Estimation of Regional Electrical Properties of the Heart from 12-Lead ECG and Images

Philipp Seegerer
19.05.2014
Pattern Recognition Lab (CS 5)

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TECHNISCHE FAKULTÄT

Outline

Introduction

Cardiac Motion Estimation

Electrophysiology Modeling

Evaluation

Conclusion and Outlook

Introduction

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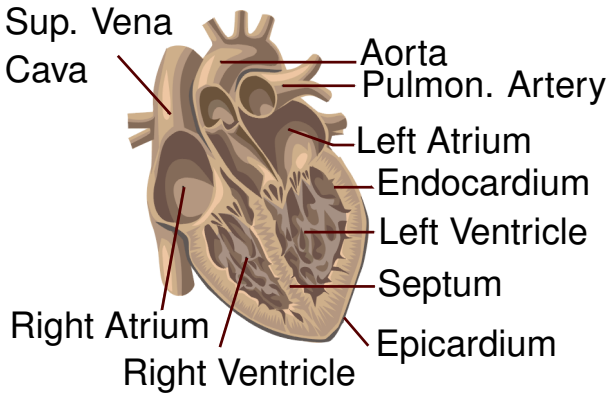
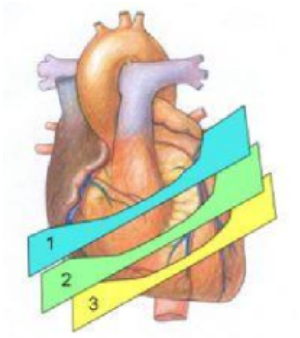
Cardiac Anatomy

- Blood flow by contraction of myocardium
- Myocardium encased by endocardium and epicardium
- Divided into two parts by septum
- Each half divided into atrium and ventricle
- Short axis view





Short Axis Slices

Figures:
Top: Courtesy of Family Practice Notebook (*http://www.fpnotebook.com/*)
Bottom: Courtesy of Stanford University (*http://www.stanford.edu/*)

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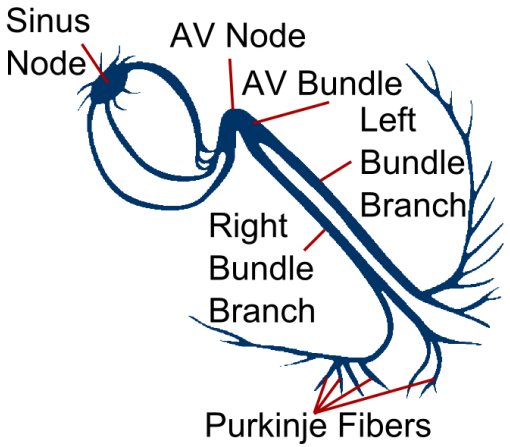
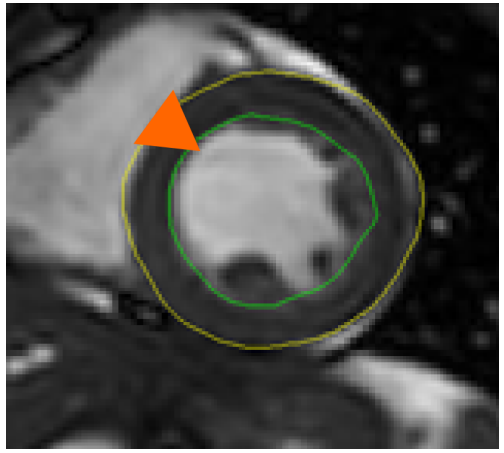
- Cardiac conduction system
- Varying conduction velocity
- Healthy heart: uniform wave propagation





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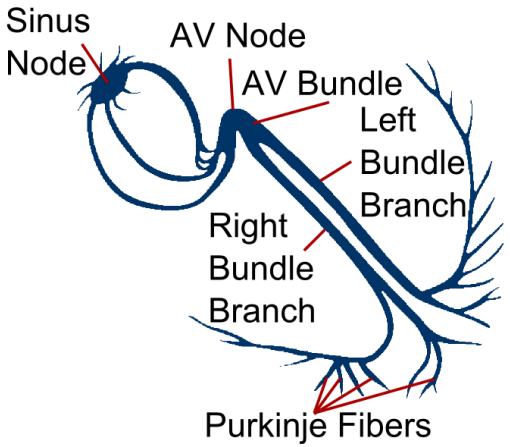

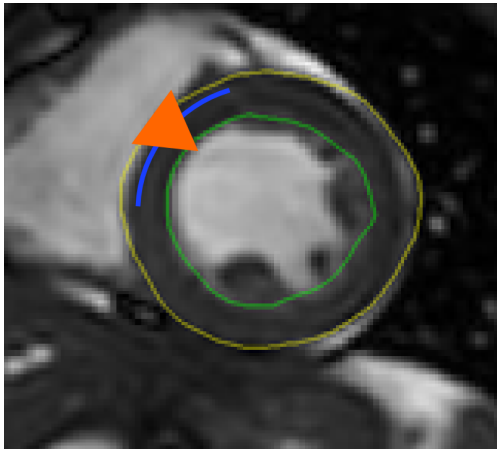

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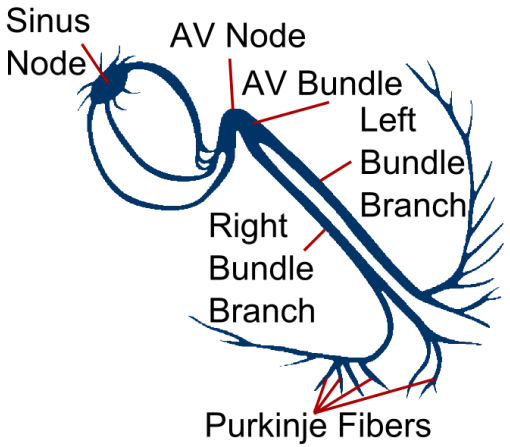

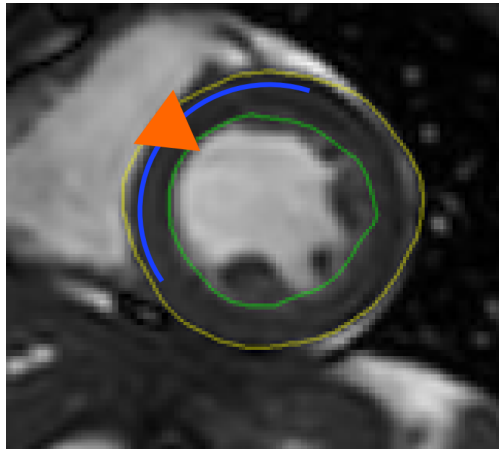

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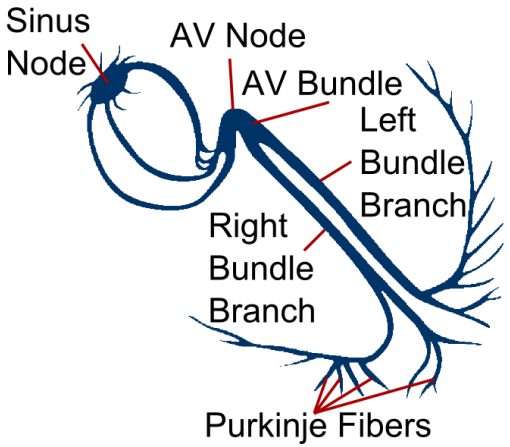

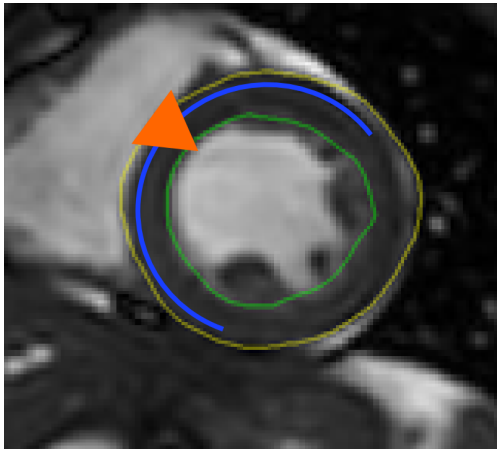

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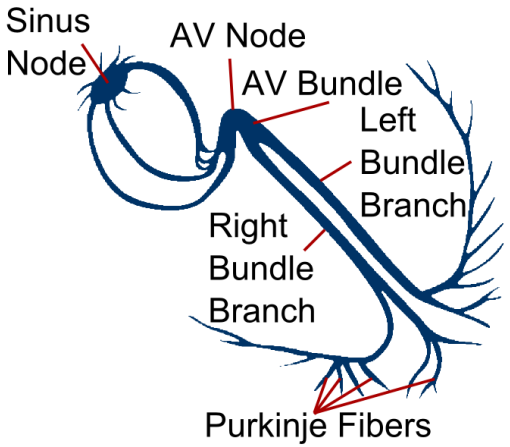

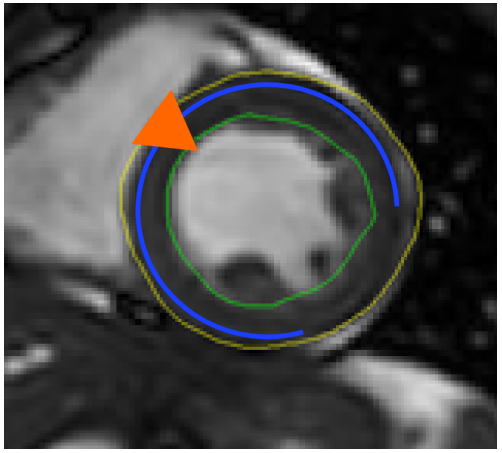

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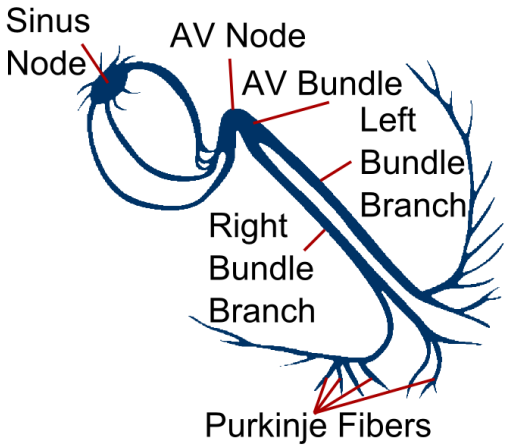

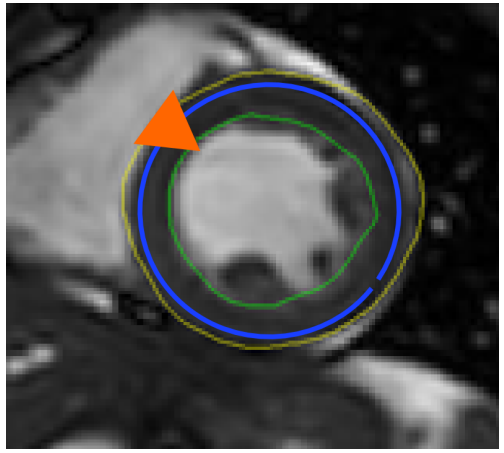

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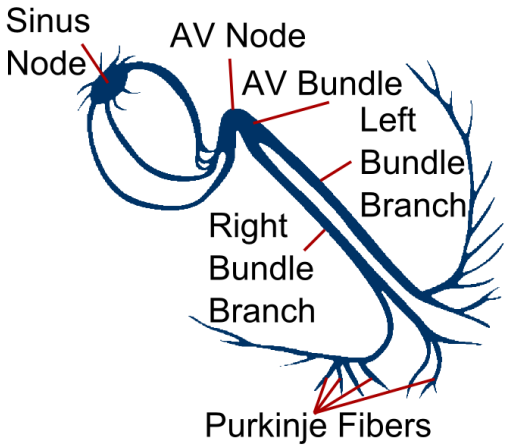

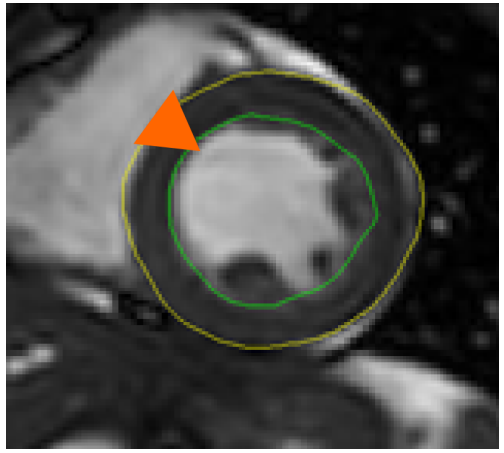

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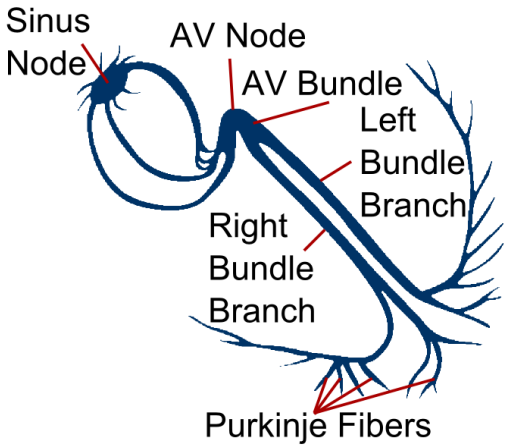

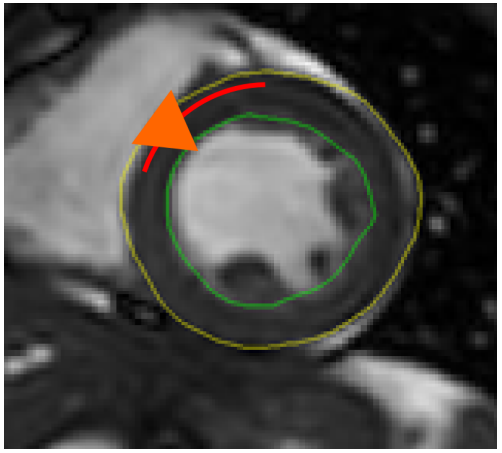

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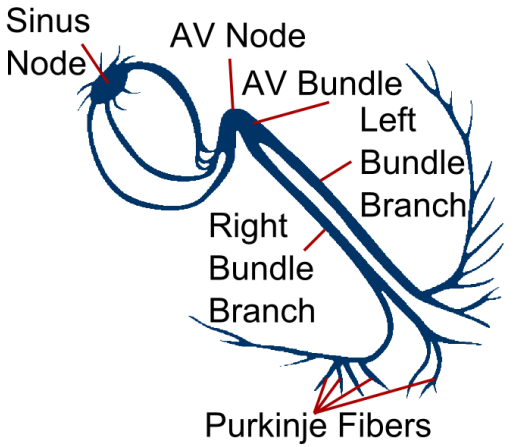

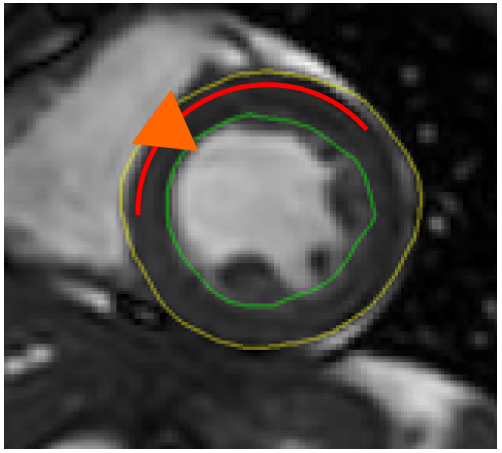

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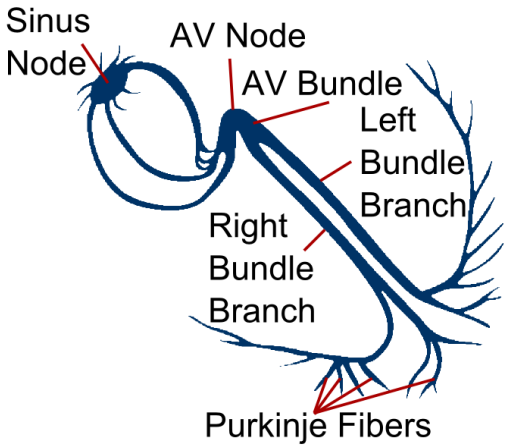

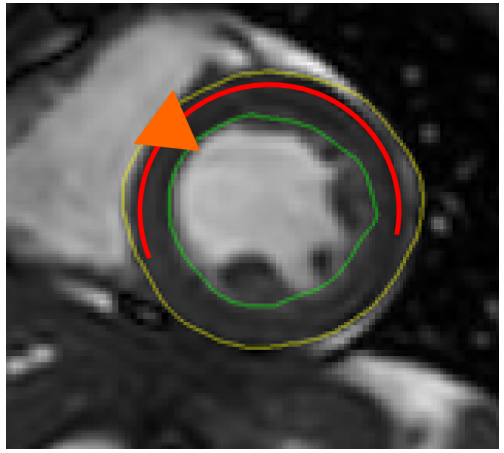

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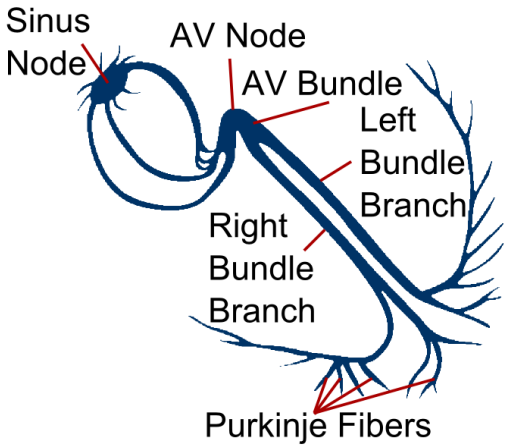

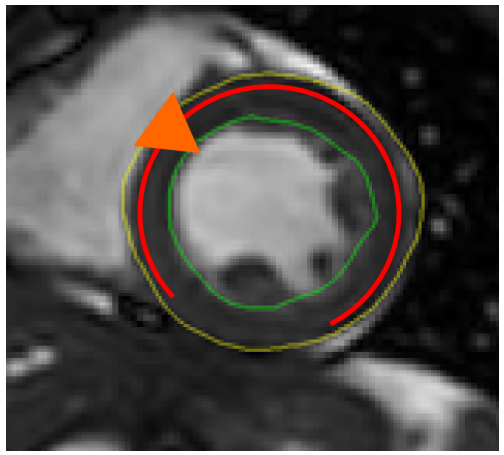

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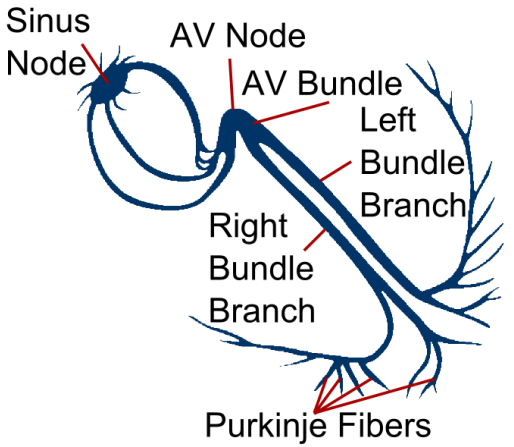

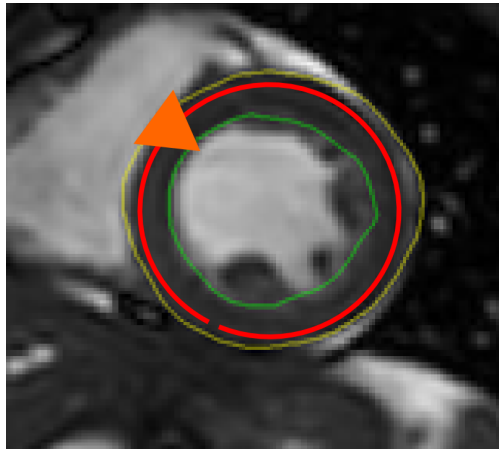

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Models of Cardiac Electrophysiology

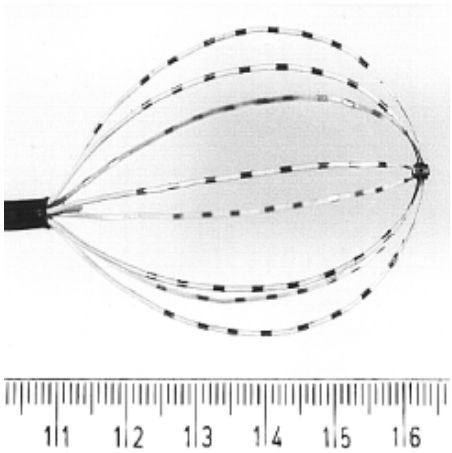
- Goal: simulation of electrical wave propagation
- Clinical applications
  - Patient selection
  - Therapy planning
  - Outcome prediction

Important: model personalization

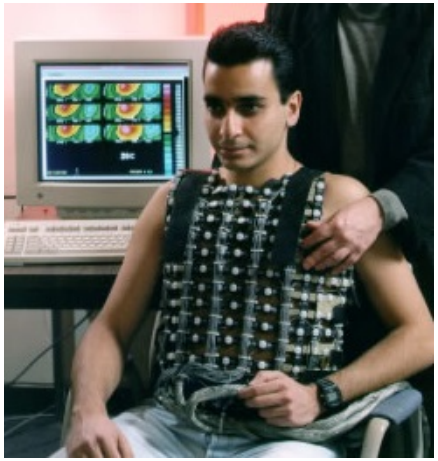
State of the Art

Data acquisition for personalization based on:

- Endocardial Mapping [Relan et al., 2011]
- Body Surface Potential Mapping (BSPM) [Doessel et al., 2011]
- 12-lead ECG [Neumann et al., 2014]



Endocardial Mapping Catheter



BSPM Acquisition

ECG Trace

Figures:
Left: Courtesy of AHA Journals (*http://circ.ahajournals.org/*)
Middle: Courtesy of Rudy Laboratory (*http://rudylab.wustl.edu/*)

Problems

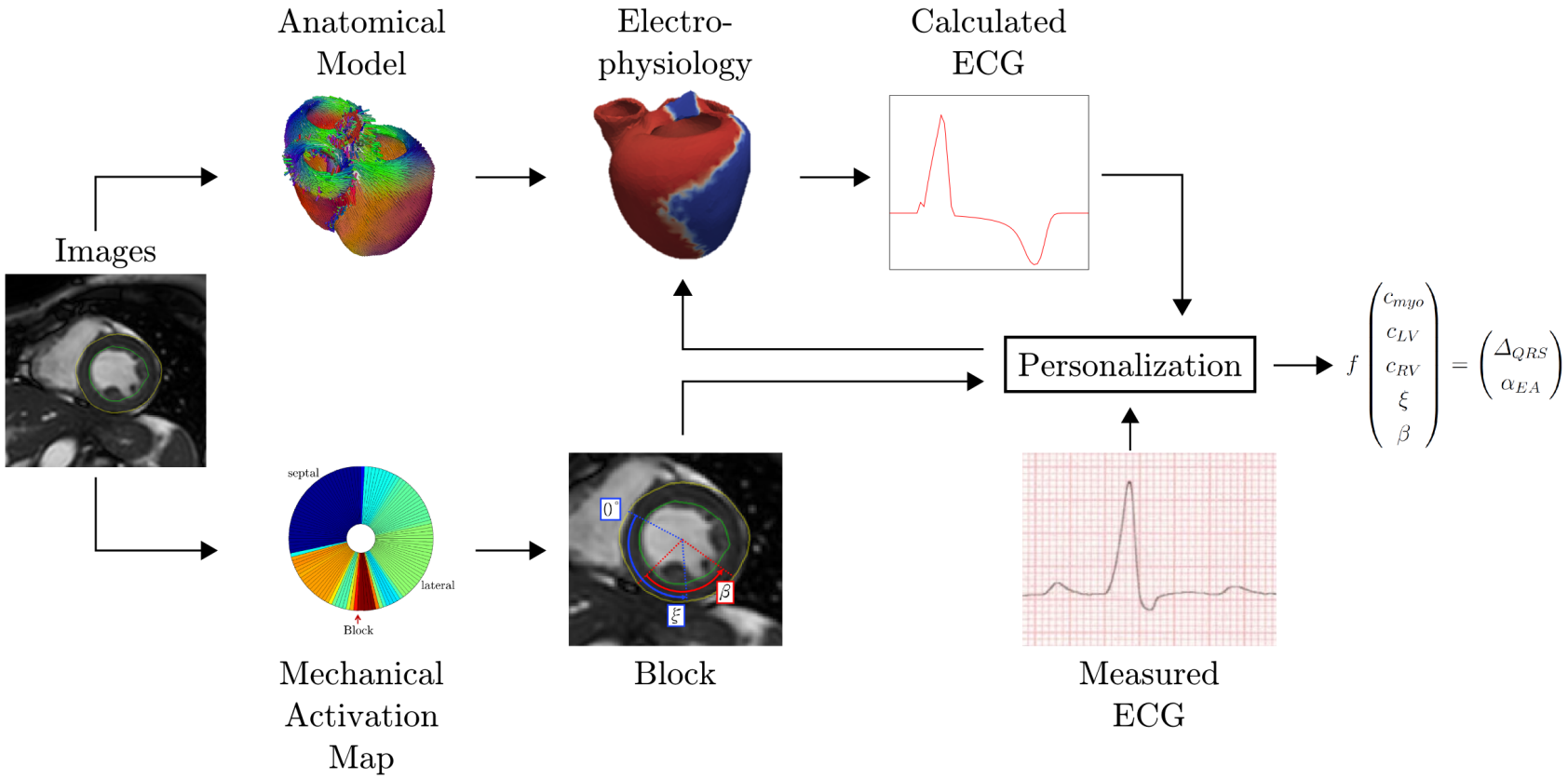
- Endocardial mapping: invasive
- Body Surface Potential Mapping: seldom available
- 12-lead ECG: global

Our solution: 12-lead ECG and motion information for regional properties

Advantages:

- Non-invasive
- Widely available
- Regional

Workflow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septal
lateral
Block
0°
β
ξ
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Cardiac Motion Estimation

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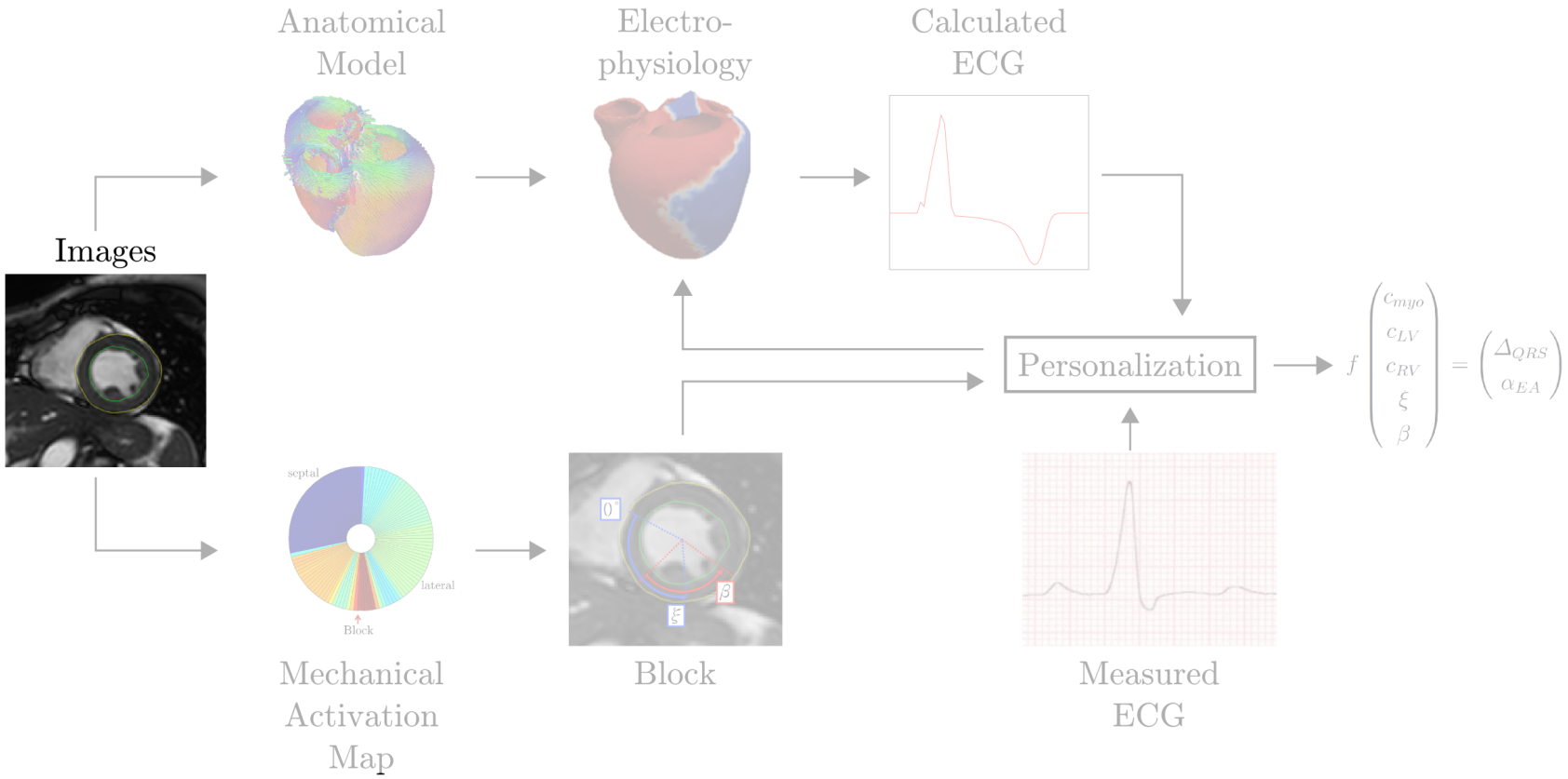
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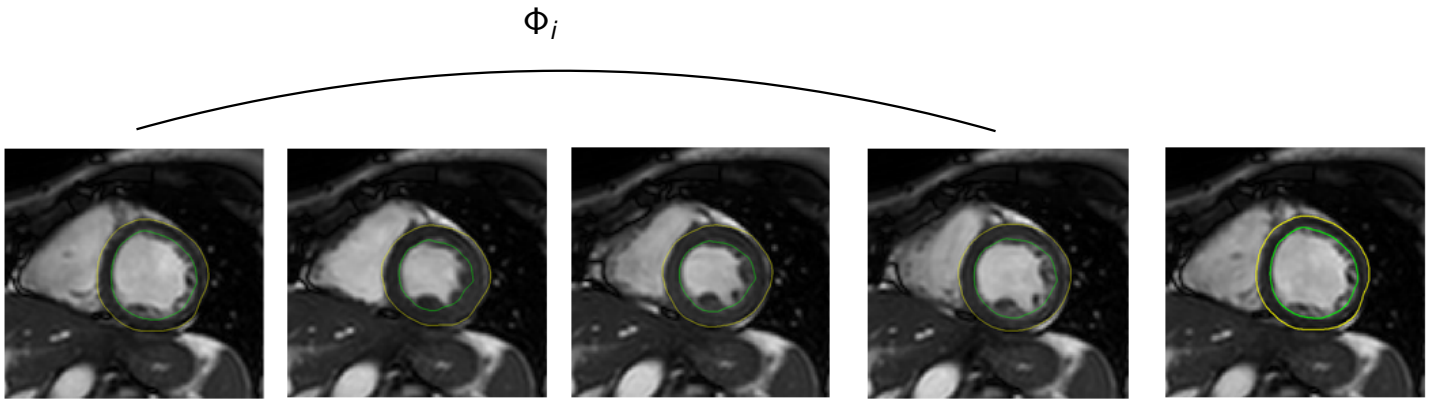
Image Registration and Tracking

- Dynamic cardiac images (Cine MRI)
- Automatic segmentation and tracking of left-ventricular myocardium
- Registration by inverse-consistent, diffeomorphic algorithm [Guetter et al., 2011]
- Dense deformation field Φ_i for each frame f_i
  $\rightarrow$ Registration to first (end-diastolic) frame f_0



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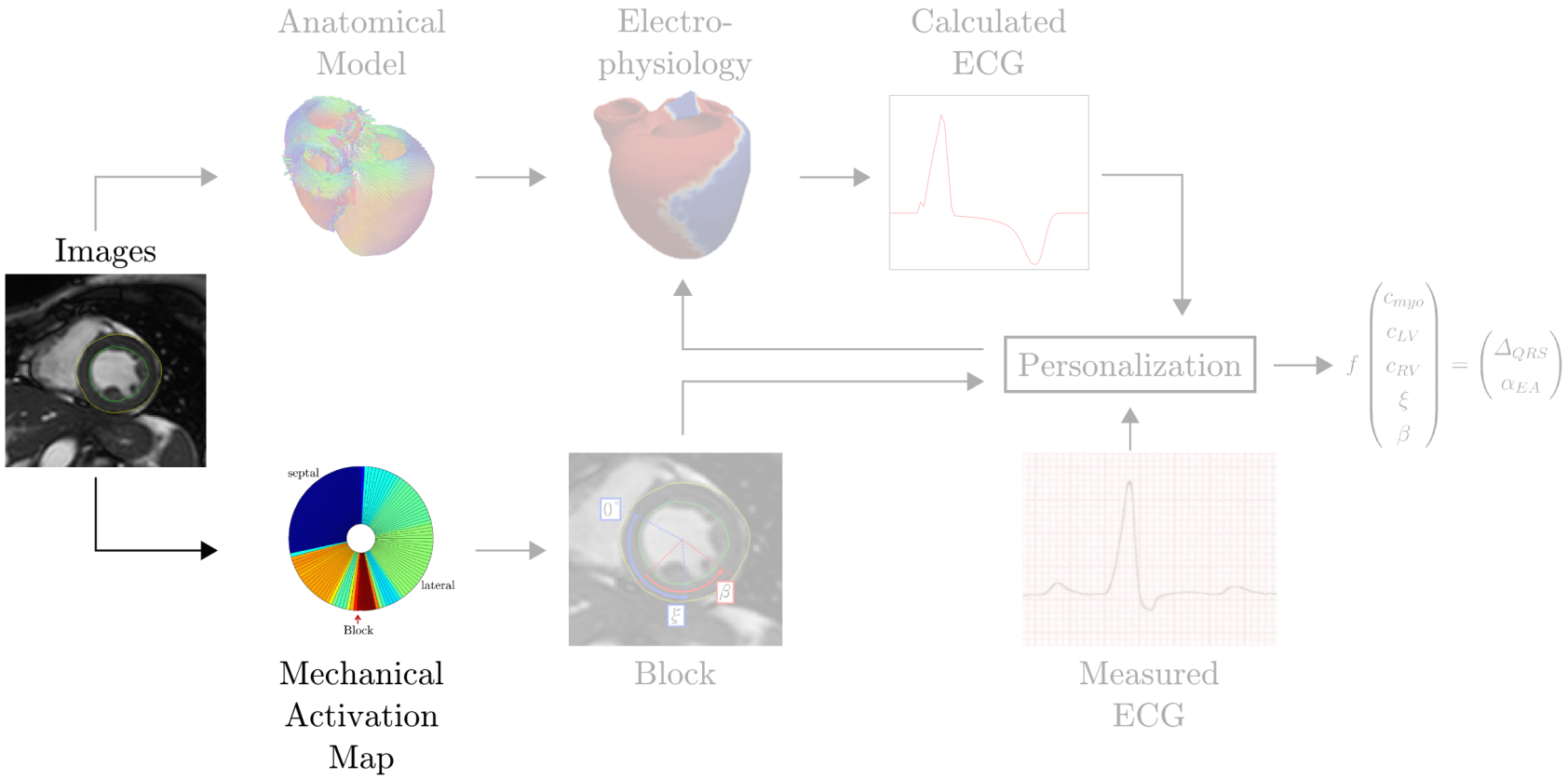
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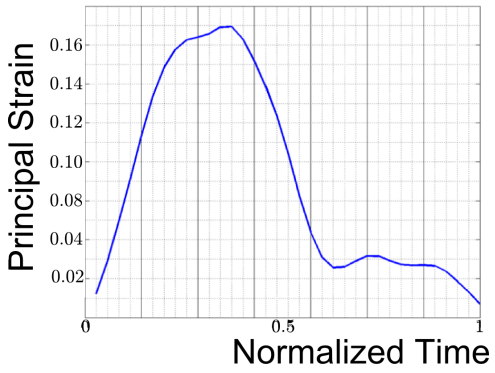
Strain Computation

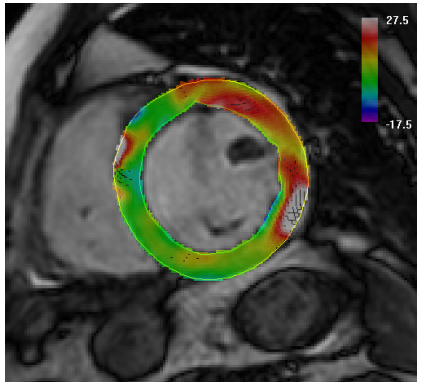
- Aim: detecting myocardial contraction
- Lagrangian Strain Tensor:

$$E = \frac{1}{2}\left(\nabla\Phi_i + \nabla\Phi_i^T + \nabla\Phi_i\nabla\Phi_i^T\right) \tag{1}$$

- Principal strain (first eigenvalue of E)

  $\Rightarrow$ Temporally resolved map of myocardial strain

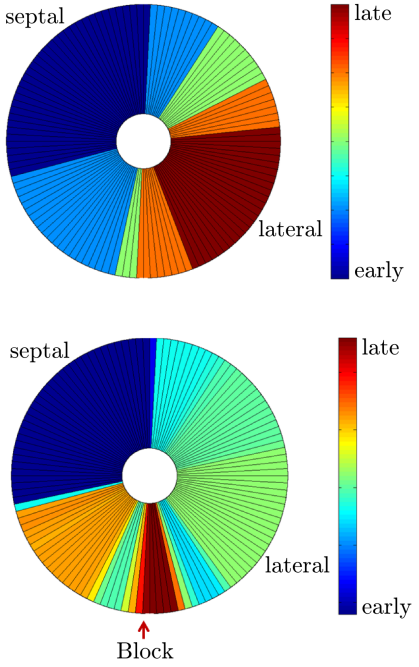




Strain Map at End-Systole

Block Detection from Mechanical Activation Maps

- Division of left ventricle into 120 segments (in short axis plane)
- Averaging
- Maximal contraction (peak of strain) indicates mechanical activation time
  $\rightarrow$ Polar map of mechanical activation
- U-shaped contraction pattern
  $\rightarrow$ Block at the latest activated segment



Electrophysiology Modeling

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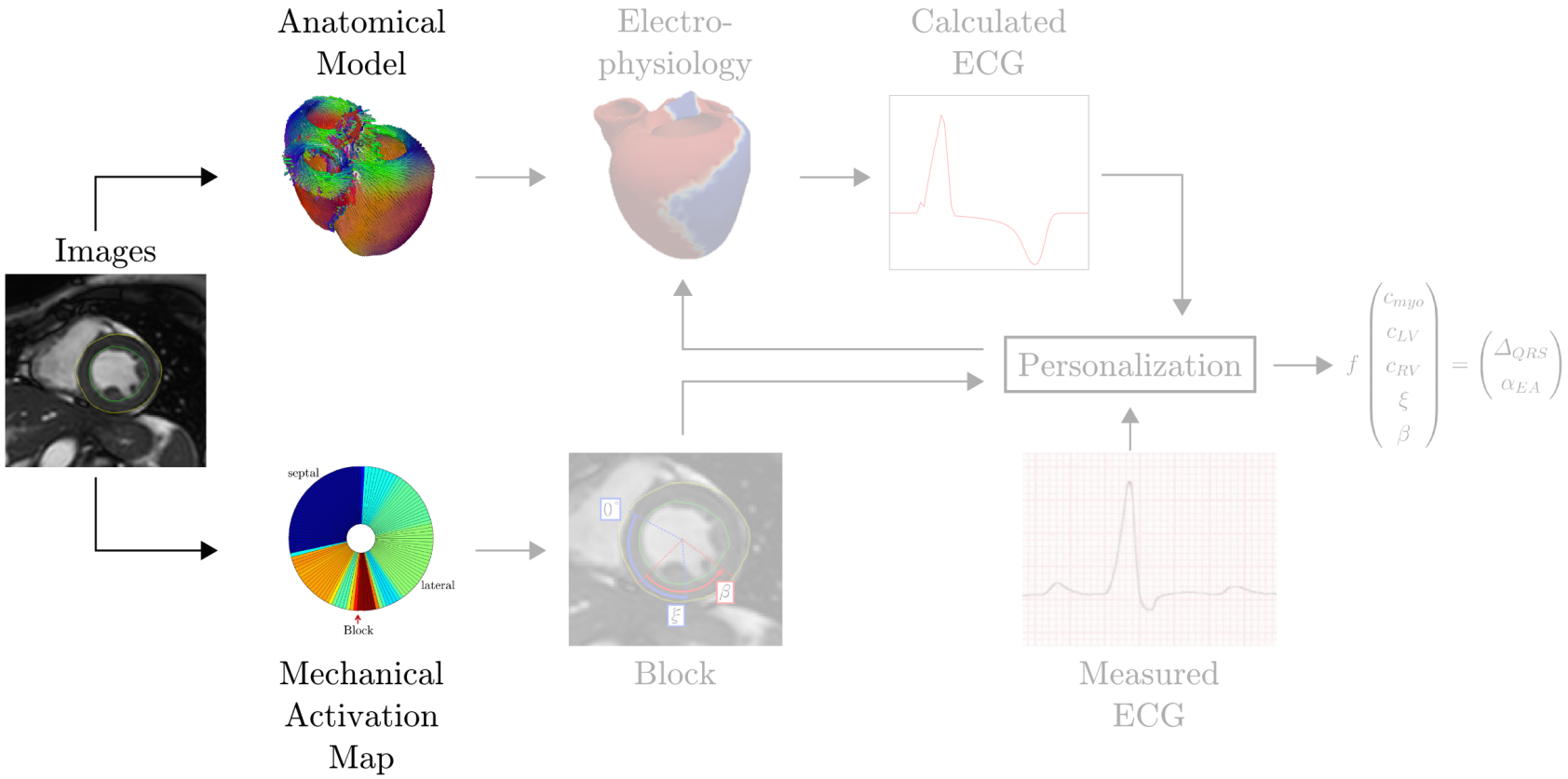
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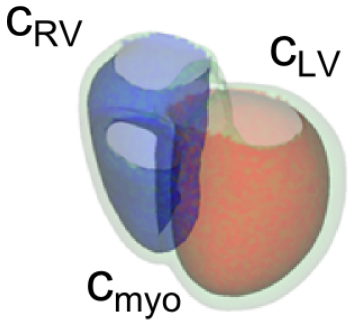
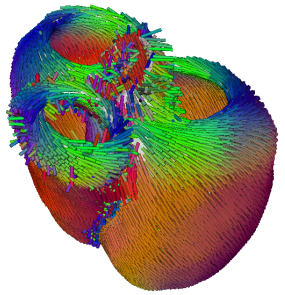
Anatomical Model

- Semi-automatic heart segmentation [Zheng et al., 2008]
- Tetrahedral finite element model
- Three domains for electrophysiology:
  - Myocardium (c_{myo})
  - Left-ventricular endocardium (c_{LV})
  - Right-ventricular endocardium (c_{RV})
- Fiber architecture for anisotropy
- Torso registration for ECG calculation





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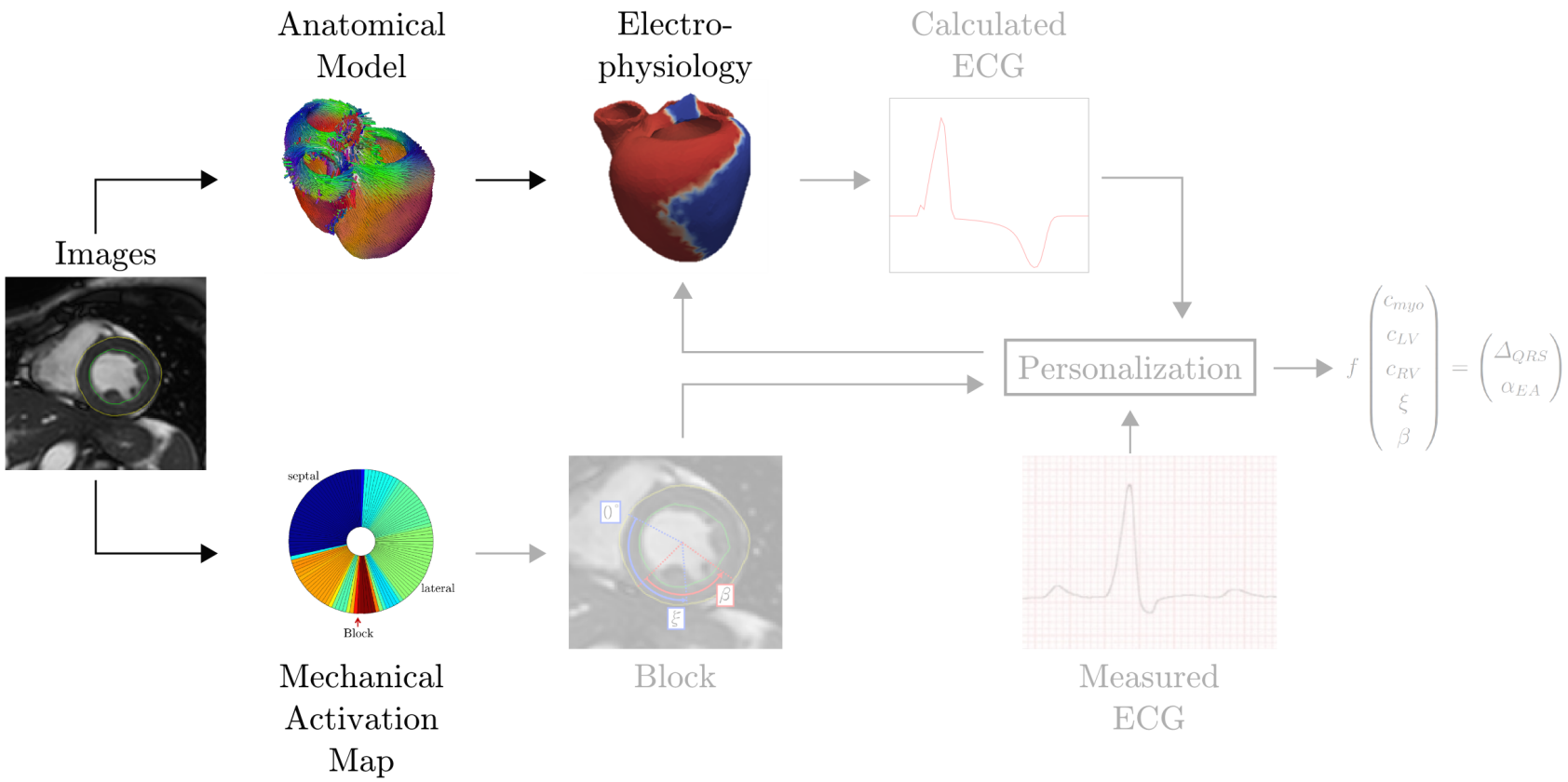
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Action Potential

- Mitchell-Schaeffer model [Mitchell et al., 2003]
- Potentials $v(t)$ according to:

$$\frac{\partial v}{\partial t} = I_{in} + I_{out} + I_{stim} + c\nabla \cdot D\nabla v \tag{2}$$

- Parameters:
  - Transmembrane currents I_{in} and I_{out}: voltage in- and decrease
  - Stimulation current I_{stim}
  - Diffusion tensor D: anisotropy
- Crucial parameter: electrical diffusion $c \rightarrow$ Propagation of electrical wave $\Rightarrow$ Low diffusion in the myocardium, high diffusion in the endocardia (simulation of Purkinje system)

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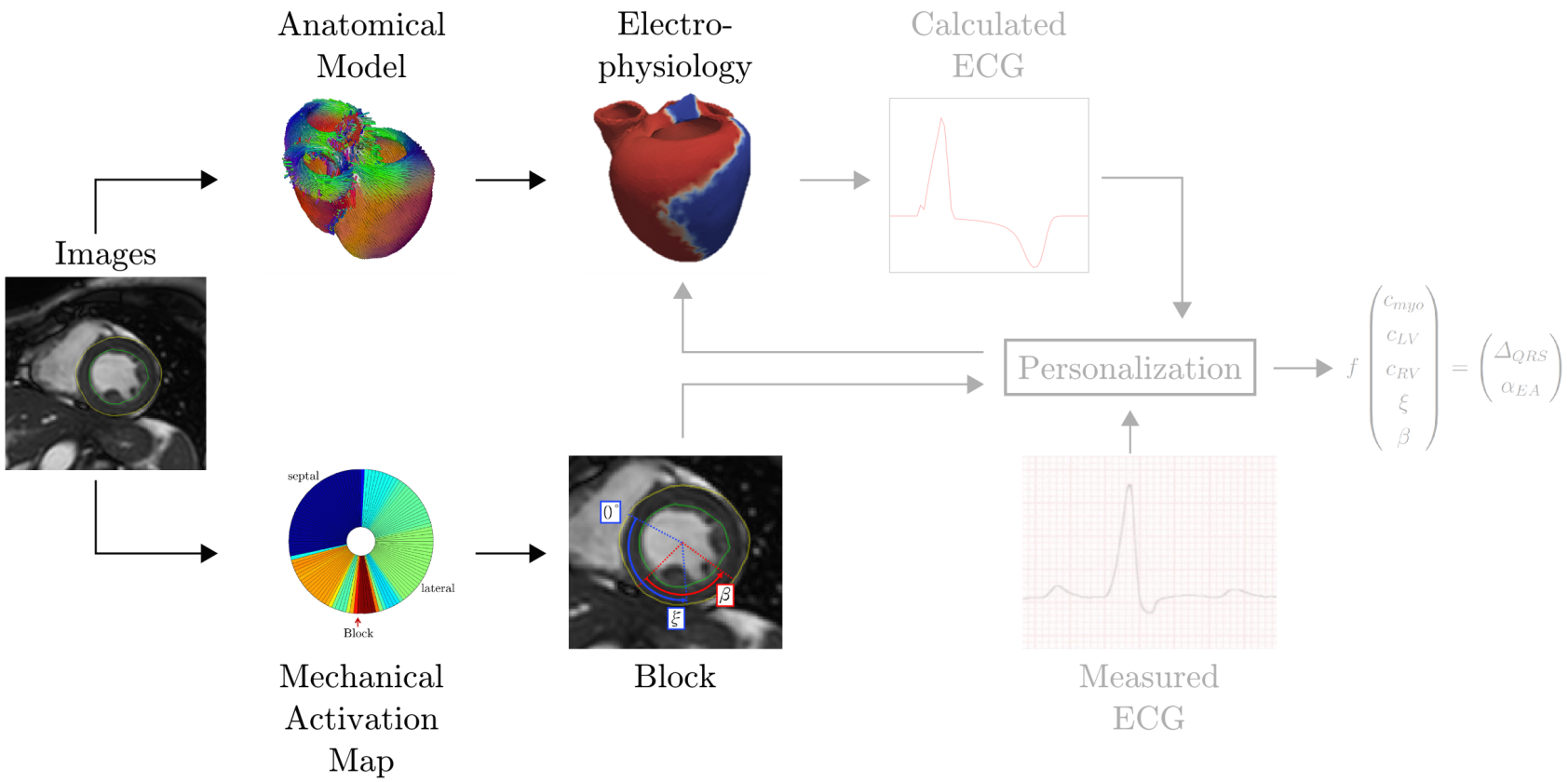
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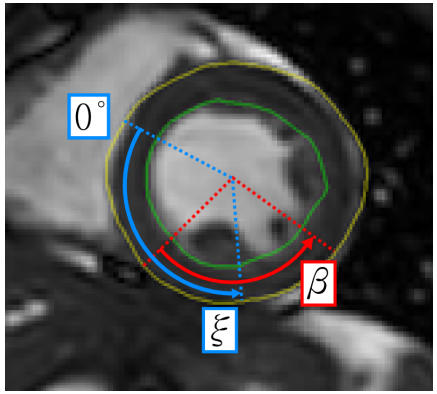
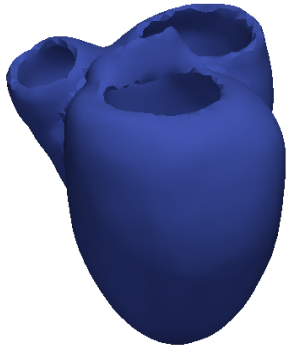
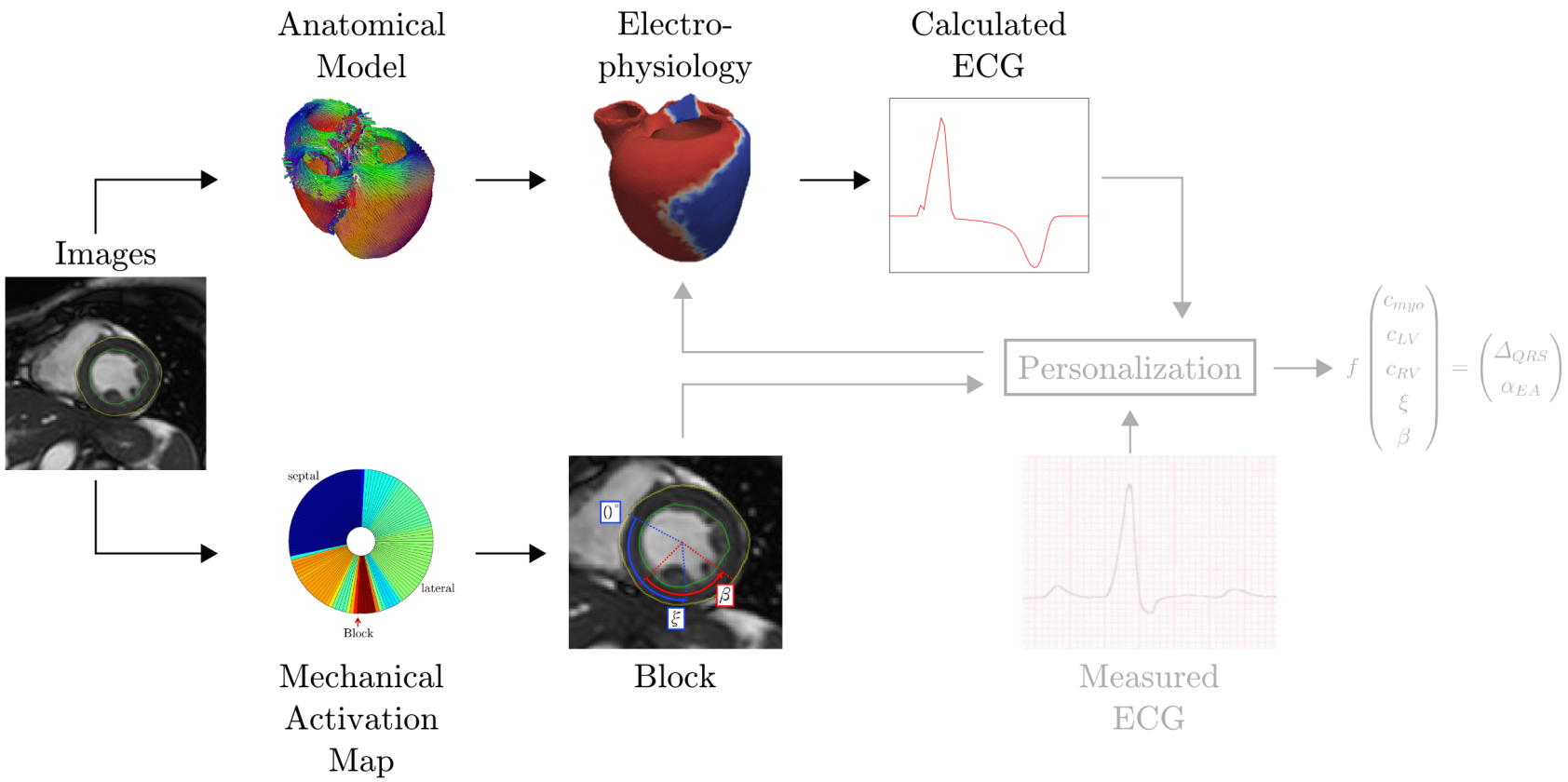
Incorporation of Block

- Block: new domain in the electrophysiology model
- Determined by:
  - Block angle β
  - Block position ξ
- Block centered around ξ
- Diffusion value $c_{Block} = c_{myo}$
  (wave propagates over myocytes)
- Purpose: regional deceleration of electrical wave
  $\Rightarrow$ U-shaped propagation pattern





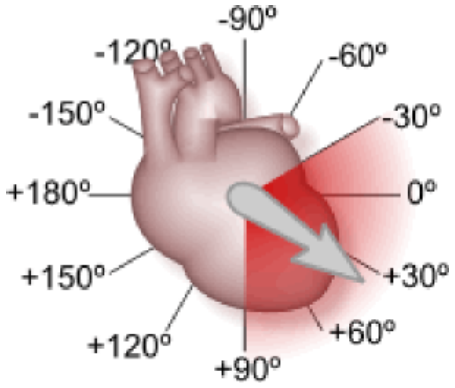
Workflow


Anatomical Model
Electro-physiology
Calculated ECG
Images
Personalization
$f \begin{pmatrix} c_{myo} \\ c_{LV} \\ c_{RV} \\ \xi \\ \beta \end{pmatrix} = \begin{pmatrix} \Delta_{QRS} \\ \alpha_{EA} \end{pmatrix}$
septal
lateral
Block
0°
β
ξ
Mechanical Activation Map
Block
Measured ECG

ECG Calculation

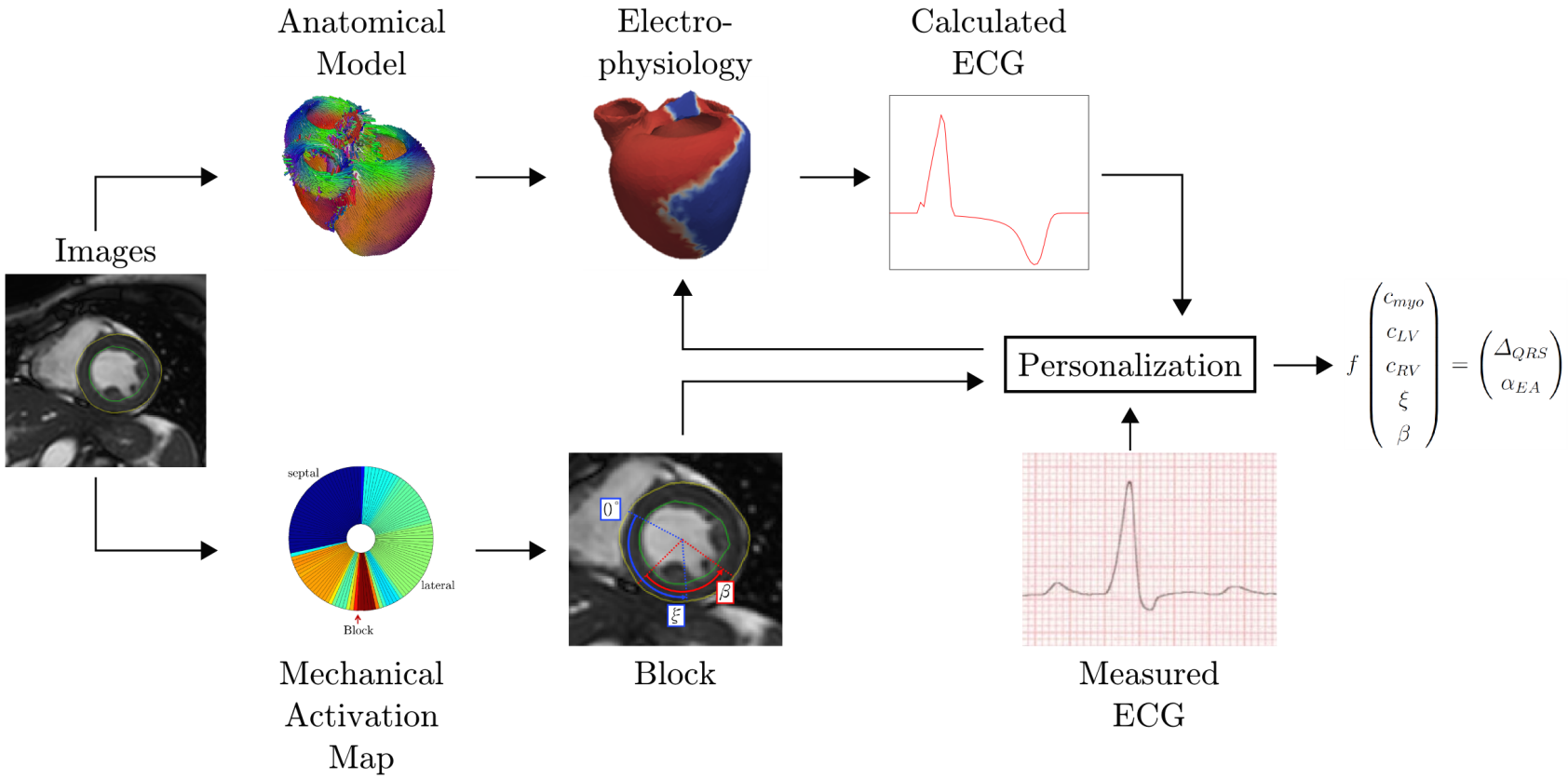
- Clinically measured 12-lead ECG is used for personalization
- Transformation of heart potentials to torso
- 12-lead ECG calculation
- Features from measured and calculated ECG: QRS duration Δ_{QRS} and electrical axis angle α_{EA}

QRS Duration



Electrical Axis

Workflow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septal
lateral
Block
0°
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ξ
Mechanical Activation Map
Block
Measured ECG

Model Personalization

- Optimization using a gradient-free estimation framework (BOBYQA) [Powell 2009]
- Personalization of:
  - Diffusion parameters c_{myo}, c_{LV}, c_{RV}
  - Block parameters β, ξ
- Block location ξ from mechanical activation maps (adjusted to cope with spatial inaccuracies)

$$\text{Model:} \quad f\left(c_{myo}, c_{LV}, c_{RV}, \xi, \beta\right) = \begin{pmatrix} \Delta_{QRS} \\ \alpha_{EA} \end{pmatrix} \tag{3}$$

$$\text{Optimization:} \quad \underset{c_{myo},c_{LV},c_{RV},\xi,\beta}{\arg\min} \left| f - \begin{pmatrix} \Delta_{QRS,meas} \\ \alpha_{EA,meas} \end{pmatrix} \right| \tag{4}$$

Evaluation

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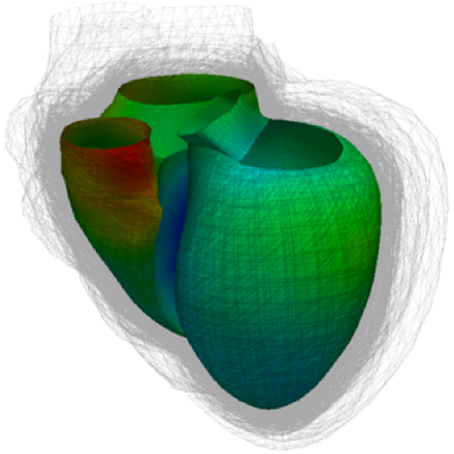
Investigated Data

- 47 pathological datasets (University Hospital Heidelberg)
  - 12-lead ECG
  - Cine MRI
- Estimated mechanical activation maps on all cases
- U-shape pattern for 14 cases
- Evaluation of personalization on these 14 cases



Sensitivity Analysis

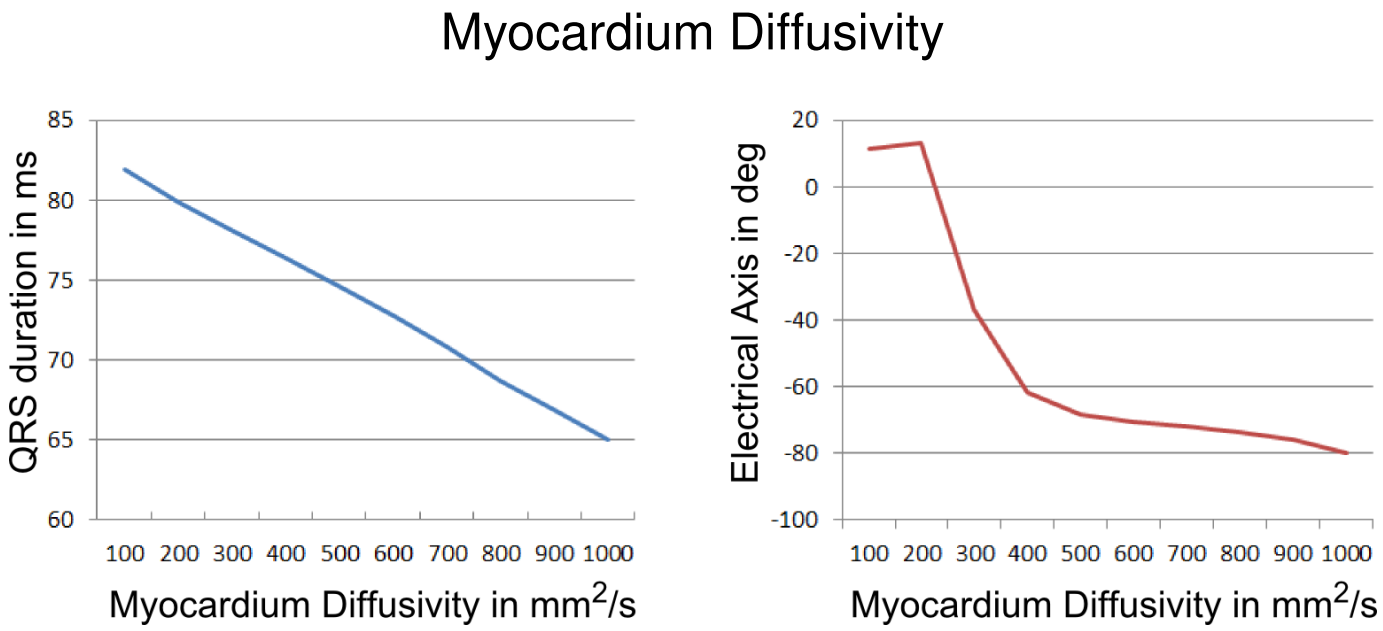
- One representative patient set
- Investigated parameters:
  - Diffusion values
  - Action potential duration
  - Fiber angles
  - Resolution of mechanical activation maps
  - Block parameters

$\Rightarrow$ Justification of simplifications

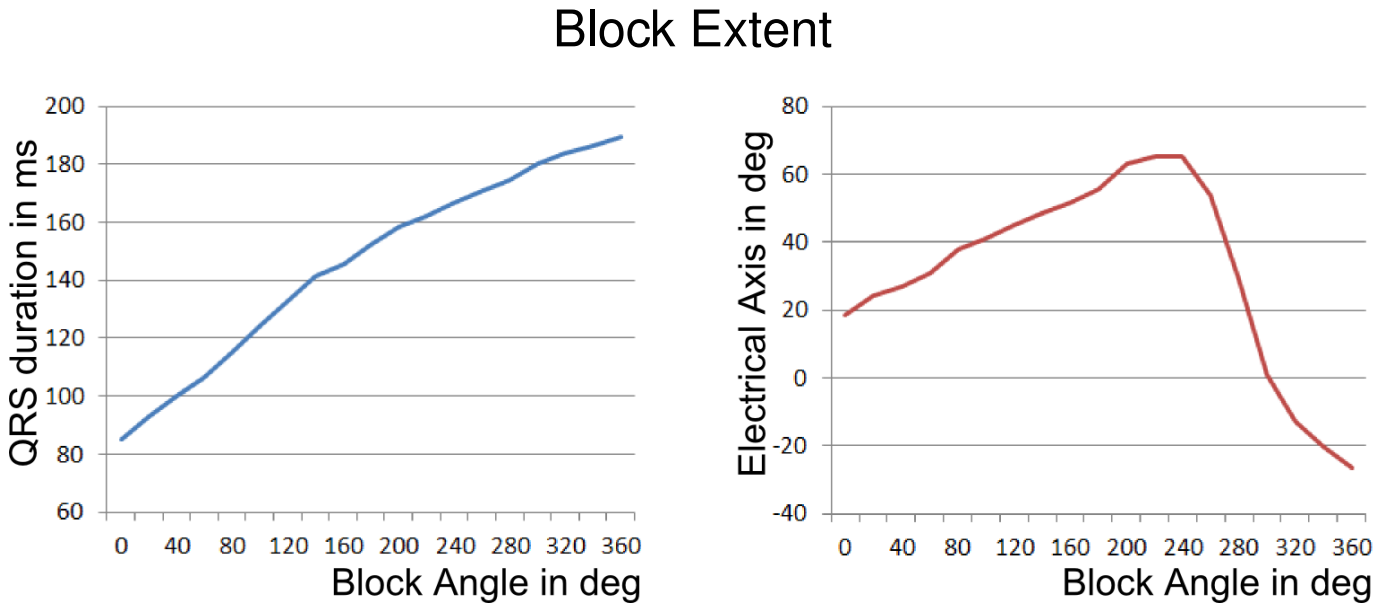
$\Rightarrow$ Justification of personalization

$\Rightarrow$ Reasonable diffusion values

Sensitivity Analysis – Example



Sensitivity Analysis – Examples



Quantitative Evaluation

- Acceptance criteria:
  - $\varepsilon_{QRS} = |\Delta_{QRS,meas} - \Delta_{QRS}| \leq 20\,\text{ms}$
  - $\varepsilon_{EA} = |\alpha_{EA,meas} - \alpha_{EA}| \leq 30^\circ$
- Comparison to personalization method with global diffusion values

- Improvements in average errors:
  - $\bar{\varepsilon}_{QRS,global} = 15\,\text{ms} \rightarrow \bar{\varepsilon}_{QRS,regional} = 1\,\text{ms}$
  - $\bar{\varepsilon}_{EA,global} = 42^\circ \rightarrow \bar{\varepsilon}_{EA,regional} = 18^\circ$
- Improvement in number of matched cases:
  - QRS duration: $n_{QRS,global} = 11 \rightarrow n_{QRS,regional} = 14$
  - Electrical axis: $n_{EA,global} = 7 \rightarrow n_{EA,regional} = 10$
  - Both features: $n_{global} = 5 \rightarrow n_{regional} = 10$

Quantitative Evaluation (cont.)

	Δ_{QRS} (ms)			α_{EA} (°)		
Patient	Measured	Regional	Global	Measured	Regional	Global
0006	146	146	135	-99	-106	-99
0009	174	174	189	-3	-3	-35
0010	170	184	203	-40	-40	-60
3519	89	88	101	112	115	-102
3577	122	122	123	-15	20	-15
3972	98	98	109	32	-40	-48
4446	90	90	95	-12	31	-12
4845	96	96	105	57	57	18
7874	166	163	137	90	89	-47
7957	124	124	123	-17	42	-7
8214	117	117	74	21	-7	21
8561	83	83	93	45	45	-32
8889	148	148	157	60	60	16
9583	130	130	149	-12	-12	-19

Conclusion and Outlook

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Conclusion

- Personalized computational electrophysiology models:
  - Better patient selection
  - Better therapy planning
- Current personalization methods based on rarely available or global data
- Our approach: regional personalization based on:
  - 12-lead ECG
  - Cine MRI

Conclusion (cont.)

- Basic components:
  - Motion information by image registration
  - Regional manipulation by block region
- Data:
  - Non-invasive acquisition
  - Wide availability
- Significant improvement compared to standard global method

Future Work

- Further regionality (right ventricle, inferior blocks)
- Exploitation of additional motion parameters or ECG features
- Evaluation on a larger database
- Investigation of predictive power
  $\rightarrow$ Simulated therapies

Thank you for your attention!

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