IN PARTNERSHIP WITH:
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Université Pierre et Marie Curie (Paris 6)

Activity Report 2015

Project-Team REO

Numerical simulation of biological flows

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

RESEARCH CENTER
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THEME
Modeling and Control for Life Sciences

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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 [73] in the frame of combustion. It was later used to develop the Kiva code [63] at the Los Alamos National Laboratory, or the Hesione code [68], for example. It has a wide range of applications, besides the nuclear setting: diesel engines, rocket engines [66], 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 [69]. 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.
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 [72], and Biot [64] 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 [65]), 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.

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

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.* [67], [71], [70] 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

Irène Vignon-Clementel: Article [16] selected for journal cover in Cardiovascular Engineering and Technology.

5.1.1. Awards

Jessica Oakes was awarded an American Lung Association Senior Research Training Grant for salary support for 1-2 years.

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

6.2. LIFE-V

KEYWORD: Finite element modelling
FUNCTIONAL DESCRIPTION

LiFE-V is a finite element library providing implementations of state of the art mathematical and numerical methods. It serves both as a research and production library. LiFE-V is the joint collaboration between three institutions: Ecole Polytechnique Fédérale de Lausanne (CMCS) in Switzerland, Politecnico di Milano (MOX) in Italy and Inria (REO) in France. It is a free software under LGPL license.

- Participants: Jean-Frédéric Gerbeau and Miguel Angel Fernandez Varela
- Partners: EPFL - Ecole Polytechnique Fédérale de Lausanne - MOX Politecnico di Milano
- Contact: Miguel Angel Fernández Varela
- URL: http://www.lifev.org/

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, Patrick Le Tallec and Marina Vidrascu
- 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, Faisal Amlani, Benoit Fabrèges, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Mikel Landajuela Larma, Damiano Lombardi, Marina Vidrascu.

In [55] we present a numerical study in which several partitioned solution procedures for incompressible fluid-structure interaction are compared and validated against the results of an experimental FSI benchmark. The numerical methods discussed cover the three main families of coupling schemes: strongly coupled, semi-implicit and loosely coupled. Very good agreement is observed between the numerical and experimental results. The comparisons confirm that strong coupling can be efficiently avoided, via semi-implicit and loosely coupled schemes, without compromising stability and accuracy.

In [14] we introduce a Nitsche-XFEM method for fluid-structure interaction problems involving a thin-walled elastic structure (Lagrangian formalism) immersed in an incompressible viscous fluid (Eulerian formalism). The fluid domain is discretized with an unstructured mesh not fitted to the solid mid-surface mesh. Weak and strong discontinuities across the interface are allowed for the velocity and pressure, respectively. The fluid-solid coupling is enforced consistently using a variant of Nitsche's method with cut-elements. Robustness with respect to arbitrary interface intersections is guaranteed through suitable stabilization. Several coupling schemes with different degrees of fluid-solid time splitting (implicit, semi-implicit and explicit) are investigated. A series of numerical tests in 2D, involving static and moving interfaces, illustrates the performance of the different methods proposed.

In [15] we investigated the autoregulation in the retinal haemodynamics by means of three-dimensional simulations. The autoregulation is a key phenomenon from a physiological standpoint, consisting in the ability of the vasculature to control the flow in different pressure conditions. A simplified fluid-structure interaction method was devised in order to render the vessels wall contraction in a large network, with an affordable computational cost. Several test cases were performed on a patient-specific arteriolar network, whose geometry was reconstructed by using fundus camera images. The tests were in agreement with experimental trends and confirm the ability of the approach to reproduce the phenomena involved.

In [33] we study an unsteady nonlinear fluid-structure interaction problem which is a simplified model to describe blood flow through viscoelastic arteries. 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 viscoelastic beam equation. The fluid and the structure are fully coupled via interface conditions prescribing the continuity of the velocities at the fluid-structure interface and the action-reaction principle. We prove that strong solutions to this problem are global-in-time. We obtain in particular that contact between the viscoleastic wall and the bottom of the fluid cavity does not occur in finite time. To our knowledge, this is the first occurrence of a no-contact result, but also of existence of strong solutions globally in time, in the frame of interactions between a viscous fluid and a deformable structure.

In [27] and [45] we study the effect of wall bending resistance on the motion of an initially spherical capsule freely suspended in shear flow or in a a planar hyperbolic flow. We consider a capsule with a given thickness made of a three–dimensional homogeneous elastic material. A numerical method is used to model the coupling of a boundary integral method for the fluids with a shell finite element method for the capsule envelope. For a given wall material, the capsule deformability strongly decreases when the wall bending resistance increases. In addition, if one expresses the same results as a function of the two–dimensional mechanical properties of the mid–surface, which is how the capsule wall is modeled in the thin–shell model, the capsule deformed shape is identical to the one predicted for a capsule devoid of bending resistance. The bending rigidity is found to have a negligible influence on the overall deformation of an initially spherical capsule, which therefore depends only on the elastic stretching of the mid–surface. Still, the bending resistance of the wall must be accounted for to model the buckling phenomenon, which is observed locally at low flow strength and persist at steady state. We show that the wrinkle wavelength only depends on the bending number, which compares the relative importance of bending and shearing phenomena, and provide the correlation law. Such results can then be used to infer values of the bending modulus and wall thickness from experiments on spherical capsules in simple shear flow.

In [57] we consider the motion of an elastic structure represented by the nonlinear Saint-Venant Kirchhoff model immersed in a compressible fluid modeled by the compressible Navier-Stokes equations. Existence and uniqueness of a regular solution defined locally in time is proved.

7.2. Numerical methods for biological flows

Participants: Chloé Audebert, Benoit Fabrèges, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Céline Grandmont, Sanjay Pant, Marc Thiriet, Irène Vignon-Clementel.

In [37] we present a closed-loop global lumped parameter model for pre stage-II single-ventricle physiology. This model, which is built on a fibre mechanics based description of the heart chambers, benefits from a novel method to describe regurgitant valves. As many as 33 model parameters are estimated from uncertain clinical measurements in two patients—with and without atrioventricular valve regurgitation—through the method of data assimilation. Results are validated qualitatively through measurements and clinical estimates that were not included in the parameter estimation procedure. The methods are shown to successfully capture patient-specific clinical observations such as double peaked nature of valvular flows and abnormalities in electrocardiogram readings.

In [39] we propose a methodology for full propagation of uncertainty from clinical data to model results that enables estimation of the confidence associated with model predictions. We illustrate this problem in a pre stage-II single-ventricle physiology, for which coherence of simulations and clinical data indicated that the flow split to the right lung was highly uncertain. We want to assess here how such uncertainty translates into surgical planning of removing the stenosis or not. Taking into account the effect of the rest of the circulation is also studied in the uncertainty propagation.

In [21] 3D blood flow simulations are carried out for the design of a stented valve reducer in enlarged ventricular outflow tracts. Different device designs are built and compared with the initial device-free state, or with the reducer alone. Results suggest that pressure loss is higher for the reducer alone than for the full device, and that the latter successfully restores hemodynamics to a healthy state. Pressure forces on the reducer and on the valve have the same magnitudes. Migration would occur towards the right ventricle rather than the pulmonary arteries.

In [44] we aim at developing a mathematical model in order to reproduce hemodynamics changes due to liver ablation surgeries. First, a 0D closed-loop model is developed, to simulate hepatectomy and compute post-operative average values. Due to the closed loop, the surgery impact both on and from the whole circulation can be captured, including bleeding and infusion. Then, a one-dimensional artery model is implemented to improve the closed-loop model and simulate better the changes in arterial waveforms due to surgery.

In [54] we investigate the spatial and time discretization of the transient Oseen equations. Finite elements with symmetric stabilization in space are combined with several time-stepping schemes (monolithic and fractional-step). Quasi-optimal (in space) and optimal (in time) error estimates are established for smooth solutions in all flow regimes. We first analyze monolithic time discretizations using the Backward Differentation Formulas of order 1 and 2 (BDF1 and BDF2). We derive a new estimate on the time-average of the pressure error featuring the same robustness with respect to the Reynolds number as the velocity estimate. Then, we analyze fractional-step pressure-projection methods using BDF1. The stabilization of velocities and pressures can be treated either implicitly or explicitly. Numerical results illustrate the main theoretical findings.

In [26] we study the effects of inserted needle on the subcutaneous interstitial flow. A goal is to describe the physical stress affecting cells during acupuncture treatment. The model consists of the convective Brinkman equations to describe the flow through a fibrous medium. Numerical studies in FreeFem++ are performed to illustrate the acute physical stress developed by the implantation of a needle that triggers the physiological reactions of acupuncture. We emphasize the importance of numerical experiments for advancing in modeling in acupuncture. In [40] we show that the acupoint must contain a highly concentrated population of mastocytes (e.g., very-high–amplitude, small-width Gaussian distribution) to get an initial proper response. Permanent signaling is provided by chemotaxis and continuous recruitment of mastocytes. Therefore, the density and distribution of mastocytes are crucial factors for efficient acupuncture as well as availability of circulating and neighboring pools of mastocytes.

In [61] we carry out a three-dimensional blood flow simulation through a complete macrovascular circuit, the cerebral venous network, rather than using reduced order simulation and partial vascular network. The bio-mechanical modeling step is carefully performed and leads to the description of the flow governed by the

Navier-Stokes equations for an incompressible viscous fluid. We then numerically solve the equations with a free finite element software in five meshes of a realistic geometry obtained from medical images to prove the feasibility of the pipeline. Some particularities of the venous network, as asymmetry for example, are discussed.

7.3. Numerical methods for cardiac electrophysiology

Participants: Muriel Boulakia, Jean-Frédéric Gerbeau, Damiano Lombardi.

In [58] we investigate the monodomain equation which describes the evolution of the cardiac electrical potential and which corresponds to a coupled system involving a reaction-diffusion equation and an ordinary differential equation. Lipschitz stability inequalities are shown for the identification of some parameters of the model from measurements on the cardiac potential and the ionic variable.

In [32] we studied the application of a Reduced-Order Modeling method (Approximated Lax Pairs) to the solution of the partial differential equations describing the polarisation of tissues. Due to the complexity of the scenarios involved and the presence of propagating waves, the performances of the standard methods proposed in the literature to provide a low computational cost solution are not always satisfactory. The ALP method consists of the construction of an adaptive time dependent basis that diagonalises, at each time, a Schrödinger-type operator. Its application to several 2D and 3D test-cases on the equations arising in electrophysiology was investigated, showing that the performances of the method in terms of speed-up and accuracy are promising.

In [62] we considered the simulation of full cycles of the electrical activity of the heart and the corresponding body surface potential. The model is based on a realistic torso and heart anatomy, including ventricles and atria. One of the specificities of our approach is to model the atria as a surface, which is the kind of data typically provided by medical imaging for thin volumes. The bidomain equations are considered in their usual formulation in the ventricles, and in a surface formulation on the atria. Two ionic models are used: the Courtemanche-Ramirez-Nattel model on the atria, and the " Minimal model for human Ventricular action potentials " (MV) by Bueno-Orovio, Cherry and Fenton in the ventricles. The heart is weakly coupled to the torso by a Robin boundary condition based on a resistor-capacitor transmission condition. Various ECGs are simulated in healthy and pathological conditions (left and right bundle branch blocks, Bachmann's bundle block, Wolff-Parkinson-White syndrome). To assess the numerical ECGs, we use several qualitative and quantitative criteria found in the medical literature. Our simulator can also be used to generate the signals measured by a vest of electrodes. This capability is illustrated at the end of the article.

In [24] we address the inverse problem of electrocardiography from a new perspective, by combining electrical and mechanical measurements. Our strategy relies on the definition of a model of the electromechanical contraction which is registered on ECG data but also on measured mechanical displacements of the heart tissue typically extracted from medical images. In this respect, we establish in this work the convergence of a sequential estimator which combines for such coupled problems various state of the art sequential data assimilation methods in a unified consistent and efficient framework. Indeed we aggregate a Luenberger observer for the mechanical state and a Reduced Order Unscented Kalman Filter applied on the parameters to be identified and a POD projection of the electrical state. Then using synthetic data we show the benefits of our approach for the estimation of the electrical state of the ventricles along the heart beat compared with more classical strategies which only consider an electrophysiological model with ECG measurements. Our numerical results actually show that the mechanical measurements improve the identifiability of the electrical problem allowing to reconstruct the electrical state of the coupled system more precisely. Therefore, this work is intended to be a first proof of concept, with theoretical justifications and numerical investigations, of the advantage of using available multi-modal observations for the estimation and identification of an electromechanical model of the heart.

7.4. Lung and respiration modeling

Participants: Laurent Boudin, Muriel Boulakia, Céline Grandmont, Jessica Oakes, Nicolas Pozin, Irène Vignon-Clementel.

In silico models of flow and transport in the lung are increasingly being used to predict regional deposition in healthy and diseased lungs. However, very few models have been validated with in vivo human or animal experimental data. In [36], we create a physiologically-based simulation of airflow and particle transport in healthy and emphysematous rat lungs. Excellent agreement between the numerical predictions and experimental data is found for the healthy lungs. However, the numerical predictions are unable to predict the experimental findings of enhanced deposition in the normal regions of the emphysematous lungs and thus more sophisticated models of transport in the deep regions of the lung are needed. This is what is being explored in [42], where interactions of flow and transport between 3D upper-parts and 1D downstream respiratory trees are captured for inspiration and expiration for the first time.

While several groups have investigated detailed flow and particle transport in the acinar regions of the healthy lung, little is currently known about diseased acini. In [35] we perform numerical simulations of flow and transport in healthy and emphysematous acini. As the alveolar septa is deteriorated in emphysema there is less surface area available for particles to deposit on. Therefore, fewer particles deposit in the diseased models. In addition, we find that particle deposition is more heterogeneously distributed in emphysema, a phenomenon that was also found in the in vivo animal experiments.

7.5. Methods for the interaction data - simulation

Participants: Jean-Frédéric Gerbeau, Damiano Lombardi, Sanjay Pant, Irène Vignon-Clementel.

In [38] we proposed an information theoretical framework to study the practical identifiability of dynamical systems. The fundamental question arising in parameter estimation problems is whether, given a set of observations of the system, it is possible to retrieve the parameters values. The method proposed exploits a database of direct numerical simulations and study the parameters-to-observables map by means of differential entropies. Contrary to other approaches proposed in the literature it is not restricted to ordinary differential equations and take the experimental noise into account. Several test cases were performed on a large spectrum of bio-physical systems, providing promising results.

In [60] we studied a differential entropy estimator based on $kp-$neighbours, aiming at applying a Bayesian framework and some information-theoretic ideas to inverse problems. The goal of this work is to estimate the Shannon differential entropy in high dimensional settings, in possible presence of functional or nearly functional dependences. A modification of the Kozachenko-Leonenko estimator is proposed, consisting of introducing a local gaussian approximation to the probability measure. Test-cases were performed to assess the properties of the method and to compare its performances with other methods proposed in the literature.

The articles [37], presented in the section about biological flows, and [24], presented in the section about electrophysiology, also present methods concerning the interaction data - simulation.

7.6. Miscellaneous

Participants: Laurent Boudin, Irène Vignon-Clementel.

In [34] we develop a quantitative single cell-based model for multi-cellular tumor spheroids of a specific lung cancer cell line, growing under various nutrient conditions: we confront the simulations performed with this model with data on the growth kinetics and spatial labeling patterns for cell proliferation, extracellular matrix, cell distribution and cell death. We stepwise arrive at a model that mimics the spheroid growth under two conditions, and can predict two other ones. The number of mechanisms the model contains is necessary and sufficient to explain the data.

In [19] we consider a kinetic model describing some mechanisms of opinion formation in the framework of referendums, where the individuals, who can interact between themselves and modify their opinion by means of spontaneous self-thinking, are moreover under the influence of mass media. We study, at the numerical level, both the transient and the asymptotic regimes. In particular, we point out that a plurality of media, with different orientations, is a key ingredient to allow pluralism and prevent consensus. The forecasts of the model are compared to some surveys related to the Scottish independence referendum of 2014.

In [56] we review various results on the compactness of the linearized Boltzmann collision operator and of its generalization to mixtures of non-reactive monatomic gases.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. CIFRE convention

Participants: Céline Grandmont, Nicolas Pozin, Irène 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).

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. ANR Project "EXIFSI"

Participants: Benoit Fabrèges, Miguel Ángel Fernández Varela [Principal Investigator], 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-sructure 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 modelling and simulation solutions and provide to 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, Irène Vignon-Clementel [co-Principal Investigator].

Period: 2013-2017.
This ANR-TecSan, co-managed by Eric Vibert (Paul Brousse Hospital) and Irène 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

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 several algorithms included in the shelddon and Modulef library, in particular shell elements and domain decomposition methods.

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.

9.3. International Initiatives

9.3.1. Inria International Labs

Participants: Céline Grandmont, Jessica Oakes, Irène Vignon-Clementel [correspondant].

Period: 2014-2015

Jessica Oakes was awarded an Inria@SiliconValley Grant for a post-doc at UC Berkeley to work on aerosol deposition in the lung.

9.3.2. Trans-Atlantic Network of Excellence for Cardiovascular Research

Participants: Jean-Frédéric Gerbeau, Sanjay Pant, Irène Vignon-Clementel [correspondant].

Period: 2010-2015

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

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

9.3.3. German BMBF national project Lungsys II

Participant: Irène Vignon-Clementel.

Period: 2012-2015

"Systems Biology of Lung Cancer: Dynamic Properties of Early Spread and Therapeutic Options". In collaboration with Dirk Drasdo (EPI Mamba).

Other partners: see http://www.lungsys.de.

9.3.4. Participation In other International Programs

- Laurent Boudin
  - Member of the French-Italian Galileo PHC on the kinetic modelling and numerical simulation of gaseous mixtures and plasmas, supervised by F. Charles (UPMC) for France.
  - Member of a French-Serbian CNRS PICS on the kinetic modelling of gaseous mixtures, supervised by B. Grec (Université Paris-Descartes) for France.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

9.4.1.1. Internships

Visiting PhD student: Stephanie Lindsey, Cornell University (May 4th - May 20th)

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-Rocquencourt
- Laurent Boudin
  - Member of the scientific committee of the "EDP Normandie 2015" conference.
- Sanjay Pant
  - Program committee member for the Australasian Conference on Artificial Life and Computational Intelligence (ACALCI), 2016.
- Jessica Oakes
  - ISAM Student Leader and 2015 Student Activity Conference Organizer
- I. Vignon-Clementel
  - Organizer of a minisymposium at the 4th International Conference on Computational & Mathematical Biomedical Engineering, July 2015, Cachan, France
  - Organizer of the monthly seminar at Inria Paris-Rocquencourt on "modeling and scientific computing"

10.1.2. Scientific events selection

10.1.2.1. Member of the conference program committees

- J-F. Gerbeau
  - Scientific Committee of the ENUMATH 2015 conference. Ankara, Turkey.
  - International Advisory Committee of the 2nd International Workshop on Latest Advances in Cardiac Modeling, 2015. Munich, Germany.

10.1.2.2. Reviewer

- J-F. Gerbeau
  - Expert evaluator for Horizon2020 FET OPEN RIA Call 2015/2.
  - Member of the Mathematics panel of the FCT, the national funding agency of Portugal (*Fundação para a Ciência e a Tecnologia*).
- M. Thiriet
  - European Research Council - Advanced Grant (run 2)
  - ANRT
  - Fund for Scientific Research - FNRS, Belgium

10.1.3. Journal

10.1.3.1. Member of editorial boards

- Jean-Frédéric Gerbeau
  - Editor-in-Chief of Mathematical Modelling and Numerical Analysis (M2AN).
  - Series editor of "SEMA SIMAI Springer Series".
  - Member of the editorial board of International Journal for Numerical Methods in Biomedical Engineering (IJNMBE).
  - Member of the editorial board of Communications in Applied and Industrial Mathematics.
  - Member of the editorial board of Journal for Modeling in Ophthalmology.
- I. Vignon-Clementel
  - Editor of Frontiers in Pediatric Cardiology
- M. Thiriet
  - Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization.

10.1.4. Research administration

- Laurent Boudin
  - 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-Rocquencourt

- Jean-Frédéric Gerbeau
  - Service activity at Inria: Délégué Scientifique / Chairman of the project-teams' committee of Inria Paris-Rocquencourt research center; Member of the Inria Evaluation Committee; Member of the Inria International Chairs committee.
  - Service activity in other French institutions: member of the research committee of Sorbonne Universités; 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 CNU 26 (2011–2015). Member of the CNU extended board.
  - Member of the Evaluation Committee Inria (2015-. . .)
- I. Vignon-Clementel
  - Mediator between PhD students and their supervisors for Inria Paris-Rocquencourt

10.1.5. Conferences

- Matteo Aletti
  - Minisymposium talk, 4th International Conference on Computational & Mathematical Biomedical Engineering (CMBE2015), June 29 - July 1, 2015, Cachan, France
  - Minisymposium talk, 13th U.S. National Congress on Computational Mechanics (USNCCM13), July 27 - July 30, 2015, San Diego, CA
  - Presentation at REVAMMAD (EU Marie Curie ITN) meeting, September 2015, Padova, Italy
- Chloé Audebert
  - Minisymposium talk, 4th International Conference on Computational and Mathematical Biomedical Engineering - CMBE2015, June 29th - July 1st, 2015, Cachan, France
  - PhD students seminar, Inria-Rocquencourt Junior Seminar, October 20th, 2015, Paris, France
  - Seminar, Laboratoire de mathématiques de Besançon, Université de Franche-Comté, November 12th, 2015, Besançon, France
  - PhD students seminar, Laboratoire de mathématiques de Versailles, Université Versailles St-Quentin, December 3rd, 2015, Paris, France
- Laurent Boudin
  - Seminar, Analysis, LMPT, Univ. Tours, France, March 2015.
  - Seminar, Applied Mathematics, LMNO, Univ. Caen, France, March 2015.
  - Invited speaker, Workshop "From opinion dynamics to voting, conflict and terrorism", Sciences Po Paris, France, March 2015
  - Invited speaker, Labex SMART Summer School on "Computational Social and Behavioral Sciences", UPMC, France, September 2015
  - Seminar, Numerical analysis and PDEs, LMO, Univ. Paris-Sud, France, December 2015
- Muriel Boulakia
  - November 2015 : Seminar at University College London
  - August 2015 : Workshop PDE, optimal design and numerics, Benasque (Spain)
  - April 2015 : Seminar at Université d'Orsay Paris-Sud
- Miguel Ángel Fernández Varela

  - Invited speaker, Workshop on fluid-structure interactions: an asymptotic approach, A Coruña, Spain, October 8-9, 2015
  - Minisymposium talk, X-DMS 2015 eXtended Discretization MethodS conference, Ferrara, Italy, September 9-11, 2015
  - Invited speaker, Workshop on Control and Numerics for Fluid-Structure Interaction Problems, TFIR CAM, Bangalore, India, June 29-July 1, 2015
  - Invited speaker, Numerical analysis week of Besançon on XFEM, Nitsche FEM, adaptive FEM and artificial boundary contitions, Besançon, France, June 15-19, 2015
  - Seminar, Modeling and Scientific Computing Seminar, Inria Paris-Rocquencourt, March 3, 2015
- Benoit Fabrèges
  - Seminar, MOX Seminar at Politenico di Milano, Milan, Italy, July 28, 2015
- Jean-Frédéric Gerbeau
  - Invited lecture at the Edinburgh Mathematical Society, 2015
  - Invited lecture, 2d International Workshop on Latest Advances in Cardiac Modeling (LACM), Munich, 2015
  - Invited lecture, 3rd Workshop on Model Reduction (MORE), Pilsen, Czech Republic, 2015
  - Seminar, MOX, Politecnico di Milan, Italy, March, 2015
  - Seminar, ENS Rennes, Dec 16, 2015
  - Minisymposium talk, USNCCM, San Diego, USA, 2015
- Céline Grandmont
  - Invited speaker, Lions-Magenes day, April 2015, Pavia, Italy
  - Invited Speaker, Workshop on Control and Numerics for Fluid-Structure Interaction Problems, TFIR CAM, Bangalore, India, June 29-July 1, 2015
- Mikel Landajuela
  - Contributed talk, 13th U.S. National Congress on Computational Mechanics, San Diego, USA, July 26–30, 2015
  - Seminar, 2nd UCL/Inria Workshop on embedded interfaces, UPMC, Paris, France, April 8, 2015
  - Seminar, MOX, Milano, Italy, December 10, 2015
- Damiano Lombardi
  - Invited talk, Optimal Transport workshop, Bordeaux, October 16 2015
  - Seminar, Bordeaux, *On the Backward Uncertainty Quantification problem*, March 2015
  - Seminar, Laboratoire Jacques Louis Lions, UPMC, December, Paris, 2015
  - Minisymposium talk, 1st Pan-American Congress on Computational Mechanics, Buenos Aires, Argentina, April 27-29, 2015
- Jessica Oakes
  - Invited talk, Computational Fluid Dynamics in Medicine and Biology. Albufeira, Portugal. September 2015
  - Seminar, University at Buffalo, December 2015
  - Seminar, University of California, Los Angeles. November 2015
  - Seminar, University of California, Irvine. October 2015
  - Seminar, University of Arizona, Tucson. February 2015

  - Seminar, University of California, Davis. January 2015
  - Contributed talk 13th U.S. National Congress on Computational Mechanics. San Diego, California. July 2015
  - Contributed talk 4th International Conference on Computational and Mathematical Biomedical Engineering. June 2015
  - Poster, International Society of Aerosol Medicine. Munich, Germany. June 2015
- Sanjay Pant
  - Seminar, King's College London, UK, October 2015
  - Seminar, Great Ormond Street Hospital, London, UK, October 2015
  - Contributed talk, 13th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering, CMBBE , Montreal, Canada, September 2015
  - Contributed talk, 4th International Conference on Computational & Mathematical Biomedical Engineering, CMBE, Cachan, France, June–July, 2015
- Nicolas Pozin
  - Poster, 20th International Congress on Aerosols in Medicine and Pulmonary Drug Delivery, May 30 - June 3, 2015, Munich, Germany
- Marc Thiriet
  - Invited speaker, Second Tbilisi-Salerno Workshop on Modeling in Mathematics, Tbilisi, Mars 16-18, 2015
  - Keynote speaker, First Computational Mechanics Conference in Taiwan (ACMT), minisymposium MS017. Computational Biomedicine and Biomechanics, October 21–23, 2015, National Taiwan University, Taipei
  - Invited speaker, First Computational Mechanics Conference in Taiwan (ACMT), minisymposium MS017. Computational Biomedicine and Biomechanics, October 21–23, 2015, National Taiwan University, Taipei
- Eliott Tixier
  - Invited speaker, Lions-Magenes Days Scientific Meeting, April 13-14, 2015, Pavia, Italy.
  - Minisymposium talk, 1st International Conference on Uncertainty Quantification in Computational Sciences (UNCECOMP 2015), May 25-27, 2015, Crete Island, Greece.
  - Minisymposium talk, 4th International Conference on Computational & Mathematical Biomedical Engineering (CMBE 2015), June 29 - July 1, 2015, Cachan, France.
- Marina Vidrascu
  - Invited speaker, Workshop on numerical approximations of PDEs Honoring the 60th birthday of Fréderic Hecht, Málaga, Apri20-22
  - Invited speaker, Progrès récents en mécanique des fluides numérique. Colloque en l'honneur d'Alain Dervieux, april 10, Inria Sophia-Antipolis
- Irène Vignon-Clementel
  - Invited talk, Workshop DHU Hepatinov, Dec. 4th, Paul Brousse Hospital, Villejuif, France
  - Invited talk, CEA-GAMNI workshop, Feb. 5th, Paris, France
  - Invited talk, Computational Fluid Dynamics (CFD) in Medicine and Biology II, Sept. 2nd, Albufeira, Portugal
  - Seminar, Laboratoire Jacques Louis Lions, UPMC, April 3rd, Paris, France
  - Seminar, Paul Brousse Hospital meeting with ESPCI, March 16th, Villejuif, France
  - Talk, 4th International Conference on Computational & Mathematical Biomedical Engineering, July, Cachan, France

  - Evaluation seminar, ANR iFLOW midterm review, Nov 3rd, Paris, France

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence :

- Chloé Audebert
  - Sequences and series of functions, series, generalised integrals, 20h, L2-CNED, UPMC
- Laurent Boudin
  - Introduction to series for signal theory, 18h, L2, UPMC
  - Shared studies supervision in mathematics licence for approximately 500 students, 30h, L2-L3, UPMC
  - Mathematics licence supervision of all the “Double majeure” intensive bi-disciplinary curriculum, 4h, L2, UPMC
- Muriel Boulakia
  - Scilab, 35h, L2, UPMC
  - Hilbertian analysis, 30h, L3, Polytech’Paris
  - Oral tests in numerical analysis, 20h, L3, UPMC
- Miguel Ángel Fernández Varela
  - Scientific Computing, 32h, L3, ENPC
  - Analysis and Scientific Computing, 31h, L3, ENPC
- Céline Grandmont
  - Professional insertion and orientation, 24h, L2, UPMC
  - EDO, 24h, L3, UPM
- Damiano Lombardi
  - Numerical methods, 48h, L3, Polytech’Paris
- Eliott Tixier
  - Matrix calculus, 36h, L1, UPMC
  - Linear algebra, 60h, L2, UPMC
- Irène Vignon-Clementel
  - Mathematics for biology, 54h, L1, Université de Versailles Saint Quentin
  - Numerical simulations of blood flow, 1,5h, 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
- Jean-Frédéric Gerbeau
  - Numerical methods in hemodynamics (20h), M2, UPMC / Univ Paris-Sud / Ecole Polytechnique.

- Seminar for the M2 students of the master “Math SV” (1h), M2, Univ Paris-Sud, December, 2015
- Seminar for the Ecole des Mines students (3h), M2, Paris, February, 2015

Thematic schools:

- Laurent Boudin
  - Invited lecturer: "Aerosol in the lung: what mathematics can bring", Univ. Pavia, Italy. 4h. Doctoral level
- Miguel Ángel Fernández Varela
  - Invited lecturer: Summer school on "Control and numerics in fluid-structure interaction problems", TFIR CAM, Bangalore, India, June 22-26, 2015. 10h. Master and doctoral level
  - Invited lecturer: Autumn School on "Data driven computations in the life sciences", IST, Lisbon, Portugal, November 9-13, 2015. 7,5h. Master and doctoral level
- Céline Grandmont
  - Invited lecturer: Summer school on "Control and numerics in fluid-structure interaction problems", TFIR CAM, Bangalore, India, June 22-26, 2015. 10h. Master and doctoral level
  - Invited lecturer: CEMRACS "Coupling multi-physics models involving fluids", July 20 - August 28, 2015, CIRM, Marseille. 6h. Master and doctoral level

10.2.2. Supervision

PhD: Justine Fouchet-Incaux, Mathematical and numerical modeling of the human breathing, Supervisors: C. Grandmont & B. Maury, Defended on April 2015, Orsay.

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

PhD in progress: Francesco Bonaldi, *Modélisation Mathématique et Numérique de Multi-Structures avec couplage Magnéto-Electro-Thermo-Elastique*, since October 2013, Supervisors: F Krasucki & M. Vidrascu

PhD in progress: Mikel Landajuela, *Coupling schemes and unfitted mesh methods for fluid-structure interaction*, since October 2012, 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 2014. Supervisors: J-F. Gerbeau & Damiano 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.

10.2.3. Juries

- Laurent Boudin
  - Member of the PhD committee of Justine Fouchet-Incaux, Univ. Paris-Sud, April 2015
- Muriel Boulakia
  - Member of the PhD committee of Gwladys Ravon, Inria Bordeaux Sud-Ouest (referee)
- Jean-Frédéric Gerbeau

  - PhD committees: Francesco Ballarin, Politecnico di Milano (referee); Romain Lacroix, SupTelecom (referee); Alessandra Menafoglio, Politecnico di Milano; Victorien Menier, UPMC (chairman); Simone Palamara, Politecnico di Milano; Alexander Serov, Ecole Polytechnique (referee).
  - Hiring committee: Inria Rennes (CR2); UTC (Assistant Professor).
- Céline Grandmont
  - Hiring committee: Toulouse Univ. (Professor position), Bordeaux Univ. (Head of the hiring committee, Professor position), Orleans Univ. (Professor position).
  - Phd Referee: Philipp Nägele, Friburg University, Germany, June 2015
  - HDR Committee: Muriel Boulakia, UPMC, October 2015
- Marc Thiriet
  - Member of the PhD committee of Sami Hached, Ecole Polytechnique de Montréal (referee)
  - Member of the PhD committee of Tamara El Bouti, Université de Versailles Saint Quentin en Yvelines (referee)
  - Member of the PhD committee of Mohammad Haddadi, Université Paris Est–Créteil (referee)
  - President of thematic comittee CT3 (Biomedical Simulation and Applications to Health) of GENCI (Grand Equipement National de Calcul Intensif – National Large Equipement for Intensive Computation).
  - Member of Evaluation Groups of the Canadian Granting Agency NSERC
- Irène Vignon-Clementel
  - Member of the PhD committee of Damon Afquari, Universidad Politecnica de Madrid, Spain, December 2015
  - Member of the PhD committee of Stephanie Lindsey, Cornell University, USA, August 2015
  - Member of the PhD committee of Tamara El Bouti, Université Versailles Saint Quentin, July 2015

10.3. Popularization

- Matteo Aletti
  - presentation, "Raconte-moi ta thèse", Fête de la science, October 10th, 2015, Paris, France
- Chloé Audebert
  - poster session, Journée "Correspondances", Projet PEPS-égalité "Correspondances de Langlands", April 10th, 2015, Paris, France
  - presentation, "Raconte-moi ta thèse", Fête de la science, October 10th, 2015, Paris, France
- Jessica Oakes
  - Tutor and mentor to an under-represented minority student struggling in mathematics (1h per week)
  - SECO: Visit local elementary schools to assist students with hands on science activities (1h per month)
- Irène Vignon-Clementel
  - Intervention at the conference "Research: challenges and adventures", at which the research national strategic plan was presented to the French Prime Minister, in presence of the Minister for Education, Higher Education and Research, Dec 14th., Paris, France https://www.inria.fr/actualite/actualites-inria/la-strategie-nationale-de-recherche-presentee-au-premier-ministre

11. Bibliography

Major publications by the team in recent years

[1] L. BOUDIN, L. DESVILLETTES, R. MOTTE. *A modeling of compressible droplets in a fluid*, in "Commun. Math. Sci.", 2003, vol. 1, n^{o} 4, pp. 657–669

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