IN PARTNERSHIP WITH:
CNRS

Université Pierre et Marie Curie (Paris 6)

Activity Report 2017

Project-Team REO

Numerical simulation of biological flows

IN COLLABORATION WITH: Laboratoire Jacques-Louis Lions (LJLL)

RESEARCH CENTER
Paris

THEME
Modeling and Control for Life Sciences

Table of contents

1. Personnel **1**
2. Overall Objectives **2**
3. Research Program **2**
3.1. Multiphysics modeling 2
3.1.1. Fluid-structure interaction 2
3.1.2. Aerosol 3
3.2. Multiscale modeling 3
3.2.1. Arterial tree modeling 4
3.2.2. Heart perfusion modeling 4
3.2.3. Tumor and vascularization 5
3.2.4. Respiratory tract modeling 5
4. Application Domains **5**
4.1. Blood flows 5
4.2. Respiratory tracts 6
4.3. Cardiac electrophysiology 6
5. Highlights of the Year **7**
6. New Software and Platforms **7**
6.1. FELiScE 7
6.2. MODULEF 7
6.3. SHELDDON 7
7. New Results **8**
7.1. Mathematical and numerical analysis of fluid-structure interaction problems 8
7.2. Numerical methods for biological flows 8
7.3. Numerical methods for cardiac electrophysiology 9
7.4. Lung and respiration modeling 9
7.5. Miscellaneous 10
8. Bilateral Contracts and Grants with Industry **10**
8.1.1. Air Liquide Santé International 10
8.1.2. Philips Research 10
8.1.3. Kephalios & Epygon 11
8.1.4. Instem/NOTOCORD 11
9. Partnerships and Cooperations **11**
9.1. National Initiatives 11
9.1.1. ANR 11
9.1.1.1. ANR Project “iFLOW” 11
9.1.1.2. ANR Project “IFSMACS” 11
9.1.1.3. Participation to other ANR projects 11
9.1.2. Inria initiatives 11
9.2. European Initiatives 12
9.2.1. FP7 & H2020 Projects 12
9.2.2. Collaborations in European Programs, Except FP7 & H2020 12
9.3. International Research Visitors 12
10. Dissemination **12**
10.1. Promoting Scientific Activities 12
10.1.1. Scientific Events Organisation 12
10.1.2. Scientific Events Selection 13
10.1.2.1. Chair of Conference Program Committees 13
10.1.2.2. Member of the Conference Program Committees 13
10.1.2.3. Reviewer 13

10.1.3. Journal 13
10.1.4. Leadership within the Scientific Community 13
10.1.5. Research Administration 14
10.1.6. Conferences 14
10.2. Teaching - Supervision - Juries 16
10.2.1. Teaching 16
10.2.2. Supervision 17
10.2.3. Juries 18
10.3. Popularization 18
11. Bibliography **19**

Project-Team REO

Creation of the Project-Team: 2005 April 01

Keywords:

Computer Science and Digital Science:

A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.4. - Multiscale modeling
A6.1.5. - Multiphysics modeling
A6.2.1. - Numerical analysis of PDE and ODE
A6.3.1. - Inverse problems
A6.3.2. - Data assimilation
A6.3.4. - Model reduction

Other Research Topics and Application Domains:

B2.2.1. - Cardiovascular and respiratory diseases
B2.2.3. - Cancer
B2.4.1. - Pharmaco kinetics and dynamics

1. Personnel

Research Scientists

Jean-Frédéric Gerbeau [Team leader, Inria, Senior Researcher, HDR]
Miguel Ángel Fernández Varela [Inria, Senior Researcher, HDR]
Céline Grandmont [Inria, Senior Researcher, HDR]
Damiano Lombardi [Inria, Researcher]
Marc Thiriet [CNRS, Researcher, HDR]
Marina Vidrascu [Inria, Senior Researcher]
Irene Vignon Clementel [Inria, Senior Researcher, HDR]

Faculty Members

Laurent Boudin [Univ Pierre et Marie Curie, Associate Professor, HDR]
Muriel Boulakia [Univ Pierre et Marie Curie, Associate Professor, HDR]

Post-Doctoral Fellows

Dena Kazerani [Inria, until Sep 2017]
Lara Trussardi [Inria, until Sep 2017]
Florian Joly [Inria]

PhD Students

Matteo Aletti [Inria, until May 2017]
Chloé Audebert [Inria, until Jul 2017]
Ludovic Boilevin-Kayl [Inria]
Chen-Yu Chiang [Univ Pierre et Marie Curie]
Felipe Galarce Marin [Inria, from Dec 2017]
Nicolas Golse [MD, part-time project-team MIMESIS]
Nicolas Pozin [ALSI (Air Liquide Sante International) until Feb 2017, Inria until Aug 2017]
Alexandre This [Philips, PhD Student, granted by CIFRE]
Eliott Tixier [Univ Pierre et Marie Curie]

Technical staff

Gautier Bureau [Inria]
Axel Fourmont [Inria, until Sep 2017]
Fabien Raphel [Inria, granted by NOTOCORD]

Interns

Pierre Colas [Instem, from Jun 2017 until Jul 2017]
Felipe Galarce Marin [Inria, from Apr 2017 until Aug 2017]
Alberto Noferi [Inria, from Mar 2017 until Aug 2017]
Gabriel Rezende Nahas [Inria, from Apr 2017 until Aug 2017]

Administrative Assistant

Maryse Desnous [Inria]

Visiting Scientists

Gonzalo Castineira Veiga [Universidade da Coruña, from Apr 2017 until Jun 2017]
Marthe(prisca) Combari [Hopital Paul Brousse, from Nov 2017]

2. Overall Objectives

2.1. Overall Objectives

REO is a joint project-team of the Inria Research Center of Paris and the Jacques-Louis Lions Laboratory (LJLL) of the Pierre and Marie Curie University (Sorbonne Universités, UPMC Paris 6) and CNRS (UMR7598). Its main objectives are:

- the modeling of blood flow in large vessels, air flow in the respiratory tract, and the cardiac electrophysiology;
- the design and the analysis of efficient and robust numerical methods for these problems;
- the development of numerical software to assist medical decisions and to contribute to the design of medical devices.

REO put a strong effort in working with real data, coming either from clinicians or industrial partners. The development of methods for the interaction of data and simulation is therefore an important aspect of the activity of the team.

3. Research Program

3.1. Multiphysics modeling

In large vessels and in large bronchi, blood and air flows are generally supposed to be governed by the incompressible Navier-Stokes equations. Indeed in large arteries, blood can be supposed to be Newtonian, and at rest air can be modeled as an incompressible fluid. The cornerstone of the simulations is therefore a Navier-Stokes solver. But other physical features have also to be taken into account in simulations of biological flows, in particular fluid-structure interaction in large vessels and transport of sprays, particles or chemical species.

3.1.1. Fluid-structure interaction

Fluid-structure coupling occurs both in the respiratory and in the circulatory systems. We focus mainly on blood flows since our work is more advanced in this field. But the methods developed for blood flows could be also applied to the respiratory system.

Here “fluid-structure interaction” means a coupling between the 3D Navier-Stokes equations and a 3D (possibly thin) structure in large displacements.

The numerical simulations of the interaction between the artery wall and the blood flows raise many issues: (1) the displacement of the wall cannot be supposed to be infinitesimal, geometrical nonlinearities are therefore present in the structure and the fluid problem have to be solved on a moving domain (2) the densities of the artery walls and the blood being close, the coupling is strong and has to be tackled very carefully to avoid numerical instabilities, (3) "naive" boundary conditions on the artificial boundaries induce spurious reflection phenomena.

Simulation of valves, either at the outflow of the cardiac chambers or in veins, is another example of difficult fluid-structure problems arising in blood flows. In addition, very large displacements and changes of topology (contact problems) have to be handled in those cases.

Due to stability reasons, it seems impossible to successfully apply in hemodynamics the explicit coupling schemes used in other fluid-structure problems, like aeroelasticity. As a result, fluid-structure interaction in biological flows raise new challenging issues in scientific computing and numerical analysis : new schemes have to be developed and analyzed.

We have proposed and analyzed over the last few years several efficient fluid-structure interaction algorithms. This topic remains very active. We are now using these algorithms to address inverse problems in blood flows to make patient specific simulations (for example, estimation of artery wall stiffness from medical imaging).

3.1.2. Aerosol

Complex two-phase fluids can be modeled in many different ways. Eulerian models describe both phases by physical quantities such as the density, velocity or energy of each phase. In the mixed fluid-kinetic models, the biphasic fluid has one dispersed phase, which is constituted by a spray of droplets, with a possibly variable size, and a continuous classical fluid.

This type of model was first introduced by Williams [57] in the frame of combustion. It was later used to develop the Kiva code [45] at the Los Alamos National Laboratory, or the Hesione code [52], for example. It has a wide range of applications, besides the nuclear setting: diesel engines, rocket engines [49], therapeutic sprays, *etc.* One of the interests of such a model is that various phenomena on the droplets can be taken into account with an accurate precision: collision, breakups, coagulation, vaporization, chemical reactions, *etc.*, at the level of the droplets.

The model usually consists in coupling a kinetic equation, that describes the spray through a probability density function, and classical fluid equations (typically Navier-Stokes). The numerical solution of this system relies on the coupling of a method for the fluid equations (for instance, a finite volume method) with a method fitted to the spray (particle method, Monte Carlo).

We are mainly interested in modeling therapeutic sprays either for local or general treatments. The study of the underlying kinetic equations should lead us to a global model of the ambient fluid and the droplets, with some mathematical significance. Well-chosen numerical methods can give some tracks on the solutions behavior and help to fit the physical parameters which appear in the models.

3.2. Multiscale modeling

Multiscale modeling is a necessary step for blood and respiratory flows. In this section, we focus on blood flows. Nevertheless, similar investigations are currently carried out on respiratory flows.

3.2.1. Arterial tree modeling

Problems arising in the numerical modeling of the human cardiovascular system often require an accurate description of the flow in a specific sensible subregion (carotid bifurcation, stented artery, *etc.*). The description of such local phenomena is better addressed by means of three-dimensional (3D) simulations, based on the numerical approximation of the incompressible Navier-Stokes equations, possibly accounting for compliant (moving) boundaries. These simulations require the specification of boundary data on artificial boundaries that have to be introduced to delimit the vascular district under study. The definition of such boundary conditions is critical and, in fact, influenced by the global systemic dynamics. Whenever the boundary data is not available from accurate measurements, a proper boundary condition requires a mathematical description of the action of the reminder of the circulatory system on the local district. From the computational point of view, it is not affordable to describe the whole circulatory system keeping the same level of detail. Therefore, this mathematical description relies on simpler models, leading to the concept of *geometrical multiscale* modeling of the circulation [53]. The underlying idea consists in coupling different models (3D, 1D or 0D) with a decreasing level of accuracy, which is compensated by their decreasing level of computational complexity.

The research on this topic aims at providing a correct methodology and a mathematical and numerical framework for the simulation of blood flow in the whole cardiovascular system by means of a geometric multiscale approach. In particular, one of the main issues will be the definition of stable coupling strategies between 3D and reduced order models.

To model the arterial tree, a standard way consists of imposing a pressure or a flow rate at the inlet of the aorta, *i.e.* at the network entry. This strategy does not allow to describe important features as the overload in the heart caused by backward traveling waves. Indeed imposing a boundary condition at the beginning of the aorta artificially disturbs physiological pressure waves going from the arterial tree to the heart. The only way to catch this physiological behavior is to couple the arteries with a model of heart, or at least a model of left ventricle.

A constitutive law for the myocardium, controlled by an electrical command, has been developed in the CardioSense3D project [1]. One of our objectives is to couple artery models with this heart model.

A long term goal is to achieve 3D simulations of a system including heart and arteries. One of the difficulties of this very challenging task is to model the cardiac valves. To this purpose, we investigate a mix of arbitrary Lagrangian Eulerian and fictitious domain approaches or x-fem strategies, or simplified valve models based on an immersed surface strategy.

3.2.2. Heart perfusion modeling

The heart is the organ that regulates, through its periodical contraction, the distribution of oxygenated blood in human vessels in order to nourish the different parts of the body. The heart needs its own supply of blood to work. The coronary arteries are the vessels that accomplish this task. The phenomenon by which blood reaches myocardial heart tissue starting from the blood vessels is called in medicine perfusion. The analysis of heart perfusion is an interesting and challenging problem. Our aim is to perform a three-dimensional dynamical numerical simulation of perfusion in the beating heart, in order to better understand the phenomena linked to perfusion. In particular the role of the ventricle contraction on the perfusion of the heart is investigated as well as the influence of blood on the solid mechanics of the ventricle. Heart perfusion in fact implies the interaction between heart muscle and blood vessels, in a sponge-like material that contracts at every heartbeat via the myocardium fibers.
Despite recent advances on the anatomical description and measurements of the coronary tree and on the corresponding physiological, physical and numerical modeling aspects, the complete modeling and simulation of blood flows inside the large and the many small vessels feeding the heart is still out of reach. Therefore, in order to model blood perfusion in the cardiac tissue, we must limit the description of the detailed flows at a given space scale, and simplify the modeling of the smaller scale flows by aggregating these phenomena into macroscopic quantities, by some kind of "homogenization" procedure. To that purpose, the modeling of the fluid-solid coupling within the framework of porous media appears appropriate.

[1] http://www-sop.inria.fr/CardioSense3D/

Poromechanics is a simplified mixture theory where a complex fluid-structure interaction problem is replaced by a superposition of both components, each of them representing a fraction of the complete material at every point. It originally emerged in soils mechanics with the work of Terzaghi [56], and Biot [46] later gave a description of the mechanical behavior of a porous medium using an elastic formulation for the solid matrix, and Darcy's law for the fluid flow through the matrix. Finite strain poroelastic models have been proposed (see references in [47]), albeit with *ad hoc* formulations for which compatibility with thermodynamics laws and incompressibility conditions is not established.

3.2.3. Tumor and vascularization

The same way the myocardium needs to be perfused for the heart to beat, when it has reached a certain size, tumor tissue needs to be perfused by enough blood to grow. It thus triggers the creation of new blood vessels (angiogenesis) to continue to grow. The interaction of tumor and its micro-environment is an active field of research. One of the challenges is that phenomena (tumor cell proliferation and death, blood vessel adaptation, nutrient transport and diffusion, etc) occur at different scales. A multi-scale approach is thus being developed to tackle this issue. The long term objective is to predict the efficiency of drugs and optimize therapy of cancer.

3.2.4. Respiratory tract modeling

We aim at developing a multiscale model of the respiratory tract. Intraprenchymal airways distal from generation 7 of the tracheabronchial tree (TBT), which cannot be visualized by common medical imaging techniques, are modeled either by a single simple model or by a model set according to their order in TBT. The single model is based on straight pipe fully developed flow (Poiseuille flow in steady regimes) with given alveolar pressure at the end of each compartment. It will provide boundary conditions at the bronchial ends of 3D TBT reconstructed from imaging data. The model set includes three serial models. The generation down to the pulmonary lobule will be modeled by reduced basis elements. The lobular airways will be represented by a fractal homogenization approach. The alveoli, which are the gas exchange loci between blood and inhaled air, inflating during inspiration and deflating during expiration, will be described by multiphysics homogenization.

4. Application Domains

4.1. Blood flows

Cardiovascular diseases like atherosclerosis or aneurysms are a major cause of mortality. It is generally admitted that a better knowledge of local flow patterns could improve the treatment of these pathologies (although many other biophysical phenomena obviously take place in the development of such diseases). In particular, it has been known for years that the association of low wall shear stress and high oscillatory shear index give relevant indications to localize possible zones of atherosclerosis. It is also known that medical devices (graft or stent) perturb blood flows and may create local stresses favorable with atherogenesis. Numerical simulations of blood flows can give access to this local quantities and may therefore help to design new medical devices with less negative impacts. In the case of aneurysms, numerical simulations may help to predict possible zones of rupture and could therefore give a guide for treatment planning.

In clinical routine, many indices are used for diagnosis. For example, the size of a stenosis is estimated by a few measures of flow rate around the stenosis and by application of simple fluid mechanics rules. In some situations, for example in the case a sub-valvular stenosis, it is known that such indices often give false estimations. Numerical simulations may give indications to define new indices, simple enough to be used in clinical exams, but more precise than those currently used.

It is well-known that the arterial circulation and the heart (or more specifically the left ventricle) are strongly coupled. Modifications of arterial walls or blood flows may indeed affect the mechanical properties of the left ventricle. Numerical simulations of the arterial tree coupled to the heart model could shed light on this complex relationship.

One of the goals of the REO team is to provide various models and simulation tools of the cardiovascular system. The scaling of these models will be adapted to the application in mind: low resolution for modeling the global circulation, high resolution for modeling a small portion of vessel.

4.2. Respiratory tracts

Breathing, or "external" respiration ("internal" respiration corresponds to cellular respiration) involves gas transport though the respiratory tract with its visible ends, nose and mouth. Air streams then from the pharynx down to the trachea. Food and drink entry into the trachea is usually prevented by the larynx structure (epiglottis). The trachea extends from the neck into the thorax, where it divides into right and left main bronchi, which enter the corresponding lungs (the left being smaller to accommodate the heart). Inhaled air is then convected in the bronchus tree which ends in alveoli, where gaseous exchange occurs. Surfactant reduces the surface tension on the alveolus wall, allowing them to expand. Gaseous exchange relies on simple diffusion on a large surface area over a short path between the alveolus and the blood capillary under concentration gradients between alveolar air and blood. The lungs are divided into lobes (three on the right, two on the left) supplied by lobar bronchi. Each lobe of the lung is further divided into segments (ten segments of the right lung and eight of the left). Inhaled air contains dust and debris, which must be filtered, if possible, before they reach the alveoli. The tracheobronchial tree is lined by a layer of sticky mucus, secreted by the epithelium. Particles which hit the side wall of the tract are trapped in this mucus. Cilia on the epithelial cells move the mucous continually towards the nose and mouth.

Each lung is enclosed in a space bounded below by the diaphragm and laterally by the chest wall and the mediastinum. The air movement is achieved by alternately increasing and decreasing the chest pressure (and volume). When the airspace transmural pressure rises, air is sucked in. When it decreases, airspaces collapse and air is expelled. Each lung is surrounded by a pleural cavity, except at its hilum where the inner pleura give birth to the outer pleura. The pleural layers slide over each other. The tidal volume is nearly equal to 500 ml.

The lungs may fail to maintain an adequate supply of air. In premature infants surfactant is not yet active. Accidental inhalation of liquid or solid and airway infection may occur. Chronic obstructive lung diseases and lung cancers are frequent pathologies and among the three first death causes in France.

One of the goals of REO team in the ventilation field is to visualize the airways (virtual endoscopy) and simulate flow in image-based 3D models of the upper airways (nose, pharynx, larynx) and the first generations of the tracheobronchial tree (trachea is generation 0), whereas simple models of the small bronchi and alveoli are used (reduced-basis element method, fractal homogenization, multiphysics homogenization, lumped parameter models), in order to provide the flow distribution within the lung segments.

4.3. Cardiac electrophysiology

The purpose is to simulate the propagation of the action potential in the heart. A lot of works has already been devoted to this topic in the literature (see *e.g.* [50], [55], [54] and the references therein), nevertheless there are only very few studies showing realistic electrocardiograms obtained from partial differential equations models. Our goal is to find a compromise between two opposite requirements: on the one hand, we want to use predictive models, and therefore models based on physiology, on the other hand, we want to use models simple enough to be parametrized (in view of patient-specific simulations). One of the goal is to use our ECG simulator to address the inverse problem of electrocardiology. In collaboration with the Macs/M3disym project-team, we are interested in the electromechanical coupling in the myocardium. We are also interested in various clinical and industrial issues related to cardiac electrophysiology, in particular the simulation of experimental measurement of the field potential of cardiac stem cells in multi-electrode arrays.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

Mikel Landajuela Larma was awarded the 2017 SMAI-GAMNI PhD thesis prize by the French Society of Industrial and Applied Mathematics for his thesis supervised by Miguel Fernández.

6. New Software and Platforms

6.1. FELiScE

Finite Elements for Life SCiences and Engineering problems
KEYWORDS: Finite element modelling - Cardiac Electrophysiology - Cardiovascular and respiratory systems
FUNCTIONAL DESCRIPTION: FELiScE is a finite element code which the M3DISIM and REO project-teams have decided to jointly develop in order to build up on their respective experiences concerning finite element simulations. One specific objective of this code is to provide in a unified software environment all the state-of-the-art tools needed to perform simulations of the complex respiratory and cardiovascular models considered in the two teams – namely involving fluid and solid mechanics, electrophysiology, and the various associated coupling phenomena. FELISCE is written in C++, and may be later released as an opensource library. FELiScE was registered in July 2014 at the Agence pour la Protection des Programmes under the Inter Deposit Digital Number IDDN.FR.001.350015.000.S.P.2014.000.10000.

- Participants: Axel Fourmont, Benoit Fabreges, Damiano Lombardi, Dominique Chapelle, Faisal Amlani, Irène Vignon-Clementel, Jean-Frédéric Gerbeau, Marina Vidrascu, Matteo Aletti, Miguel Angel Fernandez Varela, Mikel Landajuela Larma, Philippe Moireau and Sébastien Gilles
- Contact: Jean-Frédéric Gerbeau
- URL: http://felisce.gforge.inria.fr

6.2. MODULEF

FUNCTIONAL DESCRIPTION: The numerical method to approximate the constitutive laws for rubber elasticity derived from polymer physics are implemented in the Inria software Modulef.

It is based on : - algorithms from stochastic geometry to generate suitable polymer networks, - Delaunay tessellation algorithms to deal with steric effects (courtesy of the Inria project-team GAMMA2), - the introduction of 1-dimensional finite elements for the polymer-chains in Modulef.

- Participants: Antoine Gloria and Marina Vidrascu
- Contact: Marina Vidrascu
- URL: https://www.rocq.inria.fr/modulef/

6.3. SHELDDON

SHELls and structural Dynamics with DOmain decomposition in Nonlinear analysis
FUNCTIONAL DESCRIPTION: SHELDDON is a finite element library based on the Modulef package which contains shell elements, nonlinear procedures and PVM subroutines used in domain decomposition or coupling methods, in particular fluid-structure interaction.

- Participants: Dominique Chapelle, Marina Vidrascu and Patrick Le Tallec
- Contact: Marina Vidrascu
- URL: https://gforge.inria.fr/projects/shelddon/

7. New Results

7.1. Mathematical and numerical analysis of fluid-structure interaction problems

Participants: Matteo Aletti, Ludovic Boilevin-Kayl, Chen-Yu Chiang, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Céline Grandmont, Damiano Lombardi, Marc Thiriet, Marina Vidrascu.

In [15] a reduced order modeling method is developed to simulate multi-domain multi-physics problems. In particular we considered the case in which one problem of interest, described by a generic non-linear partial differential equation is coupled to one or several problems described by a set of linear partial differential equations. In order to speed up the resolution of the coupled system, a low-rank representation of the Poincaré-Steklov operator is built by a reduced-basis approach. A database for the secondary problems is built when the interface condition is set to be equal to a subset of the Laplace-Beltrami eigenfunctions on the surface. The convergence of the method is analysed and several 3D fluid-fluid and fluid-structure couplings are presented as numerical experiments.

In [43] we study an unsteady nonlinear fluid–structure interaction problem. We consider a Newtonian incompressible two-dimensional flow described by the Navier-Stokes equations set in an unknown domain depending on the displacement of a structure, which itself satisfies a linear wave equation or a linear beam equation. We prove existence of a unique local-in-time strong solution. In the case of the wave equation or a beam equation with inertia of rotation, this is, to our knowledge the first result of existence of strong solutions for which no viscosity is added. One key point, is to use the fluid dissipation to control, in appropriate function spaces, the structure velocity.

In [26] a fluid-structure interaction solver based on 3D Eulerian monolithic formulation for an incompressible Newtonian fluid coupled with a hyperelastic incompressible solid has been implemented, verified, and validated. It is based on a Eulerian formulation of the full system. After a fully implicit discretization in time, displacement is eliminated and the variational equation is solved for the velocity and pressure. Its main application in medicine is venous flow in inferior limbs.

7.2. Numerical methods for biological flows

Participants: Chloé Audebert, Ludovic Boilevin-Kayl, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Florian Joly, Alexandre This, Marc Thiriet, Irene Vignon Clementel.

Peripheral pulmonary artery stenosis (PPS) is a congenital abnormality resulting in pulmonary blood flow disparity and right ventricular hypertension, for which optimal surgical strategies remain unclear. In [35], we conduct a pilot study to use recently refined computational simulation in the setting of multiple surgical strategies and to examine the influence of pulmonary artery reconstruction on hemodynamics in this population. Obstruction relief along with pulmonary artery vasodilation determines postoperative pulmonary flow distribution and newer methods can incorporate these physiologic changes.

Incoming velocity at open boundaries, or backflow, often yields to unphysical instabilities already for moderate Reynolds numbers. Several treatments to overcome these backflow instabilities have been proposed in the literature. In [17], we present a set of benchmark problems in order to compare different methods in different backflow regimes (with a full reversal flow and with propagating vortices after a stenosis). The examples are implemented in FreeFem++ and the source code is openly available.

The simulation of cardiac blood flow using patient-specific geometries can help for the diagnosis and treatment of cardiac diseases. Current patient-specific cardiac flow simulations requires a significant amount of human expertise and time to pre-process image data and obtain a case ready for simulations. In [38] a new procedure is proposed to alleviate this pre-processing by registering a unique generic mesh on patient-specific cardiac segmentations and transferring appropriately the spatiotemporal dynamics of the ventricle. The method is applied on real patient data acquired from 3D ultrasound imaging. Both a healthy and a pathological conditions are simulated. The resulting simulations exhibited physiological flow behavior in cardiac cavities and the experiments confirm a significant reduction in pre-processing work.

In order to reduce the complexity of heart hemodynamics simulations, one-way coupling approaches are often considered as an alternative to fluid-structure interaction (FSI) models. A possible shortcoming of these simplified approaches is the difficulty to correctly capture the pressure dynamics during the isovolumetric phases. In [39] we propose an enhanced resistive immersed surface (RIS) model of cardiac valves which overcomes this issue. The benefits of the model are investigated and tested in blood flow simulations of the left heart.

In [51], a computational model of unsteady blood flow in the cerebral venous circuit inside the skull reconstructed from medical images has been carried out. This venous network runs separately from the arterial bed perfusing the brain. The major aspects are boundary conditions and flow governing parameters.

7.3. Numerical methods for cardiac electrophysiology

Participants: Muriel Boulakia, Jean-Frédéric Gerbeau, Damiano Lombardi, Fabien Raphel, Eliott Tixier.

In [32], we propose a model to represent the electrical potential of cardiomyocytes derived from stem cells in Multi Electrodes Arrays (MEA). This model based on the bidomain equations and a model for the MEA electrodes is used to analyze experimental signals. Our numerical algorithm is able to provide for different drugs dose-response curves which are in very good agreement with known values.

In [14], we are interested in the electrical activity of cardiomyocytes under the action of drugs in MEA devices. We present numerical simulations based on the same model as in [32] enriched with a pore block model to assay the action of drugs. The simulation results show that the model properly reflects the main effects of several drugs on the electrical potential.

In [33] the variability of phenomena in cardiac electro-physiology is investigated by using a moment matching approach. The cells activity is described by parametric systems of Ordinary Differential Equations. Given the population statistics on a system observables (which is the action potential of the cells), the probability density distribution of the parameters is sought such that the statistics of the model outputs match the observed ones. An uncertainty quantification step is solved once for all by using a non-instrusive approach, and then the inverse problem is solved by introducing an entropy regularisation. Several numerical experiments are considered to validate the approach on realistic datasets.

In [34] a realistic application on the classification of the drugs effect on cardiac cells is investigated. In particular, the electrical activity of the cells is recorder by Micro Electrode Arrays in normal conditions and under drugs, at different concentrations. In order to perform a classification of a drug in terms of promoting or inhibit the activity of certain ion channels a machine learning approach is used (support vector machine). Since the data amount is not big and the variability and alea sources have a large impact on the signals recorded, the data set is augmented by in silico experiments. Several tests on realistic data are performed.

7.4. Lung and respiration modeling

Participants: Céline Grandmont, Dena Kazerani, Nicolas Pozin, Marina Vidrascu, Marc Thiriet, Irene Vignon Clementel.

In [30] we use the coupled model tree-parenchyma model introduced in [31] to study the impact of asthma on effort and ventilation distribution along with the effect of Heliox compared to air. Indeed, in spite of numerous clinical studies, there is no consensus on the benefit Heliox mixtures can bring to asthmatic patients in terms of work of breathing and ventilation distribution. For this study, lung surface displacement fields extracted from computed tomography medical images are used to prescribe realistic boundary conditions to the system. Asthma is simulated by imposing bronchoconstrictions to some airways of the tracheo-bronchial tree based on statistical laws deduced from the literature. This study illuminates potential mechanisms for patient responsiveness to Heliox when affected by obstructive pulmonary diseases. Responsiveness appears to be function of the pathology severity, as well as its distal position in the tracheo-bronchial tree and geometrical position within the lung. Moreover, as already stated, in asthma and COPD, some airways of the tracheo-bronchial tree can be constricted, from moderate narrowing up to closure. These pathological patterns affect

the lung ventilation distribution. While some imaging techniques enable visualization and quantification of constrictions in proximal generations, no non-invasive technique provides precise insights on what happens in more distal areas. In [44] we propose a process that exploits dynamical lung ventilation measurements to access positions of airways closures in the tree. This identification approach combines our lung ventilation model along with a machine learning approach. Based on synthetic data generated with typical temporal and spatial resolutions as well as reconstruction errors, we obtain encouraging results with a detection rate higher than 90%.

The human tracheobronchial tree surface is covered with mucus that ensures clearance of foreign material. An alteration of mucus or its environment such as in cystic fibrosis dramatically impacts the mucociliary clearance. In [48] the numerical method is able to manage variations of more than 5 orders of magnitude in the shear rate and viscosity. It leads to a cartography that enables to discuss major issues on defective mucociliary clearance in cystic fibrosis. In addition, cystic fibrosis is associated with a shear-thinning mucus that tends to aggregate in regions of lower clearance. However, a rarefaction of periciliary fluid has a greater impact than the mucus shear-thinning.

7.5. Miscellaneous

Participants: Damiano Lombardi, Irene Vignon Clementel.

In [27] an adaptive tensor method is developed to build a parsimonious discretization for the kinetic equations, starting from separated, arbitrary and a priori chosen discretizations for the space and the velocity variables. The method automatically adapts the rank of the decomposition in order to ensure that a criterion on the residual of the equations is satisfied, and the proof of the convergence is provided. The method is tested on the Vlasov-Poisson equation but can be extended to other kinetic equations and to systems in which the domain is the cartesian product of separated domains.

In [42] an a posteriori error estimator for hermitian positive eigenvalue problem is proposed. This estimator, which is based on a residual formulation, is constructed by shifting the operators in such a way that the error between the exact eigenvalues and the approximated ones can be estimated efficiently. It is conditionally certified and sharp.

Diffusion-weighted magnetic resonance imaging (DWI) is a key non-invasive imaging technique for cancer diagnosis and tumor treatment assessment; yet its relation to the underlying tissue structure is not clear. In [36], in order to link low-resolution but non-invasive DWI data with high resolution (invasive) histological information, we developed an image processing and analysis chain, which was used to study the correlation between the DWI diffusion coefficient and tumor cellularity from serial histological slides of a resected non-small cell lung cancer tumor.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Air Liquide Santé International

Participants: Céline Grandmont, Nicolas Pozin, Irene Vignon Clementel.

CIFRE convention and contract with Air Liquide Santé International (March 2014 - December 2017) in the context of the ANRT on “Multiscale lung ventilation modeling in health and disease”, for the PhD thesis of Nicolas Pozin.

8.1.2. Philips Research

Participants: Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Alexandre This.

CIFRE convention and contract with Philips Research for the PhD thesis of Alexandre This (January 2016 - December 2018) on fusion data/simulation for the assessment of mitral regurgitation.

8.1.3. Kephalios & Epygon

Participants: Gautier Bureau, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Ludovic Boilevin-Kayl, Marina Vidrascu.

REO is an academic partner of the industrial project MIVANA, dedicated to the development of new technologies for mitral valve treatment. It is led by the start-up company Kephalios, with the participation of the start-up company Epygon, by the company MDB Texinov and the research institute IFTH. In this framework, REO has two bilateral contracts with Kephalios and Epygon on the modeling and simulation of two medical devices for mitral valve repair.

8.1.4. Instem/NOTOCORD

Participants: Muriel Boulakia, Damiano Lombardi, Jean-Frédéric Gerbeau, Fabien Raphel, Eliott Tixier.

REO partners with the software company NOTOCORD. The collaboration started in 2013 the framework of the LabCom "cardioXcomp". In 2016, the ANR funding came to an end, and NOTOCORD was acquired by the company Instem. Our collaboration with Instem/NOTOCORD continues as a bilateral partnership with the purpose of developing the software cardioXcomp dedicated to the safety pharmacology industry. This project is also supported by a grant by AMIES (Agency for Interaction in Mathematics with Business and Society).

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. ANR Project "iFLOW"

Participants: Chloé Audebert, Jean-Frédéric Gerbeau, Florian Joly, Irene Vignon Clementel [co-Principal Investigator].

Period: 2013-2017.
This ANR-TecSan, co-managed by Eric Vibert (Paul Brousse Hospital) and Irene Vignon Clementel, aims at developing an Intraoperative Fluorescent Liver Optimization Workflow to better understand the relationship between architecture, perfusion and function in hepatectomy.

Other partners: DHU Hepatinov - Hôpital Paul Brousse, Inria Mamba, Fluoptics, IfADo, MID.

9.1.1.2. ANR Project "IFSMACS"

Participants: Muriel Boulakia, Céline Grandmont [local coordinator].

Period: 2015-2019.
The objective of this project, coordinated by Takéo Takahashi (Inria Nancy Grand-Est), is the mathematical analysis of systems involving structures immersed in a fluid. This includes the asymptotic analysis, the study of the controllability and stabilization of fluid-structure interaction systems, the understanding of the motion of self-propelled structures and the analysis and development of numerical methods to simulate fluid-structure systems.

9.1.1.3. Participation to other ANR projects

- Laurent Boudin is a member of the ANR Blanc project Kibord on kinetic models in biology and related domains
- Laurent Boudin is a member of the ANR TecSan Oxhelease
- Céline Grandmont is a member of the ANR TecSan Oxhelease
- Marina Vidrascu is a member of the ANR ARAMIS
- Irene Vignon Clementel is a member of the project iLite (09/16-), RHU-santé grant, a large French hospital-medical research consortium that aims at developing innovations for liver and tissue engineering (Inria PI: Dirk Drasdo).

9.1.2. Inria initiatives

9.1.2.1. ADT Project "PARASOL"

Participants: Miguel Ángel Fernández Varela [Principal Investigator], Axel Fourmont, Marina Vidrascu.

Period: 2016-2017
The aim of this project, coordinated by Miguel Ángel Fernández Varela, is to implement in the FELiScE library several balancing domain decomposition methods (BDD) for solid-mechanics.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

9.2.1.1. REVAMMAD

Title: "Retinal Vascular Modeling, Measurement and Diagnosis"

Programm: FP7

Duration: April 2013 - March 2017

Coordinator: University of Lincoln

Partners: : See the web site http://revammad.blogs.lincoln.ac.uk/partners/

Inria contact: J-F Gerbeau

REVAMMAD is a European Union project aimed at combatting some of the EU's most prevalent chronic medical conditions using retinal imaging. The project aims to train a new generation of interdisciplinary scientists for the academic, clinical and industrial sectors, and to trigger a new wave of biomedical interventions. The role of REO team within this consortium is to propose a mathematical model and a simulation tool for the retina hemodynamics. See http://revammad.blogs.lincoln.ac.uk for more details.

9.2.2. Collaborations in European Programs, Except FP7 & H2020

9.2.2.1. SimInhale COST

Participant: Irene Vignon Clementel.

Action MP1404, a pan-European network of experts in the field of inhaled medicine

9.3. International Research Visitors

9.3.1. Internships

- Gonzalo Castineira Veiga, Visiting PhD student, Universidade da Coruña, Apr 2017–Jun 2017

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

- Céline Grandmont
  - Co-organizer of Inria-LJLL meeting in scientific computing
  - Co-organizer of the conference in the honor of Y. Maday for his 60th birthday, may 2017, Roscoff
  - Co-organizer of the conference "Analysis and control of fluid-structure interaction systems", october 2017, IMB, Bordeaux University
- Irene Vignon Clementel
  - Organized a minisymposium at the ICCB conference, September 2017, Compiègne

  - Organized a minisymposium with A. Marsden (Stanford U.) at the 5th International Conference on Computational & Mathematical Biomedical Engineering, April 2017, Pittsburg, USA.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- Laurent Boudin
  - Coordinator of the 6th "Forum Emploi Maths 2017" organizing committee, with Bertrand Michel (École Centrale Nantes), December 2017, Paris, France

10.1.2.2. Member of the Conference Program Committees

- Jean-Frédéric Gerbeau
  - 5th International conference on Computational & Mathematical Biomedical Engineering (CMBE 2017), Pittsburgh, USA.
  - ENUMATH 2017 conference. Voss, Norway.
  - 9th International Conference on Functional Imaging and Modeling of the Heart (FIMH 2017). Toronto, Canada.
- Céline Grandmont
  - Member of the scientific committee of the "EDP Normandie 2017" conference
- Irene Vignon Clementel
  - Programme committee member, Computational and Mathematical Biomedical Engineering Conference, Pittsburgh 2017
  - Conference steering committee, International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease, 2015-present

10.1.2.3. Reviewer

- Jean-Frédéric Gerbeau
  - Member of the Scientific Program Committee of the Millennium Science Initiative, a program of the Ministry of Economy of Chile.
- Irene Vignon Clementel
  - Reviewer for the Netherlands Organisation for Scientific Research (NWO)

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Jean-Frédéric Gerbeau
  - Member of the editorial board of the SIAM Journal of Scientific Computing (SISC).
  - Series editor of "SEMA SIMAI Series", Springer.
  - Member of the editorial board of Journal Advances in Computational Mathematics (ACOM), Springer
  - Member of the editorial board of International Journal for Numerical Methods in Biomedical Engineering (IJNMBE), Wiley.
  - Member of the editorial board of Communications in Applied and Industrial Mathematics, SIMAI/De Gruyter.
  - Member of the editorial board of Journal for Modeling in Ophthalmology, Kugler.
- Marc Thiriet
  - Member of the editorial board of Digital Medicine

10.1.4. Leadership within the Scientific Community

- Jean-Frédéric Gerbeau
  - Elected member of the Board of Directors of SMAI (French Society for Industrial and Applied Mathematics), in charge of the SMAI publications (M2AN, COCV, *etc.*)

10.1.5. Research Administration

- Muriel Boulakia
  - Supervisor of the teaching of mathematics at the engineer school Polytech Paris-UPMC
- Miguel Ángel Fernández Varela
  - Deputy Head of Science, Inria Paris (from Sept. 2017)
  - Member of the Inria Evaluation Committee (from Sept. 2017)
  - Co-president of the Scientific Positions Commission, Inria Paris
- Jean-Frédéric Gerbeau
  - Head of science, Inria Paris (until Sept. 2017)
  - Member of the Inria Evaluation Committee (until Sept. 2017)
  - Member of the scientific committee of Labex NUMEV, Montpellier.
  - Service activity abroad: member of the Reference Committee of the PhD program Mathematical Models and Methods in Engineering (Politecnico di Milano, Italy).
- Céline Grandmont
  - Member of the Inria Evaluation Committee
  - Member of the Inria Parity Committee
- Irene Vignon-Clementel
  - Committee member for PhD students at Inria "Commission consultative des doctorants", since July 2016.
  - Mediator between PhD students and their supervisors for Inria Paris

10.1.6. Conferences

- Matteo Aletti
  - Minisymposium talk, International conference on Finite elements in flow problems (FEF), Rome (Italy), 2017
- Chloé Audebert
  - Invited speaker, GDR Mamovi, Sep 27-29, Lyon, France.
  - Minisymposium talk, International Conference on Computational Bioengineering, Sep 6-8, Compiègne, France.
  - Talk, Colloquium 595 Biomechanics and computer assisted surgery meets medical reality, Aug 29-31, Lille, France.
  - Weekend de l'innovation chirurgicale (WIC), Jun 23-25, Cabourg, France.
  - Talk, Congrès SMAI 2017, 8e Biennale Française des Mathématiques Appliquées et Industrielles, Jun 5-9, Ronce-les-bains, France.
  - Minisymposium talk, Computational and mathematical Biomedical Engineering (CMBE) , Apr 10-12, Pittsburgh, USA.
  - Seminar, bioMMeda group, Mar 8th, Ghent University, Ghent, Belgium.
  - Seminar, Laboratoire de mathématique MAP5, Mar 3rd, Université Paris Descartes, Paris, France.
- Ludovic Boilevin-Kayl

  - Minisymposium talk, 5th International Conference on Computational and Mathematical Biomedical Engineering (CMBE), April 10th-12th, Pittsburgh, PA, United States.
- Laurent Boudin
  - Contributed talk, Workshop "Franco-Italian meeting on kinetic theory and singular parabolic equations", Mar 16-17, Paris, France
  - Invited talk, "Aerosolstorming" meeting of the "Société de Pneumologie en Langue Française", May 2017, Paris, France
  - Invited talk, Summer School on Computational Social and Behavioral Sciences, Sep 2017, Paris, France
  - Seminar, ENS Paris-Saclay Starters scientific talks in mathematics and computer science, Sep 2017, Cachan, France
  - Invited talk, Workshop "Modelling, simulation and study of social behaviour", Oct 2017, Nancy, France
  - Invited talk, Conference on Partial differential equations and semi-groups, Dec 2017, Besançon, France
- Muriel Boulakia
  - Seminar Analysis, Ceremade, Univ. Paris Dauphine, December 2017
  - Seminar, Univ. Paris Descartes, November 2017
  - Seminar PDE, Univ. Versailles, May 2017
- Miguel Ángel Fernández Varela
  - Invited semi-plenary lecture, International conference on Finite elements in flow problems (FEF), Rome (Italy), 2017
- Jean-Frédéric Gerbeau
  - Invited lectures (6 hours), Maxwell Institute Graduate School on Evolution Equations, ICMS, Edinburgh, UK, 2017
  - Invited lecture, Conference "Quiet 2017", Quantification of Uncertainty: Improving Efficiency and Technology, SISSA, Trieste, Italy, July 2017
  - Invited lecture, Workshop "In Silico Human drug safety and efficacy", Oxford, UK, September 2017
  - Invited lecture, Workshop GDR Mamovi.
  - Seminar, Weierstrass Institute for Applied Analysis and Stochastics (WIAS), Berlin, Germany, November 2017
  - Minisymposium talk, ICCB conference, Compiègne, France, September 2017
- Céline Grandmont
  - ULB Maths Colloquium, Bruxelles, april 2017
  - Colloquium Univ. Lille, december 2017
- Florian Joly
  - Weekend de l'innovation chirurgicale (WIC), Jun 23-25, Cabourg, France.
  - Talk, GRIC Journées Françaises de Radiologie, Oct 12th, Paris, France.
- Damiano Lombardi
  - CMBE 2017, Pittsburgh (US), invited to the minisymposium on *Adaptation, growth and remodelling*
  - CMBE 2017, Pittsburgh (US), organiser of the minisymposium on *Reliable predictions in biomedical applications*
- Dena Kazerani

  - Talk, Groupe de travail de biologie, Tours-Orléans, October 2017, Orléans, France.
  - Poster, Congrès SMAI 2017, 8e Biennale Française des Mathématiques Appliquées et Industrielles, June 2017, Ronce-les-bains, France.
  - Talk, Ecole EGRIN: Ecoulements Gravitaires et Risques Naturels, June 2017, Cargèse, France.
  - Talk, Séminaire du Laboratoire Hydraulique Saint-Venant, January 2017, Chatou, France
  - Poster, vingt-neuème séminaire sur "la mécanique des fluides numériques" organised by GAMNI-CEA, Institut Herni Poincaré (IHP), January 2017, Paris, France.
- Alexandre This
  - Poster, 9th international conference on Functional Imaging and Modeling of the Heart, FIMH, Toronto, June 2017
- Eliott Tixier
  - Invited talk, Workshop on Mathematical Methods in Cardiac Electrophysiology, Nov 4-6, Ottawa, Canada
  - Invited talk, GdR Mamovi meeting, Sep 27-29, Lyon, France
  - Poster presentation, QUIET 2017 Workshop, Jul 18-21, Trieste, Italy
- Marina Vidrascu
  - Invited talk ,The Sixth International Conference on Scientific Computing and Partial Differential Equations, Hong Kong Baptist University, June 5-8, 2017
- Irene Vignon Clementel
  - Seminar, Universittsklinikum Aachen, Dec 4th 2017, Aachen, Germany
  - Seminar, LiSyM consortium, Nov. 28th 2017, Paris, France
  - Seminar, U. de Caen, Dpt of Mathematics, Nov. 13th 2017, Caen, France
  - Invited, SimInhale workshop, Oct. 4-5th 2017, Athens, Greece
  - Seminar, Ecole Polytechnique, Oct 16th 2017, Palaiseau, France
  - Seminar, Marie-Lannelongue Hospital, Sept 18th 2017, Plessis-Robinson, France
  - Keynote (invited), Colloquium 595 Biomechanics and computer assisted surgery meets medical reality, Aug 29-31, Lille, France.
  - Invited talk, Weekend de l'innovation chirurgicale (WIC), Jun 23-25, Cabourg, France.
  - Minisymposium talk, Computational and mathematical Biomedical Engineering (CMBE), Apr 10-12, Pittsburgh, USA.
  - Seminar, Eindhoven U., Dpt of Bioengineering, March 24th 2017, Eindhoven, The Netherlands
  - Seminar, Organox - Paul Brousse Hospital, Jan 24th 2017, Villejuif, France

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence:

- Ludovic Boilevin-Kayl
  - Calculus, 80h, L1, UPMC
  - Matrix computations, 18h, L1, UPMC
- Laurent Boudin
  - Introduction to series for signal theory, 18h, L2, UPMC

  - Shared studies supervision in mathematics licence for approximately 500 students, 24h, L2, UPMC (until Aug 31, 2017)
  - Calculus, 38.5h, L1, UPMC
  - Student advising for orientation and professional insertion, 22h, L2, UPMC
  - Numerical methods for ODE, 26.5h, L3, UPMC
- Muriel Boulakia
  - Scilab, 35h, L2, UPMC
  - Nonlinear systems and optimization, 35h, L3, Polytech'Paris
  - Oral tests in in topology and differential calculus, 20h, L3
- Miguel Ángel Fernández Varela
  - Analysis and Scientific Computing, 30h, L3, ENPC
- Jean-Frédéric Gerbeau
  - Control of dynamical systems, 32h, L3, Ecole Polytechnique.
- Céline Grandmont
  - Ordinary differential equations, 24h, L3, UPMC
- Damiano Lombardi
  - Analysis and Scientific Computing, 32h, L3, ENPC
  - Numerical Methods, 48h, L3, Polytech'Paris
- Marc Thiriet
  - Modeling and Simulation for Computer-Aided Medicine and Surgery, 16h, L3-M2, National Taiwan University
- Irene Vignon Clementel
  - Numerical Methods for Ordinary Differential Equations, 24h ETD, L3, UPMC
  - Numerical simulations of blood flow, 1h30, as part of the undergraduate "continuum mechanics", AgroParisTech

Master:

- Laurent Boudin
  - Basics for numerical methods, 27h, M1, UPMC
  - Student advising for orientation and professional insertion, 20h, M1, UPMC
- Muriel Boulakia
  - Preparatory course for teaching admission examination "Agrégation", 25h, M2, UPMC
- Miguel Ángel Fernández Varela
  - Modeling and numerical methods for hemodynamics, 30h, M2, UPMC
- Jean-Frédéric Gerbeau
  - Seminar for M2 students of the master "Math SV" (1h), M2, Univ Paris-Sud, December
  - Seminar for M2 students at Ecole des Mines (3h), Paris, February
- Irene Vignon Clementel
  - Modélisation hémodynamique & simulation numérique comme outil pour la chirurgie, 1h, M2, Université Paris Sud

10.2.2. Supervision

PhD: Chloé Audebert, Modeling of liver hemodynamics, defended on February 24, 2017. Supervisors: J.-F. Gerbeau & I. Vignon Clementel.

PhD: Matteo Aletti, Multiscale retinal vascular modeling, defended on May 30, 2017. Supervisors: J.-F. Gerbeau & D. Lombardi.

PhD: Eliott Tixier, Variability modeling and numerical biomarkers design in cardiac electrophysiology, defended on December 18, 2017. Supervisors: J-F. Gerbeau & D. Lombardi.

PhD: Nicolas Pozin, Multiscale lung ventilation modeling in health and disease, defended on October 6, 2017. Supervisors: C. Grandmont & I. Vignon Clementel.

PhD in progress: Andrea Bondesan, Kinetic and fluid models, numerical and asymptotic analysis, since October 2015. Supervisors: L. Boudin, B. Grec & S. Martin.

PhD in progress: Ludovic Boilevin-Kayl, Modeling of cardiac implantable devices, since February 2016. Supervisors: J.-F. Gerbeau & M.A. Fernández Varela

PhD in progress: Alexandre This, Fusion data/simulation for the assessment of mitral regurgitation, since January 2016. Supervisor: J.-F. Gerbeau

PhD in progress: Chen-Yu Chiang, Transport on biological systems and some applications, since February 2016. Supervisor: M. Thiriet

PhD in progress: Felipe Galarce, Enhancing hemodynamics measurements with mathematical modeling, since December 2017. Supervisors: J.-F. Gerbeau & D. Lombardi.

10.2.3. Juries

- Muriel Boulakia
  - PhD committee: Charlie Douanla Lontsi, Inria Bordeaux Sud-Ouest
- Jean-Frédéric Gerbeau
  - PhD committees: Ivan Fumagalli, Politecnico di Milano (referee); Rajnesh Lal, Univ Montpellier (referee).
  - HDR committees: Edmond Vigmond, Univ Bordeaux; Sébastien Boyaval, Univ Paris-Est.
  - Hiring committee: Inria Paris (CR2).
- Céline Grandmont
  - Member of the "agrégation" jury in mathematics.
  - Hiring committees: Inria Nancy (CR2), Inria DR2, Professor position Paris-Sud University.
  - PHD committee: M. Deville, Bordeaux University (Referee), Nicolas Pozin, UPMC (co-advisor).
- Marina Vidrascu
  - Hiring committee: IR CNRS
- Irene Vignon Clementel
  - Hiring committees: Starting Research Positions and Senior Research Positions at Inria
  - PhD comittee: Roch Mollero, University of Nice-Sophia Antipolis (Referee), Nicolas Pozin, UPMC, (co-advisor), Arthur Ghigo, UPMC, Chloé Audebert, UPMC, (co-advisor), Andie de Villiers, U. of Cape Town, (Referee), Petru Bucur, Inserm.

10.3. Popularization

- Céline Grandmont
  - Conference "Métier": Master Maths students, UPMC, Oct 2017
- Irene Vignon Clementel

– Presentation to celebrate the renewal of UPMC-Inria Paris partnership, June 22nd 2017, Paris, France

11. Bibliography

Major publications by the team in recent years

[1] L. BOUDIN, L. DESVILLETTES, C. GRANDMONT, A. MOUSSA. *Global existence of solutions for the coupled Vlasov and Navier-Stokes equations*, in "Differential and integral equations", November 2009, vol. 22, n^{o} 11-12, pp. 1247-1271, https://hal.archives-ouvertes.fr/hal-00331895

[2] L. BOUDIN, B. GREC, F. SALVARANI. *A mathematical and numerical analysis of the Maxwell-Stefan diffusion equations*, in "Discrete and Continuous Dynamical Systems - Series B", 2012, vol. 17, n^{o} 5, pp. 1427-1440 [*DOI :* 10.3934/DCDSB.2012.17.1427], https://hal.archives-ouvertes.fr/hal-00490511

[3] M. BOULAKIA, S. CAZEAU, M. A. FERNÁNDEZ, J.-F. GERBEAU, N. ZEMZEMI. *Mathematical Modeling of Electrocardiograms: A Numerical Study*, in "Annals of Biomedical Engineering", 2010, vol. 38, n^{o} 3, pp. 1071-1097 [*DOI :* 10.1007/S10439-009-9873-0], https://hal.inria.fr/inria-00400490

[4] M. BOULAKIA, S. GUERRERO. *Regular solutions of a problem coupling a compressible fluid and an elastic structure*, in "Journal de Mathématiques Pures et Appliquées", 2010, vol. 94, n^{o} 4, pp. 341-365 [*DOI :* 10.1016/J.MATPUR.2010.04.002], https://hal.inria.fr/hal-00648710

[5] J. CHRISTOPHE, T. ISHIKAWA, N. MATSUKI, Y. IMAI, K. TAKASE, M. THIRIET, T. YAMAGUCHI. *Patient-specific morphological and blood flow analysis of pulmonary artery in the case of severe deformations of the lung due to pneumothorax*, in "Journal of Biomechanical Science and Engineering", 2010, vol. 5, n^{o} 5, pp. 485-498, https://hal.inria.fr/inria-00543090

[6] M. A. FERNÁNDEZ, J. MULLAERT, M. VIDRASCU. *Explicit Robin-Neumann schemes for the coupling of incompressible fluids with thin-walled structures*, in "Computer Methods in Applied Mechanics and Engineering", 2013, vol. 267, pp. 566-593 [*DOI :* 10.1016/J.CMA.2013.09.020], https://hal.inria.fr/hal-00784903

[7] J.-F. GERBEAU, D. LOMBARDI. *Approximated Lax Pairs for the Reduced Order Integration of Nonlinear Evolution Equations*, in "Journal of Computational Physics", May 2014, vol. 265, pp. 246-269 [*DOI :* 10.1016/J.JCP.2014.01.047], https://hal.inria.fr/hal-00933172

[8] C. GRANDMONT, M. HILLAIRET. *Existence of global strong solutions to a beam-fluid interaction system*, in "Archive for Rational Mechanics and Analysis", 2016 [*DOI :* 10.1007/S00205-015-0954-Y], https://hal.inria.fr/hal-01138736

[9] P. MOIREAU, C. BERTOGLIO, N. XIAO, C. A. FIGUEROA, C. TAYLOR, D. CHAPELLE, J.-F. GERBEAU. *Sequential identification of boundary support parameters in a fluid-structure vascular model using patient image data*, in "Biomechanics and Modeling in Mechanobiology", July 2012, vol. 12, n^{o} 3, pp. 475-496 [*DOI :* 10.1007/S10237-012-0418-3], https://hal.inria.fr/hal-00760703

[10] S. PANT, B. FABRÈGES, J.-F. GERBEAU, I. VIGNON-CLEMENTEL. *A methodological paradigm for patient-specific multi-scale CFD simulations: from clinical measurements to parameter estimates for individual analysis*, in "International Journal for Numerical Methods in Biomedical Engineering", December 2014, vol. 30, n° 12, pp. 1614–1648 [*DOI :* 10.1002/CNM.2692], https://hal.inria.fr/hal-01093879

[11] I. VIGNON-CLEMENTEL, A. MARSDEN, J. FEINSTEIN. *A Primer on Computational Simulation in Congenital Heart Disease for the Clinician*, in "Progress in Pediatric Cardiology", 2010, vol. 30, n° 1-2, pp. 3-13, Fondation Leducq [*DOI :* 10.1016/J.PPEDCARD.2010.09.002], https://hal.inria.fr/inria-00542957

Publications of the year

Doctoral Dissertations and Habilitation Theses

[12] M. C. M. ALETTI. *Mathematical Modelling and Simulations of the Hemodynamics in the eye*, Université Pierre et Marie Curie (UPMC Paris 6), May 2017, https://tel.archives-ouvertes.fr/tel-01538557

[13] C. AUDEBERT. *Mathematical liver modeling: hemodynamics and function in hepatectomy*, Université Pierre & Marie Curie - Paris 6, February 2017, https://tel.archives-ouvertes.fr/tel-01512620

Articles in International Peer-Reviewed Journals

[14] E. ABBATE, M. BOULAKIA, Y. COUDIÈRE, J.-F. GERBEAU, P. ZITOUN, N. ZEMZEMI. *In silico assessment of the effects of various compounds in MEA/hiPSC-CM assays: Modelling and numerical simulations*, in "Journal of Pharmacological and Toxicological Methods", July 2017, forthcoming, https://hal.inria.fr/hal-01562673

[15] M. ALETTI, D. LOMBARDI. *A Reduced Order representation of the Poincaré-Steklov operator: an application to coupled multi-physics problems*, in "International Journal for Numerical Methods in Engineering", 2017, https://hal-auf.archives-ouvertes.fr/hal-01396286

[16] C. AUDEBERT, P. BUCUR, M. BEKHEIT, E. VIBERT, I. VIGNON-CLEMENTEL, J.-F. GERBEAU. *Kinetic scheme for arterial and venous blood flow, and application to partial hepatectomy modeling*, in "Computer Methods in Applied Mechanics and Engineering", February 2017, vol. 314, pp. 102-125 [*DOI :* 10.1016/J.CMA.2016.07.009], https://hal.archives-ouvertes.fr/hal-01347500

[17] C. BERTOGLIO, A. CAIAZZO, Y. BAZILEVS, M. BRAACK, M. ESMAILY, V. GRAVEMEIER, A. MARSDEN, O. PIRONNEAU, I. VIGNON-CLEMENTEL, W. A. WALL. *Benchmark problems for numerical treatment of backflow at open boundaries*, in "International Journal for Numerical Methods in Biomedical Engineering", 2017 [*DOI :* 10.1002/CNM.2918], https://hal.inria.fr/hal-01569770

[18] F. BONALDI, G. GEYMONAT, F. KRASUCKI, M. VIDRASCU. *Mathematical and numerical modeling of plate dynamics with rotational inertia*, in "Journal of Numerical Mathematics", 2017, pp. 1 - 20 [*DOI :* 10.1515/JNMA-2016-1020], https://hal.inria.fr/hal-01413037

[19] L. BOUDIN, C. GRANDMONT, A. MOUSSA. *Global existence of solutions to the incompressible Navier-Stokes-Vlasov equations in a time-dependent domain*, in "Journal of Differential Equations", February 2017 [*DOI :* 10.1016/J.JDE.2016.10.012], https://hal.inria.fr/hal-01312262

[20] L. BOUDIN, B. GREC, V. PAVAN. *The Maxwell-Stefan diffusion limit for a kinetic model of mixtures with general cross sections*, in "Nonlinear Analysis: Theory, Methods and Applications", February 2017, vol. 159, pp. 40-61 [*DOI :* 10.1016/J.NA.2017.01.010], https://hal.inria.fr/hal-01303312

[21] M. BOULAKIA, S. GUERRERO. *On the interaction problem between a compressible fluid and a Saint-Venant Kirchhoff elastic structure*, in "Advances in Differential Equations", January 2017, vol. 22, n° 1-2, https://hal.inria.fr/hal-01229577

[22] M. BOULAKIA, E. SCHENONE. *Stability estimates for some parameters of a reaction-diffusion equation coupled with an ODE*, in "Applicable Analysis", 2017, vol. 96, n° 7, https://hal.inria.fr/hal-01227427

[23] P. O. BUCUR, M. BEKHEIT, C. AUDEBERT, A. OTHMAN, S. HAMMAD, M. SEBAGH, M. A. ALLARD, B. DECANTE, A. FRIEBEL, D. DRASDO, E. MIQUELESTORENA-STANDLEY, J. G. HENGSTLER, I. VIGNON-CLEMENTEL, E. VIBERT. *Modulating Portal Hemodynamics With Vascular Ring Allows Efficient Regeneration After Partial Hepatectomy in a Porcine Model*, in "Annals of Surgery", February 2017 [*DOI :* 10.1097/SLA.0000000000002146], https://hal.archives-ouvertes.fr/hal-01494844

[24] P. BUCUR, M. BEKHEIT, C. AUDEBERT, I. E. VIGNON-CLEMENTEL, E. VIBERT. *Simplified technique for 75% and 90% hepatic resection with hemodynamic monitoring in large white swine model*, in "Journal of Surgical Research", March 2017, vol. 209, pp. 122-130 [*DOI :* 10.1016/J.JSS.2016.09.018], https://hal.archives-ouvertes.fr/hal-01405171

[25] E. BURMAN, A. ERN, M. A. FERNÁNDEZ. *Fractional-step methods and finite elements with symmetric stabilization for the transient Oseen problem*, in "ESAIM: Mathematical Modelling and Numerical Analysis", March 2017, vol. 51, n° 2, pp. 487-507 [*DOI :* 10.1051/M2AN/2016028], https://hal.inria.fr/hal-01218328

[26] C.-Y. CHIANG, O. PIRONNEAU, T. W. H. SHEU, M. THIRIET. *Numerical Study of a 3D Eulerian Monolithic Formulation for Incompressible Fluid-Structures Systems*, in "Fluids", June 2017, vol. 2, n° 2, pp. 34-53 [*DOI :* 10.3390/FLUIDS2020034], http://hal.upmc.fr/hal-01558747

[27] V. EHRLACHER, D. LOMBARDI. *A dynamical adaptive tensor method for the Vlasov-Poisson system*, in "Journal of Computational Physics", 2017, vol. 319, pp. 285-306, https://hal.archives-ouvertes.fr/hal-01335507

[28] M. LANDAJUELA, M. VIDRASCU, D. CHAPELLE, M. A. FERNÁNDEZ. *Coupling schemes for the FSI forward prediction challenge: comparative study and validation*, in "International Journal for Numerical Methods in Biomedical Engineering", 2017, vol. 33, n° 4, e02813 p. [*DOI :* 10.1002/CNM.2813], https://hal.inria.fr/hal-01239931

[29] S. PANT, C. CORSINI, C. BAKER, T.-Y. HSIA, G. PENNATI, I. VIGNON-CLEMENTEL. *Inverse problems in reduced order models of cardiovascular haemodynamics: aspects of data-assimilation and heart-rate variability*, in "Journal of the Royal Society Interface", 2017, https://hal.inria.fr/hal-01413446

[30] N. POZIN, S. MONTESANTOS, I. KATZ, M. PICHELIN, C. GRANDMONT, I. VIGNON-CLEMENTEL. *Calculated Ventilation and Effort Distribution as a Measure Of Respiratory Disease and Heliox Effectiveness*, in "Journal of Biomechanics", June 2017, n° 60C, pp. 100-109 [*DOI :* 10.1016/J.JBIOMECH.2017.06.009], https://hal.archives-ouvertes.fr/hal-01468861

[31] N. POZIN, S. MONTESANTOS, I. KATZ, M. PICHELIN, I. E. VIGNON-CLEMENTEL, C. GRANDMONT. *A tree-parenchyma coupled model for lung ventilation simulation*, in "International Journal for Numerical Methods in Biomedical Engineering", February 2017 [*DOI :* 10.1002/CNM.2873], https://hal.archives-ouvertes.fr/hal-01407055

[32] F. RAPHEL, M. BOULAKIA, N. ZEMZEMI, Y. COUDIÈRE, J.-M. GUILLON, P. ZITOUN, J.-F. GERBEAU. *Identification of ion currents components generating field potential recorded in MEA from hiPSC-CM*, in "IEEE Transactions on Biomedical Engineering", 2017, In press [*DOI :* 10.1109/TBME.2017.2748798], https://hal.archives-ouvertes.fr/hal-01570341

[33] E. TIXIER, D. LOMBARDI, B. RODRIGUEZ, J.-F. GERBEAU. *Modeling Variability in Cardiac Electrophysiology: A Moment Matching Approach*, in "Journal of the Royal Society Interface", August 2017, vol. 14, n° 133 [*DOI :* 10.1098/RSIF.2017.0238], https://hal.archives-ouvertes.fr/hal-01570828

[34] E. TIXIER, F. RAPHEL, D. LOMBARDI, J.-F. GERBEAU. *Composite biomarkers derived from Micro-Electrode Array measurements and computer simulations improve the classification of drug-induced channel block*, in "Frontiers in Physiology", 2018, vol. 8, n° 1096, pp. 1-30 [*DOI :* 10.3389/FPHYS.2017.01096], https://hal.archives-ouvertes.fr/hal-01570819

[35] W. YANG, F. L. HANLEY, F. P. CHAN, A. L. MARSDEN, I. E. VIGNON-CLEMENTEL, J. A. FEINSTEIN. *Computational simulation of postoperative pulmonary flow distribution in Alagille patients with peripheral pulmonary artery stenosis*, in "Congenital Heart Disease", 2017 [*DOI :* 10.1111/CHD.12556], https://hal.inria.fr/hal-01657634

[36] Y. YIN, O. SEDLACZEK, B. MÜLLER, A. WARTH, M. GONZÁLEZ-VALLINAS, B. LAHRMANN, N. GRABE, H.-U. KAUCZOR, K. BREUHAHN, I. VIGNON-CLEMENTEL, D. DRASDO. *Tumor cell load and heterogeneity estimation from diffusion-weighted MRI calibrated with histological data: an example from lung cancer*, in "IEEE Transactions on Medical Imaging", 2017 [*DOI :* 10.1109/TMI.2017.2698525], https://hal.inria.fr/hal-01421398

International Conferences with Proceedings

[37] E. LLUCH, R. DOSTE, S. GIFFARD-ROISIN, A. THIS, M. SERMESANT, O. CAMARA, M. DE CRAENE, H. G. MORALES. *Smoothed Particle Hydrodynamics for Electrophysiological Modeling: An Alternative to Finite Element Methods*, in "Functional imaging and modelling of the heart 2017", Toronto, Canada, Functional imaging and modelling of the heart 2017 Proceedings, Springer International Publishing, June 2017, vol. 141, pp. 333-343 [*DOI :* 10.1007/978-3-319-59448-4_32], https://hal.inria.fr/hal-01533371

[38] A. A. THIS, L. BOILEVIN-KAYL, H. G. MORALES, O. BONNEFOUS, P. A. ALLAIN, M. A. FERNÁNDEZ, J.-F. GERBEAU. *One Mesh To Rule Them All: Registration-Based Personalized Cardiac Flow Simulations*, in "FIMH 2017 - 9th international conference on Functional Imaging and Modeling of the Heart", Toronto, Canada, LNCS - Lecture Notes in Computer Science, Springer, June 2017, vol. 10263, https://hal.inria.fr/hal-01512309

Conferences without Proceedings

[39] L. BOILEVIN-KAYL, A. THIS, M. A. FERNÁNDEZ, J.-F. GERBEAU. *An efficient valve model based on resistive immersed surfaces enhanced with physiological data*, in "5th International Conference on Computational & Mathematical Biomedical Engineering", Pittsburgh, United States, Etienne Boileau and David Nordsletten, April 2017, https://hal.inria.fr/hal-01519602

Scientific Books (or Scientific Book chapters)

[40] D. ANNE-ARCHARD, R. CHATELIN, M. MURRIS-ESPIN, D. SANCHEZ, M. THIRIET, A. DIDIER, P. PONCET. *Modeling Cystic Fibrosis and Mucociliary Clearance*, in "Modeling of microscale transport in biological processes", S. M. BECKER (editor), Academic Press, 2017, pp. 113-154 [*DOI :* 10.1016/B978-0-12-804595-4.00005-5], https://hal.inria.fr/hal-01476216

Research Reports

[41] A. NICOLOPOULOS, N. RIANE, A. SAINT-DIZIER, L. TRUSSARDI. *Analyse d'images de pales d'éoliennes. Semaine d'étude maths-entreprises, Paris, 11-15 septembre 2017*, AMIES, November 2017, pp. 1-18, https://hal.archives-ouvertes.fr/hal-01651796

Other Publications

[42] A. BAKHTA, D. LOMBARDI. *An a posteriori error estimator based on shifts for positive hermitian eigenvalue problems*, September 2017, working paper or preprint, https://hal.inria.fr/hal-01584180

[43] C. GRANDMONT, M. HILLAIRET, J. LEQUEURRE. *Existence of local strong solutions to fluid-beam and fluid-rod interaction systems* , July 2017, working paper or preprint, https://hal.inria.fr/hal-01567661

[44] N. POZIN, S. MONTESANTOS, I. KATZ, M. PICHELIN, I. VIGNON-CLEMENTEL, C. GRANDMONT. *From dynamical lung ventilation data to plugs distribution in asthma – A numerical diagnosis tool*, July 2017, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01568065

References in notes

[45] A. AMSDEN, P. O'ROURKE, T. BUTLER. *A computer program for chemically reactive flows with sprays*, Los Alamos National Laboratory, 1989, n^{o} LA-11560-MS

[46] M. A. BIOT. *Theory of propagation of elastic waves in a fluid-saturated porous solid. II higher frequency range*, in "J. Acoust. Soc. Am.", 1956, vol. 28, pp. 179–191

[47] D. CHAPELLE, J. SAINTE-MARIE, J.-F. GERBEAU, I. VIGNON-CLEMENTEL. *A poroelastic model valid in large strains with applications to perfusion in cardiac modeling*, in "Computational Mechanics", 2010, vol. 46, n^{o} 1, pp. 91-101 [*DOI :* 10.1007/s00466-009-0452-x]

[48] R. CHATELIN, D. ANNE-ARCHARD, M. MURRIS-ESPIN, M. THIRIET, P. PONCET. *Numerical and experimental investigation of mucociliary clearance breakdown in cystic fibrosis*, in "Journal of Biomechanics", 2017, 8 p. [*DOI :* 10.1016/j.jbiomech.2016.12.026], https://hal.inria.fr/hal-01476172

[49] J. DUPAYS, Y. FABIGNON, P. VILLEDIEU, G. LAVERGNE, G. ESTIVALEZES. *Some aspects of two phase flows in solid propellant rocket motors, in Solid propellant chemistry, combustion and interior ballistics*, in "Progress in Astronautics and Aeronautics", V. YANG, T. BRILL, W. PEN (editors), Academic Press, 2000, vol. 185

[50] G. LINES, P. GROTTUM, A. TVEITO. *Modeling the electrical activity of the heart. A bidomain model of the ventricles embedded in a torso*, in "Comput. Visual. Sci.", 2003, vol. 5, pp. 195-213

[51] O. MIRAUCOURT, S. SALMON, M. SZOPOS, M. THIRIET. *Blood flow in the cerebral venous system: modeling and simulation*, in "Computer Methods in Biomechanics and Biomedical Engineering", 2016 [*DOI :* 10.1080/10255842.2016.1247833], http://hal.upmc.fr/hal-01384285

[52] R. MOTTE. *A numerical method for solving particle-fluid equations*, in "Trends in numerical and physical modeling for industrial multiphase flows", Cargèse, France, 2000

[53] A. QUARTERONI, S. RAGNI, A. VENEZIANI. *Coupling between lumped and distributed models for blood flow problems*, in "Comput. Visual Sci.", 2001, vol. 4, pp. 111–124

[54] F. SACHSE. *Computational Cardiology: Modeling of Anatomy, Electrophysiology, and Mechanics*, Springer-Verlag, 2004

[55] J. SUNDNES, G. LINES, X. CAI, B. NIELSEN, K.-A. MARDAL, A. TVEITO. *Computing the electrical activity in the heart*, Springer-Verlag, 2006

[56] K. TERZAGHI. *Theoretical Soil Mechanics*, John Wiley and Sons, New-York, 1943

[57] F. WILLIAMS. *Combustion theory*, 2nd, Benjamin Cummings, 1985