MICROCARD: Numerical modeling of cardiac electrophysiology at the cellular scale

Introduction

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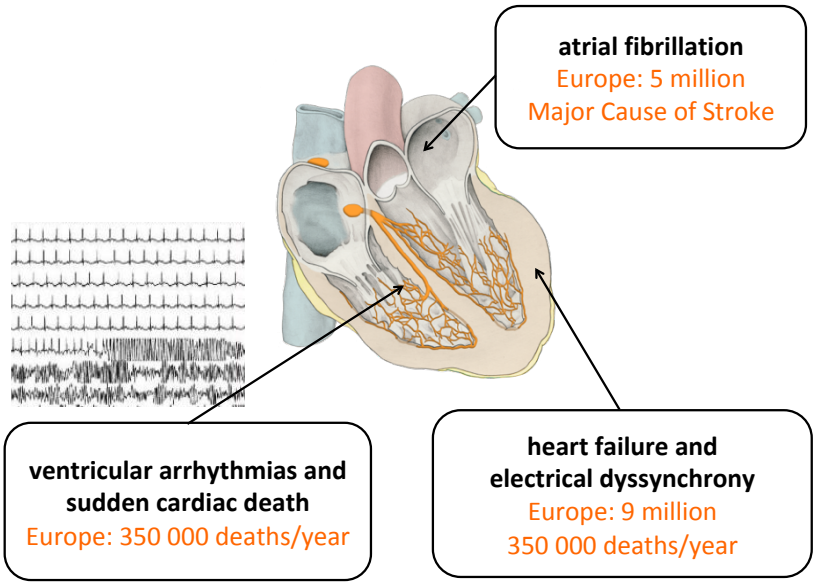
EuroHPC
Joint Undertaking

This project has received funding from the European High-Performance Computing Joint Undertaking EuroHPC (JU) under grant agreement No 955495. The JU receives support from the European Union's Horizon 2020 research and innovation programme and France, Italy, Germany, Austria, Norway, and Switzerland.

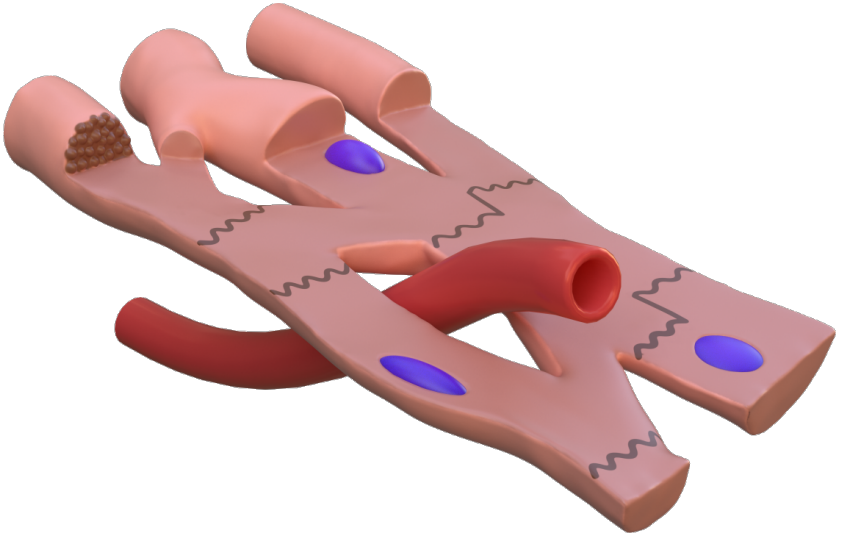
Our cause

Our challenge

- cardiac disease is the #1 cause of death in Europe and half of these deaths are caused by electrical malfunctions
- structural muscle damage is crucial in most of these



Cardiac muscle has a unique structure and electrophysiology



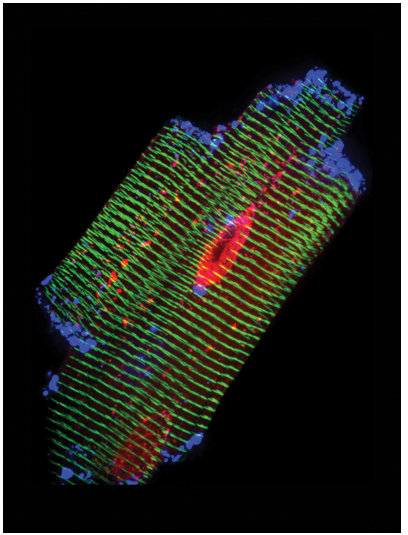
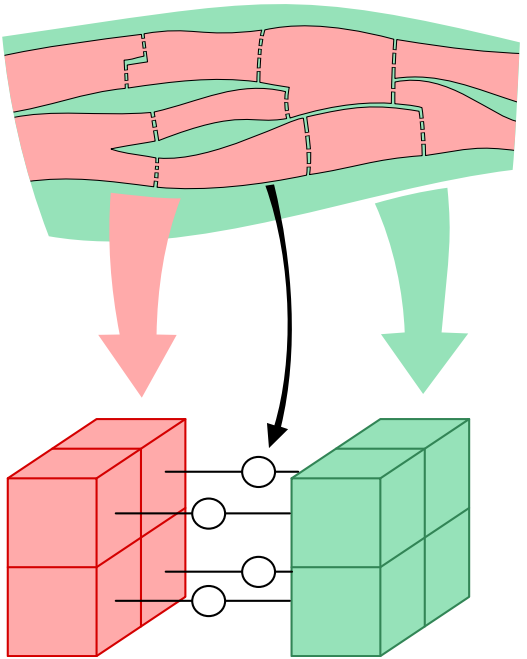


illustration Dana Hamers Scientific Art

The present: bidomain model

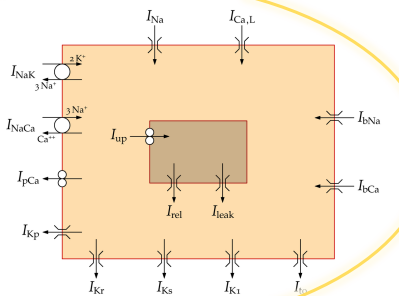


$$\begin{cases} \nabla \cdot (\mathbf{G}_\mathrm{i} \nabla \phi_\mathrm{i}) = I_\mathrm{m} \\ \nabla \cdot (\mathbf{G}_\mathrm{e} \nabla \phi_\mathrm{e}) = -I_\mathrm{m} \end{cases}$$

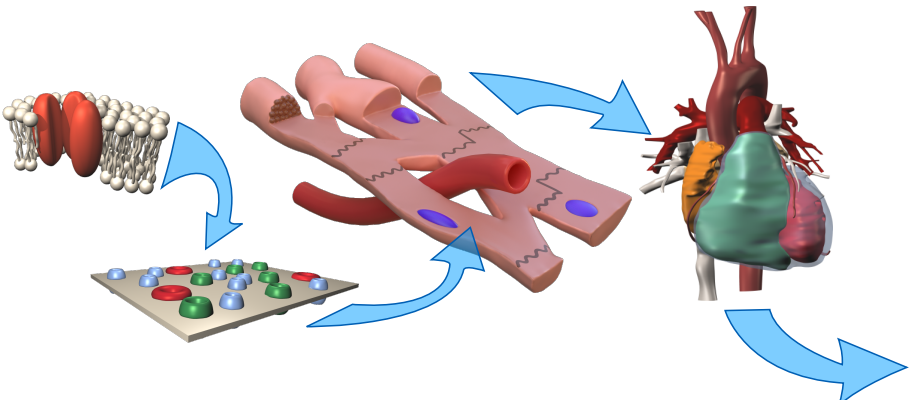
$$V_\mathrm{m} = \phi_\mathrm{i} - \phi_\mathrm{e}$$

$$I_\mathrm{m} = \beta C_\mathrm{m} \frac{\partial V_\mathrm{m}}{\partial t} + I_\mathrm{ion} + I_\mathrm{s}$$

membrane:
20-50 ODEs
per node



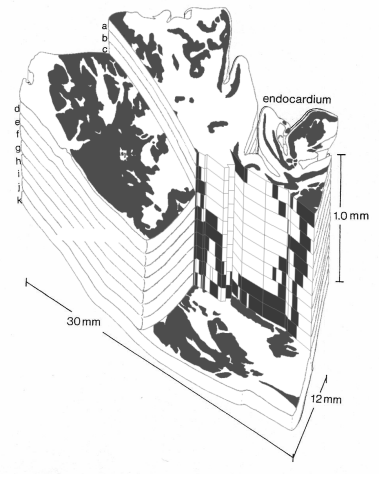
The present in cardiac electrophysiology: bidomain model



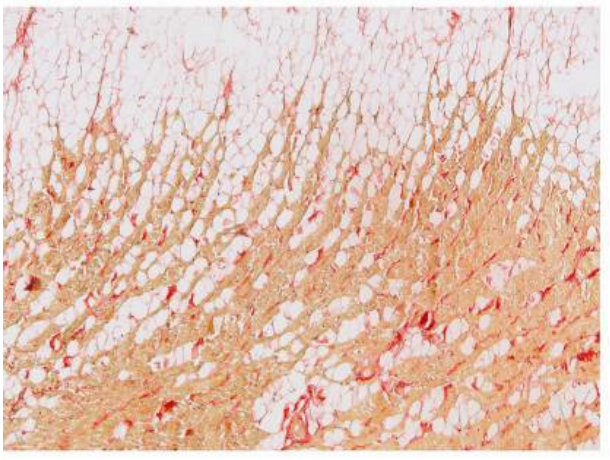
The present: bidomain model

Limitations of the bidomain model

- no notion of individual cells
- cannot represent damaged tissue
- damaged tissue is everywhere (ageing, infarction scars, cardiomyopathies, . . .)



De Bakker et al. *JACC* 15:1594-1607 (1990)

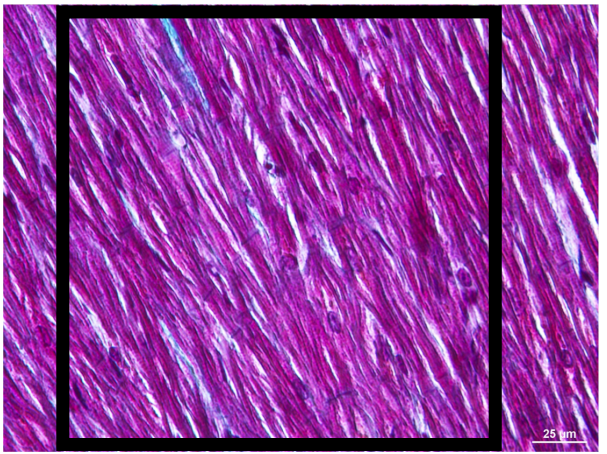


Hoogendijk et al. *Heart Rhythm* 7:238–248 (2010)

Solution: Build a model in which individual cells are discretized

before

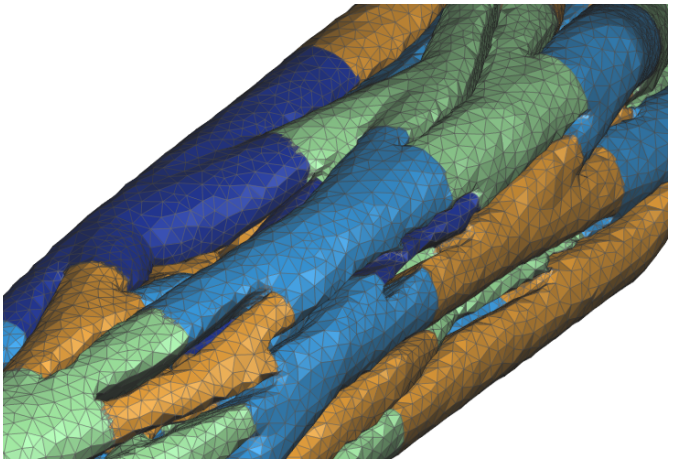
about 200 cells per model element



200 µm

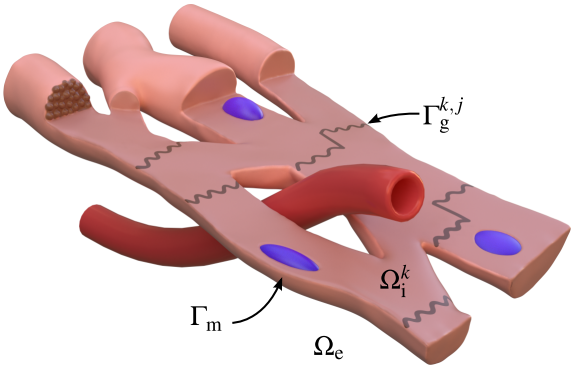
after

about 1000 model elements per cell



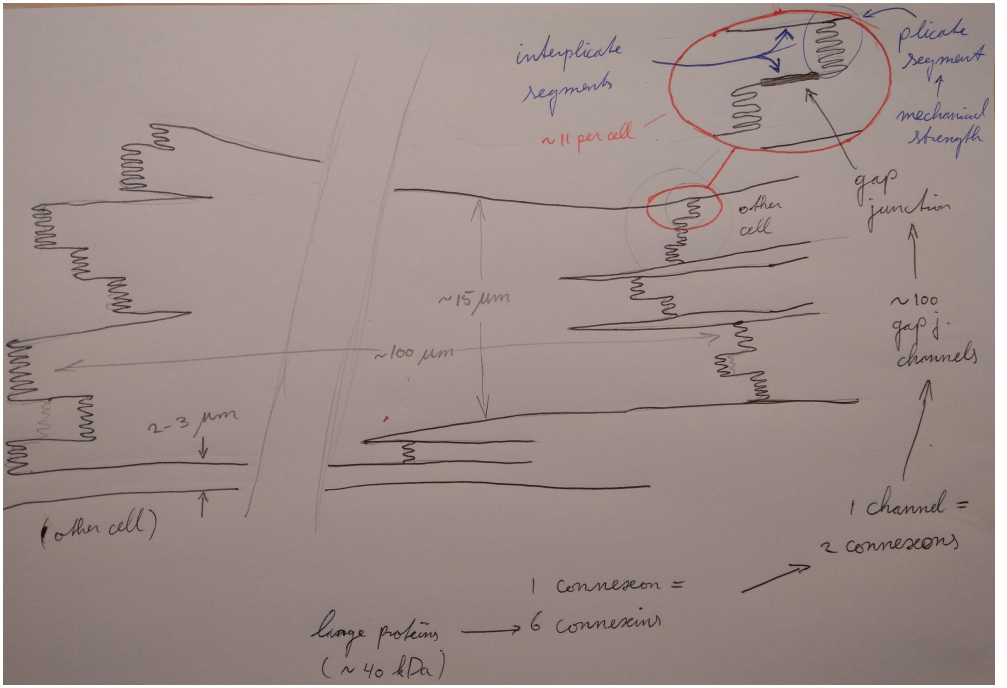
micrograph courtesy of Dr David Benoist, IHU Liryc

A more complicated model formulation

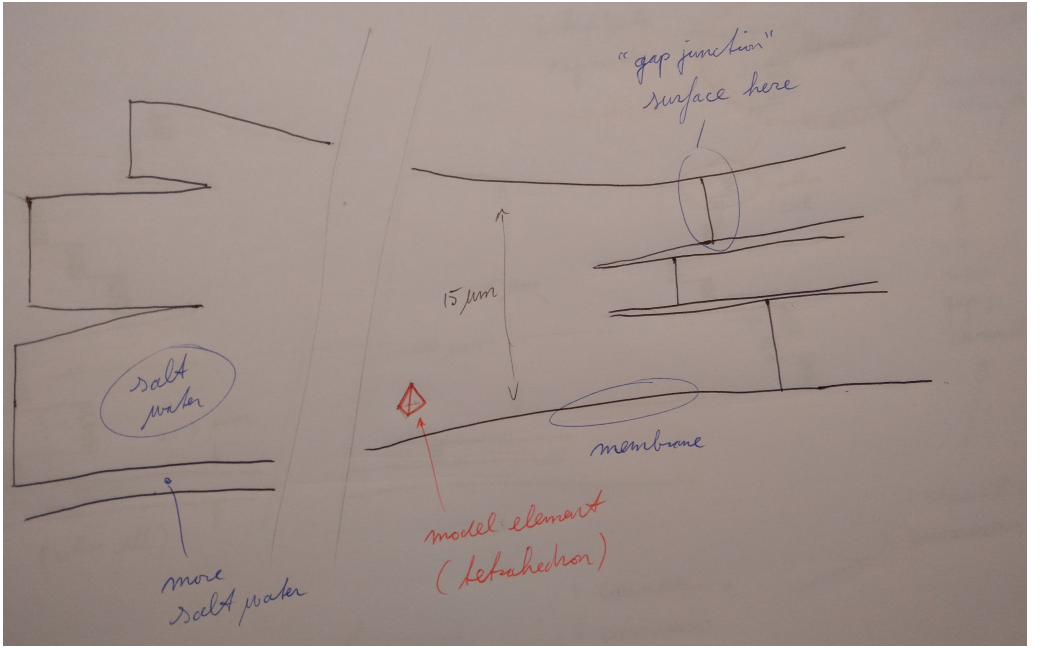


$$
\begin{cases}
\nabla \cdot (G_{\mathrm{i}}^{k} \nabla \phi_{\mathrm{i}}^{k}) = 0, & \text{on } \Omega_{\mathrm{i}}^{k}, \\
\nabla \cdot (G_{\mathrm{e}} \nabla \phi_{\mathrm{e}}) = 0, & \text{on } \Omega_{\mathrm{e}}, \\
V_{m}^{k} = \phi_{i}^{k} - \phi_{e}, & \text{on } \Gamma_{\mathrm{m}}^{k}, \quad \text{(Transmem. voltages)} \\
-G_{\mathrm{i}}^{k} \nabla \phi_{\mathrm{i}}^{k} \cdot \mathbf{n} = G_{\mathrm{e}} \nabla \phi_{\mathrm{e}} \cdot \mathbf{n} = C_{\mathrm{m}} \partial_t V_{\mathrm{m}}^{k} + I_{\mathrm{ion}}(V_{\mathrm{m}}^{k}, \mathbf{y}), & \text{on } \Gamma_{\mathrm{m}}^{k}, \quad \text{(Transmem. currents)} \\
-G_{\mathrm{i}}^{k} \nabla \phi_{\mathrm{i}}^{k} \cdot \mathbf{n} = G_{\mathrm{i}}^{j} \nabla \phi_{\mathrm{i}}^{j} \cdot \mathbf{n} = \kappa(\phi_{\mathrm{i}}^{k} - \phi_{\mathrm{i}}^{j}), & \text{on } \Gamma_{\mathrm{g}}^{k,j}, \quad \text{(Gap junctions)} \\
\partial_t \mathbf{y} = \mathbf{F}(V_{\mathrm{m}}, \mathbf{y}), & \text{on } \Gamma_{\mathrm{m}}^{k}
\end{cases}
$$

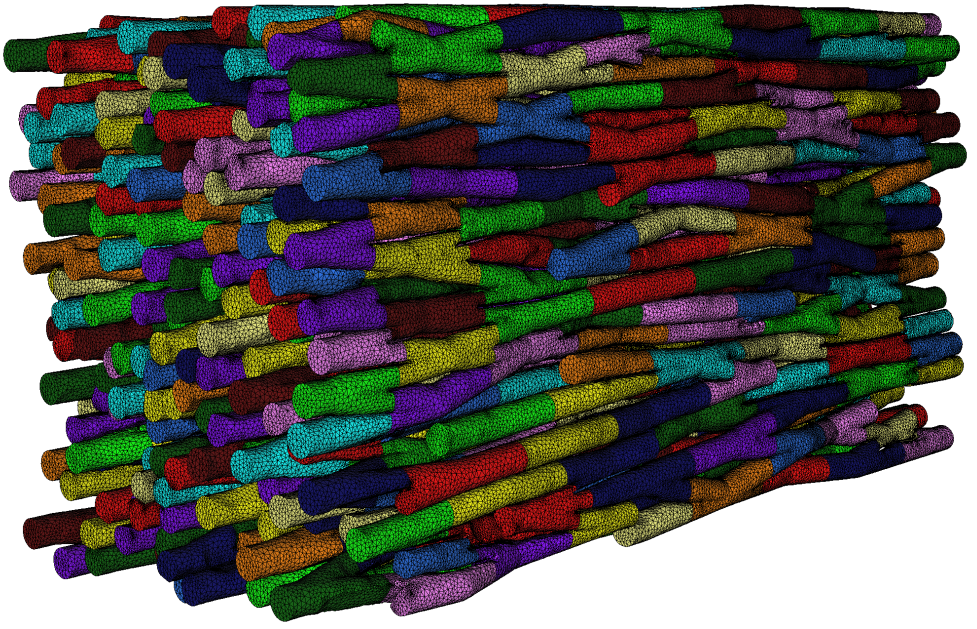
An interesting geometry



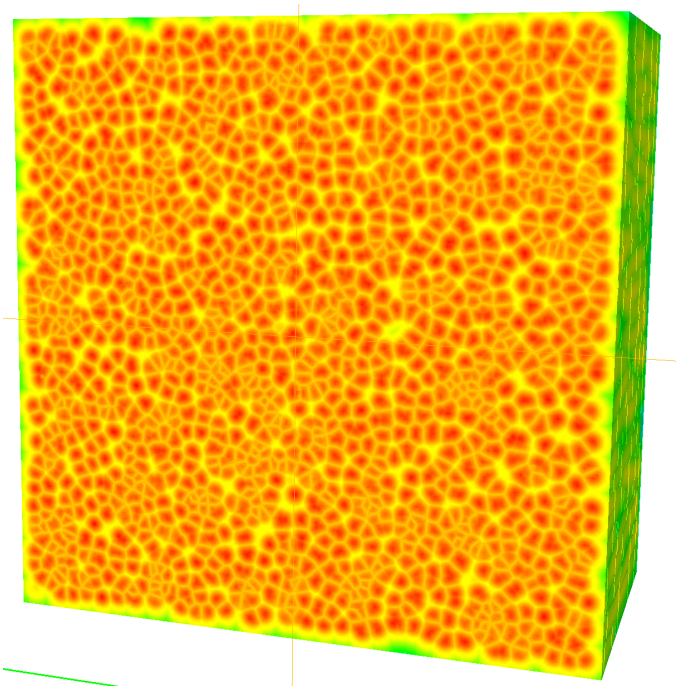
An interesting geometry



An interesting geometry



An interesting geometry



1 mm^3
7538 cells
271 million tetrahedra
15 GB storage

Our problem

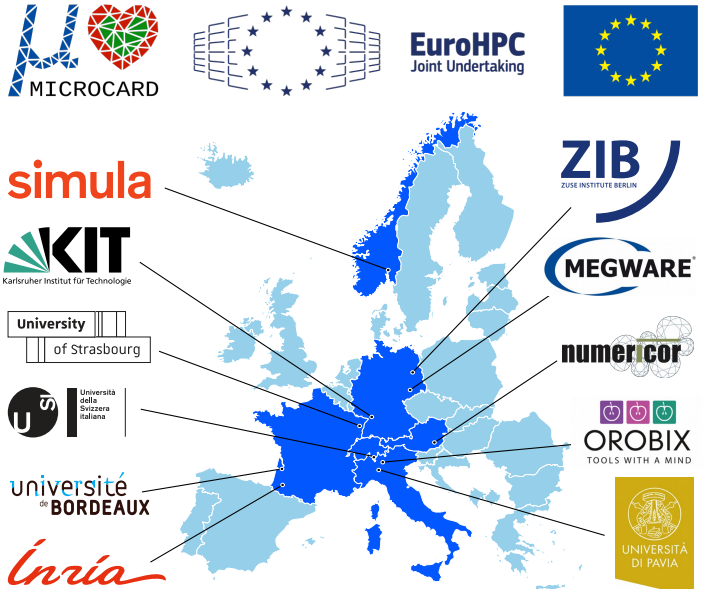
- equations that are hard to solve on a large scale (numerical science)
- very large computations will require exascale hardware
  - very high parallelism
  - heterogeneous hardware (CPU, GPU, . . . ; SIMD, RISC, . . .)
  - need resilience to hardware failures
  - need to mitigate energy consumption
- realistic physiology (biomedical engineering)
- realistic anatomy (image segmentation)
- will need much more powerful meshing software (informatics)

Solution

- A EuroHPC grant for a multidisciplinary collaborative project → MICROCARD

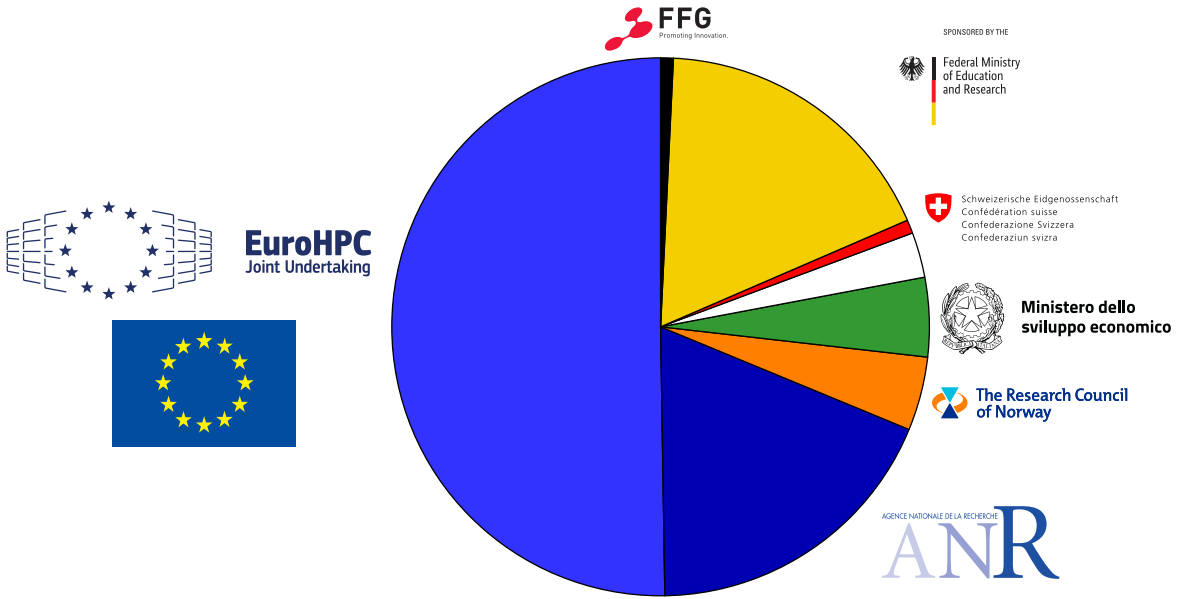
The project

The MICROCARD project

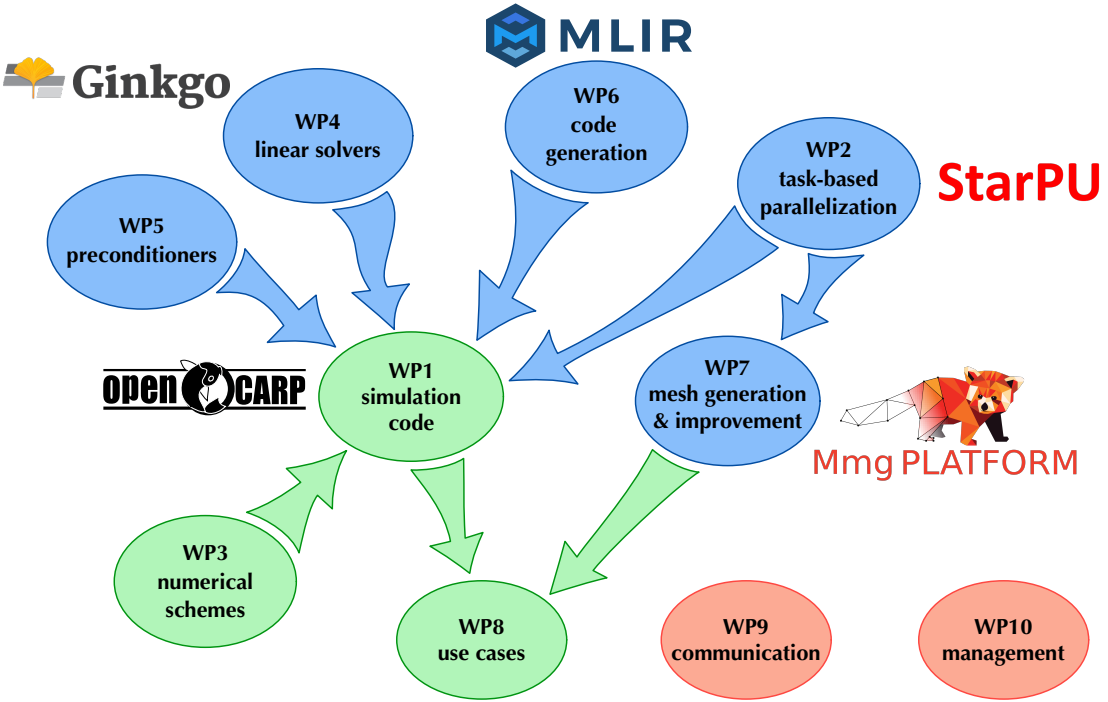


Funding

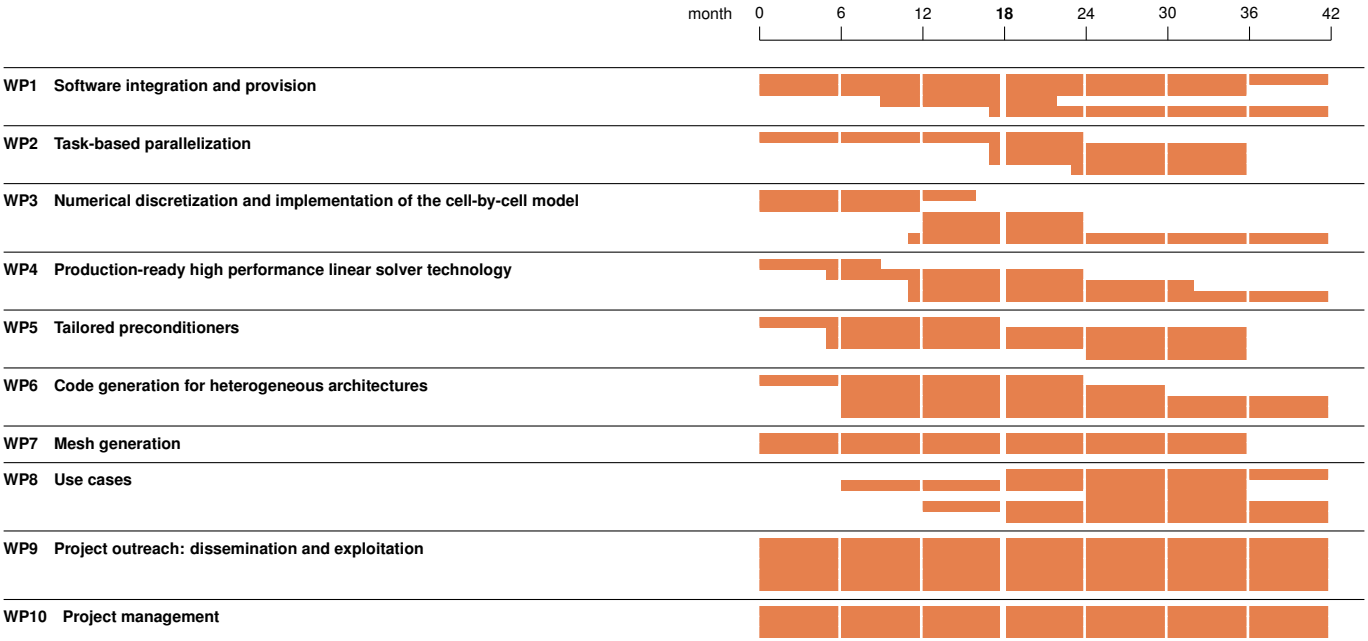
5.8 M€ total (2.7M€ from the JU)



Project outline



Timeline


month
0
6
12
18
24
30
36
42
WP1 Software integration and provision
WP2 Task-based parallelization
WP3 Numerical discretization and implementation of the cell-by-cell model
WP4 Production-ready high performance linear solver technology
WP5 Tailored preconditioners
WP6 Code generation for heterogeneous architectures
WP7 Mesh generation
WP8 Use cases
WP9 Project outreach: dissemination and exploitation
WP10 Project management

Summary of staff effort

Participant Nr	name	WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8	WP9	WP10	Total PM
1	UBx	6	**33**	50			39	**75**	55	**11**	**14**	283
2	Unistra	4	3		2		**69**				1	79
3	Simula	8			8		8		**24**		1	49
4	UPavia	2			20	**54**		4		2	1	83
5	USI	4		28		12			12		1	57
6	KIT	**53**			**46**	25			25	13	2	164
7	ZIB	4	2	**48**		30					1	85
8	MW	12			3							15
9	NC	12								6		18
10	ORO	3	6					36	3		1	49
total		108	44	126	79	121	116	115	119	32	22	882

Organization

Management team

Andréa Alexander project manager

Mark Potse scientific coordinator

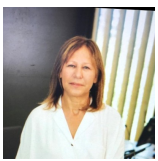
Yves Coudière scientific and technical manager

End-user Advisory Board

Larissa Fabritz
Professor of Cardiovascular Sciences
University of Birmingham

Carol Ann Remme
Associate Professor Basic and Translational Electrophysiology
Amsterdam University Medical Center

Eva Rog-Zielinska
Head of 4D Imaging Section
Institute for Experimental Cardiovascular Medicine, Freiburg



Mélèze Hocini
Cardiologist, deputy director, Liryc
University Hospital Bordeaux

General Assembly

Mark Potse UBx

Vincent Loechner UniStra

Xing Cai SIMULA

Luca Pavarino UniPV

Rolf Krause USI

Axel Loewe KIT

Martin Weiser ZIB

Axel Auweter MEGWARE

Aurel Neic Numericor

Luca Antiga Orobix

Executive Board


Mark Potse
SC,WP9,10


Algiane Froehly
WP7


Hermenegild Arevalo
WP8


Aurel Neic
WP1


Yves Coudière
WP10


Hartwig Anzt
WP4


Axel Loewe
WP1,WP9


Vincent Loechner
WP2,6


Nico Mittenzwey
MEGWARE


Rolf Krause
WP5


Amina Guermouche
WP2,6


Edward Vigmond
WP8


Simone Scacchi
WP4


Martin Weiser
WP3


Luca Pavarino
WP5


Luca Antiga
WP7


Simone Pezzuto
WP3

Career moves affecting the project

Simone Pezzuto (USI) → assistant professor at U. Trento

Hartwig Anzt (KIT) → associate professor at U. Tennessee

Amina Guermouche (UBx) → assistant professor (MdC) at Bordeaux INP

Denis Barthou (UBx) → industry; WP2 will be led by **Amina Guermouche**

Achievements

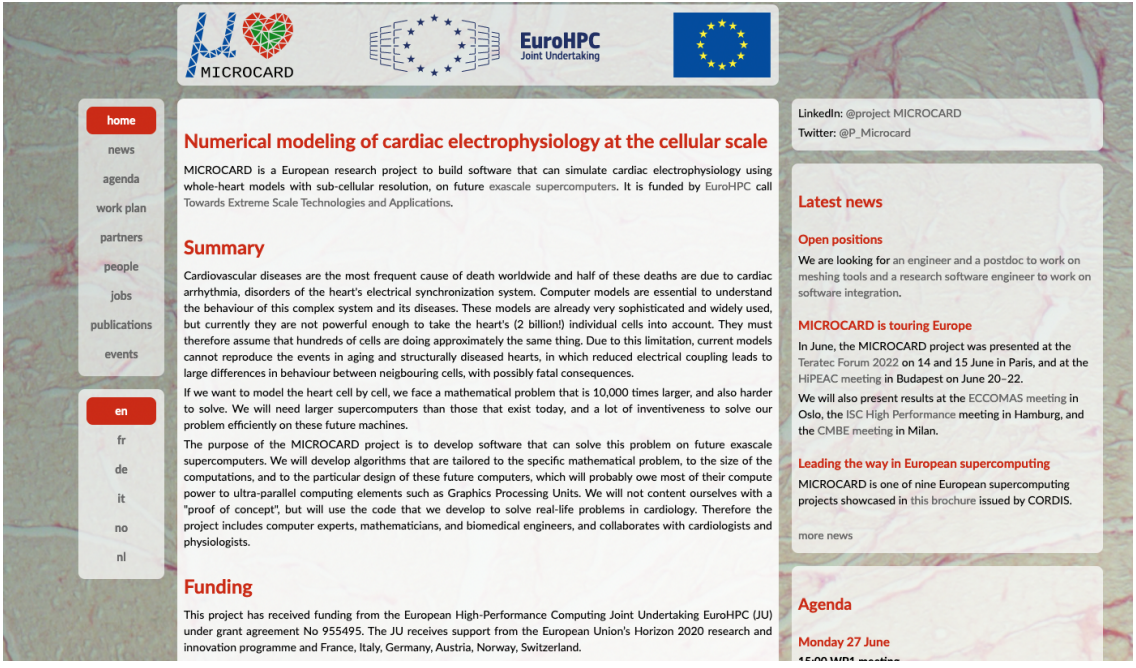
Dissemination overview

- accelerated ionic models in openCARP (500 users)
- Ginkgo providing GPU acceleration in openCARP
- improvements in Mmg
- 9 journal papers
- 21 invited lectures
- 16 other conference contributions
- >350 followers on LinkedIn

prototype

work of Fatemeh Chegini and Martin Weiser

Website: microcard.eu



Thank you!

MICROCARD

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