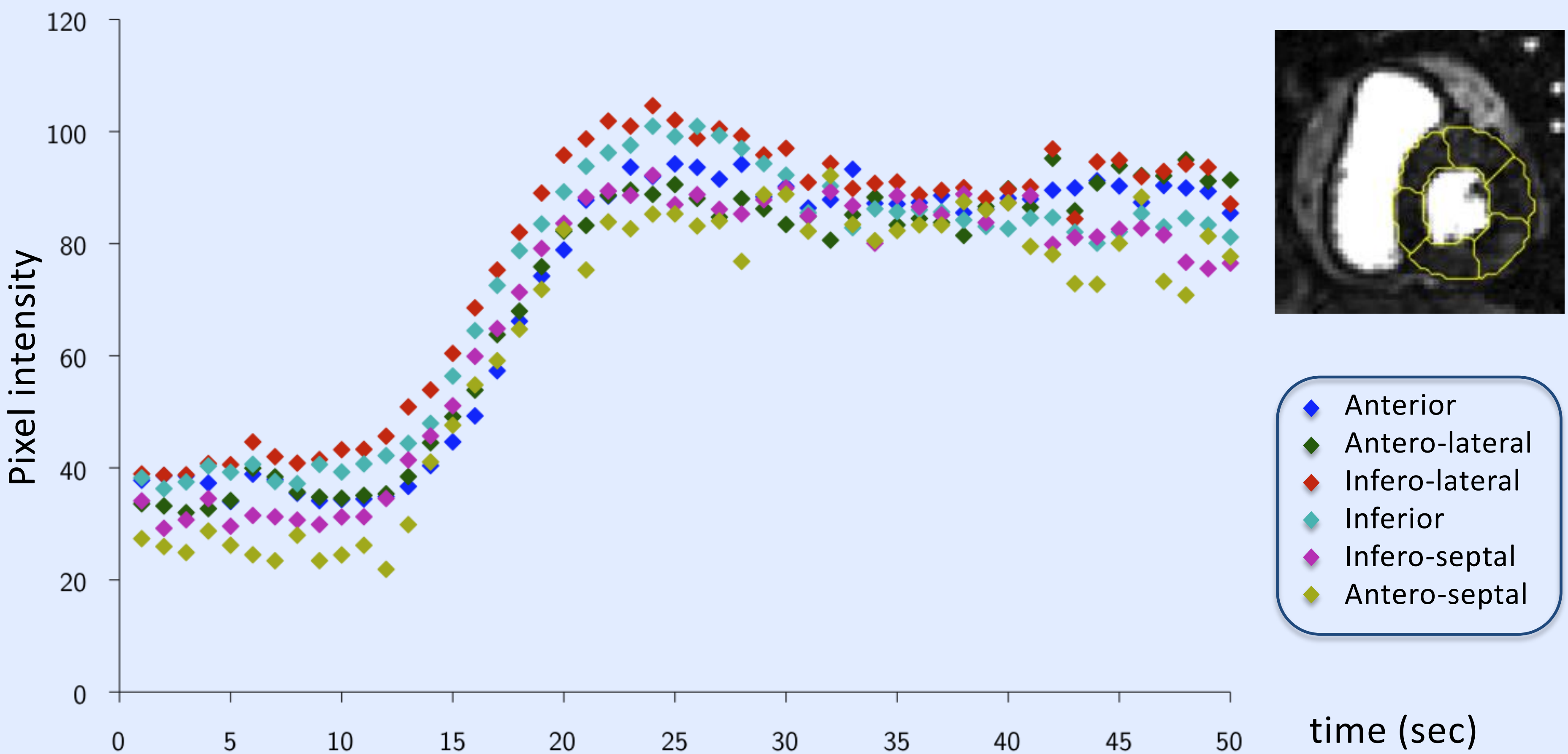


With registration

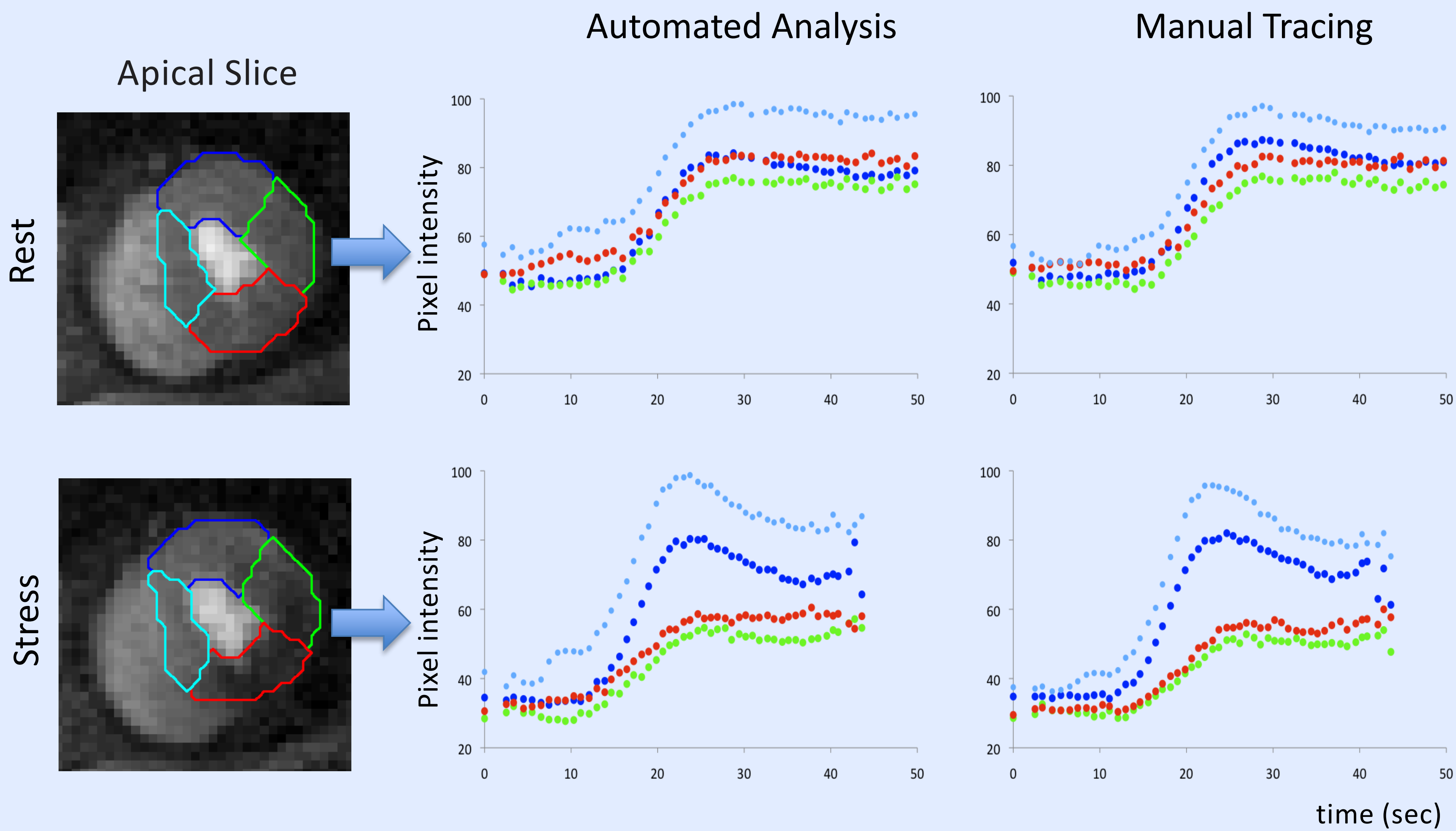
Required time ≈ 12 s

Contrast-enhancement Curves

Extracted curves showed the typical pattern of first-pass perfusion and featured low noise levels both at rest and stress



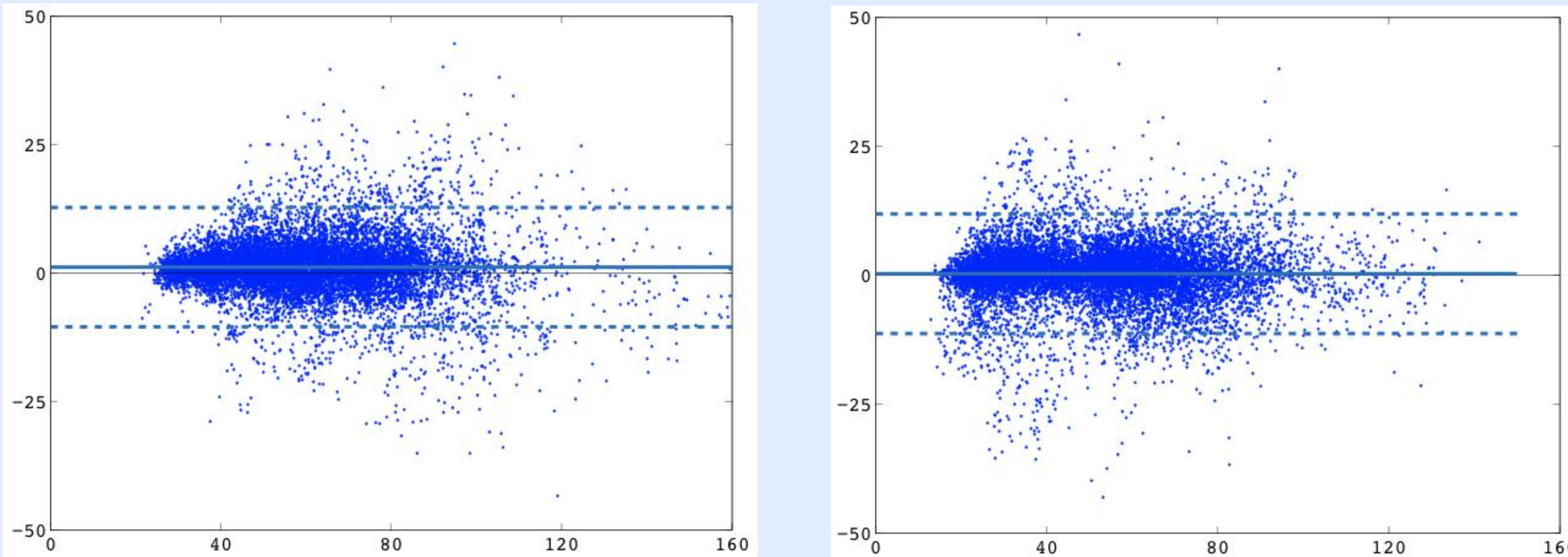
Automated vs Manual: Example



Automated vs Manual: Bland-Altman Analysis

Rest | Stress

Intensity (manual - automated)



Mean intensity (manual, automated) | Mean intensity (manual, automated)

Bias = 1.18

LOA = 11.60

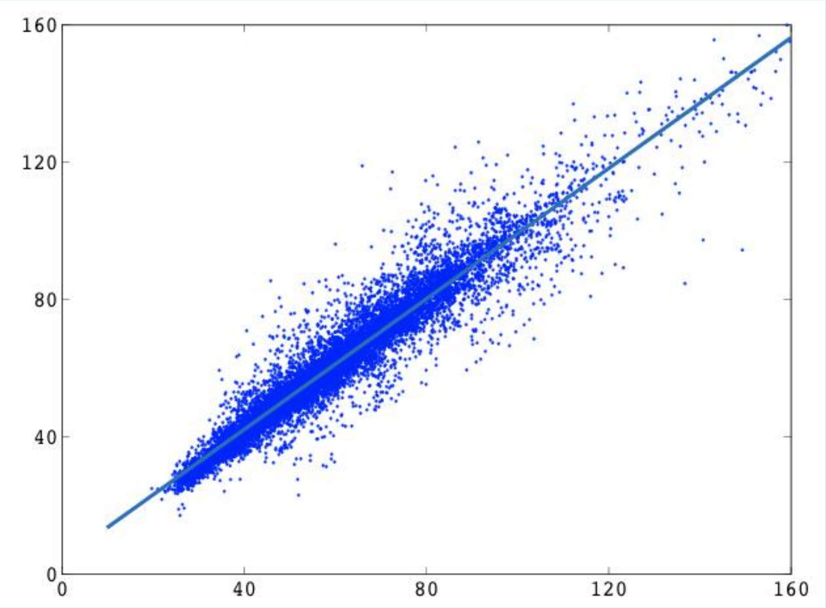
Bias = 0.31

LOA = 11.58

Automated vs Manual: Linear Regression & Correlation

Intensity (automated)

Rest

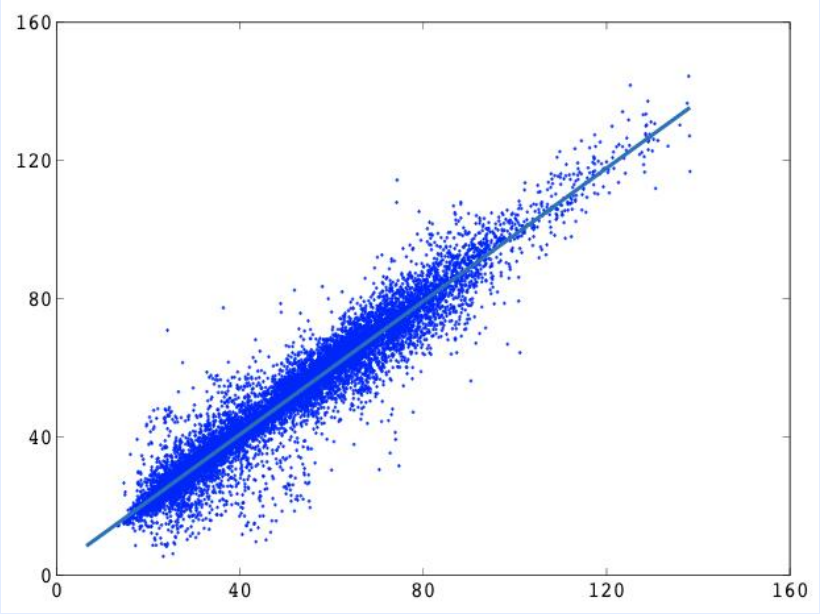


Intensity (manual)

$y = 0.95\,x + 4.16$

$R = 0.96$

Stress



Intensity (manual)

$y = 0.96\,x + 2.23$

$R = 0.96$

Limitations

Limitations of the proposed approach:

- Very low spatial resolution
- Very thin myocardium (≈ 1 pixel width)
- Huge changes in shape of the myocardium throughout the sequence

Conclusions

- We developed an automated technique to quantify intra-myocardial contrast on CMR images using noise distribution segmentation and non-rigid multi-scale registration
- Dynamic detection of myocardial segments and quantification of intra-myocardial contrast using this approach is feasible and fast compared to conventional manual tracing
- This approach results in regional contrast enhancement curves with excellent noise levels, which showed high levels of agreement compared to curves extracted by manual analysis