

RESEARCH CENTRE
Bordeaux - Sud-Ouest

IN PARTNERSHIP WITH:
Université de Bordeaux

2021
ACTIVITY REPORT

Project-Team
CARMEN

**Modélisation et calculs pour
l'électrophysiologie cardiaque**

IN COLLABORATION WITH: Institut de Mathématiques de Bordeaux
(IMB)

DOMAIN

Digital Health, Biology and Earth

THEME

Modeling and Control for Life Sciences

Contents

Project-Team CARMEN	1
1 Team members, visitors, external collaborators	2
2 Overall objectives	3
3 Research program	3
3.1 Complex models for the propagation of cardiac action potentials	3
3.2 Simplified models and inverse problems	4
3.3 Numerical techniques	4
3.4 Cardiac electrophysiology at the microscopic scale	5
3.5 Models and tools for ablative therapies	5
4 Application domains	6
4.1 Scientific context: IHU Liryc	6
4.2 Basic experimental electrophysiology	6
4.3 Clinical electrophysiology	6
4.4 Application in Deep Brain Stimulation	7
5 Highlights of the year	7
6 New software and platforms	8
6.1 2021 Facts and Features	8
6.1.1 CEPS	8
6.1.2 CEMPACK and Propag	8
6.1.3 MUSIC - Carmen Plugins	8
6.1.4 OptimDBS	8
6.2 New software	9
6.2.1 CEPS	9
6.2.2 OptimDBS	9
6.2.3 MUSIC - Carmen plugins	9
6.3 New platforms	10
7 New results	11
7.1 Partial differential equations analysis	11
7.2 Numerical analysis and development of numerical methods	12
7.3 Modeling	12
7.4 Modeling and inverse problems	13
7.5 High performance computing	14
8 Partnerships and cooperations	15
8.1 International initiatives	15
8.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program	15
8.1.2 Participation in other International Programs	15
8.2 International research visitors	16
8.2.1 Visits of international scientists	16
8.2.2 Visits to international teams	16
8.3 European initiatives	16
8.4 National initiatives	17
8.5 Regional initiatives	18

9 Dissemination	19
9.1 Promoting scientific activities	19
9.1.1 Scientific events: organisation	19
9.1.2 Scientific events: selection	19
9.1.3 Journal	19
9.1.4 Research administration	19
9.2 Teaching - Supervision - Juries	20
9.2.1 Teaching	20
9.2.2 Supervision	20
9.2.3 Juries	20
9.3 Popularization	21
9.3.1 Education	21
10 Scientific production	21
10.1 Major publications	21
10.2 Publications of the year	21
10.3 Cited publications	23

Project-Team CARMEN

Creation of the Project-Team: 2016 June 01

Keywords

Computer sciences and digital sciences

- A6.1.1. – Continuous Modeling (PDE, ODE)
- A6.1.2. – Stochastic Modeling
- A6.1.4. – Multiscale modeling
- A6.2.1. – Numerical analysis of PDE and ODE
- A6.2.6. – Optimization
- A6.2.7. – High performance computing
- A6.2.8. – Computational geometry and meshes
- A6.3. – Computation-data interaction
 - A6.3.1. – Inverse problems
 - A6.3.2. – Data assimilation
 - A6.3.3. – Data processing
 - A6.3.4. – Model reduction
 - A6.3.5. – Uncertainty Quantification
- A9.3. – Signal analysis

Other research topics and application domains

- B1.1.2. – Molecular and cellular biology
- B1.1.8. – Mathematical biology
- B2.2.1. – Cardiovascular and respiratory diseases
- B2.2.6. – Neurodegenerative diseases
- B2.4.1. – Pharmacokinetics and dynamics
- B2.4.3. – Surgery
- B2.6.1. – Brain imaging
- B2.6.2. – Cardiac imaging

1 Team members, visitors, external collaborators

Research Scientists

- Jacques Henry [Inria, Emeritus, HDR]
- Amel Karoui [Univ de Bordeaux, Researcher, until Aug 2021]
- Peter Langfield [Inria, Researcher, from Oct 2021]
- Michael Leguèbe [Inria, Researcher]
- Mark Potse [Univ de Bordeaux, Researcher]
- Bachar Tarraf [Univ de Bordeaux, Researcher, from Oct 2021]
- Nejib Zemzemi [Inria, Researcher]

Faculty Members

- Yves Coudiere [Team leader, Univ de Bordeaux, Professor, HDR]
- Mostafa Bendahmane [Univ de Bordeaux, Associate Professor, HDR]
- Jerome Fehrenbach [Univ Paul Sabatier, Associate Professor, until Aug 2021, HDR]
- Lisl Weynans [Univ de Bordeaux, Associate Professor, HDR]

Post-Doctoral Fellow

- Mohamadou Malal Diallo [Univ de Bordeaux]

PhD Students

- Andony Arrieula [Inria]
- Oumayma Bouhamama [Univ de Bordeaux]
- Syed Hassaan Ahmed Bukhari [Université de Saragosse - Espagne]
- Zeina Chehade [Univ de Bordeaux, from Oct 2021]
- Narimane Gassa [Univ de Bordeaux]
- Niami Nasr [Univ de Bordeaux]
- Valentin Pannetier [Univ de Bordeaux, from Oct 2021]
- Bachar Tarraf [Inria, until Sep 2021]

Technical Staff

- Mehdi Juhoor [Inria, Engineer, until Oct 2021]
- Pauline Migerditichan [Inria, Engineer]

Interns and Apprentices

- Felix Dusart [Inria, May 2021]
- Valentin Pannetier [Inria, from Feb 2021 until Jul 2021]
- Marion Panouilleres [Univ de Bordeaux, from Apr 2021 until Sep 2021]

Administrative Assistant

- Nathalie Robin [Inria]

Visiting Scientists

- Abir Amri [Ecole Nationale d'Ingénieur de Tunis - Tunisie, from Oct 2021]
- Khouloud Kordoghli [Ecole Nationale d'Ingénieur de Tunis - Tunisie, from Oct 2021]

External Collaborator

- Edward Vigmond [Univ de Bordeaux]

2 Overall objectives

The Carmen team develops and uses models and numerical methods to simulate the electrophysiology of the heart from the molecular to the whole-organ scale, and its relation to measurable signals inside the heart and on the body surface. It aims at:

- improving understanding of normal and pathological cardiac electrophysiology,
- improving the efficiency and accuracy of numerical models,
- exploiting all available electrical signals for diagnosis,
- improving understanding and guidance of ablative treatment of cardiac arrhythmia.

The numerical models developed, analyzed, and used by the team incorporate essentially the gating dynamics of the ion channels in the cardiac cell membranes and the heterogeneities of the cardiac tissue, coupling processes on the cellular scale into macroscopic reaction-diffusion models. The team also work on incorporating any new biological knowledge, at any scale, that helps to understand the mechanisms of arrhythmias, their diagnosis or treatment. At the same time we use simpler or reduced models to solve the inverse problems related to non-invasive electrical imaging of the heart.

The fields involved in our research are: ordinary and partial differential equations (PDE), inverse problems, numerical analysis, high-performance computing, image segmentation, and mesh construction.

A main goal of the team is to contribute to the work packages defined in the project of [IHU Liryc](#), an institute founded in 2011 that focuses on cardiac arrhythmia.

We cooperate with physiologists and cardiologists on several projects. The team is building new models and powerful simulation tools that will help to understand the mechanisms behind cardiac arrhythmias and to establish personalized and optimized treatments. A particular challenge consists in making the simulations reliable and accessible to the medical community.

3 Research program

3.1 Complex models for the propagation of cardiac action potentials

The contraction of the heart is coordinated by a complex electrical activation process which relies on about a million ion channels, pumps, and exchangers of various kinds in the membrane of each cardiac cell. Their interaction results in a periodic change in transmembrane potential called an action potential. Action potentials in the cardiac muscle propagate rapidly from cell to cell, synchronizing the contraction of the entire muscle to achieve an efficient pump function. The spatio-temporal pattern of this propagation is related both to the function of the cellular membrane and to the structural organization of the cells into tissues. Cardiac arrhythmias originate from malfunctions in this process. The field of cardiac electrophysiology studies the multiscale organization of the cardiac activation process from the subcellular scale up to the scale of the body. It relates the molecular processes in the cell membranes to

the propagation process through the multiscale structure of the tissue and organ, to measurable signals in the heart and to the electrocardiogram, an electrical signal on the torso surface.

Several improvements of current models of the propagation of action potentials are being developed in the Carmen team, based on previous work [36] and on the data available at IHU Liryc:

- Enrichment of the current monodomain and bidomain models [36, 50] by accounting for structural heterogeneities of the tissue at cellular and intermediate scales. Here we focus on multiscale analysis techniques applied to the various high-resolution structural data available at IHU Liryc.
- Coupling of the tissues from the different cardiac compartments and conduction systems. Here, we develop models that couple 1D, 2D and 3D phenomena described by reaction- diffusion PDEs.

These models are essential to improve our understanding of cardiac electrical dysfunction. To this aim, we use high-performance computing techniques in order to numerically explore the complexity of these models.

We use these model codes for applied studies in two important areas of cardiac electrophysiology: atrial fibrillation [42] and sudden-cardiac-death (SCD) syndromes [7], [6] [45]. This work is performed in collaboration with several physiologists and clinicians both at IHU Liryc and abroad.

3.2 Simplified models and inverse problems

The medical and clinical exploration of the cardiac electric signals is based on accurate reconstruction of the patterns of propagation of the action potential. The correct detection of these complex patterns by non-invasive electrical imaging techniques has to be developed. This involves solving inverse problems that cannot be addressed with the more complex models. We want both to develop simple and fast models of the propagation of cardiac action potentials and improve the solutions to the reconstruction questions of cardiac electrical imaging techniques.

These questions concern the reconstruction of diverse information, such as cardiac activation maps or, more generally, the whole cardiac electrical activity, from high-density body surface electrocardiograms. It is a possibly powerful diagnosis technique, which success would be considered as a breakthrough. Although widely studied during the last decade, the reconstructed activation maps, for instance, are highly inaccurate and have a poor clinical interest. It remains a challenge for the scientific community to understand how body surface signals can better inform on the fine details of arrhythmic mechanisms.

The most usual method consists in solving a Laplace equation on the volume delimited by the body surface and the epicardial surface, for which we contribute by:

- studying in depth the dependance of the inverse problem on inhomogeneities in the torso, conductivity values, the geometry, electrode positions, etc.,
- improving the solution to the inverse problem by using new regularization strategies, factorization of boundary value problems, and the theory of optimal control.

In addition, we have started to explore many alternative approaches including:

- using complete propagation models in the inverse problem, like the bidomain or monodomain equations, for instance in order to localize electrical sources,
- constructing data-based models using *e.g.* statistical learning techniques, which would accurately represent some families of well-identified pathologies, or allow to combine physics and biology-informed models and clinical data, and
- constructing simpler models of the propagation of the activation front, based on eikonal or level-set equations.

3.3 Numerical techniques

We want our numerical simulations to be efficient, accurate, and reliable with respect to the needs of the medical community. Based on previous work on solving the monodomain and bidomain equations [37, 38, 48, 28], we will focus on:

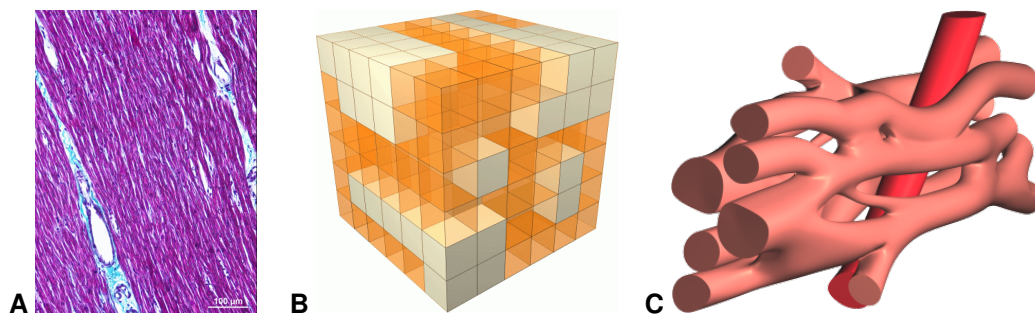


Figure 1: **A:** The cardiac muscle consists of a branching network of elongated muscle cells, interspersed with other structures. Sheets of connective tissue (blue) can grow between the muscle cells and become pathogenic. **B:** Current models can only represent such alterations in a coarse way by replacing model elements with different types; each cube in this illustration would represent hundreds of cells. **C:** This hand-crafted example illustrates the type of geometric model we are experimenting with. Each cell is here represented by hundreds of elements.

- High-order numerical techniques with respect to the variables with physiological meaning, like velocity, AP duration and restitution properties,
- Efficient, dedicated preconditioning techniques coupled with parallel computing.

Existing simulation tools used in our team rely, among others, on mixtures of explicit and implicit integration methods for ODEs, hybrid MPI-OpenMP parallelization, algebraic multigrid preconditioning, and Krylov solvers. New developments include high-order explicit integration methods and task-based dynamic parallelism.

3.4 Cardiac electrophysiology at the microscopic scale

Traditional numerical models of whole-heart physiology are based on the approximation of a perfect muscle using homogenisation methods. However, due to aging and cardiomyopathies, the cellular structure of the tissue changes. These modifications can give rise to life-threatening arrhythmias. For our research on this subject and with cardiologists of the IHU Liryc, we aim to design and implement models that describe the strong heterogeneity of the tissue at the cellular level and to numerically explore the mechanisms of these diseases.

The literature on this type of model is still very limited [54]. Existing models are two-dimensional [46] or limited to idealized geometries, and use a linear (purely resistive) behaviour of the gap-junction channels that connect the cells. We propose a three-dimensional approach using realistic cellular geometry (Fig. 1), nonlinear gap-junction behaviour, and a numerical approach that can scale to hundreds of cells while maintaining a sub-micrometer spatial resolution (10 to 100 times smaller than the size of a cardiomyocyte). Following preliminary work in this area by us [31, 30, 29] and by others [54] we proposed a European project with 10 partner institutes and a 5.8M€ budget to develop software that can simulate such models, with micrometer resolution, on the scale of millions of cells, using future exascale supercomputers (microcard.eu). This project runs from April 2021 to October 2024, and involves also the Inria teams CAMUS, STORM and CARDAMOM as well as the Inria-led MMG Consortium.

3.5 Models and tools for ablative therapies

Today, the most effective way to treat arrhythmias is to ablate selected regions of the cardiac tissue. As the lesions have no particular electric property, this creates conduction blocks that stop the disorganized propagation of action potentials. The ablation procedure consists in placing a catheter in contact with the targeted site and deliver energy into the tissue. The energy can be overheating by radio-frequency current, electroporating electric pulses or temperature drop (cryotherapy). In practice, the choice of the

ablation site is done by the clinician based on previous signal measurements and imagery, and is also guided during the procedure with real-time measurement of the electric signal.

Our team works on several subjects related to ablation techniques that may improve the success rate of the treatments:

- accurate computation of electric fields generated by catheters : complex catheter shapes, contact models, tissue heterogeneities,
- models of creation of the lesions, either through temperature rise (radio-frequency) or electroporation,
- localization tools to help clinicians target the optimal ablation sites, based on both data of previously ablated patients and synthetic data.

4 Application domains

4.1 Scientific context: IHU Liryc

The University Hospital of Bordeaux (*CHU de Bordeaux*) is equipped with a specialized cardiology hospital, the *Hôpital Cardiologique du Haut-Lévêque*, where the group of Professor Michel Haïssaguerre has established itself as a global leader in the field of cardiac electrophysiology [43, 44, 33]. Their discoveries in the area of atrial fibrillation and sudden cardiac death syndromes are widely acclaimed, and the group is a national and international referral center for treatment of cardiac arrhythmia. Thus the group also sees large numbers of patients with rare cardiac diseases.

In 2011 the group has won the competition for a 40 million euro *Investissements d'Avenir* grant for the establishment of **IHU Liryc**, an institute that combines clinical, experimental, and numerical research in the area of cardiac arrhythmia. The institute works in all areas of modern cardiac electrophysiology: atrial arrhythmias, sudden death due to ventricular fibrillation, heart failure related to ventricular dyssynchrony, and metabolic disorders. It is recognized worldwide as one of the most important centers in this area.

The Carmen team was founded as a part of IHU Liryc. We bring applied mathematics and scientific computing closer to experimental and clinical cardiac electrophysiology. In collaboration with experimental and clinical researchers at Liryc we work to enhance fundamental knowledge of the normal and abnormal cardiac electrical activity and of the patterns of the electrocardiogram, and we develop new simulation tools for training, biological, and clinical applications.

4.2 Basic experimental electrophysiology

Our modeling is carried out in coordination with the experimental teams from IHU Liryc. It helps to write new concepts concerning the multiscale organisation of the cardiac action potentials that will serve our understanding in many electrical pathologies. For example, we model the structural heterogeneities at the cellular scale [32] (the **MICROCARD project**), and at an intermediate scale between the cellular and tissue scales.

At the atrial level, we apply our models to understand the mechanisms of complex arrhythmias and the relation with the heterogeneities at the insertion of the pulmonary veins. We will model the heterogeneities specific to the atria, like fibrosis or fatty infiltration [52, 42]. These heterogeneities are thought to play a major role in the development of atrial fibrillation.

At the ventricular level, we focus on (1) modeling the complex coupling between the Purkinje network and the ventricles, which is supposed to play a major role in sudden cardiac death, and (2) modeling the heterogeneities related to the complex organization and disorganization of the myocytes and fibroblasts, which is important in the study of infarct scars for instance.

4.3 Clinical electrophysiology

Treatment of cardiac arrhythmia is possible by pharmacological means, by implantation of pacemakers and defibrillators, and by curative ablation of diseased tissue by local heating, freezing or electroporation.

In particular the ablative therapies create challenges that can be addressed by numerical means. Cardiologists would like to know, preferably by noninvasive means, where an arrhythmia originates and by what mechanism it is sustained.

We address this issue in the first place using inverse models, which attempt to estimate the cardiac activity from a (high-density) electrocardiogram. A new project aims at performing this estimation on-site in the catheterization laboratory and presenting the results, together with the cardiac anatomy, on the screen that the cardiologist uses to monitor the catheter positions [47].

4.4 Application in Deep Brain Stimulation

Since 2017, we have been working with neurosurgeons from the Bordeaux University Hospital (Pr Cuny and Dr. Engelhardt) on improving the planning technique for deep brain surgery (DBS) for Parkinson's and Essential tremor diseases. DBS is the last resort to treat the symptoms of Parkinson's disease after the drug Levodopa. The surgery consists in placing electrodes in very specific regions of the patient's brain. These regions are unfortunately not visible on the 1.5 Tesla MRI, the most widely available MRI machines in hospitals. The most effective solution to date is to introduce 5 micro-electrodes (MER) to record the activity of neurons in the patient's brain and to prospect by moving the electrodes in order to find the best location. However, this approach renders the surgery very cumbersome because the patient must be awake during the exploration phase. In addition, this phase takes at least 3 hours and mobilizes a neurologist with his staff. The total duration of the operation is between 7 and 8 hours. Many elderly patients do not tolerate this surgery. We have proposed an approach that avoids the prospecting phase and performs surgery under general anesthesia. The idea is to learn on pairs of clinical landmarks and the position of active electrodes in order to predict the optimal position of the DBS from a pre-operative image. This approach simplifies and standardizes surgery planning. We tested several approaches [doi:10.3389/fneur.2021.620360](https://doi.org/10.3389/fneur.2021.620360). We continue to seek approaches to fully automate the targeting process. We carried out a proof of concept by learning on the clinical database of the Bordeaux University Hospital. The clinical validation of our approach is in progress through a clinical trial which includes patients from the University Hospitals of Bordeaux and Lyon. Pr Cuny has submitted a phase 3 national clinical research hospital project (PHRCN) including 11 CHUs in France which has been accepted by the General Directorate for Care Offers (DGOS). The aim is to compare our new approach to the ones used in the other centers. Inria Bordeaux is a partner in this project and we maintain the OptimDBS software and solve any technical problem related to the compatibility of the MRIs exported by our software and the surgical robots in the different centers.

5 Highlights of the year

- Two european H2020 projects started in 2021 : SimCardioTest and MICROCARD (see section 8.3) for details about each project. The MICROCARD project is coordinated by Mark Potse.
- Start of a new associate team called SPICY, following the previous EPICARD associate team (section 8.1.1). Start of a partnership within the ECOS Chile program.
- Nejib Zemzemi co-founded the [Rebrain](#) Startup with collaborators from the CHU de Bordeaux. The startup employs 2 engineers and will recruit Louise-Amelie Schmidt after the end of the maturation contract signed between Inria and AST.
- Lisl Weynans initiated the mentoring program which started this year at the IMB, Mathematics Institute of Bordeaux. The program consists in forming pairs of scientists in which a newcomer to the institute, either junior or senior, can get advice from a more experienced colleague about their everyday work or career.
- Narimane Gassa won the machine-learning challenge organized by IHU Liryc in April 2021. This challenge consisted in proposing a machine-learning-based model that is able to tell from implantable cardiac devices (ICD) recordings, if the recorded signals are relevant for interpretation or are too noisy due to extra-cardiac muscular activity or interference from electrical devices. This noise can modify an ECG and thus reduce the quality of ICD monitoring. The aim of this project

was to improve the distant monitoring of ICDs, using automated learning, allowing an automated analysis of cardiac arrhythmia signals prior to human assessment. The management of patients could be potentially optimized by providing only relevant signals to the medical staff. Results were presented at the Computing In Cardiology 2021 conference [25].

- The team participated in the IHU Liryc workshop on Dec. 1st-2nd, with presentations and posters of results and projects, targetted towards the International Scientific Advisory Board of Liryc in view of its annual evaluation, and the whole institute.

6 New software and platforms

The two last parts of this section are generated automatically. The first section lists the new features of the software listed afterwards.

6.1 2021 Facts and Features

6.1.1 CEPS

- first public release,
- automation of numerical convergence tests, for any (time evolving) PDE problem,
- new implementation for more generic boundary conditions and more realistic stimulations,
- utilization in the H2020 project SimCardioTest in the framework of a collaboration with industrial partners ([Microport CRM](#) and [InSilicoTrials](#)).

6.1.2 CEMPACK and Propag

- New approaches to parallelism are tested in a simplified version of Propag, as part of the ANR Exacard project.

6.1.3 MUSIC - Carmen Plugins

New features:

- Create, visualize and export annotations for meshes and map.
- Perform point data interpolation on meshes and EP maps.
- Project any mesh or map onto another mesh or map.
- Compute electroanatomical mapping point distribution (mean and standard deviation) in user defined regions.
- Finite elements method for solving the ECGI inverse problem combined with the regularization methods including CRESO, Zero Crossing GCV, RGCV, ADPC and Ucurve.
- Export masks of segmented structures to DICOM-RTSTRUCT format (used in radiotherapy planning).

6.1.4 OptimDBS

Inria gave a licence to the SATT AST on OptimDBS for maturation and valorization. A licencing contract was signed by AST for the transfer of the software to the Rebrain startup company. Therefore, the website is not public anymore.

6.2 New software

6.2.1 CEPS

Name: Cardiac ElectroPhysiology Simulation

Keywords: Simulation, Health, Mesh, Cardiac, 3D, Cardiac Electrophysiology

Scientific Description: As compared to other existing softwares, CEPS aims at providing a more general framework of integration for new methods or models and a better efficiency in parallel. CEPS is designed to run on massively parallel architectures, and to make use of state-of-the-art and well known computing libraries to achieve realistic and complex heart simulations. CEPS also includes software engineering and validation tools.

Functional Description: CEPS is a modular high-performance computing software for performing numerical simulations in cardiac electrophysiology. It is based on modules : - management of geometries represented by meshes in 3D, 2D or 1D (volumes, surfaces, trees), - model simulation of cellular electrophysiology, - calculating the tissue propagation of the action potentials in the cardiac geometries, - calculation of extracardiac potentials, - time approximation methods in order 2, 3 and 4 specific to electrocardiography.

URL: <https://gitlab.inria.fr/carmen/ceps>

Contact: Michael Leguebe

Participants: Mehdi Juhoor, Nejib Zemzemi, Antoine Gerard, Charlie Douanla Lontsi, Pierre-Elliott Bécue, Marc Fuentes, Yves Coudière, Michael Leguebe, Andjela Davidovic, Pauline Migerditichan, Florian Caro

Partners: Université de Bordeaux, Fondation Bordeaux Université, CHU de Bordeaux, Inria

6.2.2 OptimDBS

Name: Optimizing the Deep Brain Stimulation

Keywords: Image analysis, Deep brain stimulation, Statistical learning

Functional Description: Targeting software for deep brain stimulation

URL: <https://gitlab.inria.fr/optimdbs/optimdbs-medinria/-/wikis/home>

Contact: Nejib Zemzemi

Participants: Nejib Zemzemi, Louise-Amelie Schmitt, Emmanuel Cuny, Julien Engelhardt

Partner: CHU de Bordeaux

6.2.3 MUSIC - Carmen plugins

Name: Carmen plugins for multi-modality imaging in Cardiology

Keywords: Image segmentation, Mesh generation, Image filter, Numerical simulations, Cardiac Electrophysiology, Inverse problem, Finite element modelling, Visualization, 3D interaction, Registration

Scientific Description: Carmen plugins is a collection of toolboxes and pipelines allowing the following functionalities: - Segmenting and filtering the heart, the surrounding organs and the body surface. - Generate/optimize surface and volume of computational meshes for the segmented organs. - Generate fibers orientations for Atria and Ventricles. - Interactively annotate meshes. - Read map and visualize electrical information collected from medical devices. - Numerical simulation of the forward problem using finite elements method. - Method of fundamental solutions for solving the ECGI inverse problem combined with the regularization methods including CRESO, Zero Crossing GCV, RGCV, ADPC and Ucurve. - Landmark based mesh registration. - ECGI pipeline: including segmentation, mesh generation, identification of the vest electrodes.

Functional Description: Carmen plugins is a collection of toolboxes and pipelines allowing the following functionalities: - Segmenting and filtering the heart, the surrounding organs and the body surface. - Generate/optimize surface and volume of computational meshes for the segmented organs. - Generate fibers orientations for Atria and Ventricles. - Interactively annotate meshes. - Read map and visualize electrical information collected from medical devices. - Numerical simulation of the forward problem using finite elements method. - Method of fundamental solutions for solving the ECGI inverse problem combined with the regularization methods including CRESO, Zero Crossing GCV, RGCV, ADPC and Ucurve. - Landmark based mesh registration. - ECGI pipeline: including segmentation, mesh generation, identification of the vest electrodes.

Publications: [hal-01923927](#), [hal-01923763](#), [hal-01400889](#)

Contact: Nejib Zemzemi

Participants: Hubert Cochet, Florent Collot, Mathilde Merle, Maxime Sermesant, Julien Castelneau, Mehdi Juhoor, Pauline Migerditichan, Nejib Zemzemi, Yves Coudière

Partners: Université de Bordeaux, IHU - LIRYC

6.3 New platforms

CEMPACK

CEMPACK is a new collection of software that was previously archived in different places. It includes the high-performance simulation code Propag and a suite of software for the creation of geometric models, preparing inputs for Propag, and analysing its outputs. In 2017 the code was collected in an archive on Inria's GitLab platform. The main components of CEMPACK are the following.

Propag-5.1 Applied modeling studies performed by the Carmen team in collaboration with IHU Liryc and foreign partners [7] [53, 42, 41, 34] rely on high-performance computations on the national supercomputers Irene, Occigen, and Turing. The Propag-5 code is optimized for these systems. It is the result of a decades-long development first at the *Université de Montréal* in Canada, then at Maastricht University in the Netherlands, and finally at the Institute of Computational Science of the *Università della Svizzera italiana* in Lugano, Switzerland. Since 2016 most of the development on Propag has been done by M. Potse at the Carmen team [49]. The code scales excellently to large core counts and, as it is controlled completely with command-line flags and configuration files, it can be used by non-programmers. It also features:

- a plugin system for membrane models,
- a completely parallel workflow, including the initial anatomy input and mesh partitioning, which allows it to work with meshes of more than 10^9 nodes,
- a flexible output scheme allowing hundreds of different state variables and transient variables to be output to file, when desired, using any spatial and temporal subsampling,
- a configurable, LUSTRE-aware parallel output system in which groups of processes write HDF5/netCDF files, and
- CWEB documentation of the entire code base.

The code has been stable and reliable for several years. It can be considered the workhorse for our HPC work until CEPS takes over.

Gepetto The Gepetto suite, named after a famous model maker, transforms a surface mesh of the heart into a set of (semi-)structured meshes for use by the Propag software or others. It creates the different fiber orientations in the model, including the transmurally rotating ventricular fibers and the various bundle structures in the atria (figure 2), and creates layers with possibly different electrophysiological properties across the wall. A practically important function is that it automatically builds the matching heart and torso meshes that Propag uses to simulate potentials in the torso (at a resolution of 1 mm) after projecting simulation results from the heart model (at 0.1 to

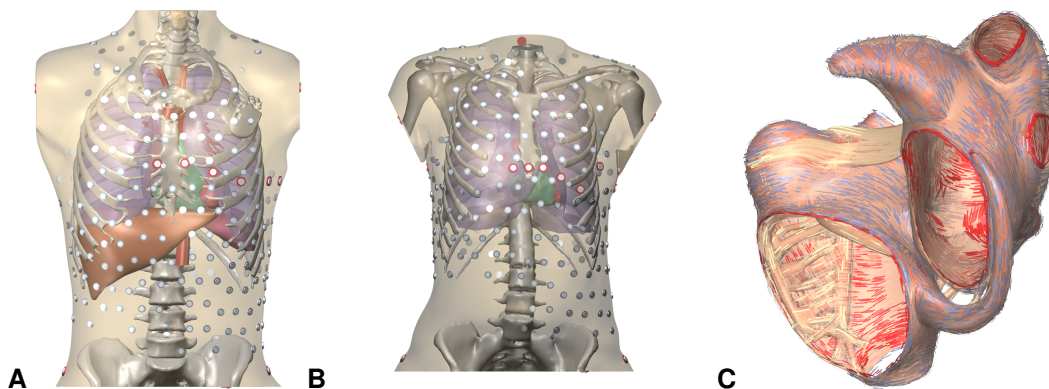


Figure 2: **A and B:** Complete heart-torso geometries created with CEMPACK tools. **C:** Bundle structures and different layers of fiber orientation created by the Gepetto software.

0.2 mm) on the coarser torso mesh [51]. Like Propag, the Gepetto software results from a long-term development that started in Montreal, Canada, around 2002. The code for atrial fiber structure was developed by our team.

Blender plugins **Blender** is a free software package for the production of 3-D models, renderings, and animations, comparable to commercial software such as Cinema4D. CEMPACK includes a set of plugins for Blender that facilitate the production of anatomical models and the visualization of measured and simulated data. It uses the MMG remeshing library, which is developed by the CARDAMOM team at Inria Bordeaux.

7 New results

7.1 Partial differential equations analysis

- Three Scale Unfolding Homogenization Method Applied to Cardiac Bidomain Model [12, 11]. In this work, we are dealing with a rigorous homogenization result at two different levels for the bidomain model of cardiac electrophysiology. The first level associated with the mesoscopic structure such that the cardiac tissue consists of extracellular and intracellular domains separated by an interface (the sarcolemma). The second one related to the microscopic structure in such a way that the intracellular medium can only be viewed as a periodical layout of unit cells (mitochondria). At the interface between intra- and extracellular media, the fluxes are given by nonlinear functions of ionic and applied currents. A rigorous homogenization process based on unfolding operators is applied to derive the macroscopic (homogenized) model from our meso-microscopic bidomain model. We apply a three-scale unfolding method in the intracellular problem to obtain its homogenized equation at two levels. The first level upscaling of the intracellular structure yields the mesoscopic equation. The second step of the homogenization leads to obtain the intracellular homogenized equation. To prove the convergence of the nonlinear terms, especially those defined on the microscopic interface, we use the boundary unfolding method and a Kolmogorov-Riesz compactness's result. Next, we use the standard unfolding method to homogenize the extracellular problem. Finally, we obtain, at the limit, a reaction-diffusion system on a single domain (the superposition of the intracellular and extracellular media) which contains the homogenized equations depending on three scales. Such a model is widely used for describing the macroscopic behavior of the cardiac tissue, which is recognized to be an important messengers between the cytoplasm (intracellular) and the other extracellular inside the biological cells.
- Optimal control for nonlocal reaction-diffusion system describing calcium dynamics in cardiac cell [13]. In this work, we introduce an optimal control for a nonlocal calcium dynamic model

in a cardiac cell acting on ryanodine receptors. The optimal control problem is considered as a coupled nonlocal reaction-diffusion system with a transmission boundary condition covering the sarcoplasmic reticulum and cytosolic domain. We establish the well-posedness result of the adjoint problem using Faedo-Galerkin approximation, a priori estimates, and compactness arguments. The numerical discretization of direct and adjoint problems is realized by using the implicit Euler method in time and the finite element for spatial discretization. Moreover, we obtain the stability result in the L2-norm for the direct and the adjoint discrete problems. Finally, in order to illustrate the control of our calcium dynamic model, we present some numerical experiments devoted to constant and nonlocal diffusions using the proposed numerical scheme.

7.2 Numerical analysis and development of numerical methods

- Development of an Eulerian method to numerically solve incompressible bifluid problems with high density ratios with the specificity of a sharp second-order numerical scheme for the spatial resolution of the discontinuous elliptic problem for the pressure [15].
- A positive cell vertex Godunov scheme for a Beeler-Reuter based model of cardiac electrical activity [14]. The monodomain model is a widely used model in electrocardiology to simulate the propagation of electrical potential in the myocardium. In this work, we investigate a positive nonlinear control volume finite element scheme, based on Godunov's flux approximation of the diffusion term, for the monodomain model coupled to a physiological ionic model (the Beeler–Reuter model) and using an anisotropic diffusion tensor. In this scheme, degrees of freedom are assigned to vertices of a primal triangular mesh, as in conforming finite element methods. The diffusion term which involves an anisotropic tensor is discretized on a dual mesh using the diffusion fluxes provided by the conforming finite element reconstruction on the primal mesh and the other terms are discretized by means of an upwind finite volume method on the dual mesh. The scheme ensures the validity of the discrete maximum principle without any restriction on the transmissibility coefficients. By using a compactness argument, we obtain the convergence of the discrete solution and as a consequence, we get the existence of a weak solution of the original model. Finally, we illustrate by numerical simulations that the proposed scheme successfully removes nonphysical oscillations in the propagation of the wavefront and maintains conduction velocity close to physiological values.

7.3 Modeling

- We proposed a model of cardiac mitochondria using a simplification approach in order to calibrate the model parameters to experimental data [21]. The model describes the major features of mitochondrial activity willingly omitting detailed descriptions of these features in order to reduce its complexity (Fig. 3). In the end, our model consists of 6 state variables and 32 parameters, which is much less than the current models proposed by biologists. Preliminary sensitivity analysis was done on our model using Sobol indices, so as to run the calibration with identifiable parameters only. Our calibrated model was able to reproduce robustly respiration data.

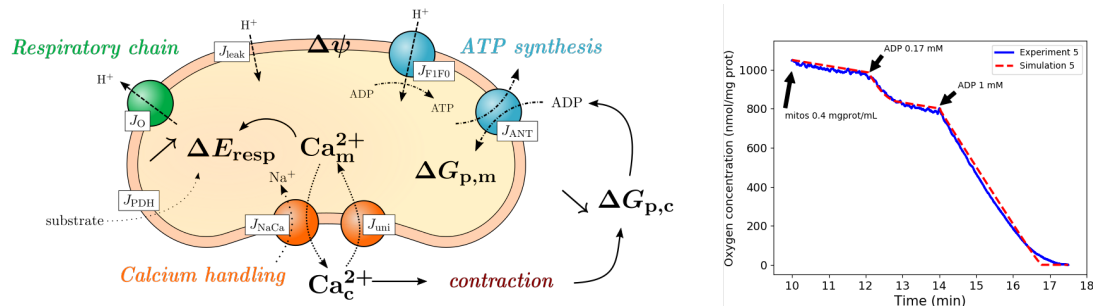


Figure 3: Left : Schematic of the phenomena taken into account in our mitochondrial model. Right : reproduction of respiration data using our calibrated model.

This model is now being extended to include the effects of Reactive Oxygen Species (ROS) and the mitochondrial permeability transition pore (mPTP). Further data analysis and likelihood function tuning are required to calibrate this extended model to fluorescence data of individual mitochondria, using bayesian techniques. Ph.D. thesis of Bachar Tarraf. Interdisciplinary work between Liryc teams (modeling and metabolism) and other laboratories (ISM Bordeaux and LASS Toulouse), in the framework of the ANR Mitocard project.

- We modeled microstructural heterogeneities in the cardiac tissue by mean of a homogenized model. It enables to include, into macroscopic equivalent conductivity coefficients, quantitative information about the microstructure available from high resolution imaging modalities, such as fibrosis or diverse types of inclusions (follow up of Andjela Davidovic Ph.D thesis). The complete procedure to derive the macroscopic coefficients from MR images, first published online in 2020, was finally published in a special issue of the International Journal on Numerical Methods in Biomedical Engineering [40].
- Spiral Waves Generation Using an Eikonal-Reaction Cardiac Electrophysiology Model [27] In this work, we used the conduction velocity adapted eikonal model [35] in order to simulate reentry spiral waves. The new model that we present here combines the CV-adapted eikonal model with a specific parametrized stimulation current obtained from the diffusion term of the monodomain model. The monodomain model is computed once off-line and the generated diffusion current has been approximated, parametrized and used to stimulate the MS ode system. The preliminary results showed that with this model we have been able to simulate spiral waves with the same pattern as the monodomain model. To the best of our knowledge, this is the first work able to generate spiral waves using the eikonal model. Differently from the monodomain model, [8], the EK-CV-DIFF formulation captures the correct value of the conduction velocity even using a coarse resolution. This eikonal model is easy to parametrize and thus could be a good candidate to conduct personalized simulations in order to simulate the electrical wave of a given patient. Our future work will be to parametrize this model in order to provide a new electrocardiography imaging tool especially in atrial fibrillation conditions

7.4 Modeling and inverse problems

- Cardiac Activation Maps Reconstruction: A Comparative Study Between Data-Driven and Physics-Based Methods [20]. Proof of concept of AI based methods for the development of new ECGi algorithms: second part of Amel Karoui Ph.D. thesis. The PhD was defended in 2021.
- Validation on experimental data of the *patchwork method*, a ECGi method selecting among several numerical method the one minimizing the residuals on the torso [23]. (Ph.D thesis of Oumayma Bouhamama, co-supervised with Laura Bear from Signal Processing team).
- Resolution of the inverse problem of Electrical Impedance Tomography with an immersed boundary method on a cartesian grid in 2 dimensions (Ph.D thesis of Niami Nasr, co-supervised by J. Dardé, IMT Toulouse).
- Development and validation on academic test-cases of an eikonal model to solve the inverse problem of the propagation of the front on the heart surface from body-surface measurements, in collaboration with J. Fehrenbach (IMT, Toulouse).
- We developed a new machine-learning approach for the localization of tissue that is provoking premature ventricular contractions (PVC) [22]. The approach is original in several ways. Firstly, as it is meant to be used during an intervention, it has to be very fast – eventually close to real-time. Secondly, it was trained on simulated data only, but then showed good performance for real patients. This was possible due to the use of highly realistic patient-based models to produce the training data. Finally, it uses only the 8 ECG electrodes that are needed to record a standard electrocardiogram, in contrast to traditional inverse models which use hundreds of electrodes. This limited lead set could be used because the problem of PVC localisation is intrinsically very constrained. The use of a limited lead set is very important for clinical applicability.

- A volume source method for solving ECGI inverse problem. [26] In this paper, we present a volumic model to solve the electrocardiography inverse problem that takes into account structural informations obtained by imaging techniques. The direct problem maps a volumic current in the cardiac muscle (ventricles) to the body surface electrical measures. The model is based on coupling bidomain heart model with torso conduction. The corresponding inverse problem is solved with the Tikhonov regularization. Simulated public database EDGAR is used for the evaluation of this method and we compared them to standard method of fundamental solutions (MFS). The sensitivity to noise is also assessed. The correlation coefficients and the relative error of activation times were computed. Results show that the volume method performs better than MFS for any noise level, and reconstruct in addition endocardial information.

7.5 High performance computing

- For the MICROCARD project, we developed a prototype software that creates artificial geometric models of cardiac muscle tissue at the cellular scale. We need such models for our simulations, because current imaging data at this scale is limited to a handful of cells, while we require thousands to, ultimately, billions of cells (each represented by roughly a thousand tetrahedral elements). Our software defines a level-set function on a tailored mesh. The MMG software is then used to discretize the level set and improve the mesh quality. With the current prototype it is feasible to produce networks of a few hundred cells, and using replication techniques we can make these meshes as large as can be stored: our largest test so far required 16TB storage, while a full human heart would require in the order of 2PB. These results will be presented at the ECCOMAS meeting in June 2022.

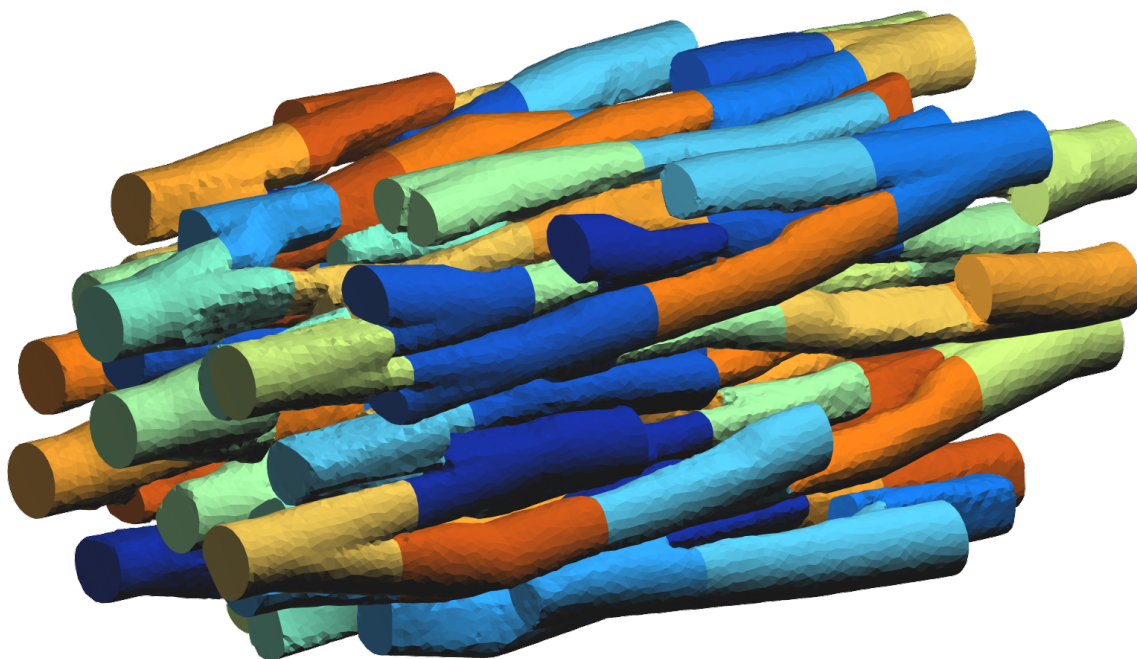


Figure 4: Synthetic model of cardiac tissue created with our software. Colors identify individual cells.

- With R. Turpault and K. Khadra, collaborators from IMB (Institut de Mathématiques de Bordeaux), we continue the development of a very high order finite volume method for the monodomain equation, following the method published in [39]. During 2021, we developed and started to test the MPI parallel version that will be used to extend our numerical experiments to large three-dimensional models. The numerical scheme also serves as a sandbox for the method to be developed in the MICROCARD project. This foreseen method will have to account for the Laplace equation in the whole computational domain, like the previous one, and in addition with jumps on all the cell membranes, which are spread among the whole computational domain.

8 Partnerships and cooperations

8.1 International initiatives

8.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program

SPICY

Title: Stochastic forward and inverse Problems In Cardiac electrophysiology

Duration: 2021 ->

Coordinator: Mourad Bellasoued (mourad.bellassoued@enit.utm.tn)

Partners:

- Université de Tunis El Manar

Inria contact: Mostafa Bendahmane

Summary: Compared to classical method in electrophysiology, in this project we use the stochastic bidomain model on the heart to add constraints when solving the inverse problem. The problem is then reduced to an optimal control question. We intend to construct a general stochastic monodomain or stochastic bidomain models type, to identify the parameters that correspond to the working hypothesis and see that it is possible to reproduce the observed ECG signal in patients with arrhythmias. From these stochastic models we will questions and problems of control and stabilization in order to find strategies to prevent or reverse the arrhythmic activity.

8.1.2 Participation in other International Programs

ECOS Nord

Title: Quantitative and numerical analysis of inverse problems in cardiology

Partner Institution(s): • University of Puebla, Mexico, with Prof. A. Fraguella Colar

Date/Duration: 2020, reconducted in 2021

ECOS Sud

Title: Virtual Element Methods for Bidomain Model For Cardiac Electrophysiology

Partner Institution(s): • University of the Bío-Bío, Concepción, Chile

Summary: This project is framed within the area of mathematical modeling and numerical simulations in physiology, particularly we explore the cardiac electrical potentials and we develop several applications using VEM discretizations to bidomain model. For instance, primal and mixed formulations will be considered. The main motivation to study this model is that it constitutes a stepping stone towards the more complex models with important applications in cardiac dynamics where we could have complex domains. Thus, we can explore the capability of VEM to use general meshes. We also plan to derive *a posteriori* error estimators for the VEM and use it to drive space/time adaptive schemes.

Note that there was no activity in the ECOS nord project, due to the Covid crisis, and the postdoctoral researchers involved in the project not being present anymore. There has been a very reduced activity in the ECOS sud project, mainly through a small number of visioconferences. In both projects, no visit could be carried out.

8.2 International research visitors

8.2.1 Visits of international scientists

Khouloud Kordoghli

Status PhD

Institution of origin: Université de Tunis El Manar

Country: Tunisia

Dates: October to December 2021

Context of the visit: the visit was part of the SPICY associated team.

Mobility program/type of mobility: research stay

Abir Amri

Status PhD

Institution of origin: Université de Tunis El Manar

Country: Tunisia

Dates: October to December 2021

Context of the visit: the visit was part of the SPICY associated team.

Mobility program/type of mobility: research stay

8.2.2 Visits to international teams

Narimane Gassa

Visited institution: EP solutions SA (industrial partner)

Country: Swiss

Dates: September to October 2021 (2 months)

Context of the visit: The visit is part of Narimane Gassa's secondment in the PersonalizedAF project, see below.

Mobility program/type of mobility: research stay

8.3 European initiatives

EuroHPC MICROCARD. The **MICROCARD** project, co-funded by EuroHPC, ANR, and five other national organizations, is a medium-size European project (10 partners, 5.8M€ budget) aiming to build software that can simulate cardiac tissue cell by cell, on future exascale supercomputers. It is led by the CARMEN team (Mark Potse, scientific coordinator; Yves Coudière, technical and scientific manager). The project was granted in June 2020 and started in April 2021 when all national co-funding procedures had been completed. Although the project is coordinated by Université de Bordeaux, Inria is strongly involved with four of its project teams (CARMEN, CAMUS, CARDAMOM, STORM) and the Inria-led MMG Consortium. The project further involves Inria's strategic partner SIMULA (Norway), five more universities, and three industrial partners including one manufacturer of large-scale computers. The software built in this project will be used for research into life-threatening cardiac arrhythmia mechanisms, in particular those that involve subtle structural tissue damage.

The scale of simulations envisaged in the MICROCARD project is enormous. The human heart has two billion muscle cells. A cell-by-cell model, in which each of these cells would be discretized with in the

order of a thousand tetrahedral elements, would thus lead to a problem with $2 \cdot 10^{12}$ unknowns. Initial tests have shown that the geometrical model, if it could be produced, would require 2PB storage. To represent the complex electrophysiology on each model element, the computation would involve in the order of 10^{15} variables, which will have to be integrated over thousands to millions of time steps. The project is therefore challenging from a numerical as well as an informatics point of view. The MICROCARD consortium involves applied mathematicians, specialists in numerical science, software engineers, and biomedical engineers representing a large spectre of expertise to meet these challenges.

H2020 RIA SimCardioTest. The **SimCardioTest** project is a collaborative project between 10 organizations from 6 European countries and United States funded by the European Commission (EU H2020). This project will provide new insight into designing new predictive tools in cardiac pathologies and will accelerate the uptake of computer simulations for testing medicines and medical devices. It is lead by Inria, and the Carmen team participates in this project as affiliated to the University of Bordeaux (UBx). Yves Coudière is the coordinator for the UBx partner, and in particular work package leader for WP2.

WP2 aims at designing and implementing numerical models of cardiac pacemakers or implantable defibrillators, in view of designing in-silico trials useful for assessing the security or efficacy of these devices. This work is based on clinical images, on our software CEPS and the platform **SOFA**. It is carried out in collaboration with the Inria teams EPIONE (Sophia-Antipolis) and DEFROST (Lille), and with the industrial partners **Microport CRM** and **InSilicoTrials**.

Within the Carmen team, we focus on the simulation of the electrical behavior of industrial pacemakers, in order to output numerical quantities related to their pacing and sensing functions in a heart.

H2020 MSCA-ITN PersonalizeAF. The **PersonalizeAF** project is a Marie-Curie translational training project. It addresses the challenge of understanding and treating atrial arrhythmias, by delivering an innovative multinational, multi-sectorial, and multidisciplinary research and training programme in new technologies and novel strategies for individualized characterization of AF substrate to and increase treatments' efficiency.

From the research point of view, PersonalizeAF integrates data and knowledge from in-vitro, in silico, ex vivo and in vivo animal and human models to: 1) generate an individual description of the state of the atrial muscle identifying the disease mechanisms and characteristics; 2) understanding the potential effect that different therapies have on different atrial substrates; and 3) combining this information to generate a specific profile of the patient and the best therapy for each patient.

In the Carmen team, we supervise 1 PhD student (ESR11, Narimane Gassa) from PersonalizeAF. She is working on simplified models of atrial fibrillation based on eikonal equations coupled to the Mitchell-Schaeffer ionic model. She aim at personalizing such a simple model using aclinical anatomical data and body surface potential recordings. Her first secondment, carried out in 2021, was to vissent the company **EP Solutions SA** that produces a technology able to record such electrical maps.

8.4 National initiatives

ANR Exacard. Granted by ANR in July 2018, EXACARD is a collaborative project with computer scientists from Labri that targets hexascale computing in cardiac electrophysiology, it serves as a sandbox to prepare the project EuroHPC MICROCARD. PI for Bordeaux University/Liry: Yves Coudière.

ANR MITOCARD.

The MITOCARD project (Electrophysiology of Cardiac Mitochondria), coordinated by S. Arbault (Université de Bordeaux, ISM), was granted by the ANR in July 2017. The objective of MITOCARD is to improve understanding of cardiac physiology by integrating the mitochondrial properties of cell signaling in the comprehensive view of cardiac energetics and rhythm pathologies. It was recently demonstrated that in the heart, in striking contrast with skeletal muscle, a parallel activation by calcium of mitochondria and myofibrils occurs during contraction, which indicates that mitochondria actively

participate in Ca^{2+} signaling in the cardiomyocyte. We hypothesize that the mitochondrial permeability transition pore (mPTP), by rhythmically depolarizing inner mitochondrial membrane, plays a crucial role in mitochondrial Ca^{2+} regulation and, as a result, of cardiomyocyte Ca^{2+} homeostasis. Moreover, mitochondrial reactive oxygen species (ROS) may play a key role in the regulation of the mPTP by sensing mitochondrial energetics balance. Consequently, a deeper understanding of mitochondrial electrophysiology is mandatory to decipher their exact role in the heart's excitation-contraction coupling processes. However, this is currently prevented by the absence of adequate methodological tools (lack of sensitivity or selectivity, time resolution, averaged responses of numerous biological entities). The MITOCARD project will solve that issue by developing analytical tools and biophysical approaches to monitor kinetically and quantitatively the Ca^{2+} handling by isolated mitochondria in the cardiomyocyte.

MITOCARD is a multi-disciplinary project involving 4 partners of different scientific fields: the CARMEN team as well as:

ISM, the largest chemistry laboratory of the Université de Bordeaux, where the necessary measurement methods will be developed,

Liry, where mitochondria are studied at all levels of integration from the isolated mitochondrion to the intact heart,

LAAS, the MiCrosystèmes d'Analyse (MICA) group at the Laboratory of Analysis and Architecture of Systems, which develops the biological microsensors for this project.

The project will:

- develop chips integrating 4 different electrochemical microsensors to monitor in real-time key mitochondrial signaling parameters: Ca^{2+} , membrane potential, quinone reduction status, O_2 consumption, and ROS production,
- develop microwell arrays integrating ring nanoelectrodes to trap single mitochondria within micro-metric chambers and measure locally by combined fluorescence microscopy and electrochemical techniques intra- (by fluorescence) and extra-mitochondrial (electrochemistry) metabolites,
- develop a mathematical model of mitochondrial Ca^{2+} and ROS handling built on existing knowledge, new hypotheses, and the measured data.

The model may serve both to assess biological assumptions on the role of mitochondria in Ca^{2+} signaling and to integrate pathological data and provide clues for their global understanding.

ANR MAESTRO. The ANR project MAESTRO (Magnetic Signal detection of ventricular arrhythmogenic substrates), coordinated by Prof. Michel Haïssaguerre (IHU Liry), has a computational component for which we hope to recruit a postdoc in early 2022, to be directed by Mark Potse.

GENCI. GENCI project A0110307379, "Interaction between tissue structure and ion-channel function in cardiac arrhythmia," coordinated by Mark Potse, comprises 4 million core-hours on the supercomputer Jean-Zay at IDRIS. Compared to previous years it is a modest allocation. This is because most of our computational needs in 2022 are either smaller or larger than the national scale.

8.5 Regional initiatives

Labex CIMI (Toulouse). "Electrical Impedance Tomography for the Inverse Problem of Electrocardiographic Imaging" PI Jérémie Dardé (IMT, Toulouse) The project gathers complementary areas of applied mathematics and signal processing to address all relevant aspects of the problem, including modelling, numerical experiments and statistical analysis. Furthermore, if these new methods prove to increase the accuracy of ECGi, the project would lead to in-vivo experiments in collaboration with the Electrophysiology and Heart Modelling Institute (IHU-Liry)

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Scientific events: organisation

General chair, scientific chair

- Peter Langfield : session chair for the World Congress on Biomechanics 2022

9.1.2 Scientific events: selection

Member of the conference program committees

- Yves Coudière : program committee member, FIMH 2021, the international conference of Functional Imaging and Modeling of the Heart
- Nejib Zemzemi : program committee member, FIMH 2021, the international conference of Functional Imaging and Modeling of the Heart

9.1.3 Journal

Member of the editorial boards

- Mark Potse: associate editor of *Frontiers in Cardiac Electrophysiology* and *Journal of Electrocardiology*; guest associate editor for *Frontiers in Cardiovascular Medicine*.

Reviewer - reviewing activities

- Mark Potse: *Frontiers in Computational Electrophysiology*, *Journal of Electrocardiology*, *IEEE Access*, *Computing in Cardiology* (congress),
- Peter Langfield: *Journal of Computational Dynamics*,
- Lisl Weynans: *ESAIM: Mathematical Modelling and Numerical Analysis*, *Computers in Biology and Medicine*,
- Yves Coudière: *Mathematical Biosciences and Engineering*, *Computers in Biology and Medicine*, *Annals of Biomedical Engineering*, *FIMH 2021* (conference).

9.1.4 Research administration

- Yves Coudière: executive director of IMB (Institut de Mathématiques de Bordeaux, UMR 5251 CNRS, UB, Bdx-INP)
- Yves Coudière: member of the Scientific Committee of IHU Liryc
- Mark Potse: council member of the International Society of Electrocardiology
- Mark Potse: member of the user board (*Comité d'utilisateurs*) of IDRIS
- Mark Potse: management of the website of the [International Society of Electrocardiology](#).

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

The 2 assistant professors and 1 professor of the team teach at several levels of the Bordeaux University programs in Mathematics, Neurosciences, and Medicine (respectively, 192, 192 and 96 h/year on average). The researchers also have a regular teaching activity, contributing to several courses in the Applied Mathematics at the Bachelor and Master levels (between 16 and 72 h/year).

The PhD students who ask for it are used to teach between 32 and 64 h/year, usually courses of general mathematics in L1 or mathematics for biologists in L1 or L2.

Teaching responsibilities at the University of Bordeaux:

- Yves Coudière: Master MAS (Mathématiques Appliquées, Statistiques), parcours MNCHP (Modélisation Numérique Calcul Haute Performance),
- Yves Coudière then Lisl Weynans: Licence Mathématique parcours ingénierie mathématique,
- Lisl Weynans: Mineure Mathématiques du parcours International de la Licence,
- Mostafa Bendahmane: Responsable de la mobilité internationale des étudiants de Licence MIASHS.

Courses (L for Bachelor level, M for Master level):

- Numerical analysis (L2)
- Programming for scientific computing with C++ (L3)
- Programming projects with Python (M1)
- Numerical approximation of PDEs: Finite Differences, Finite Elements, Finite Volumes (M1, M2)
- Supervision of programming projects (L3, M1)
- Mathematical modelling in L2 parcours medicine and physics
- Linear Algebra, Optimization under constraints (L2 and Essca school)
- Analysis, L2
- Computational Neurosciences, M2
- Neuropsychology and Psychophysiology, L3
- Graduate program EUR Digital Public Health, Bordeaux University, March 2019. Philosophy of science and the role of numerical models: introductory course in the module Modeling in life science

9.2.2 Supervision

In addition to the PhD students of the team (7 on Jan 1st, 8 on Dec 31st), team members were the co-supervisors of the following students:

- Fakhrieddine Bader (Ecole centrale de Nantes) : "Homogénéisation et convergence double échelle du modèle bidomaine en électrocardiologie". Defended in 2021.

9.2.3 Juries

- Lisl Weynans: reviewer of PhD thesis of Georis BILLO (M2P2, Marseille)
- Yves Coudière: reviewer and jury member of Tania Bacoyannis (Université Côte d'Azur); jury member of Fakhrieddine Bader (Ecole centrale de Nantes).

9.3 Popularization

9.3.1 Education

- Yves coudière : Chiche! December 2021

10 Scientific production

10.1 Major publications

- [1] B. Andreianov, M. Bendahmane, K. H. Karlsen and C. Pierre. ‘Convergence of discrete duality finite volume schemes for the cardiac bidomain model’. Anglais. In: *Networks and Heterogeneous Media* 6.2 (2011), pp. 195–240. URL: <http://hal.archives-ouvertes.fr/hal-00526047>.
- [2] A. Azzouzi, Y. Coudière, R. Turpault and N. Zemzemi. ‘A mathematical model of Purkinje-Muscle Junctions’. In: *Mathematical Biosciences and Engineering* 8.4 (2011), pp. 915–930.
- [3] Y. Coudière and C. Pierre. ‘Stability And Convergence Of A Finite Volume Method For Two Systems Of Reaction-Diffusion Equations In Electro-Cardiology’. In: *Nonlinear Anal. Real World Appl.* 7.4 (2006), pp. 916–935. URL: <http://hal.archives-ouvertes.fr/hal-00016816/fr>.
- [4] Y. Coudière, C. Pierre, O. Rousseau and R. Turpault. ‘A 2D/3D Discrete Duality Finite Volume Scheme. Application to ECG simulation’. In: *International Journal on Finite Volumes* 6.1 (2009). URL: <http://hal.archives-ouvertes.fr/hal-00328251/fr>.
- [5] Y. Bourgault, Y. Coudière and C. Pierre. ‘Existence And Uniqueness Of The Solution For The Bidomain Model Used In Cardiac Electrophysiology’. In: *Nonlinear Anal. Real World Appl.* 10.1 (2009), pp. 458–482. URL: <http://hal.archives-ouvertes.fr/hal-00101458/fr>.
- [6] P. W. Macfarlane, C. Antzelevitch, M. Haïssaguerre, H. V. Huikuri, M. Potse, R. Rosso, F. Sacher, J. T. Tikkanen, H. Wellens and G.-X. Yan. ‘The Early Repolarization Pattern; A Consensus Paper’. In: *Journal of the American College of Cardiology* 66 (2015), pp. 470–477. URL: <http://dx.doi.org/10.1016/j.jacc.2015.05.033>.
- [7] V. M. F. Meijborg, M. Potse, C. E. Conrath, C. N. W. Belterman, J. M. T. de Bakker and R. Coronel. ‘Reduced Sodium Current in the Lateral Ventricular Wall Induces Inferolateral J-Waves’. In: *Front Physiol* 7.365 (Aug. 2016). DOI: [10.3389/fphys.2016.00365](https://doi.org/10.3389/fphys.2016.00365). URL: <https://hal.inria.fr/hal-01386905>.
- [8] C. Pierre. ‘Preconditioning the bidomain model with almost linear complexity’. In: *Journal of Computational Physics* 231.1 (Jan. 2012), pp. 82–97. DOI: [10.1016/j.jcp.2011.08.025](https://doi.org/10.1016/j.jcp.2011.08.025). URL: <http://www.sciencedirect.com/science/article/pii/S0021999111005122>.

10.2 Publications of the year

International journals

- [9] S. Abu-Alrub, M. Strik, P. Huntjens, F. D. Ramirez, M. Potse, H. Cochet, H. Marchand, S. Buliard, R. Eschalier, M. Haïssaguerre, P. Bordachar and S. Ploux. ‘Left-axis deviation in patients with nonischemic heart failure and left bundle branch block is a purely electrical phenomenon’. In: *Heart Rhythm* 18.8 (Aug. 2021), pp. 1352–1360. DOI: [10.1016/j.hrthm.2021.03.042](https://doi.org/10.1016/j.hrthm.2021.03.042). URL: <https://hal.inria.fr/hal-03452310>.
- [10] A. Amri, M. Bellassoued, M. Mahjoub and N. Zemzemi. ‘Analysis of the heart-torso conductivity parameters recovery inverse problem in cardiac electrophysiology ECG modelling’. In: *Applicable Analysis* (9th July 2021), pp. 1–30. DOI: [10.1080/00036811.2021.1955861](https://doi.org/10.1080/00036811.2021.1955861). URL: <https://hal.inria.fr/hal-03301127>.
- [11] F. Bader, M. Bendahmane, M. Saad and R. Talhouk. ‘Derivation of a new macroscopic bidomain model including three scales for the electrical activity of cardiac tissue’. In: *Journal of Engineering Mathematics* 131.1 (Dec. 2021), p. 3. DOI: [10.1007/s10665-021-10174-8](https://doi.org/10.1007/s10665-021-10174-8). URL: <https://hal.archives-ouvertes.fr/hal-03534680>.

- [12] F. Bader, M. Bendahmane, M. Saad and R. Talhouk. ‘Three Scale Unfolding Homogenization Method Applied to Cardiac Bidomain Model’. In: *Acta Applicandae Mathematicae* 176.1 (Dec. 2021), p. 14. DOI: [10.1007/s10440-021-00459-6](https://doi.org/10.1007/s10440-021-00459-6). URL: <https://hal.archives-ouvertes.fr/hal-03517657>.
- [13] M. Bendahmane, E. Erraji and F. Karami. ‘Optimal control for nonlocal reaction-diffusion system describing calcium dynamics in cardiac cell’. In: *Mathematical Methods in the Applied Sciences* 44.6 (Apr. 2021), pp. 4802–4834. DOI: [10.1002/mma.7071](https://doi.org/10.1002/mma.7071). URL: <https://hal.inria.fr/hal-03534731>.
- [14] M. Bendahmane, F. Mroué and M. Saad. ‘A positive cell vertex godunov scheme for a beeler-reuter based model of cardiac electrical activity’. In: *Numerical Methods for Partial Differential Equations* 37.1 (Jan. 2021), pp. 262–301. DOI: [10.1002/num.22528](https://doi.org/10.1002/num.22528). URL: <https://hal.inria.fr/hal-03534773>.
- [15] M. Bergmann and L. Weynans. ‘A Cartesian Method with Second-Order Pressure Resolution for Incompressible Flows with Large Density Ratios’. In: *Fluids* 6.11 (6th Nov. 2021), p. 402. DOI: [10.3390/fluids6110402](https://doi.org/10.3390/fluids6110402). URL: <https://hal.inria.fr/hal-03506971>.
- [16] B. Boukens, M. Potse and R. Coronel. ‘Fibrosis and Conduction Abnormalities as Basis for Overlap of Brugada Syndrome and Early Repolarization Syndrome’. In: *International Journal of Molecular Sciences* 22.4 (4th Feb. 2021), p. 1570. DOI: [10.3390/ijms22041570](https://doi.org/10.3390/ijms22041570). URL: <https://hal.inria.fr/hal-03133273>.
- [17] H. A. Bukhari, F. Palmieri, J. Ramirez, P. Laguna, J. E. Ruiz, D. Ferreira, M. Potse, C. Sánchez and E. Pueyo. ‘Characterization of T Wave Amplitude, Duration and Morphology Changes During Hemodialysis: Relationship with Serum Electrolyte Levels and Heart Rate’. In: *IEEE Transactions on Biomedical Engineering* 68 (Aug. 2021), pp. 2467–2478. DOI: [10.1109/TBME.2020.3043844](https://doi.org/10.1109/TBME.2020.3043844). URL: <https://hal.inria.fr/hal-03076879>.
- [18] R. Coronel, M. Potse, M. Haïssaguerre, N. Derval, M. Rivaud, V. Meijborg, M. Cluitmans, M. Hocini and B. Boukens. ‘Why Ablation of Sites With Purkinje Activation Is Antiarrhythmic: The Interplay Between Fast Activation and Arrhythmogenesis’. In: *Frontiers in Physiology* 12 (23rd Mar. 2021), p. 648396. DOI: [10.3389/fphys.2021.648396](https://doi.org/10.3389/fphys.2021.648396). URL: <https://hal.inria.fr/hal-03452281>.
- [19] J. Engelhardt, E. Cuny, D. Guehl, P. Burbaut, N. Damon-Perrière, C. Dallies-Labourdette, J. Thomas, O. Branchard, L.-A. Schmitt, N. Gassa and N. Zemzemi. ‘Prediction of Clinical Deep Brain Stimulation Target for Essential Tremor From 1.5 Tesla MRI Anatomical Landmarks’. In: *Frontiers in Neurology* 12 (27th Oct. 2021). DOI: [10.3389/fneur.2021.620360](https://doi.org/10.3389/fneur.2021.620360). URL: <https://hal.inria.fr/hal-03409356>.
- [20] A. Karoui, M. Bendahmane and N. Zemzemi. ‘Cardiac Activation Maps Reconstruction: A Comparative Study Between Data-Driven and Physics-Based Methods’. In: *Frontiers in Physiology* 12 (26th Aug. 2021). DOI: [10.3389/fphys.2021.686136](https://doi.org/10.3389/fphys.2021.686136). URL: <https://hal.inria.fr/hal-03382399>.
- [21] B. Tarraf, E. Suraniti, C. Colin, S. Arbault, P. Diolez, M. Leguèbe and Y. Coudière. ‘A simple model of cardiac mitochondrial respiration with experimental validation’. In: *Mathematical Biosciences and Engineering* 18.5 (June 2021), pp. 5758–5789. DOI: [10.3934/mbe.2021291](https://doi.org/10.3934/mbe.2021291). URL: <https://hal.inria.fr/hal-03272432>.

International peer-reviewed conferences

- [22] A. Arrieula, H. Cochet, P. Jaïs, M. Haïssaguerre, N. Zemzemi and M. Potse. ‘In-Silico Data Based Machine Learning Technique Predicts Premature Ventricular Contraction Origin Coordinates’. In: *Computing in Cardiology 2021 - 48th Computing in Cardiology Conference*. Brno / Virtual, Czech Republic, 12th Sept. 2021. URL: <https://hal.inria.fr/hal-03364532>.
- [23] O. Bouhamama, L. Weynans and L. Bear. ‘Evaluation of the ECGI Patchwork Method Using Experimental Data in Sinus Rhythm’. In: *CinC 2021 - Computing in Cardiology*. Brno, Czech Republic, 12th Sept. 2021. URL: <https://hal.inria.fr/hal-03370881>.

- [24] H. A. Bukhari, P. Laguna, M. Potse, C. Sánchez and E. Pueyo. ‘QRS Slopes for Potassium and Calcium Monitoring in End-Stage Renal Disease Patients’. In: *Computing in Cardiology 2021 - 48th Computing in Cardiology Conference*. Brno / Virtual, Czech Republic, 12th Sept. 2021. URL: <https://hal.inria.fr/hal-03452385>.
- [25] N. Gassa, B. Sacristan, N. Zemzemi, M. Laborde, J. G. Oliver, C. M. Perabla, G. Jimenez-Perez, O. Camara, S. Ploux, M. Strik, P. Bordachar and R. Dubois. ‘Benchmark of deep learning algorithms for the automatic screening in electrocardiograms transmitted by implantable cardiac devices’. In: *CINC 2021 - Computing In Cardiology*. Brno, Czech Republic, 12th Sept. 2021. URL: <https://hal.inria.fr/hal-03485146>.

Scientific book chapters

- [26] M. M. Diallo, Y. Coudière and R. Dubois. ‘A Volume Source Method for Solving ECGI Inverse Problem’. In: *Functional Imaging and Modeling of the Heart*. Vol. 12738. Lecture Notes in Computer Science. Springer International Publishing, 18th June 2021, pp. 551–560. DOI: [10.1007/978-3-030-78710-3_53](https://doi.org/10.1007/978-3-030-78710-3_53). URL: <https://hal.archives-ouvertes.fr/hal-03507452>.
- [27] N. Gassa, N. Zemzemi, C. Corrado and Y. Coudière. ‘Spiral Waves Generation Using an Eikonal-Reaction Cardiac Electrophysiology Model’. In: *Functional Imaging and Modeling of the Heart 2021: International Conference on Functional Imaging and Modeling of the Heart*. 18th June 2021, pp. 523–530. DOI: [10.1007/978-3-030-78710-3_50](https://doi.org/10.1007/978-3-030-78710-3_50). URL: <https://hal.inria.fr/hal-03301186>.

10.3 Cited publications

- [28] B. Andreianov, M. Bendahmane, K. H. Karlsen and C. Pierre. ‘Convergence of discrete duality finite volume schemes for the cardiac bidomain model’. Anglais. In: *Networks and Heterogeneous Media* 6.2 (2011), pp. 195–240. URL: <http://hal.archives-ouvertes.fr/hal-00526047>.
- [29] P.-E. Bécue, F. Caro, M. Bendahmane and M. Potse. ‘Modélisation et simulation de l’électrophysiologie cardiaque à l’échelle microscopique’. In: *43e Congrès National d’Analyse Numérique (CANUM)*. SMAI. Obernai, Alsace, France, May 2016. URL: <http://smi.emath.fr/canum2016/resumes/PDF/peb/Abstract.pdf>.
- [30] P.-E. Bécue, F. Caro, M. Potse and Y. Coudière. *Theoretical and Numerical Study of Cardiac Electrophysiology Problems at the Microscopic Scale*. SIAM Conference on the Life Sciences (LS16). Poster. July 2016. URL: <https://hal.inria.fr/hal-01405837>.
- [31] P.-E. Bécue, M. Potse and Y. Coudière. ‘A Three-Dimensional Computational Model of Action Potential Propagation Through a Network of Individual Cells’. In: *Computing in Cardiology 2017*. Rennes, France, Sept. 2017, pp. 1–4. URL: <https://hal.inria.fr/hal-01592178>.
- [32] P.-E. Bécue, M. Potse and Y. Coudière. ‘Microscopic Simulation of the Cardiac Electrophysiology: A Study of the Influence of Different Gap Junctions Models’. In: *Computing in Cardiology*. Maastricht, Netherlands, Sept. 2018. URL: <https://hal.inria.fr/hal-01910679>.
- [33] B. Berte, F. Sacher, S. Mahida, S. Yamashita, H. S. Lim, A. Denis, N. Derval, M. Hocini, M. Haïssaguerre, H. Cochet and P. Jaïs. ‘Impact of Septal Radiofrequency Ventricular Tachycardia Ablation; Insights From Magnetic Resonance Imaging’. In: *Circulation* 130 (2014), pp. 716–718.
- [34] J. Chamorro Servent, L. Bear, J. Duchateau, M. Potse, R. Dubois and Y. Coudière. ‘Do we need to enforce the homogeneous Neuman condition on the Torso for solving the inverse electrocardiographic problem by using the method of fundamental solution?’ In: *Computing in Cardiology 2016*. Vol. 43. Computing in Cardiology 2016. Vancouver, Canada, Sept. 2016, pp. 425–428. URL: <https://hal.inria.fr/hal-01379236>.
- [35] C. Corrado and N. Zemzemi. ‘A conduction velocity adapted eikonal model for electrophysiology problems with re-excitability evaluation’. In: *Medical Image Analysis* 43 (Jan. 2018), pp. 186–197. DOI: [10.1016/j.media.2017.11.002](https://doi.org/10.1016/j.media.2017.11.002). URL: <https://hal.inria.fr/hal-01655410>.
- [36] Y. Coudière, Y. Bourgault and M. Rioux. ‘Optimal monodomain approximations of the bidomain equations used in cardiac electrophysiology’. In: *Mathematical Models and Methods in Applied Sciences* 24.6 (Feb. 2014), pp. 1115–1140. URL: <https://hal.inria.fr/hal-00644257>.

- [37] Y. Coudière and C. Pierre. ‘Stability And Convergence Of A Finite Volume Method For Two Systems Of Reaction-Diffusion Equations In Electro-Cardiology’. In: *Nonlinear Anal. Real World Appl.* 7.4 (2006), pp. 916–935. URL: <http://hal.archives-ouvertes.fr/hal-00016816/fr>.
- [38] Y. Coudière, C. Pierre, O. Rousseau and R. Turpault. ‘A 2D/3D Discrete Duality Finite Volume Scheme. Application to ECG simulation’. In: *International Journal on Finite Volumes* 6.1 (2009). URL: <http://hal.archives-ouvertes.fr/hal-00328251/fr>.
- [39] Y. Coudière and R. Turpault. ‘A domain decomposition strategy for a very high-order finite volumes scheme applied to cardiac electrophysiology’. In: *Journal of Computational Science* 37 (2019), p. 101025. DOI: <https://doi.org/10.1016/j.jocs.2019.101025>. URL: <http://www.sciencedirect.com/science/article/pii/S1877750319303862>.
- [40] A. Davidović, Y. Coudière and Y. Bourgault. ‘Modelling the action potential propagation in a heart with structural heterogeneities: From high-resolution MRI to numerical simulations’. In: *International Journal for Numerical Methods in Biomedical Engineering* (Feb. 2020), e3322. DOI: [10.1002/cnm.3322](https://doi.org/10.1002/cnm.3322). URL: <https://hal-pasteur.archives-ouvertes.fr/pasteur-03402684>.
- [41] J. Duchateau, M. Potse and R. Dubois. ‘Spatially Coherent Activation Maps for Electrocardiographic Imaging’. In: *IEEE Transactions on Biomedical Engineering* 64 (May 2017), pp. 1149–1156. DOI: [10.1109/TBME.2016.2593003](https://doi.org/10.1109/TBME.2016.2593003). URL: <https://hal.inria.fr/hal-01386890>.
- [42] A. Gharaviri, M. Potse, S. Verheule, R. Krause, A. Auricchio and U. Schotten. ‘Epicardial Fibrosis Explains Increased Transmural Conduction in a Computer Model of Atrial Fibrillation’. In: *Computing in Cardiology*. Vancouver, Canada, Sept. 2016. URL: <https://hal.inria.fr/hal-01386916>.
- [43] M. Haïssaguerre, P. Jaïs, D. C. Shah, S. Garrigue, A. Takahashi, T. Lavergne, M. Hocini, J. T. Peng, R. Roudaut and J. Clémenty. ‘Spontaneous initiation of atrial fibrillation by ectopic beats originating in the pulmonary veins’. In: *N. Engl. J. Med.* 339 (1998), pp. 659–666.
- [44] M. Haïssaguerre, N. Derval, F. Sacher, L. Jesel, I. Deisenhofer, L. de Roy, J. L. Pasquié, A. Nogami, D. Babuty, S. Yli-Mayry, C. De Chillou, P. Scanu, P. Mabo, S. Matsuo, V. Probst, S. Le Scouarnec, P. Defaye, J. Schlaepfer, T. Rostock, D. Lacroix, D. Lamaison, T. Lavergne, Y. Aizawa, A. Englund, F. Anselme, M. O’Neill, M. Hocini, K. T. Lim, S. Knecht, G. D. Veenhuyzen, P. Bordachar, M. Chauvin, P. Jaïs, G. Coureau, G. Chene, G. J. Klein and J. Clémenty. ‘Sudden cardiac arrest associated with early repolarization’. In: *N. Engl. J. Med.* 358 (2008), pp. 2016–2023.
- [45] M. G. Hoogendijk, M. Potse, A. C. Linnenbank, A. O. Verkerk, H. M. den Ruijter, S. C. M. van Amersfoorth, E. C. Klaver, L. Beekman, C. R. Bezzina, P. G. Postema, H. L. Tan, A. G. Reimer, A. C. van der Wal, A. D. J. ten Harkel, M. Dalinghaus, A. Vinet, A. A. M. Wilde, J. M. T. de Bakker and R. Coronel. ‘Mechanism of Right Precordial ST-Segment Elevation in Structural Heart Disease: Excitation Failure by Current-to-Load Mismatch’. In: *Heart Rhythm* 7 (2010), pp. 238–248. URL: <http://dx.doi.org/10.1016/j.hrthm.2009.10.007>.
- [46] M. L. Hubbard and C. S. Henriquez. ‘A microstructural model of reentry arising from focal breakthrough at sites of source-load mismatch in a central region of slow conduction’. In: *Am. J. Physiol. Heart Circ. Physiol.* 306 (2014), H1341–1352.
- [47] M. Kania, Y. Coudière, H. Cochet, M. Haïssaguerre, P. Jaïs and M. Potse. ‘A new ECG-based method to guide catheter ablation of ventricular tachycardia’. In: *iMAging and eLectrical Technologies*. Uppsala, Sweden, Apr. 2018. URL: <https://hal.inria.fr/hal-01910709>.
- [48] C. Pierre. ‘Preconditioning the bidomain model with almost linear complexity’. In: *Journal of Computational Physics* 231.1 (Jan. 2012), pp. 82–97. DOI: [10.1016/j.jcp.2011.08.025](https://doi.org/10.1016/j.jcp.2011.08.025). URL: <http://www.sciencedirect.com/science/article/pii/S0021999111005122>.
- [49] M. Potse. ‘Scalable and Accurate ECG Simulation for Reaction-Diffusion Models of the Human Heart’. In: *Frontiers in Physiology* 9 (Apr. 2018), p. 370. DOI: [10.3389/fphys.2018.00370](https://doi.org/10.3389/fphys.2018.00370). URL: <https://hal.inria.fr/hal-01910637>.
- [50] M. Potse, B. Dubé, J. Richer, A. Vinet and R. M. Gulrajani. ‘A Comparison of monodomain and bidomain reaction-diffusion models for action potential propagation in the human heart’. In: *IEEE Transactions on Biomedical Engineering* 53.12 (2006), pp. 2425–2435. URL: <http://dx.doi.org/10.1109/TBME.2006.880875>.

- [51] M. Potse, B. Dubé and A. Vinet. ‘Cardiac Anisotropy in Boundary-Element Models for the Electrocardiogram’. In: *Medical and Biological Engineering and Computing* 47 (2009), pp. 719–729. URL: <http://dx.doi.org/10.1007/s11517-009-0472-x>.
- [52] M. Potse, A. Gharaviri, S. Pezzuto, A. Auricchio, R. Krause, S. Verheule and U. Schotten. ‘Anatomically-induced Fibrillation in a 3D model of the Human Atria’. In: *Computing in Cardiology*. Maastricht, Netherlands, Sept. 2018. URL: <https://hal.inria.fr/hal-01910674>.
- [53] M. Potse, V. M. F. Meijborg, C. N. W. Belterman, J. M. T. de Bakker, C. E. Conrath and R. Coronel. *Regional conduction slowing can explain inferolateral J waves and their attenuation by sodium channel blockers*. Annual workshop of Liryc - Electrophysiology and heart modeling institute. Poster. Sept. 2016. URL: <https://hal.inria.fr/hal-01393102>.
- [54] A. Tveito, K. H. Jæger, M. Kuchta, K.-A. Mardal and M. E. Rognes. ‘A Cell-Based Framework for Numerical Modeling of Electrical Conduction in Cardiac Tissue’. In: *Front. Phys.* 5 (2017), p. 48.