Ural Federal University

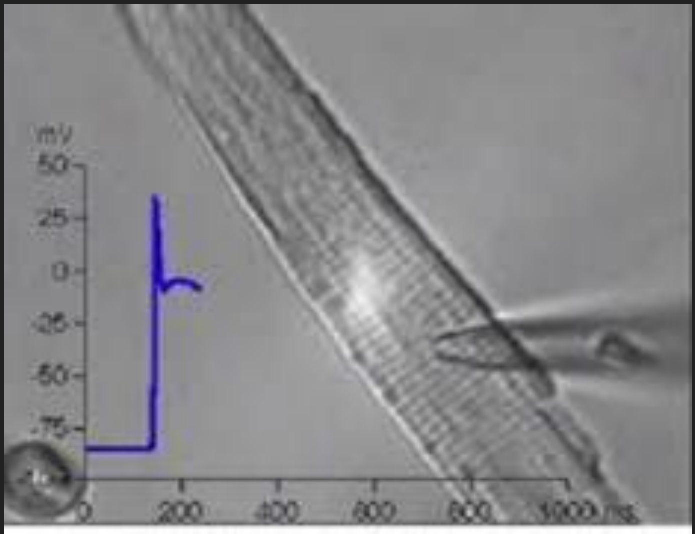
INFLUENCE OF MYOCARDIUM HETEROGENEITY ON ELECTROCARDIOGRAPHY SIGNALS IN PERSONALIZED HUMAN HEART

K.S. Ushenin[1,2], A. Dokuchaev[2], S.M. Magomedova[3], O.V. Sopov[3],
V.V. Kalinin[4], O. Solovyova[1,2]

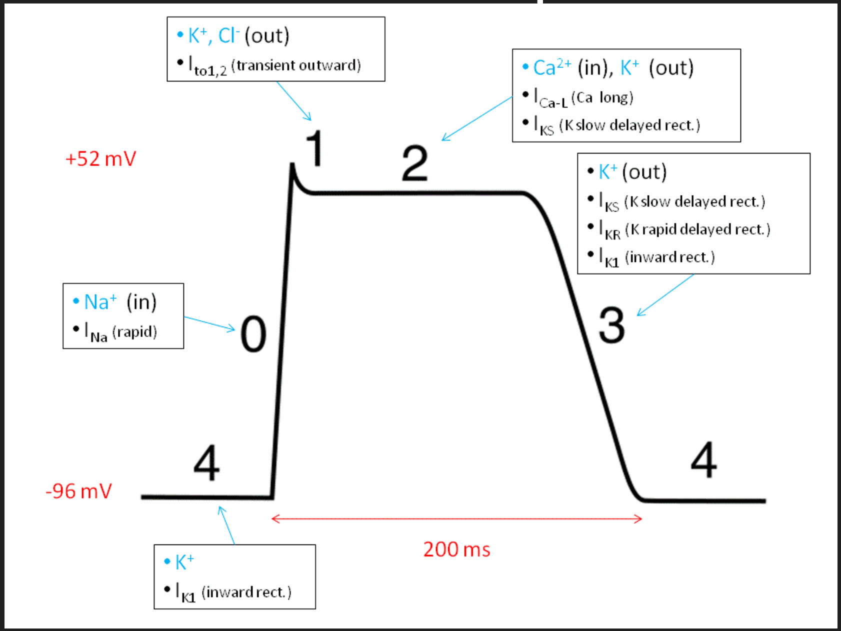
[1] Ural Federal University, Ekaterinburg, Russia
[2] Institute of Immunology and Physiology Ural Branch of RAS, Ekaterinburg, Russia
[3] A.N. Bakulev Scientific Center for Cardiovascular Surgery, Moscow, Russia
[4] EP Solutions SA, Yverdon-les-Bains, Switzerland

Cardiac electrophysiology

- The cell membrane works like the capacitor. The membrane has the transmembrane potential (about -85 mV)
- Neurons and cardiomyocytes are excitable cells. They can revert transmembrane polarity
  (from -85 mV to 25 mV)
- The electrical activation leads to mechanical contraction in cardiomyocites



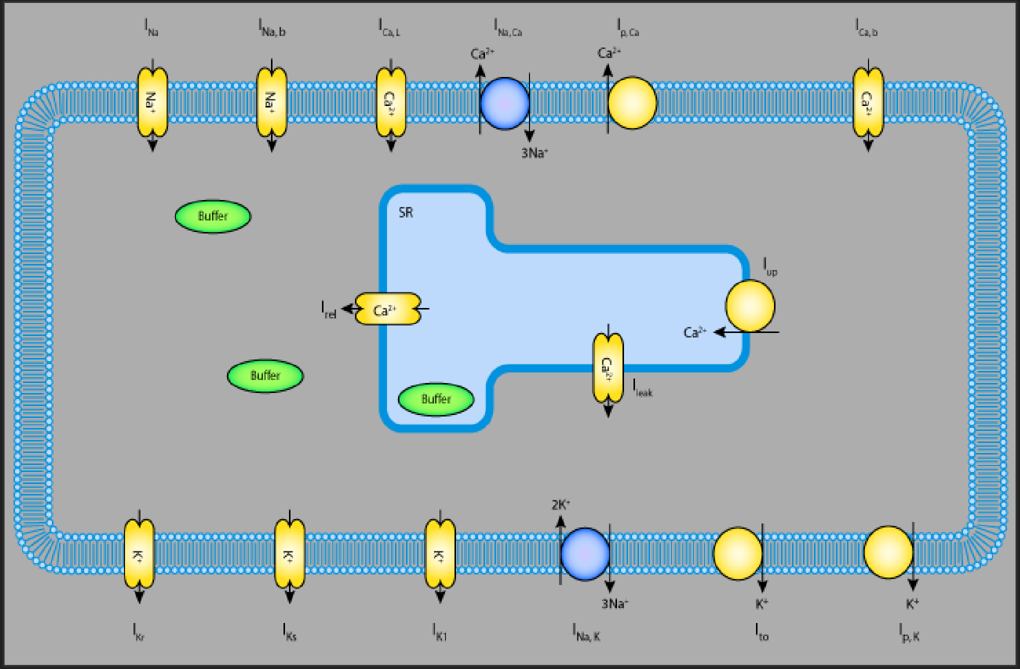
A patch-clamp register the transmembrane potential

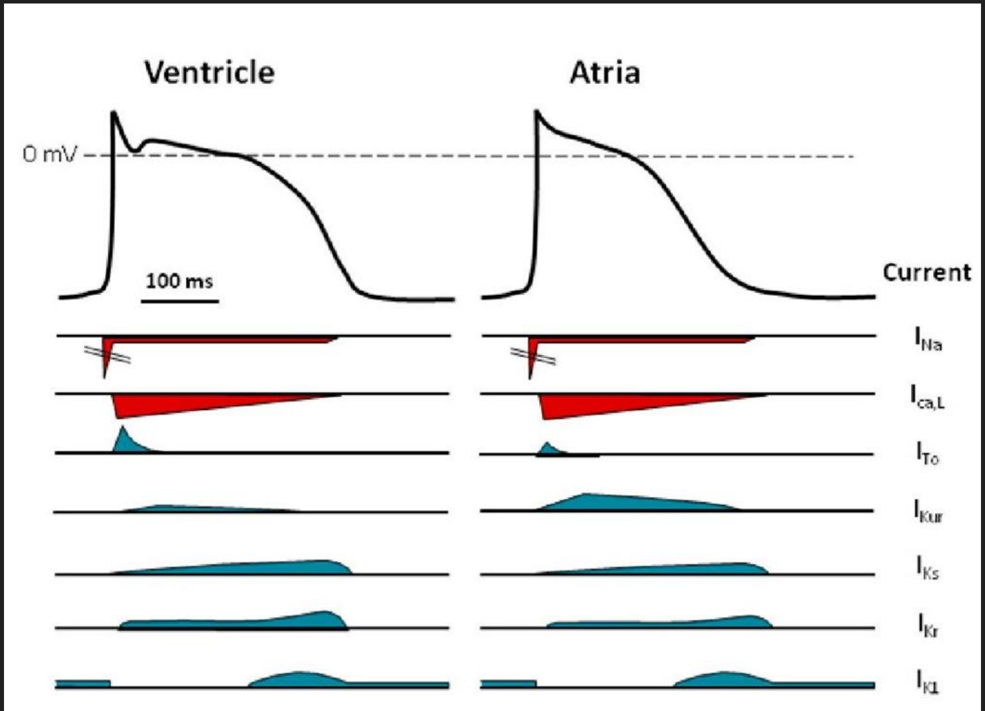


The action potential stages

Cardiac electrophysiology

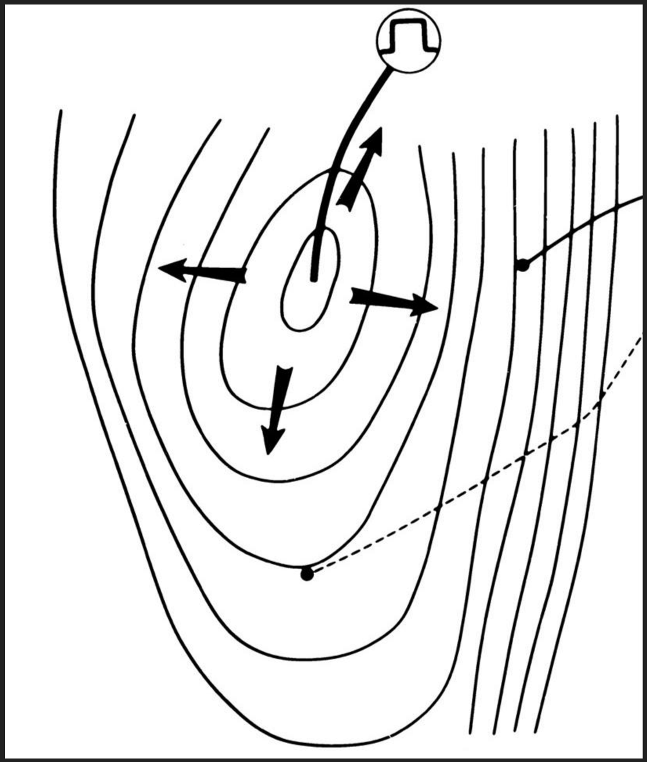
- There are several types of channels which provides different transmembrane currents.
- Also, cardiomyocytes includes the sarcoplasmic reticulum, which store Ca^{+2} ions for accelerate mechanical activation

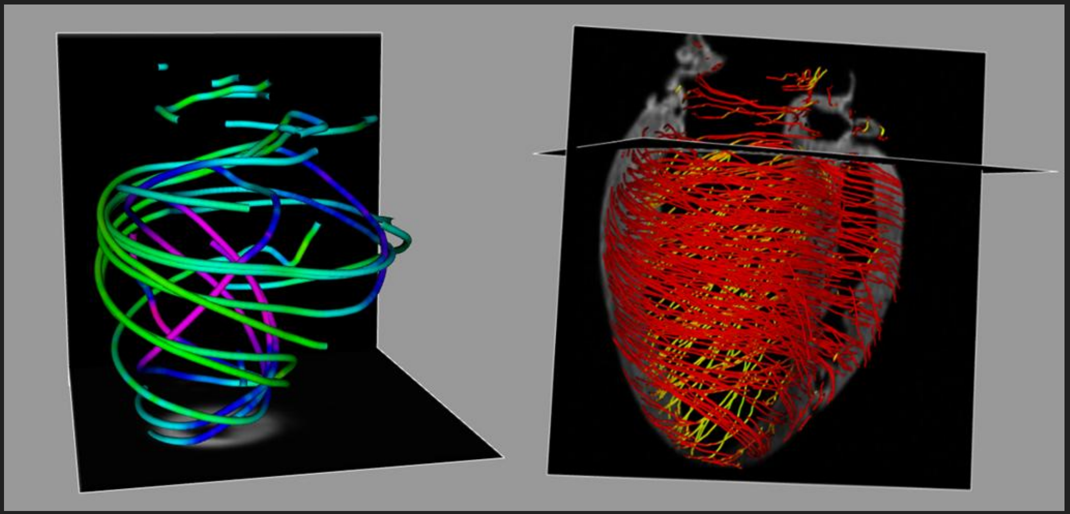


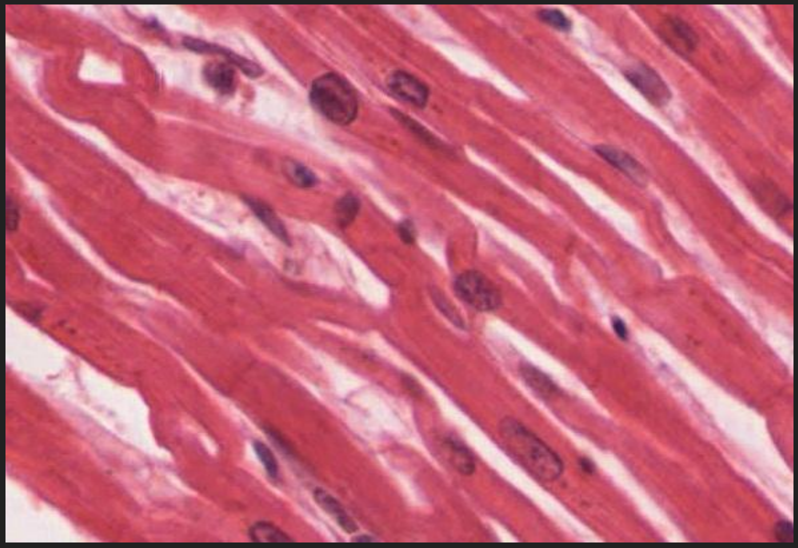


Cardiac electrophysiology

- Cardiomyocytes have the orientation in the tissue
- It is the general reason of anisotropic excitation propagation in the tissue
- The myocardium has a complex structure of fibers.

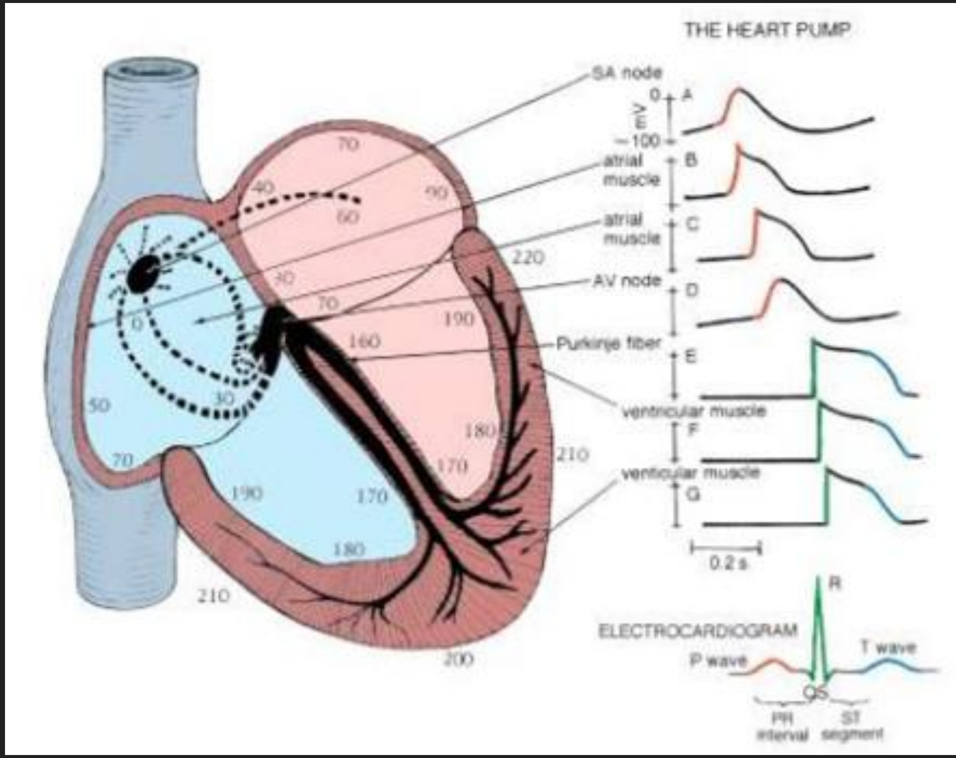


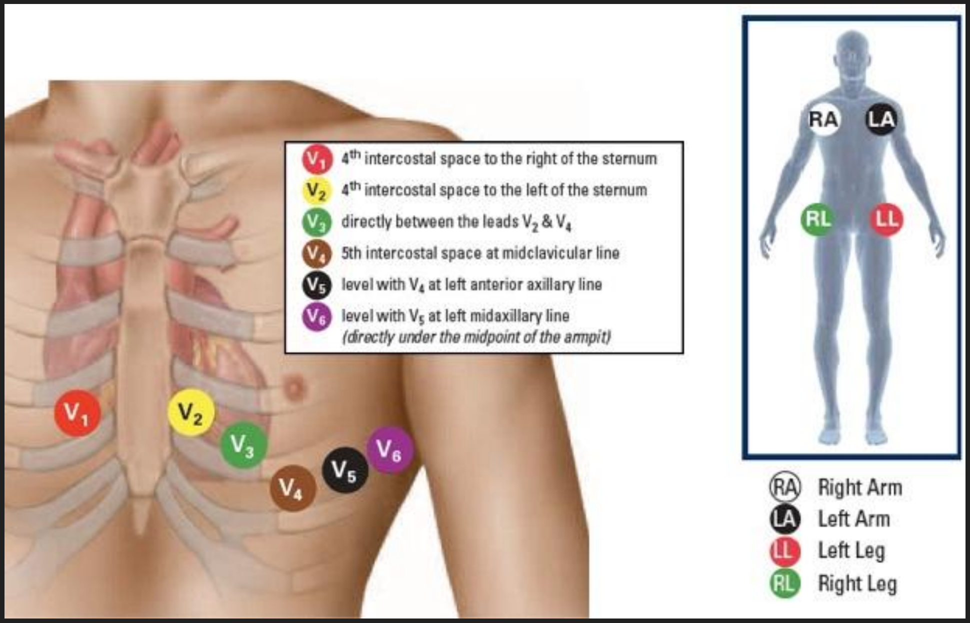


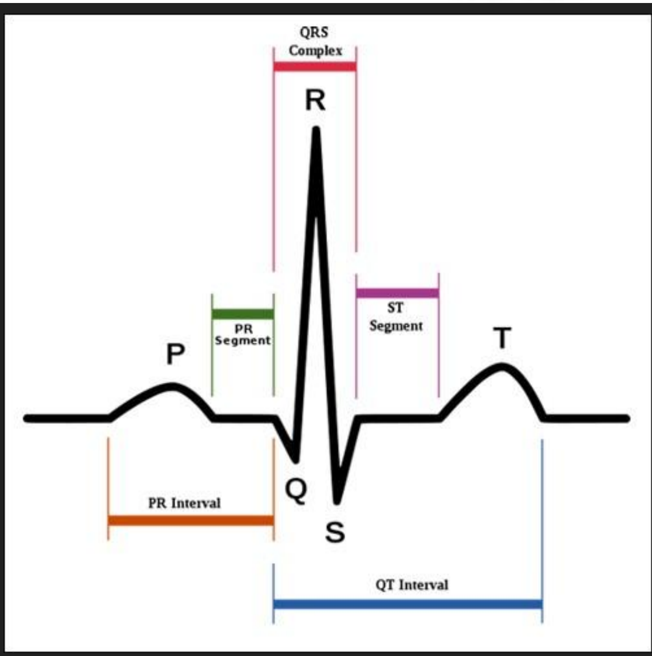


Cardiac electrophysiology

- QRS complex is a ventricular activation (depolarization).
- T wave is a ventricular recovery (repolarization).

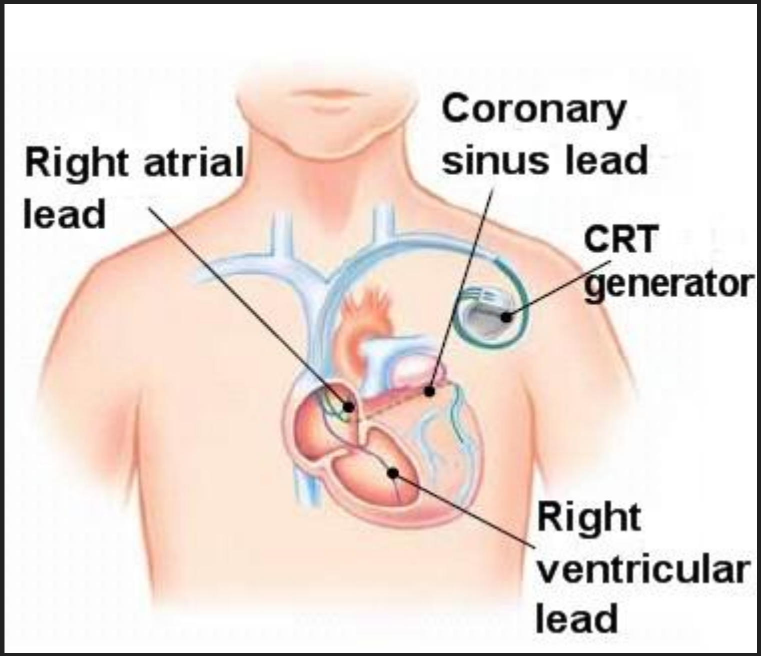






The cardiac resynchronization therapy (CRT)

The device activates the ventricles and improve the heart ejection rate



The premature ventricular beat (PVC)

Activation from the ventricles from a one point. It looks in ECG like that:

What is a model we want to create?

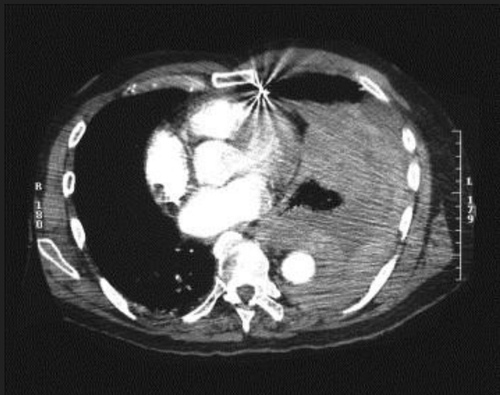
- We want to develop a heart-torso model which is based on the clinical computed tomography data
- We want to simulate activation from one--two points similar to CRT or PVC
- We want to verify the model against the clinical ECG

What do we want to study?

- An influence of a fiber anisotropy
- An influence of an apico-basal heterogeneity
- A stimulation electrode position

Design of the study: the simulation based on clinical data

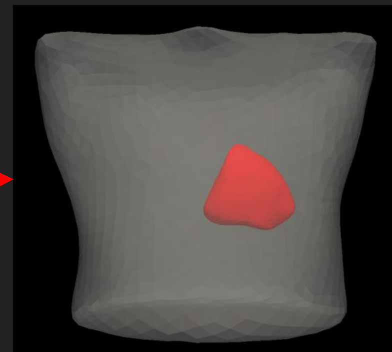
Clinical data

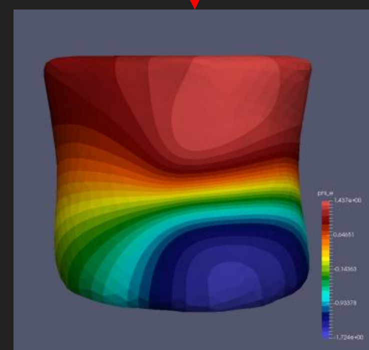


Computed tomography

240 leads ECG

Simulation

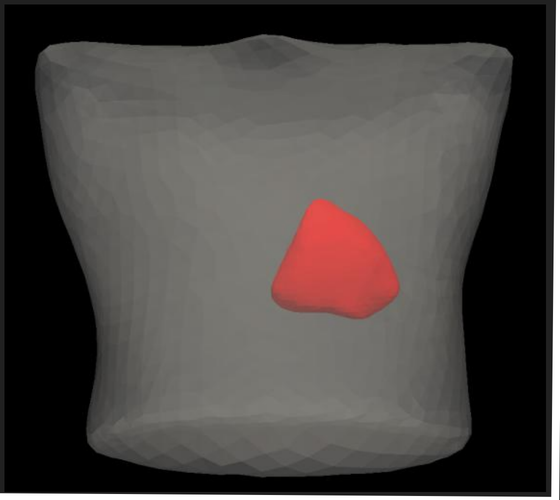


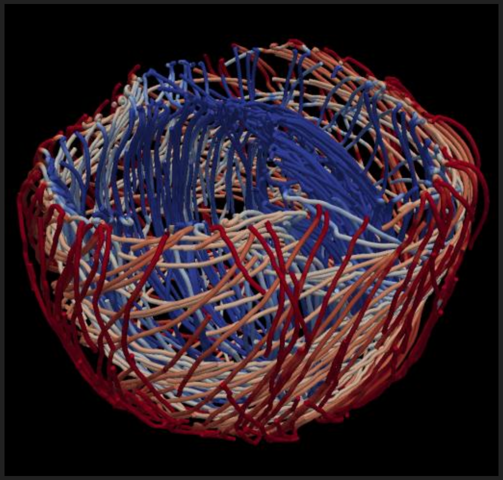


Comparison: the simulated vs the clinical data

Patient 1	Patient 2
Female	Male
67 year	56 year
Hypertrophic cardiomyopathy	Arrhythmogenic cardiomyopathy
ANTERIOR 8 segment	LATERAL 9 segment

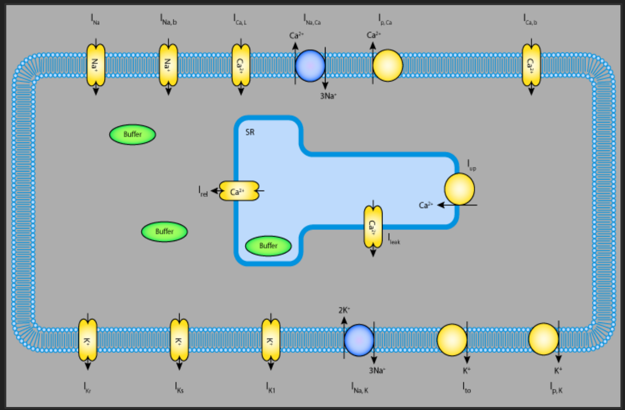
The torso is homogeneous





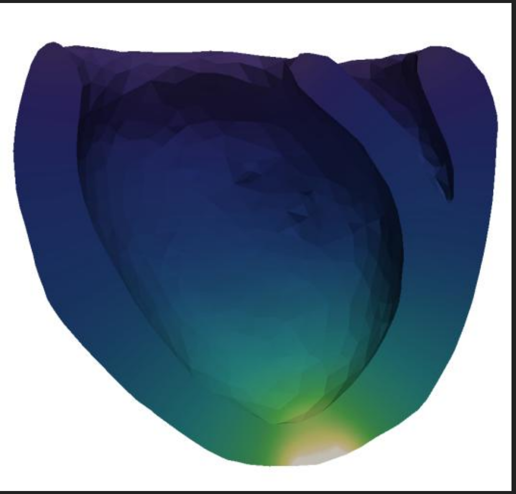
Fiber orientation
Bayer et. al. 2011

The model is physiologically accurate

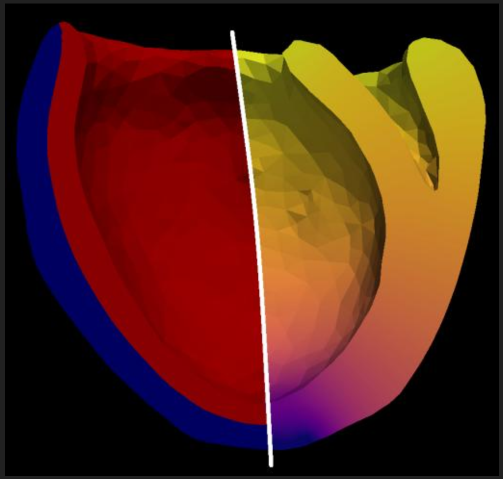


ten Tuscher et. al. 2006
Human ventricular cardiomyocyte model:

- 12 ionic currents
- the sarcoplasmic reticulum



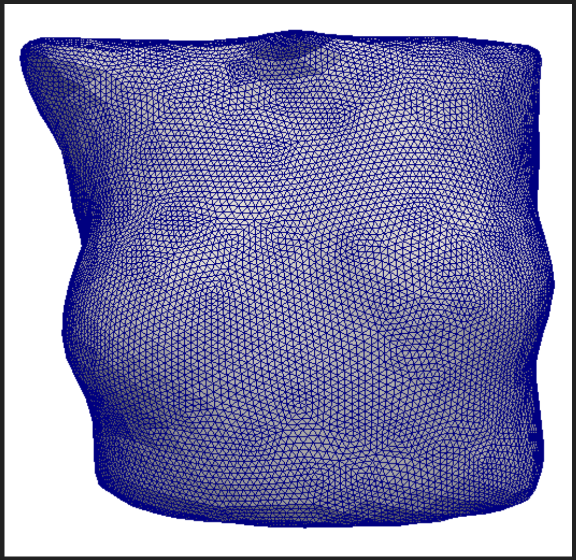
Apicobasal heterogeneity in I_{Ks}
Keller et. al. 2012

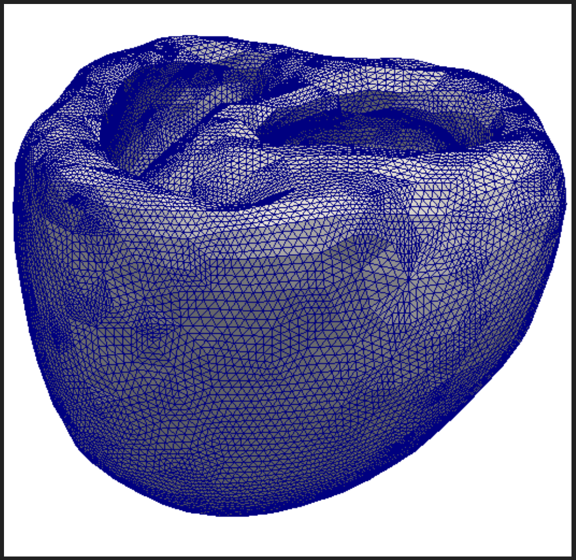


Transmural heterogeneity
50 epi. : 50 endo.

Meshes

- Number of points: 375 313
- Number of cells: 2 190 349
- Torso maximum edge length: 2 cm
- Heart maximum edge length: 0.5 cm





What do we use?

$$\nabla \cdot \mathbf{G}_i(\nabla V_m + \nabla \phi_e) = \beta_m \left(C_m \frac{\partial V_m}{\partial t} + i_{ion} \right)$$

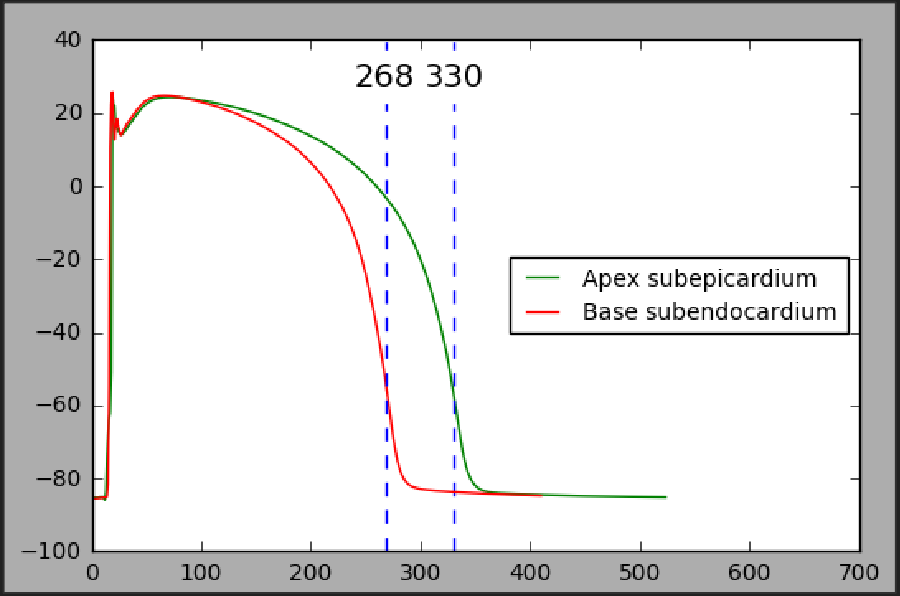
$$\nabla \cdot ((\mathbf{G}_i + \mathbf{G}_e)\nabla \phi_e) = -\nabla \cdot (G_i \nabla V_m)$$

Bidomain equations

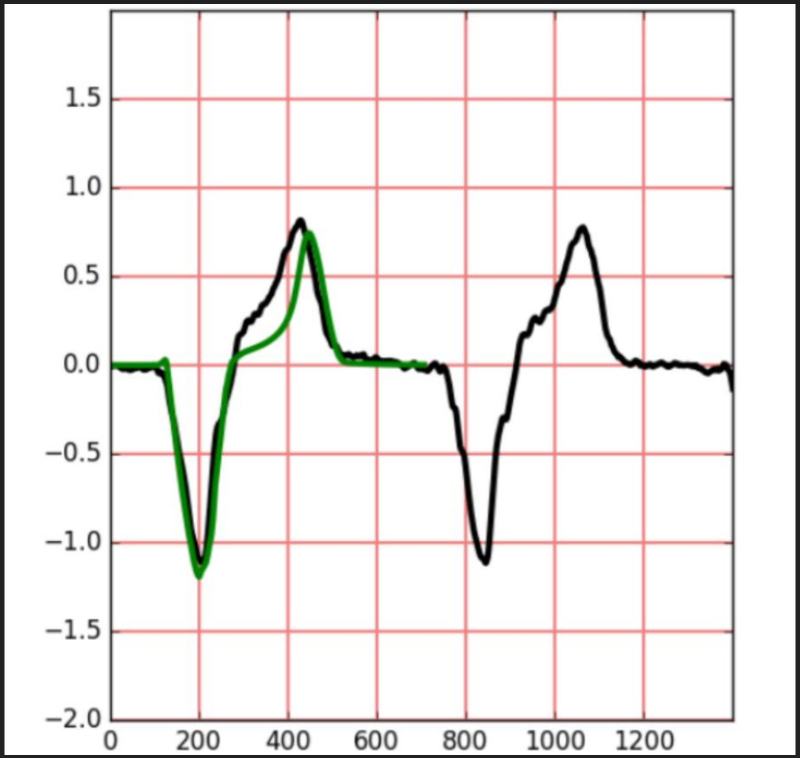
Chaste

Important markers

- The conduction velocity: 0.6m/s, 0.2 m/s
- Electrophysiological anisotropy ratio: 3/1
- APD_{90}: 268 - 330 ms

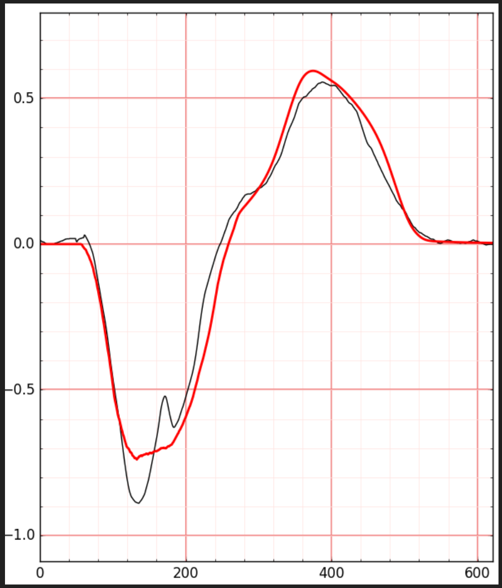


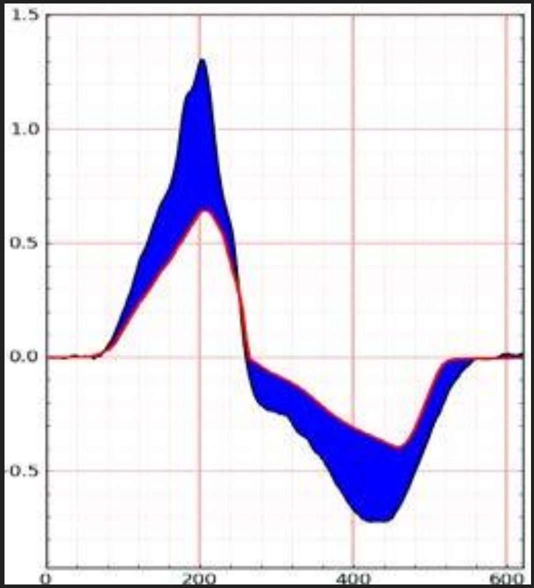
ECG comparison Eindhoven II lead



Metrics for ECG verification

$$SC(x,y) = \frac{\sum_{i=0}^{T} x_t y_t}{\sqrt{\sum_{i=0}^{T} x_t \sum_{i=0}^{T} y_t}}$$





Correlation metric (CM)

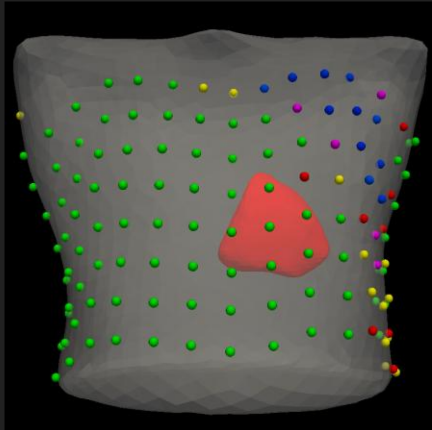
$$ED(x,y) = \sqrt{\sum_{t=0}^{T} (x_t - y_t)^2}$$

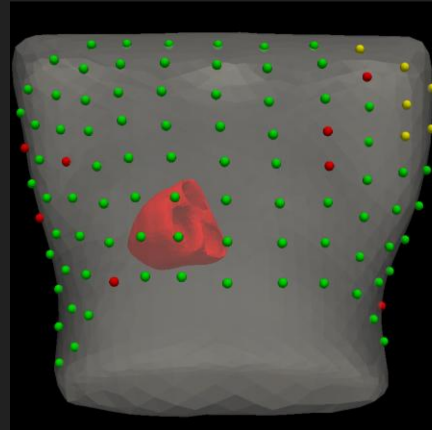
Euclidean distance (ED)

$$ZM_{\Delta t,\mu}(x,y) = \min_{\Delta t,\mu} \sqrt{\sum_{t=0}^{T} (x_t - zoom(y_{t+\Delta t}, \mu))^2}.$$

Zoom metric (ZM). It is ED with signal time scaling and shifting.

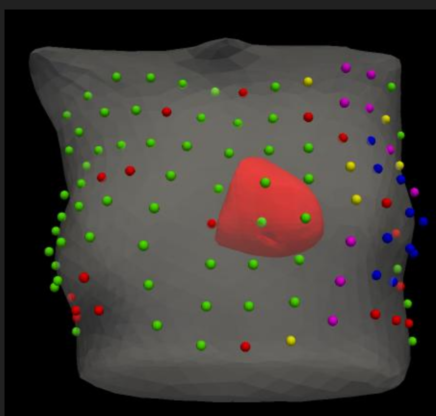
Results

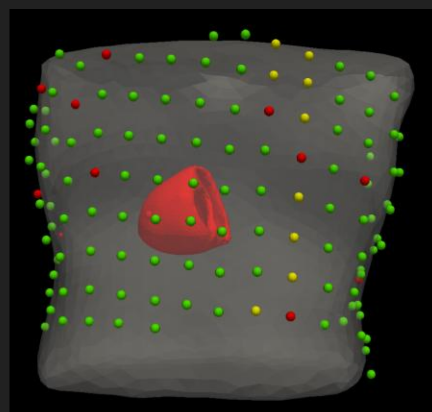


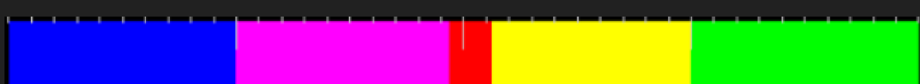


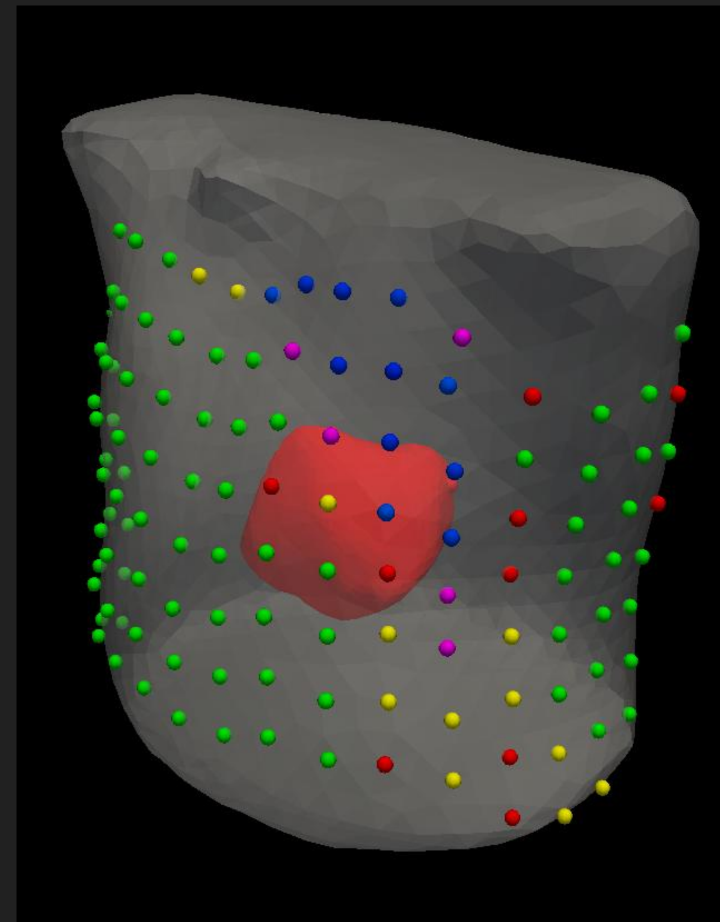
chest

back

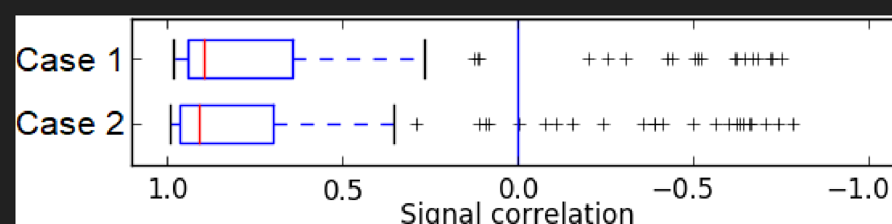








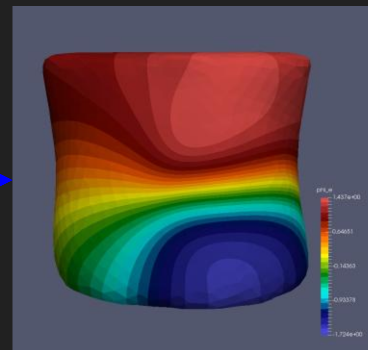
Conclusion: The simulation is correct anywhere except the small zone



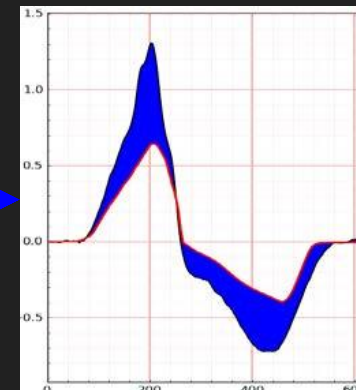
Distribution of the correlation (similar to data from Keller et. al. 2011)

Design of the study

The reference model



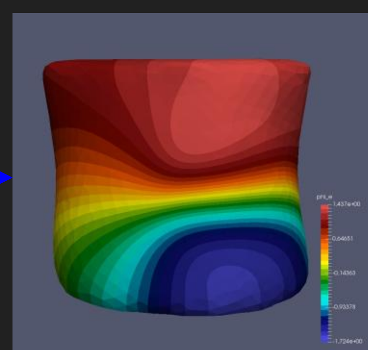
100% in Euclidean and Zoom metric (about 1100 mV*ms)

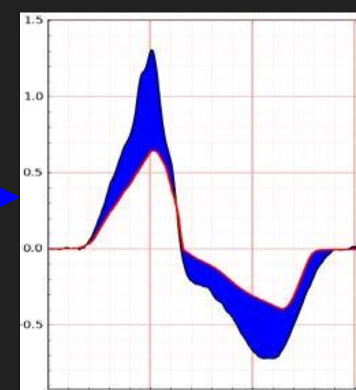


<< Changes

Evaluate an influence to ECG

The model with studied features





????% in Euclidean and Zoom metric

Anisotropy effect on ECG

	Euclidean distance		ZoomMetric	
	Case 1	Case 2	Case 1	Case 2
Isotropy (1:1)	140%	150%	114%	116%
Anisotropy (2:1)	90%	97%	88%	92%
Reference model (3:1)	**100%**	**100%**	**100%**	**100%**
Anisotropy (4:1)	107%	104%	105%	104%

Conclusion:
Myocardial anisotropy is important to simulate adequate ECG

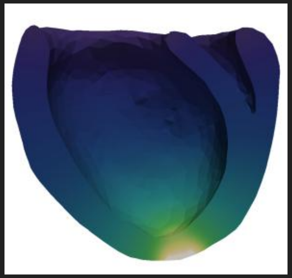
Conclusion:
Anisotropy ratio 4:1 may be more suitable. Possible reasons:

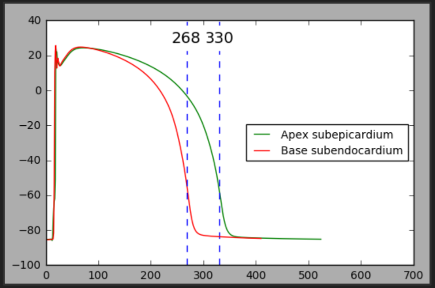
- Unhealthy myocardium
- The real anisotropy 2.3, 2.5 may be close to 2.0

Effect of the apico-basal heterogeneity on an ECG

	Euclidean distance		ZoomMetric	
	Case 1	Case 2	Case 1	Case 2
Reference model (3:1)	**100%**	**100%**	**100%**	**100%**
Without the apico-basal heterogeneity	108%	106%	101%	102%

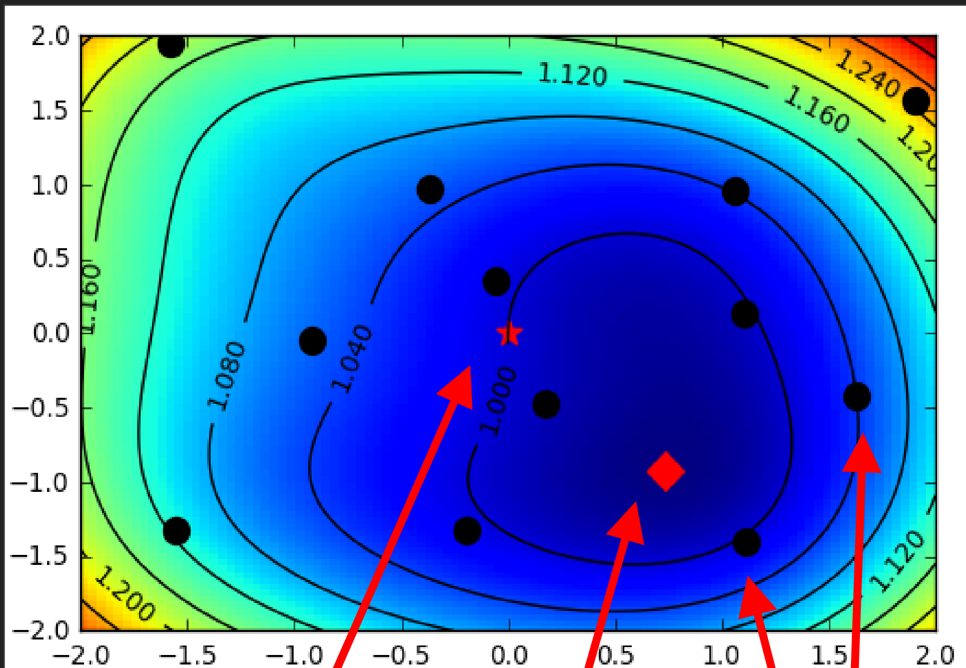
- No significant differences
- A T-wave orientation is always opposite to a QRS complex orientation. T-wave orientation is independent from the apicobasal heterogeneity in case of a point source activation.
- In contrast, an apicobasal heterogeneity is essential for QRS orientation in case of normal activation (Keller et. al. 2011).





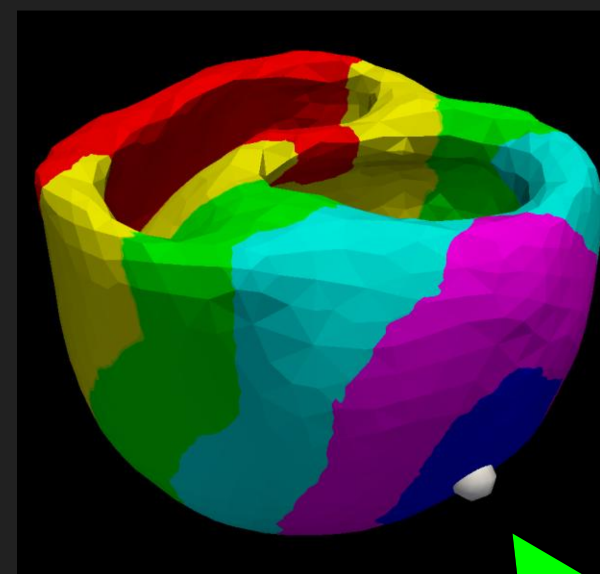
An effect of the activation point location on ECG

ECG Metric map



An euclidean distance metric map:

- Convex function
- Minimum less than 1 cm



Reference point

Minimum

Random shifted pacing points

Summary

1. We developed the heart-torso model based on the clinical CT data and was verified against the clinical ECG.
2. We want to use these simulations as a framework for our future studies.
3. The myocardial electrophysiological anisotropy due to fiber orientation is important for a realistic ECG.
4. The models simulations suggest the possibility to estimate the anisotropy ratio from an ECG data.
5. An ECG is significantly sensitive to the location of the pacing electrode tip in the paced heart.

Publication

K.S. Ushenin, A. Dokuchaev, S.M. Magomedova, O.V. Sopov, V.V. Kalinin, O. Solovyova, Role of myocardial properties and pacing lead location on ECG in personalized paced heart models, Computing in Cardiology, 2017 (in-print)

Acknowledgments

We are grateful to Gunner Siman and Eike Moritz from the Institute of Experimental Cardiovascular Surgery, Freiburg, Germany, for teaching and mentoring the simulation approach.

We are grateful to colleagues from A.N. Bakulev Scientific Center for Cardiovascular Surgery, Moscow, Russia for collect the clinical data for our studies.

Thank you for your attention!

konstantin.ushenin@urfu.ru,
kostaNew@gmail.com,
skype: kostaNew

Ural Federal University