



INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

*Project-Team reo*

*Numerical simulation of biological flows*

*Paris - Rocquencourt*

Theme : Observation, Modeling, and Control for Life Sciences

*Activity*  
*R* *eport*

2010



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# 1. Team

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# 2. Overall Objectives

## 2.1. Introduction

REO is a joint project of the INRIA Research Center of Paris-Rocquencourt and the Jacques-Louis Lions Laboratory (LJLL) of the Pierre and Marie Curie (Paris 6) University. Its research activities are aimed at

- modeling some aspects of the cardiovascular and respiratory systems, both in normal and pathological states;
- developing and analyzing efficient, robust and reliable numerical methods for the simulation of those models;
- developing simulation software to guide medical decision and to design more efficient medical devices.

## 2.2. Highlights

- J-F. Gerbeau was awarded the 2010 Alcan prize by the French Academy of Sciences (shared with T. Lelièvre, Ecole des Ponts ParisTech)
- C. Grandmont got a position of *Directeur de Recherche*
- L. Dumas got a position of Professor at UVSQ.
- M. Fernández defended his habilitation thesis (HDR).

## 3. Scientific Foundations

### 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.

Because of the above mentioned difficulties, the interaction between the blood flow and the artery wall has often been neglected in most of the classical studies. The numerical properties of the fluid-structure coupling in blood flows are rather different from other classical fluid-structure problems. In particular, due to stability reasons it seems impossible to successfully apply the explicit coupling schemes used in 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.

#### 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 [55] in the frame of combustion. It was later used to develop the Kiva code [41] at the Los Alamos National Laboratory, or the Hesione code [50], for example. It has a wide range of applications, besides the nuclear setting: diesel engines, rocket engines [47], 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 [51]. 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 <sup>1</sup>. One of our objectives is to couple artery models with this heart model.

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<sup>1</sup><http://www-sop.inria.fr/CardioSense3D/>

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 plan to mix arbitrary Lagrangian Eulerian and fictitious domain approaches, 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 [54], and Biot [42] 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 already been proposed (see references in [17]), 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 to develop a multiscale modeling of the respiratory tract. Intraparenchymal airways distal from generation 7 of the tracheobronchial 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 these 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 of 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 through 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. This activity has been carried out in the framework of successive research programs: RNTS “R-MOD” until 2005, ACI “le-poumon-vous-dis-je” until 2007 and ANR M3RS until 2013.

### 4.3. Cardiac electrophysiology

The numerical simulation of the electrical activity of the heart is a new topic in our team. It is motivated by our participation in the CardioSense3D project and by a collaboration initiated with the ELA Medical company (pacemaker manufacturer).

Our 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.* [49], [53], [52] 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). Our strategy is to select the level of complexity with respect to the “numerical electrocardiograms” produced by the model. We are also interested in various clinical and industrial issues related to cardiac electrophysiology.

## 5. Software

### 5.1. LiFE-V library

**Participants:** Julien Castelneau, Miguel Ángel Fernández Varela [correspondant], Jean-Frédéric Gerbeau.

LiFE-V<sup>2</sup> 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.

### 5.2. Mistral library

**Participants:** Cristóbal Bertoglio Beltran, Alfonso Caiazzo, Jean-Frédéric Gerbeau [correspondant], Vincent Martin, Joaquín-Alejandro Mura Mardones.

Mistral is a finite element library which implements in particular fluid-structure interaction algorithms (ALE and Fictitious domain formulations), fluid surface flow (ALE) and incompressible magnetohydrodynamics equations. Mistral results from a collaboration between INRIA and ENPC (CERMICS).

## 6. New Results

### 6.1. Mathematical analysis of fluid-structure interaction problems

**Participant:** Muriel Boulakia.

- In [46], which will appear in *J. Math. Pures App.*, we consider the interaction between a compressible fluid modeled by the compressible Navier-Stokes equations and an elastic structure. Contrarily to most of the other studies, we do not add extra regularizing terms. For this problem, we obtain the local in time existence and the uniqueness of strong solutions.
- In [40], we study the interaction between an incompressible Navier-Stokes fluid and an elastic structure whose displacement is approximated by a finite number of modes. We prove the local in time existence of strong solutions.

<sup>2</sup><http://www.lifev.org/>

## 6.2. Numerical methods for fluid mechanics. Application to blood flows

**Participants:** Alfonso Caiazzo, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Vincent Martin, Joaquín-Alejandro Mura Mardones, Marc Thiriet, Irène Vignon-Clementel.

- [35]: We analyze the Pressure Stabilized Petrov-Galerkin (PSPG) finite element approximation of the Stokes equation with an interface resistive term (modeling the presence of a porous interface). We show that this method is stable and optimally convergent, without the need for controlling the pressure jump across the interface.
- [31]: We perform the simulation of the fluid-structure interaction between the blood, the artery wall and the stent. The main difficulty in this problem is the numerical solution for the isolated portion of fluid, where the explicit coupling with standard Dirichlet-Neumann boundary conditions may lead to non uniqueness for the intra-aneurysm pressure and also to violate the divergence free condition. To address this issue we use Robin-Neumann conditions for the coupling.
- [36]: We propose two incremental displacement-correction schemes for the explicit coupling of a thin structure with an incompressible fluid. Their stability and accuracy properties are analyzed and numerically confirmed in a benchmark.
- [30]: The aim of this work is to propose a model reduction technique to perform faster patient-specific simulations with prior knowledge built from simulations on an average anatomy. Rather than simulating a full fluid problem on individual patients, we create a representative ‘template’ of the artery shape. A full flow simulation is carried out only on this template, and a reduced model is built from the results. Then this reduced model can be transported to the individual geometries, allowing faster computational analysis.
- [24]: We present some numerical methods to solve the equations of steady and unsteady flows, such as those in the microcirculatory bed and large blood vessels (arteries and veins).
- [25]: While most cardiovascular modeling work focuses on periodic solutions, this paper studies natural and abnormal non-periodic phenomena, including patient-specific cases. The relevance of using boundary conditions that accommodate transient phenomena compared with boundary conditions that assume periodicity of the solution is discussed.
- [26]: This paper is meant to be a communication tool between clinicians and applied mathematicians/engineers. It describes the main steps of a successful collaboration, presenting state of the art simulation tools and clinical data incorporation. Although conceptually more general, this article is illustrated by novel predictive computer simulations in congenital heart disease.
- [33]: In this work, multiscale simulations of tumor growth are performed to study the influence of vascularization and angiogenesis on tumor cells development. The model includes the cellular (individual cells and vessels, development and death) and the molecular (oxygen, glucose and angiogenic growth factors reaction/diffusion) interplays.
- [17]: This paper presents a new energy formulation for the fluid-solid interaction in porous media, valid for finite deformations in the incompressible limit. In addition to swelling and drainage tests, a three-dimensional case of a typical active ventricle is presented, which results exhibit the complex temporal and spatial interactions of the muscle and blood, reproducing several key phenomena observed in cardiac perfusion.
- [22] [21] [48]: These three papers present a number of modeling and computational tools to simulate blood flow and pressure in deformable patient-specific models of the aorta and the coronary arteries (feeding the heart). Using a lumped parameter coronary vascular model along with the inflow boundary condition that couples the lumped parameter heart model and the closed loop system of the circulation, we can predict coronary flow and pressure realistically using anatomic data obtained from medical imaging techniques and study how changes in cardiac and arterial properties affect coronary flow and pressure and vice versa. Rest and exercise conditions are studied.
- [18]: A patient-specific study is held to provide quantitative and qualitative informations about effects of pulmonary deformation on blood flow. This study shows, for the first time from a patient-specific numerical study, how pneumothorax can affect hemodynamics in pulmonary arteries.

### 6.3. Numerical methods for cardiac electrophysiology

**Participants:** Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Muriel Boulakia, Nejib Zemzemi.

- [15]: We present a mathematical model, based on partial differential equations, which is able to provide realistic healthy 12-lead electrocardiograms (ECG). The ECGs corresponding to some pathologies, like bundle branch blocks, are also successfully simulated.

### 6.4. Lung and respiration modeling

**Participants:** Laurent Boudin, Céline Grandmont, Marc Thiriet.

- [29]: This study presents a numerical investigation of basic interactions between respiratory mucus motion, air circulation and epithelium ciliated cells vibration.
- [43]: This work presents a result of global existence for weak solutions of the three-dimensional incompressible Vlasov-Navier-Stokes equations related to the aerosol-air interaction in the human lung.
- [27]: This article investigates the influence of a spray moving in the air. The main focus is the term of retroaction of the spray on the air. Some realistic situations for which the spray retroaction may not be neglected are exhibited.
- [28]: This paper focuses on two different diffusion models for multicomponent mixtures, Fick's and Maxwell-Stefan's. We illustrate the second type of model in various situations, such as a mixture of inhaled helium and oxygen (in the case of chronic obstructive bronchopneumopathies).
- [38]: We consider the Maxwell-Stefan model of diffusion previously introduced. We provide a qualitative and quantitative mathematical and basic numerical analysis of the model.

### 6.5. Miscellaneous

**Participant:** Laurent Boudin.

- [44]: We use the methods of nonequilibrium statistical mechanics in order to derive an equation which models some mechanisms of opinion formation through collisional Boltzmann-like operators. After proving the main mathematical properties of the model, we provide some numerical results.
- [45]: This paper is devoted to the study of the asymptotic behavior of the previously defined kinetic model for opinion formation. By supposing that the effects of self-thinking and compromise are very weak, we deduce simpler models who lose the kinetic structure, and study the asymptotic state of the equations.
- [14]: We deal with a kinetic model to describe the evolution of the opinion in a closed group with respect to a choice between multiple options, e.g. political parties, which takes into account two main mechanisms of opinion formation, namely the interaction between individuals and the effect of the mass media. We provide an existence and uniqueness result for the model and numerically test it in some relevant cases.
- [32]: This is a review article on kinetic models for opinion formation and more generally for sociophysics, .
- [39]: We investigate the numerical solution of the one-dimensional pressureless gases (or Euler pressureless) equations, which are a hydrodynamical limit for sticky particles. We point out that the natural upwind scheme does not satisfy the mathematically required one-sided Lipschitz (OSL) condition on the expansion rate, and consequently propose a diffusive scheme which allows to recover this OSL condition.
- [37]: We propose suitable parallel in time algorithms coupled with reduction methods for the stiff differential systems integration arising in chemical kinetics. Numerical efficiency of the approach is illustrated by a realistic ozone production model.

## 7. Other Grants and Activities

### 7.1. National Initiatives

#### 7.1.1. ANR Project “M3RS”

**Participants:** Laurent Boudin, Muriel Boulakia, Paul Cazeaux, Anne-Claire Egloffé, Céline Grandmont [Principal Investigator].

Period: 2008-2013.

This project, coordinated by C. Grandmont, aims at studying mathematical and numerical issues raised by the modeling of the lungs.

#### 7.1.2. ANR Project “Endocom”

**Participants:** Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau [correspondant], Joaquín-Alejandro Mura Mardones.

Period: 2008-2012.

This project <sup>3</sup> is funded by the TECSAN call (health technology) of the ANR. It aims at developing a pressure sensor embedded on an endoprosthesis.

#### 7.1.3. ANR Project “PITAC”

**Participants:** Laurent Boudin, Miguel Ángel Fernández Varela [correspondant].

Period: 2007-2011.

This project <sup>4</sup> is funded by the CIS call (High-Performance Computing and Simulation) of the ANR. It aims at developing and studying parallel-in-time numerical methods.

#### 7.1.4. INRIA Research Collaborative Action “Sirap”

**Participants:** Miguel Ángel Fernández Varela, Alfonso Caiazzo, Jean-Frédéric Gerbeau [Principal Investigator], Romain Guibert, Irène Vignon-Clementel.

Period: 2009-2010.

This project is in collaboration with Dr. Younes Boudjemline (Necker Hospital Paris) and project-team Asclepios. Its aim is to model and design an endovascular reducer for pulmonary artery outflow tract.

### 7.2. European Initiatives

#### 7.2.1. European Integrated Project “euHeart”

**Participants:** Matteo Astorino, Cristóbal Bertoglio Beltran, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau [correspondant].

Period: 2008-2012

REO is a member of the Integrated Project “euHeart”<sup>5</sup> whose goal is the development of individualized, computer-based, human heart models. The project euHeart consists of seventeen industrial, clinical and academic partners. REO is specifically involved in the modeling and simulation of cardiac valves and aorta (including inverse problems).

### 7.3. International Initiatives

#### 7.3.1. Trans-Atlantic Network of Excellence for Cardiovascular Research

**Participants:** Grégory Arbia, Matteo Astorino, Jean-Frédéric Gerbeau, Irène Vignon-Clementel [correspondant].

Period: 2010-2014

This network, funded by the Leducq fondation, is working on the multi-scale modeling of single ventricle hearts for clinical decision support<sup>6</sup>.

<sup>3</sup><http://www.endocom.upmc.fr>

<sup>4</sup><http://www.ann.jussieu.fr/PITAC/><http://www.ann.jussieu.fr/PITAC/>

<sup>5</sup><http://www.euheart.eu/>

### 7.3.2. Foreign Associated Team “Cardio”<https://idal-siege.inria.fr/cardio/> (INRIA/Stanford)

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

Period: 2008-2011.

The aim of this project is to foster the collaboration between the Cardiovascular Biomechanics Research Laboratory (CVBRL) of C.A. Taylor (Stanford University, USA) and the project-team REO, through research on cardiovascular related topics (boundary conditions for complex flow [21], [25], [22], patient-specific modeling of congenital heart disease, image-based fluid solid interaction, postprocessing of numerical simulations).

## 7.4. Visiting professors and invited researchers

- Leif Rune Hellevik has been a visiting professor until August 2010.
- Francesco Salvarani has been a visiting professor until June 2010.

# 8. Dissemination

## 8.1. Animation of the scientific community

- L. Boudin
  - Service activity in universities: member of two selection committees of UPMC, member of the board of the *Licence* of Mathematics Department (since July 2010).
- J-F. Gerbeau
  - Editorial boards : *ESAIM Proceedings* (editor-in-chief), *Mathematical modeling and Numerical Analysis M2AN*, *International Journal for Numerical Methods in Biomedical Engineering*, *Communications in Applied and Industrial Mathematics*
  - Service activity at INRIA: Member of the evaluation committee of INRIA; Vice-president of the project-teams committee at INRIA Paris-Rocquencourt.
  - Service activity in Universities: Member of the board of the Department of Mathematics of Paris 6 University (*conseil de l’UFR 929*), member of the Reference Committee of the PhD program *Mathematical Models and Methods in Engineering* (Politecnico di Milano, Italy).
  - Thesis committees: M. Fernández (HDR, Paris 6), Anne Devys, Univ. Lille 1 (president), Sebastian Minjeaud, Univ. Paul Cézanne (reviewer), Mehmet Ersoy, Univ. Chambéry (reviewer), Matteo Astorino, Paris 6 (supervisor).
- C. Grandmont
  - Vice-president of the jury for young researchers positions at INRIA Rocquencourt.
  - Member of the program committee for 4 years of the “forum des jeunes mathématiciennes”.
- M. Thiriet
  - Editorial board: *Computer Methods in Biomechanics and Biomedical Engineering*.
  - President of thematic committee 3 of GENCI (High Performance Computing of Education Ministry, France) and member of Scientific Users Selection Panel for the HPC-Europa2 project.
  - Head of ERCIM “IM2IM” working group.

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<sup>6</sup><http://modelingventricle.clemson.edu/home>

- I. Vignon-Clémentel
  - Organized the national INRIA meeting for innovative research and technological development initiatives, France, Nov 29th-Dec 1st
  - Organizing the monthly seminar at INRIA Paris-Rocquencourt on “modeling and scientific computing”. Co-organizing the weekly internal seminar at INRIA Paris-Rocquencourt “openBang” to foster cross-knowledge between the researchers at INRIA that work on bio-related topics
  - Member of the “Conseil d’orientation scientifique et technologique” (scientific and technologic orientation council) of l’INRIA, in the subgroup “GT Actions Incitatives” (incentive action working group)
  - Mediator between PhD students and their supervisors for INRIA Paris-Rocquencourt, presentation October 21st to new PhD students
  - Coordinator of the associated team CARDIO between REO and Prof. Taylor’s lab at Stanford University, USA.

## 8.2. Teaching

- Muriel Boulakia
  - “Initial training” (64h), Ecole d’ingénieurs Polytech’Paris
  - “Hilbert Analysis” (14h), Ecole d’ingénieurs Polytech’Paris
- Laurent Boudin
  - Supervisor of the bidisciplinary computer science / applied maths licence program (20h), UPMC, partially with Brown Univ
  - “Series and integrals” (30h), L2, UPMC
  - “Functions of several variables and multiple integrals” (72h), L2, UPMC
  - “Hilbertian analysis” (16h), L3, Polytech’Paris
  - “Introduction to numerical analysis” (36h), L3, UPMC
  - “Numerical analysis” (75h), M1, Polytech’Paris
- Céline Grandmont
  - “Fluid-Structure interaction” (10 h), Master 2, Paris 6 Univ.
- Miguel Á. Fernández
  - “Numerical methods in bio-fluids”, (6h), Master of Mathematical Methods and Numerical Simulation in Engineering and Applied Sciences, University of Vigo, Spain
  - “Scientific computing”, (30h), École Nationale des Ponts et Chaussées
  - “Inverse problems”, (44h), Ecole Supérieure d’Ingénieurs Léonard de Vinci
- Marc Thiriet
  - “Biofluid flows” (12 h) University Pierre et Marie Curie.
  - “Biomechanical and biomathematical modeling”, Winter school of Biomathematics, University of La Habana, Cuba, february 2010.
  - “Computer-aided medicine and surgery” (3h), Ecole Centrale de Nantes, March, 2010.
  - “Modeling and simulations of physiological flows” (36 h), Taida Institute of Mathematical Science (TIMS), Department of Mathematics, National Taiwan University
- Irène Vignon-Clementel

- “Different types of model for blood flow simulations” (3h15), May 11th, Ecole Centrale Paris, France

### 8.3. Participation in conferences, workshops and seminars

- Matteo Astorino
  - Contributed talk at “MPF2010 - IV International Symposium on Modelling of Physiological Flows”, June 2nd–5th, 2010, Sardinia island, Italy.
- Laurent Boudin
  - Contributed talk in a Mini-symposium at ECCM 2010, May 16–21, 2010, Paris, France.
  - Keynote lecture at METHODS AND MODELS OF KINETIC THEORY Summer school, June 14–19, 2010, Porto Ercole, Italy.
  - Seminar, Applied analysis, LATP, Univ. Aix-Marseille, September 14, 2010, Marseille, France.
  - Contributed talk, intern reseach day, LJLL, UPMC, October 7, 2010, Paris, France.
- Cristoba Bertoglio
  - Contributed talk at "IV European Conference on Computational Mechanics", Paris, France, May 16th-21st, 2010.
  - Contributed talk at "IV International Symposium on Modelling of Physiological Flows", June 2nd–5th, 2010, Sardinia island, Italy.
- Muriel Boulakia
  - Workshop on Control, UPMC Paris 6, January, 2010
  - Seminar, University Pau, May, 2010
  - Talk at Foundation Sciences Mathématiques, Paris, May, 2010
  - REO Workshop, November, 2010
- Alfonso Caiazzo
  - Contributed talk at “Workshop on Numerical Analysis of PDE”, January 11-15th, 2010, Concepcion, Chile.
  - Contributed talk at “MPF2010 - IV International Symposium on Modelling of Physiological Flows”, June 2nd–5th, 2010, Sardinia island, Italy.
- Miguel Ángel Fernández
  - Invited, Consulting Conference on Mathematics for Industry and Institutions, November 8–10, 2010, Santiago de Compostela, Spain.
  - Invited, Summer School on Mathematical Modeling and Numerical Simulation of the Cardiovascular System, July 7–9, 2010, A Coruña, Spain.
  - Seminar, Applied Mathematics Seminar, Collège de France, June 25, 2010, Paris, France.
  - Organization of a Mini-Symposium at the IV European Congress on Computational Mechanics (ECCM IV): Solids, Structures and Coupled Problems in Engineering, May 16–21, 2010, Paris, France.
- Jean-Frédéric Gerbeau
  - Invited lecture (2h30), School on Coupled Partial Differential Equations, Castro Urdiales, Spain, 2010



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- Invited lecture (4h), School on Math. Model. of the Cardiovascular System, A Coruña, Spain, 2010
  - Invited lecture, Trends in computational hemodynamics, EPFL, Lausanne, 2010
  - Invited lecture, 4th International Symposium on Modelling of Physiological Flows, June 2nd–5th, 2010, Sardinia island, Italy.
  - Invited lecture, Nonstandard Discretizations for Fluid Flows, Banff International Research Station, Canada, November 2010
  - Invited lecture, International workshop on Immersed boundaries and fictitious domain methods, CIRM, August 2010
  - Invited lecture, CEA Seminar of fluid mechanics, January 2010
  - Minisymposium talk, 2ème congrès international de la Société Marocaine de Math. Appli., Rabat, Morocco, 2010
  - Minisymposium talk, World Congress of Computational Mechanics (WCCM), Sydney, Australia, 2010
  - Seminar abroad: university of Münster, Germany, 2010
  - Seminars in France: université d’Orsay, Paris 6, ENS Lyon, Paris 13, Bordeaux, Versailles, Grenoble.
  - Céline Grandmont
    - Seminar, Université de Metz, February 2010.
    - Seminar, Université de Clermont Ferrand, March 2010.
    - Seminar, Collège de France, June 2010.
    - Invited speaker “Journée Fluides complexes”, Marseille, March 16, 2010.
    - Organizer of a Mini-symposium at CANUM 2010, Carcans-Maubuisson, June 2010.
    - Invited speaker at “International Workshop in Fluid-Structure Interaction Problems”, Caldas de Rainha, Portugal, 05-08/09/2010.
    - Seminar, Université d’Orléans, December 2010.
  - Joaquin Mura
    - Contributed Talk at Rencontre scientifique du Groupes de Recherche (GDR): Interaction Fluide Structure Biologique, June 3–4th 2010, Université de Technologie de Compiègne, France.
    - Contributed Talk at V European Conference on Computational Fluid Dynamics ECCOMAS CFD, June 14–17th 2010, Lisbon, Portugal.
  - Marc Thiriet
    - Seminar, Warsaw Polytechnique University, November 10, 2010, Poland.
    - Invited talk in a minisymposium, 12th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI 2009), 20–24 septembre 2009, Imperial College, London, UK.
    - Invited talk, 9th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering, 24-27 February, 2010, Valencia, Spain.
    - Cuba, Winter school of biomathematics (6 h), University of La Habana, February 2010 (“Blood and air flows: from biomechanical simulations (patient-specific macroscopic scale investigations) to biomathematical approaches (coupling of short-term cell reactions at nano- and microscopic scales to flow-induced stresses)”).

- Irène Vignon-Clementel
  - Invited talk, 1st International Conference on Computational Simulation in Congenital Heart Disease, February 26-27th, La Jolla, USA
  - Keynote speaker at a minisymposium, ECCOMAS 2010 conference, May 17th-21th, Paris, France
  - Invited talk, Workshop on “MRI-CFD coupling”, May 20th, London, UK
  - Poster presentations, “MedSys Evaluation Conference”, June 1st-2nd, Freiburg, Germany
  - Invited talk (congenital heart disease CFD), 6th World Congress on Biomechanics, August 1st-6th, Singapore
  - Contributed talk (tumor growth), 6th World Congress on Biomechanics, August 1st-6th, Singapore
  - Seminar, Institut Camille Jordan, Mathematics Lyon 1, October 19th, Lyon, France
- Nejib Zemzemi
  - Minisymposium talk, World Congress of Computational Mechanics (WCCM), Sydney, Australia, 2010

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### Major publications by the team in recent years

- [1] L. BOUDIN, L. DESVILLETES, R. MOTTE. *A modeling of compressible droplets in a fluid*, in "Commun. Math. Sci.", 2003, vol. 1, n<sup>o</sup> 4, p. 657–669.
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- [5] P. CAUSIN, J.-F. GERBEAU, F. NOBILE. *Added-mass effect in the design of partitioned algorithms for fluid-structure problems*, in "Comp. Meth. Appl. Mech. Engng.", 2005, vol. 194, n<sup>o</sup> 42-44.
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## Publications of the year

### Doctoral Dissertations and Habilitation Theses

- [12] M. ASTORINO. *Fluid-structure interaction in the cardiovascular system. Numerical analysis and simulation*, Université Paris 6, 2010.
- [13] M. A. FERNÁNDEZ VARELA. *Contributions aux méthodes numériques pour les problèmes couplés et les écoulements incompressibles*, Université Paris 6, 2010, Habilitation thesis, Ph. D. Thesis.

### Articles in International Peer-Reviewed Journal

- [14] L. BOUDIN, R. MONACO, F. SALVARANI. *A kinetic model for multidimensional opinion formation*, in "Physical Review E: Statistical, Nonlinear, and Soft Matter Physics", March 2010, 036109 [DOI : 10.1103/PHYSREVE.81.036109], <http://hal.inria.fr/hal-00426284/en>.
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- [32] L. BOUDIN, F. SALVARANI. *Modelling opinion formation by means of kinetic equations*, in "Mathematical Modeling of Collective Behavior in Socio-Economic and Life Sciences", Springer, July 2010, p. 245-270 [DOI : 10.1007/978-0-8176-4946-3\_10], <http://hal.inria.fr/hal-00447659/en>.
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### Research Reports

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