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Université Pierre et Marie Curie (Paris 6)

Activity Report 2016

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

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Project-Team REO

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- 6.1.1. - Continuous Modeling (PDE, ODE)
- 6.1.4. - Multiscale modeling
- 6.1.5. - Multiphysics modeling
- 6.2.1. - Numerical analysis of PDE and ODE
- 6.3.1. - Inverse problems
- 6.3.2. - Data assimilation
- 6.3.4. - Model reduction

Other Research Topics and Application Domains:

- 2.2.1. - Cardiovascular and respiratory diseases
- 2.2.3. - Cancer
- 2.4.1. - Pharmaco kinetics and dynamics

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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 (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 [64] in the frame of combustion. It was later used to develop the Kiva code [54] at the Los Alamos National Laboratory, or the Hesione code [59], for example. It has a wide range of applications, besides the nuclear setting: diesel engines, rocket engines [57], 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 [60]. 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 [63], and Biot [55] 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 [56]), 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.* [58], [62], [61] 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/M3DISIM 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

An important industrial partnership has been signed with the start-up companies Kephalios and Epygon, for the mathematical modeling of implantable cardiac devices.

6. New Software and Platforms

6.1. cardioXcomp

KEYWORDS: Cardiac Electrophysiology - Safety Pharmacology
FUNCTIONAL DESCRIPTION

cardioXcomp is a software dedicated to the safety pharmacology industry. It is developed in the framework of the joint laboratory (LabCom) "cardioXcomp" with the software company Notocord. Its purpose is to model the electrical potential of cardiomyocytes measured by a microelectrode array (MEA), and to model the effect of drugs on this signal. It was registered in November 2015 at the Agence pour la Protection des Programmes under the Inter Deposit Digital Number IDDNFR.001.480003.000.S.P.2015.000.31230.

- Participants: Jean-Frédéric Gerbeau, Fabien Raphel, Nejib Zemzemi
- Contact: Jean-Frédéric Gerbeau

6.2. FELiScE

Finite Elements for Life SCiences and Engineering problems
KEYWORDS: Finite element modeling - 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: Dominique Chapelle, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Philippe Moireau, Marina Vidrascu, Sebastien Gilles, Benoit Fabreges, Axel Fourmont, Mikel Landajuela Larma, Damiano Lombardi, Matteo Aletti, Irene Vignon-Clementel and Faisal Amlani
- Contact: Jean-Frédéric Gerbeau
- URL: http://felisce.gforge.inria.fr

6.3. MODULEF

FUNCTIONAL DESCRIPTION

MODULEF is a legacy finite element library developed at Inria since the 1980's. Here, we limit ourselves to recent developments done within this library.

A numerical method to approximate the constitutive laws for rubber elasticity derived from polymer physics are implemented in 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: Marina Vidrascu and Antoine Gloria
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- URL: https://www.rocq.inria.fr/modulef/

6.4. 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, Patrick Le Tallec and Marina Vidrascu
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- URL: https://gforge.inria.fr/projects/shelddon/

7. New Results

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

Participants: Matteo Aletti, Faisal Amlani, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Mikel Landajuela Larma, Damiano Lombardi, Marina Vidrascu.

In [15] a simplified fluid-structure interaction method is proposed in order to deal with the simulation of fluids in elastic pipes. The motivation of this work is the modeling of the blood flow in arterioles. The structure is modeled by a non-linear Koiter shell, without bending. In addition, the presence of active elastic fibers is considered. The structure is lumped into the boundary condition of the fluid problem leading to a generalized Robin boundary condition. A finite elements discretization is proposed and several numerical test cases are presented to assess the properties of the method.

In [45] a reduced order modeling method is investigated to deal with 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. An online update is also introduced in order to guarantee stability and robustness. Several 3D fluid-fluid and fluid-structure couplings are presented as numerical experiments.

In [44] two new numerical methods for incompressible fluid/thin-walled structure interaction problems using unfitted meshes are proposed. The spatial discretization is based on different variants of Nitsche's method with cut elements. The degree of fluid-solid splitting (semi-implicit or explicit) is given by the order in which the space and time discretizations are performed. For the semi-implicit schemes, energy-based stability and a priori error estimates are derived and which guarantee the unconditional stability and optimal accuracy in the energy-norm of one the methods. Stability and a priori error estimates are also derived for one of the explicit schemes. Numerical experiments in a benchmark illustrate the performance of the different methods proposed.

7.2. Numerical methods for biological flows

Participants: Chloé Audebert, Jean-Frédéric Gerbeau, Céline Grandmont, Sanjay Pant, Marc Thiriet, Irene Vignon-Clementel.

In [16], we present a new approach for the outflow boundary conditions of Navier-Stokes equations in hemodynamics that consists in adding a 3D artificial part where the Navier-Stokes equations are modified to obtain an equivalent energy balance to a standard coupling with a 3-element Windkessel model. We investigate theoretically the stability of the system and compare it to previously introduced methods. We compare these coupling methods for numerical simulations of blood flow in three patient-specific models, which represent different flow regimes in the pulmonary and systemic circulations.

In [36], we highlight and present solutions to several challenges of the UKF method, a data-assimilation method, pertinent to reduced models of cardiovascular haemodynamics. These include methods to a) avoid ill-conditioning of covariance matrix; b) handle a variety of measurement types; c) include a variety of prior knowledge in the method; and d) incorporate measurements acquired at different heart-rates, a common situation in the clinic where patient-state differs between various clinical acquisitions.

In [18], we introduce a kinetic scheme to solve the 1D Euler equations of hemodynamics, which solution on several benchmark tests for both arterial and venous wall laws compares well with the literature. In particular, it is shown that it has a good behavior when the section area of a vessel is close to zero, which is an important property for collapsible or clamped vessels. The application to liver surgery shows that a closed-loop model of the global circulation, including 0D and 1D equations, is able to reproduce the change of waveforms observed after different levels of hepatectomy.

In [17], we explain with a 0D closed-loop lumped model the hemodynamics changes observed during partial hepatectomy in pigs [22]. The typical increase of portal pressure, increase of liver pressure loss, slight decrease of portal flow and major decrease in arterial flow are quantitatively captured by the model for a 75% hepatectomy. The different post-operative states, observed in experiments, are reproduced with the proposed model. Thus, an explanation for inter-subjects post-operative variability is proposed. This work needs to be translated to humans, in which liver flow modulation is a subject of surgery research [39].

In [24], we propose a computational approach for efficient design study of a reducer stent to be percutaneously implanted in enlarged right ventricular outflow tracts (RVOT) of repaired Tetralogy of Fallot. Hemodynamics of different designs are simulated in the stented RVOT via a reduce order model based on proper orthogonal decomposition on a reference device configuration. To validate the approach, forces exerted on the valve and on the reducer are monitored, varying with geometrical parameters, and compared with the results of full CFD simulations.

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 [38], a proof of concept study, a constant shear stress hypothesis and structured pulmonary trees are used to derive adaptive outflow boundary conditions for 3D-0D postoperative blood flow simulations. This strategy provides better predictions of pulmonary flow distribution than the conventional strategy of maintaining outflow boundary conditions.

In [26] the effect of inserted needle on the subcutaneous interstitial flow is studied. The goal is to describe the physical stress affecting cells during acupuncture needling. The convective Brinkman equations are considered to describe the flow through a fibrous medium. Three-dimensional simulations are carried out by employing an ALE finite element model. Numerical studies illustrate the acute physical stress developed by the implantation of a needle.

In [32], a fully three-dimensional blood flow simulation through a complete rigid macrovascular circuit, namely the intracranial venous network, instead of a reduced order simulation and partial vascular network is presented. The biomechanical modeling step is carefully analyzed and leads to the description of the flow governed by the dimensionless Navier-Stokes equations for an incompressible viscous fluid. The equations are then numerically solved with a free finite element software using five meshes of a realistic geometry obtained

from medical images to prove the feasibility of the pipeline. Some features of the intracranial venous circuit in the supine position such as asymmetric behavior in merging regions are discussed.

7.3. Numerical methods for cardiac electrophysiology

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

In [51] the variability of phenomena described by parametric partial differential equations is studied. In particular, given population statistics on a system observables, 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 and compare it to other existing techniques.

In [50] a reduced order modeling method is proposed in order to speed-up the solution of reaction diffusion equations. It is based on the Approximated Lax Pair method, the discretisation is carried out by adopting an empirical interpolation framework in order to deal with non-polynomial nonlinearities. Some numerical examples on the FKPP equations as well as the equations in electrophysiology are proposed.

We published in [25] a discussion about the Comprehensive in vitro Proarrhythmia Assay (CiPA), which is a nonclinical Safety Pharmacology paradigm for discovering electrophysiological mechanisms that are likely to confer proarrhythmic liability to drug candidates intended for human use. In particular, we presented the use of mathematical modeling in Safety Pharmacology to better understand the electric signals acquired by multielectrode arrays.

7.4. Lung and respiration modeling

Participants: Laurent Boudin, Muriel Boulakia, Céline Grandmont, Nicolas Pozin, Irene Vignon-Clementel.

In [46], we proved the existence of global weak solutions to the incompressible Navier-Stokes-Vlasov system in a three-dimensional time-dependent domain with absorption boundary conditions for the kinetic part. This model arises from the study of respiratory aerosol in the human airways. The proof is based on a regularization and approximation strategy designed for our time-dependent framework.

In [52] we develop a lung-ventilation model. The parenchyma is described as an elastic homogenized media, irrigated by the tracheo-bronchial tree, a nonlinear resistive pipe network. Both are strongly coupled, and an efficient algorithm that takes advantage of the tree dyadic structure is proposed. This framework is used with different types of boundary conditions, including a nonlinear Robin model of the surrounding lung structures, to exhibit global and local coupling effects, for various ventilations. The model is also compared to a more classical exit-compartment (0D) approach.

In [34], we present a new framework that is designed to simulate ventilation and particle fate throughout the respiration cycle, both difficult to dynamically image. The flow and the particle transport and deposition models in the main bronchi are coupled to 1D models that account for the distal lobar lung structures. This enables modeling of inspiration as well as expiration. This leads to differentiated particle deposition over time, and between lobes and generations. Strong agreement to previously collected regional rat experimental data is shown, as the 1D models account for lobe-dependent morphology.

7.5. Miscellaneous

Participants: Laurent Boudin, Jean-Frédéric Gerbeau, Damiano Lombardi, Sanjay Pant, Marina Vidrascu, Irene Vignon-Clementel.

In [47], we derive the Maxwell-Stefan formalism from the Boltzmann equation for mixtures with general cross-sections. The derivation uses the Hilbert asymptotic method for systems at low Knudsen and Mach numbers. We also formally prove that the Maxwell-Stefan coefficients can be linked to the direct linearized Boltzmann operator for mixtures. That allows to compute the values of the Maxwell-Stefan diffusion coefficients with explicit and simple formulae with respect to the cross-sections. We also justify the specific ansatz we use thanks to the so-called moment method.

In [19] we give a presentation of the mathematical and numerical treatment of plate dynamics problems including rotational inertia. The presence of rotational inertia in the equation of motion makes the study of such problems interesting. We employ HCT finite elements for space discretization and the Newmark method for time discretization in FreeFEM++, and test such methods in some significant cases: a circular plate clamped all over its lateral surface, a rectangular plate simply supported all over its lateral surface, and an L-shaped clamped plate.

In [31] we investigated a modified k-nearest neighbors method to assess the differential entropy of a probability density distribution given a set of samples. Instead of considering a classical Kozachenko-Leonenko approximation, an improved parametric gaussian representation is proposed. The method aims at improving the performances of the classical estimator when considering the probability density distribution of model observations, which are featured by a strong anisotropy or functional dependency.

In [49] a dynamical adaptive tensor method is proposed to build parsimonius discretisations for systems whose domain can be naturally decomposed as a product of sets. A modified Proper Generalised Decomposition step is introduced, that allows to project the equations residual on a tensorised space. Contrary to the majority of the methods proposed, the tensor rank is adapted to guarantee a chosen precision. The method is applied to the Vlasov-Poisson system of equations. In order to preserve the hamiltonian structure of the problem, a symplectic integrator is proposed. The convergence of the method is proved and several high-dimensional test-cases are presented in order to validate the approach.

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 in the context of the ANRT on “Multiscale lung ventilation modeling in health and disease”, for the PhD thesis of Nicolas Pozin (March 2014 - February 2017).

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: 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 in the framework of the LabCom “cardioXcomp” (see ANR projects section). In 2016, the ANR funding came to an end, and NOTOCORD was acquired by the company Instem. Our collaboration with Instem/NOTOCORD will continue as a bilateral partnership with the purpose of developing the software cardioXcomp dedicated to the safety pharmacology industry.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. ANR Project "EXIFSI"

Participants: Faisal Amlani, Miguel Ángel Fernández Varela [Principal Investigator], Axel Fourmont, Mikel Landajuela Larma, Marina Vidrascu.

Period: 2012-2016

The aim of this project, coordinated by Miguel Ángel Fernández Varela, is to study mathematically and numerically new numerical methods for incompressible fluid-structure interaction.

9.1.1.2. ANR LabCom "CARDIOXCOMP"

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

Period: 2013-2016.

This project, coordinated by Jean-Frédéric Gerbeau, is carried out in the framework of a joint laboratory ("LabCom" call of ANR) with the software company NOTOCORD. The focus is the mathematical modeling of a device measuring the electrical activity of cardiomyocytes. The overall objective of CardioXcomp is to enrich NOTOCORD's software with modeling and simulation solutions and provide to safety pharmacology research a completely new set incorporating state of the art signal processing and numerical simulation.

9.1.1.3. ANR Project "iFLOW"

Participants: Chloé Audebert, Jean-Frédéric Gerbeau, 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.

9.1.1.4. 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.

9.1.1.5. 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 "MENAMES"

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

Period: 2014-2016
The aim of this project, coordinated by Miguel Ángel Fernández Varela, is to implement in the FELiScE library the shell elements included in the shelddon and Modulef libraries.

9.1.2.2. 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 Initiatives

9.3.1. Trans-Atlantic Network of Excellence for Cardiovascular Research
Participants: Jean-Frédéric Gerbeau, Sanjay Pant, Irene Vignon-Clementel [correspondant].

Period: 2010-2016

This network, funded by the Leducq foundation, is working on the multi-scale modeling of single ventricle hearts for clinical decision support.

Other partners: see http://modelingventricle.clemson.edu/home.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Visiting Professor: Rodolfo Araya, University of Concepcion (Chile), from Apr 2016 to Jul 2016
- Visiting PhD student: Michele Annese, Universita degli Studi di Brescia (Italy), from Mar to Jul 2016
- Visiting PhD student: Stefano Zonca, Politecnico di Milano (Italy), from Oct to Sep 2016

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

- Matteo Aletti
  - Co-organizer of the monthly Junior Seminar of Inria Paris.
- Laurent Boudin
  - Member of the organizing and scientific committees of the "Recent advances in kinetic equations and applications" workshop, June 2016, Paris
  - Member of the organizing committee of the 5th "Forum Emploi Maths", December 2016, Paris
- Jean-Frédéric Gerbeau
  - Local organizing Committee of the SIAM conference on Parallel Processing 2016. Paris, France.
- Sanjay Pant
  - Organizing committee member, 5th International Conference on Computational and Mathematical Biomedical Engineering (CMBE) 2017
- I. Vignon-Clementel
  - Organized a minisymposium at the COSINE conference, May 25th-26th, Bordeaux, France
  - Organized a minisymposium at the ECCOMAS congress, June 4th-9th, Crete, Greece
  - Programme committee member, Computational and Mathematical Biomedical Engineering Conference
  - Conference steering committee, International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease, 2015-present

10.1.2. Scientific Events Selection

10.1.2.1. Reviewer

- Jean-Frédéric Gerbeau
  - Member of the Scientific Program Committee of the Millennium Science Initiative, a program of the Ministry of Economy of Chile.
  - Expert for Horizon2020 FET OPEN RIA Call 2015/2.
- Irene Vignon-Clementel
  - Expert for “Appel à projets générique”, ANR 2016.
- Marina Vidrascu

  - Expert for FONDECYT - Chile “Projects for Initiation in Research” 2016

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Jean-Frédéric Gerbeau
  - Editor-in-Chief of Mathematical Modelling and Numerical Analysis (M2AN), SMAI/EDP Sciences.
  - 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. Research Administration

- Laurent Boudin
  - Expert evaluator for ANVUR (VQR 2011-2014), Italy
  - Member of the Board of Mathematics Licence (EFU de Licence de mathématiques), UPMC
  - Member of the think-tank for third-year programs in Mathematics at UPMC.
  - Member of the IREM (Institutes for Research on Mathematics Teaching) Scientific Committee.
  - Member of the SMAI (French Society for applied and industrial mathematics) Teaching Committee.
- Muriel Boulakia
  - Supervisor of the teaching of mathematics at the engineer school Polytech Paris-UPMC
- Miguel Ángel Fernández Varela
  - Co-president of the Scientific Positions Commission, Inria Paris
- Jean-Frédéric Gerbeau
  - Service activity at Inria: Délégué Scientifique / Chairman of the project-teams’ committee of Inria Paris research center; Member of the Inria Evaluation Committee.
  - Service activity in other French institutions: 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 Evaluation Committee Inria (2015–)
  - Head of the HCERES evaluation Jury of Imath lab. Toulon Univ.
- Marc Thiriet
  - Vice-President & Council Member of the International Society of Digital Medicine
- I. Vignon-Clementel

- Organizing the monthly seminar at Inria Paris on “modeling and scientific computing”, now joint seminar "Rencontres Inria-LJLL en calcul scientifique" (until June 2016)
- Committee member for PhD students at Inria "Commission consultative des doctorants", since July 2016.
- Mediator between PhD students and their supervisors for Inria Paris-Rocquencourt

10.1.5. Conferences

- Matteo Aletti
  - Minisymposium talk, SIMAI2016, Sep 13-16, 2016 Milano, Italy
  - Minisymposium talk, ECCOMAS Congress 2016, Jun 5-10, 2016, Crete, Greece
  - Presentation at REVAMMAD (EU Marie Curie ITN) meeting, Jun 2016, Lincoln, UK
- Rodolfo Araya
  - Seminar, Laboratoire de Mathématiques de Besançon, Université de Franche-Comté, Besançon, May 26
  - Seminar, Groupe de Modélisation Mathématique, Mécanique et Numérique, Université de Caen Basse-Normandie, Jun 6
  - Minisymposium talk, The Mathematics of Finite Elements and Applications 2016 (MAFELAP 2016) conference, Jun 14-17, London, UK
- Chloé Audebert
  - Seminar, Journée interne du Laboratoire Jacques-Louis Lions, Nov 16, 2016, Paris, France.
  - Seminar, BioMécanique et BioIngénierie (BMBI), UTC, Nov 15, 2016, Compiègne, France.
  - Minisymposium talk,Word Congress on Computational Mechanics (WCCM), Jul 24-29, 2016, Seoul, Korea
  - Minisymposium talk, European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Jun 5-10, 2016, Crete Island, Greece
  - Open Brain in HPB Surgery, Club Innovation ACHBT, Jun 3-5, 2016, Carnac, France.
  - Congrès National d’Analyse Numérique (CANUM), May 9-13, 2016, Obernai, France
  - Talk, Saint-Antoine hospital, May 3, 2016, Paris, France
- Laurent Boudin
  - Seminar, Applied Mathematics, Department of Mathematics and Informatics, Univ. Novi Sad, Serbia, July 2016
- Muriel Boulakia
  - Workshop ANR IFSMACS, Toulouse, Nov 2016
  - Invited talk, Workshop Carleman estimates, unique continuation, University College of London, Nov 2016
  - Seminar LMAC, Compiègne, Oct 2016
  - Workshop Mathematics and Health, LJLL, UPMC, May 2016
  - Workshop ANR IFSMACS, Paris, Mar 2016
  - Seminar PDE, IECL, Nancy, Feb 2016
- Miguel Ángel Fernández Varela
  - Invited Speaker IWH Symposium on Simulation and Optimization of Extreme Fluids, Oct 2016, Heidelberg, Germany

  - Minisymposium talk, The Mathematics of Finite Elements and Applications 2016 (MAFELAP 2016) conference, Jun 14-17, London, UK
  - Invited Speaker, Workshop on geometrically unfitted finite element methods, Jan 6-8, 2016, London, UK
- Jean-Frédéric Gerbeau
  - Invited lecturer, CISM-ECCOMAS International Summer School (6 hours), June 2016, Udine, Italia.
  - Invited lecturer, "Numerical methods for PDEs", Institut Henri Poincaré (9 hours), Oct 2016, Paris, France.
  - Invited speaker, Workshop: Mathematical Modeling in Cardiovascular Healthcare, Oct 2016, Emory University, USA
  - Invited speaker, Workshop "Boundary layer and Fluid-Structure Interaction", Jan 2016, Bordeaux, France.
  - Invited speaker, 2d conference "Mathematical Modelling of Complex Systems", Dec 2016, Châtenay Malabry, France.
  - Seminar at Collège de France, Pierre-Louis Lions chair, May 2016, Paris, France.
  - Minisymposium talk, European Congress of Mathematics (ECM), July 2016, Berlin, Germany.
  - Minisymposium talk, World Congress of Computational Mechanics (WCCM), July 2016, Seoul, Korea.
  - Minisymposium talk, SIMAI conference, Sep 2016, Milan, Italy.
- Céline Grandmont
  - Invited Speaker IWH Symposium on Simulation and Optimization of Extreme Fluids, Oct 2016, Heidelberg, Germany
  - Seminar, Ecole Centrale, Apr 2016
  - Invited Speaker, Journées Jeunes Edépistes, Mar 2016, Bordeaux
  - Invited Speaker, Boundary Layers and Fluid-Structure Interactions, Jan 2016, Bordeaux
- Mikel Landajuela
  - Seminar, Séminaire d'analyse numérique, Université de Genève, Mar 8, 2016, Geneva, Switzerland
- Damiano Lombardi
  - Invited talk, ALGORITMY 2016, Mar 13-18, 2016, Podbaske, Slovakia
  - Invited talk, SIMAI 2016, Sep 13-16, 2016, Milano, Italy
  - Contributed talk, Workshop on Reduced Order Modeling, Nov 7-10, 2016, Institut Henri Poincaré, Paris
- Sanjay Pant
  - Contributed talk, The 12th World Congress on Computational Mechanics (WCCM XII), Jul 2016, Seoul, Korea
  - Contributed talk, 5th International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease, Jun 2016 , Orlando, Florida, USA
  - Contributed talk, Computational modeling in healthcare: Making confident predictions in a world of error and uncertainty, Apr 2016, Glasgow, UK
- Nicolas Pozin
  - Minisymposium talk, European Congress on Computational Methods in Applied Sciences and Engineering - ECCOMAS 2016, Jun 5-10, 2016, Creta, Greece

- Marc Thiriet
  - Invited Speaker, 6th Annual Academic Congress of Chinese Society of Digital Medicine and1st International Conference on Digital Medicine & Medical 3D Printing, Jun 17-19, 2016, Nanjing, China
  - Minisymposium talk, 16th International Society for Therapeutic Ultrasound (ISTU), Mar 14-16, 2016, Tel-Aviv, Israel
- Alexandre This
  - Seminar, Inria Paris Junior Seminar, Oct 18, 2016, Paris
- Eliott Tixier
  - Minisymposium talk, SIAM Conference on Uncertainty Quantification, Apr 5-8, 2016, Lausanne, Switzerland
- Irene Vignon-Clementel
  - Seminar, Paul Brousse Hospital, Nov 18th, Villejuif, France
  - Seminar, DKFZ, Nov 15th, Heidelberg, Germany
  - Invited talk, SimInhale workshop, Oct 17th-19th, Prague, Czech Republic
  - Invited talk, GRIC Journées Françaises de Radiologie, Oct 13th, Paris, France
  - Minisymposium talk, CMBBE conference, September 20th-22nd, Tel Aviv, Israel
  - Seminar, Dassault Systems, July 20th, Velizy-Villacoublay, France
  - Minisymposium talk, SIAM Conference on the Life Sciences, July 11th-14th, Boston, USA
  - Presentation for the Chinese Academy of Science, June 29th, Paris, France
  - Invited talk, Inria National Scientific Days, June 20th-22th, Rennes, France
  - Invited talk, International Conference on Engineering Frontiers in Pediatric and Congenital Heart Disease, June 9th-10th, Orlando, USA
  - Minisymposim Keynote, ECCOMAS congress, June 4th-9th, Crete, Greece
  - Minisymposium talk, COSINE conference, May 25th-26th, Bordeaux, France
  - Presentation, Demi-journée Math-Industrie, LJLL-UPMC, May 10th 2016, Paris, France
  - Invited Keynote, Computational modelling in healthcare: Making confident predictions in a world of error and uncertainty (workshop), April 26th 2016, Glasgow, UK
  - Minisymposium talk, UQ SIAM conference, EPFL, April 5th-8th, 2016, Lausanne, Switzerland
  - Invited talk, workshop: towards a unified framework for benchmarking multicellular models and modelling/simulation software, Leipzig University, March 14th-16th, 2016, Leipzig, Germany
  - Podium talk, The 8th International Bio-Fluids Symposium, February 12-14, 2016, CaltechTech, Pasadena, USA
  - Seminar, Department of Mechanical Eng., UC at Berkeley, Feb. 10th, 2016, Berkeley, USA
  - Seminar, HeartFlow company, Feb. 9th, 2016, Mountain View, USA

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence :

- Ludovic Boilevin-Kayl

  - Calculus, 60h, L1, UPMC
- Laurent Boudin
  - Introduction to series for signal theory, 18h, L2, UPMC
  - Shared studies supervision in mathematics licence for approximately 500 students, 48h, L2-L3, UPMC
- Muriel Boulakia
  - Scilab, 35h, L2, UPMC
  - Nonlinear systems and optimization, 35h, L3, Polytech'Paris
  - Hilbertian analysis, 50h, L3, Polytech'Paris
  - Oral tests in numerical analysis, 20h, L3, UPMC
- Miguel Ángel Fernández Varela
  - Analysis and Scientific Computing, 30h, L3, ENPC
- Jean-Frédéric Gerbeau
  - Numerical Analysis and Optimization, 32h, L3, Ecole Polytechnique.
- Céline Grandmont
  - Ordinary differential equations, 24h, L3, UPMC
- Damiano Lombardi
  - Numerical Methods, 48h, L3, Polytech'Paris
- Eliott Tixier
  - Linear algebra, 60h, L2, Polytech'Paris
- Irene Vignon-Clementel
  - Mathematics for biology, 54h, L1, Université de Versailles Saint Quentin
  - Numerical simulations of blood flow, 1h30, as part of the undergraduate "continuum mechanics", AgroParisTech

Master :

- Laurent Boudin
  - Basics for numerical methods, 36h, M1, UPMC
- Muriel Boulakia
  - Preparatory course for teaching admission examination "Agrégation", 15h, M2, UPMC
- Miguel Ángel Fernández Varela
  - Numerical methods for bio-fluids simulation, 9h, M2, Universidade de Vigo, Spain
- Irene Vignon-Clementel
  - Modélisation hémodynamique & simulation numérique comme outil pour la chirurgie, 1h, M2, Université Paris Sud
- Jean-Frédéric Gerbeau
  - Numerical methods in hemodynamics (20h), M2, UPMC / Univ Paris-Sud / Ecole Polytechnique.
  - Seminar for M2 students of the master "Math SV" (1h), M2, Univ Paris-Sud, December, 2015
  - Seminar for M2 students at Ecole des Mines (3h), Paris, February, 2015

10.2.2. Supervision

HdR : Irene Vignon-Clementel, *Blood and air flow multi-scale simulations based on real data*, defended on March 31, 2016

PhD in progress: Chloé Audebert, *Modeling of liver hemodynamics*, since October 2013. Supervisors: J.-F. Gerbeau & I. Vignon-Clementel.

PhD : Francesco Bonaldi, *Modélisation Mathématique et Numérique de Multi-Structures avec couplage Magnéto-Electro-Thermo-Elastique*, defended on July 6, 2016. Supervisors: F. Krasucki & M. Vidrascu

PhD : Mikel Landajuela, *Coupling schemes and unfitted mesh methods for fluid-structure interaction*, defended in March 29, 2016. Supervisor: M.A. Fernández Varela.

PhD in progress: Matteo Aletti, *Multiscale retinal vascular modeling*, since January 2014. Supervisors: J.-F. Gerbeau & D. Lombardi.

PhD in progress: Eliott Tixier, *Stem cells electrophysiology*, since September 2014. Supervisors: J-F. Gerbeau & D. Lombardi.

PhD in progress: Nicolas Pozin, *Multiscale lung ventilation modeling in health and disease*, since March 2014. 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

10.2.3. Juries

- Laurent Boudin
  - PhD committee: Alexandra de Cecco, Université Paul Sabatier (referee), Anthony Preux, Université Paris-Saclay
- Muriel Boulakia
  - PhD committee: Andjela Davidovic, Inria Bordeaux Sud-Ouest; Ibtissem Ben Aïcha, Université d'Aix-Marseille
- Miguel Ángel Fernández Varela
  - PhD committee: Moctar Ndiaye, Université Paul Sabatier (president), Davide Baroli, Politecnico di Milano, Simone Brugiapaglia, Politecnico di Milano; Rocco M. Lancellotti, Politecnico di Milano (referee); Paolo Pacciarini, Politecnico di Milano
- Jean-Frédéric Gerbeau
  - PhD committees: Julien Sigüenza, Univ Montpellier (referee). Anna Tagliabue, Politecnico di Milano (referee).
  - Hiring committee: Inria Bordeaux (CR2); Inria Paris (CR2).
- Céline Grandmont
  - Hiring committee: Rennes Univ. (Professor position), Marseille Univ. (Professor position)
  - PhD committee: M. Ndiaye, Université Paul Sabatier (president), B. Polizzi, Univ. de Nice (referee), B. Burtschell, Ecole Polytechnique (referee), P. Jounieaux, UPMC (president)
  - Member of the «Agrégation» Jury in mathematics
- Marc Thiriet
  - PhD committee: M. Haddadi, Université Paris Est–Créteil (referee)

- Marina Vidrascu
  - PhD committee: F. Bonaldi, Université de Montpellier; M Hédi, Tunis El-Manar & UPMC; F. Cheick, Tunis El-Manar & UPMC
- Irene Vignon-Clementel
  - PhD committee: Gabrielle Fournet, CEA & Université Paris-Saclay (referee)

10.3. Popularization

- Céline Grandmont
  - Conference : "Filles et Maths : une équation lumineuse", 60 students secondary school level, Feb 2016
  - Popularization paper with J.-F. Gerbeau : "Maths, médecine et entreprises : des collaborations gagnantes", brochure Maths Société Express, 2016
  - Conference "Métier": Master 1 Maths students, UPMC, Nov 2016
- Irene Vignon-Clementel
  - Telerama, Interview (Richard Senejoux), Mar 10, 2016
  - Presentation, Inauguration of Inria Paris research center in presence of the Minister of Research and presidents of Universities, ANR, EPST, media, etc. Mar 10, 2016, Paris
  - High school conference, Mar 14, 2016, Lycée St François d'Assise, Montigny le Bretonneux

11. Bibliography

Major publications by the team in recent years

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