INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team reo

Numerical simulation of biological flows

Paris - Rocquencourt

THEME BIO

Activity Report

2008

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REO is a joint project of the INRIA Research Unit of Rocquencourt and the Jacques-Louis Lions Laboratory (LJLL) of the Pierre et Marie Curie (Paris 6) University.

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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 of the year

- A book (2 volumes, 652 p. and 464 p.) authored by Marc Thiriet was published by Springer.
- Jean-Frédéric Gerbeau received the *Pierre Faurre Prize 2008*[1], awarded by the French Academy of Sciences.
- Guillaume Troïanowski received the *Grand Prix de Recherche* 2008 in Applied Mathematics, awarded by the *Ecole Polytechnique* for his internship co-supervised by I. Vignon-Clementel and C. Taylor (Stanford Univ.).
- Jimmy Mullaert received the *Prix du Stage de Recherche* 2008 in Applied Mathematics, awarded by the *Ecole Polytechnique* for his internship co-supervised by M.A. Fernández and Y. Maday (Univ. Paris 6).
- Matteo Astorino received the best master student award in mathematical engineering from the *Associazione Laureati Politecnico*.
- Michael Grasseau and Elsie Phé received a *Materialise Pyramid Award*, awarded by the Materialize company [2].
- Laurent Dumas defended his *Habilitation à Diriger des Recherches* (HDR) entitled *From particle trajectories to global optimization under PDE constraints*
- I. Vignon-Clementel, J.-F Gerbeau and C. Taylor (Stanford Univ.) organized an international workshop on "blood and air flow modeling in complex moving geometries" [3]. The workshop was attended by about 60 persons from all over the world, including non-speaker attendees from all over Europe.

3. Scientific Foundations

3.1. Multiphysics modeling

Keywords: *analysis of PDE*, *fluid-structure interaction*, *numerical analysis*, *spray 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 the 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.

[1] http://www.academie-sciences.fr/prix/prix_thematiques_gal.htm
[2] http://www.materialise.com/materialise/view/en/1891538-Winners+Materialise+Pyramid+Awards+Revealed.html
[3] http://www-rocq.inria.fr/bloodairflow

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, we have to deal with very large displacements and changes of topology (contact problems).

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 fuid-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 diphasic 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 [65] in the frame of combustion. It was later used to develop the Kiva code [53] at the Los Alamos National Laboratory, or the Hesione code [60], for example. It has a wide range of applications, besides the nuclear setting: diesel engines, rocket engines [56], therapeutic sprays, *etc*. One of the interests of such a modeling 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, preliminary investigations are currently carried out in our team 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 [62]. 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 1D models that generalize the work reported in [57] to general geometries coming from medical imaging.

When modeling the arterial tree, a standard way consists in 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, is currently developed in the CardioSense3D project [4]. 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 simulate the aortic valve. To this purpose, we plan to mix arbitrary Lagrangian Eulerian and fictitious domain approaches.

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.

To perform simulations on this complex system, at the macroscopic scale we will assume that myocardial tissue and small coronary vessels can be approximated as a poroelastic medium. Thus, in this perfusion model, Darcy law for porous media is coupled to the heart structural model to link the fluid velocity to the fluid pressure gradient. The permeability of the medium takes into account the deformation of the skeleton.

3.2.3. Respiratory tract modeling

We aim to develop a multiscale modeling 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

Keywords: *blood flows*, *cardiovascular system modeling*.

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

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

Keywords: *lungs modelling*, *respiration*.

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. 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. Electrophysiology of the heart

Keywords: *bidomain equations*, *electrocardiograms*, *heart 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.* [59], [64], [63] 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 pacemakers.

5. Software

5.1. LiFE-V library

Keywords: *Finite element library*.

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

LiFE-V[5] 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. It has been used already in medical and industrial context to simulate fluid structure interaction and mass transport. 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.

6. New Results

6.1. Mathematical modelling and numerical methods in fluid dynamics

Keywords: *Analysis of Partial Differential Equations*, *Finite Element method*, *Fluid-structure interaction*, *Numerical analysis*, *Scientific computing*, *existence results*.

6.1.1. Existence results in fluid-structure interaction

Participants: Céline Grandmont, Muriel Boulakia.

C. Grandmont proved the existence of at least one weak solution for a coupled problem where a three-dimensional viscous incompressible fluid governed by the Navier-Stokes equations is interacting with an elastic plate located on one part of the fluid boundary. This result was published in [23].

[5] http://www.lifev.org/

M. Boulakia has been working with S. Guerrero on the theoretical analysis of a fluid-structure interaction problem. They are interested by a regularity result for an elastic structure immersed in a Navier-Stokes compressible fluid. Their results have been accepted for publication [42].

6.1.2. Numerical methods in fluid-structure interaction

Participants: Matteo Astorino, Franz Chouly, Miguel Ángel Fernández, Céline Grandmont, Jimmy Mullaert.

This activity on fluid-structure interaction is done in close collaboration with the MACS project-team.

A new version of the stabilized explicit coupling scheme, initially proposed in [55] has been reported by M. Fernández and E. Burman (University of Sussex, UK) in [16]. They now take the velocity and pressure in the Nitsche consistency term at time step n instead of $n+1$, hence this term is also treated explicitly. This allows them to perform the analysis without the interface viscous stress contribution in the time penalty stabilization. As a result, the scaling factor in front of the time penalty of the pressure takes the form $\gamma_0 h/(\gamma\mu)$, where γ_0 is now a dimensionless parameter, independent of the geometry of the domain. In the previous version γ_0 (see [55]) depended on the length-scale of the domain. It is worth noticing also the improved consistency with respect to the space discretization, due to the presence of the mesh parameter h.

In [37], C. Grandmont and M. Astorino have been working on the detailed numerical analysis of the semi-implicit numerical method, introduced in [6], for fluid-structure interaction problems arising in biological flows for which the fluid added mass acting on the structure is strong. The design of efficient and stable numerical schemes is particularly difficult to face in this context as it happens in hemodynamics for example. They have studied the scheme convergence (error estimates, numerical simulations) and have proven that the rate of convergence is at least in $O(\delta t^{1/2})$.

M. Astorino, F. Chouly and M. Fernández have proposed a semi-implicit coupling scheme for the numerical simulation of fluid-structure interaction systems involving a viscous incompressible fluid. The scheme is stable irrespectively of the so-called added-mass effect and allows for conservative time-stepping within the structure. The efficiency of the scheme is based on the explicit splitting of the viscous effects and geometrical/convective non-linearities, through the use of the Chorin-Temam projection scheme within the fluid. Stability relies on the implicit treatment of the pressure stresses and on the Nitsche's treatment of the viscous coupling. A summary of these results with some numerical illustrations have been reported in [36].

M. Fernández and J. Mullaert, in collaboration with Y. Maday (University of Paris 6), have investigated different defect-correction iterative procedures for the numerical solution of the coupled systems obtained from implicit coupling schemes [61]. The Robin-Neumann algorithm proposed in [54] is obtained as a particular case. A paper is under preparation.

6.1.3. Stabilized finite element methods in fluid mechanics

Participant: Miguel Ángel Fernández.

M. Fernández has analyzed, in collaboration with E. Burman (University of Sussex, UK) during his visit in the project-team as a visiting professor, a series of implicit and semi-implicit time-stepping methods for finite element approximations of singularly perturbed parabolic problems or hyperbolic problems. They are interested in problems where the advection dominates. Stability was obtained using a symmetric, weakly consistent stabilization operator in the finite element method. Several A-stable time discretizations have been analyzed and shown to lead to unconditionally stable and optimally convergent schemes. In particular, they showed that the contribution from the stabilization leading to an extended matrix pattern may be extrapolated from previous time steps, and hence handled explicitly without loss of stability and accuracy. A fully explicit treatment of the stabilization term was obtained under a CFL condition. These results and some numerical experiments have been reported in [34].

In collaboration with A. Ern (ENPC), they are now investigating the fully explicit treatment of the stabilization and the advection terms using Runge-Kutta based methods. A paper is under preparation.

6.1.4. Numerical methods for two-fluid flows

Participant: Jean-Frédéric Gerbeau.

J.-F. Gerbeau and T. Lelièvre (ENPC and project-team Micmac) have considered a two-fluid flow problem in an Arbitrary Lagrangian Eulerian (ALE) framework. The purpose of this work was twofold: first, address the problem of the moving contact line, namely the line common to the two fluids and the wall; second, perform a stability analysis in the energy norm for various numerical schemes, taking into account the gravity and surface tension effects. The problem of the moving contact line is treated with the so-called Generalized Navier Boundary Condition. Owing to these boundary conditions, it is possible to circumvent the incompatibility between the classical no-slip boundary conditions and the fact that the contact line of the interface on the wall is actually moving. The energy stability analysis is based in particular on an extension of the Geometry Conservation Law (GCL) concept to the case of moving surfaces. This extension is useful to study the contribution of the surface tension. The theoretical and computational results allow to consider a strategy which offers a good compromise between efficiency, stability and artificial diffusion. This study has been published in [22].

6.2. Respiration tree modelling

Keywords: *aerosol*, *biological flows*, *lungs*, *simulation for medicine*.

6.2.1. Airway flow

Participants: Laurent Boudin, Julien Castelneau, Céline Grandmont, Michael Grasseau, Driss Yakoubi.

A macroscopic model for a composite material made of an elastic body filled with gaseous bubbles has been published by L. Baffico, C. Grandmont, Y. Maday and A. Osses in [13]. This study is a first step towards the obtention of a viscoelastic model of the parenchyma. The next step is to connect the gaseous inclusions by a dyadic tree to take into account the bronchial tree. This will be one of the aims of a future Ph.D thesis supervised by C. Grandmont and Y. Maday (Univ. Paris 6).

A model of the air flow in the small airways, assuming that the flow is described by the Poiseuille law, has been published C. Grandmont, B. Maury and A. Soualah in [31]. They have proved that, when the velocity profiles at the outlets are given, the coupled multiscale problem is well-posed. This result has been generalized by C. Grandmont, L. Baffico and B. Maury in [38]. They have studied the well posedness of the problem, its discretization and performed $3D$ simulations on a real geometry. Moreover in [47], C. Grandmont and A. Soualah have studied the Navier-Stokes system with natural dissipative boundary conditions arising in the previous model but in the physical conditions of blood flows.

Work in progress

1. The aim of the post-doc of D. Yakoubi, supervised by C. Grandmont, is to study, in collaboration with A. Devys (project-team Simpaf, INRIA Lille), B. Maury (Univ. Orsay) a new numerical method to discretize the previous non standard natural dissipative boundary conditions. This numerical scheme is then applied to obtain numerical simulations of the air flow in the proximal part of the bronchial tree. The interest of this method is that it requires only the resolution of problems with standard boundary conditions and thus could be easily implemented in any Navier–Stokes software. This work has been initiated during the CEMRACS 2008 for which a proceeding is in preparation.
2. M. Grasseau and C. Grandmont are working on the construction of realistic geometries and meshes of the upper airway.
3. J. Castelneau and M. Grasseau are working on the parallelization of the fluid solver to perform air flow simulations in physiological conditions.

6.2.2. Modeling of the aerosol impact on the human upper airway walls

Participants: Laurent Boudin, Céline Grandmont, Michael Grasseau, Ayman Moussa, Marc Thiriet, Driss Yakoubi.

Along with L. Desvillettes (ENS Cachan), L. Boudin, C. Grandmont and A. Moussa, PhD. student supervised by L. Desvillettes and M. Filoche (CNRS Polytechnique), obtained a result of global existence for weak solutions of the three-dimensional incompressible Vlasov-Navier-Stokes equations, the coupling being done through a drag force which is linear with respect to the relative velocity of fluid and particles [39].

Works in progress:

1. During Cemracs ’08, L. Boudin, A. Devys (Lille 1 and INRIA Lille Nord Europe), C. Grandmont, B. Grec (INSA Lyon) and B. Maury (Univ. Orsay) extended the FreeFEM++ code developed in [29] to study two aspects of the aerosol flow: the behavior of particles inside the 2D domain (up to 4 bifurcations) and the influence of the aerosol on the airflow. This work is about to be submitted.
2. L. Boudin, C. Grandmont, M. Grasseau, A. Moussa and M. Thiriet are currently studying in collaboration with P. Diot and L. Vecellio (Inserm Tours U618) the behavior of an aerosol inside an experimental device U618 developed. They investigate the aerosol deposition inside the device with respect to the size distribution and average velocities of the aerosol. Our team is involved in numerical studies on a 3D mesh of the device, made by M. Grasseau, whereas U618 is conducting *in vitro* experiments.
3. L. Boudin, C. Grandmont and A. Moussa are tackling a problem close to the one of [39], but in a moving domain (ALE), i.e. a situation more realistic for the airways. Moreover, with M. Filoche, some numerical experiments are also led within this ALE framework.

6.3. Blood flows

Keywords: *biological flows*, *blood flows*, *cardiovascular system modeling*, *simulation for medicine*, *stent*, *valves*.

6.3.1. Cardiac valves simulation

Participants: Matteo Astorino, Jean-Frédéric Gerbeau.

M. Astorino, J.-F. Gerbeau and K. Traoré proposed, in collaboration with O. Pantz (Ecole Polytechnique), a partitioned procedure for fluid-structure interaction problems in which contacts among different deformable bodies can occur. A typical situation is the movement of a thin valve (*e.g.* the aortic valve, see Fig. 1) immersed in an incompressible viscous fluid (*e.g.* the blood). In the proposed strategy the fluid and structure solvers are considered as independent “black-boxes” that exchange forces and displacements; the structure solvers are moreover not supposed to manage contact by themselves. The hypothesis of non-penetration among solid objects defines a non-convex optimization problem. To solve the latter, they used an internal approximation algorithm that is able to directly handle the cases of thin structures and self-contacts. This algorithm has been published in [12].

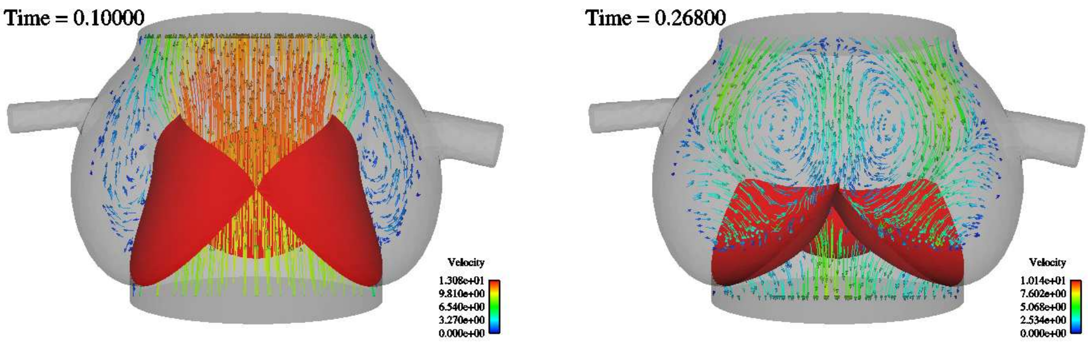

Figure 1. Fluid-structure interaction and solid-solid contact: blood velocity vectors aroung the aortic valves ([12])

6.3.2. Multiobjective optimization of a stent in a fluid-structure context

Participant: Laurent Dumas.

A stent device is a permanent metallic implant currently used to prop open arteries blocked with atherosclerotic plaques. Many classes of stents are available and mainly differ by their design. The purpose of L. Dumas, in collaboration with A. Blouza and I. M'Baye in [28], is to determine some optimal stent parameters to ensure a conforming blood flow through the stented artery. Coupling computational fluid dynamics with stochastic optimization based method is used to obtain the optimal parameters of a simplified stent. The current results indicate that there exist some important rules to fulfill in order to design appropriate stents which may avoid or at least reduce restenosis. The main rule can be summarized by saying that the characteristic ratio “strut spacing over strut height” shall be above the critical value $r_u = 5.7$ to ensure a sufficiently high wall shear stress while maintaining a low level of flow swirl. When this ratio is decreased, both performance criteria are degenerating because of the topological change of the flow between two consecutive struts.

6.3.3. Inverse problems for blood flow simulation

Participants: Cristóbal Bertoglio, Laurent Dumas, Miguel Ángel Fernández.

One-dimensional models are commonly used to model blood flows in compliant arteries. Under certain hypotheses, they provide the section area $A(t, z)$ and the flow rate $Q(t, z)$ at any longitudinal position z and time t. Such models are interesting for three main reasons: first, they drastically reduce the computational time of the 3D model, second, their two unknowns can be experimentally obtained by non invasive techniques and third, they allow to indirectly recover the blood pressure, which is known to be more difficult to measure. The general objective of [30] is to show that the parameters of this 1D model can be fitted either with the results of 3D computations or with experimental values measured at a finite number of positions z and times t. In particular, it includes the case of an artery with a large compliance step which occurs when an artery is partially obstructed by atherosclerotic plaques. By using global optimization tools associated to some error type function, it is found in particular that the knowledge of only one area section profile downstream is enough to locate the exact position of this disease portion.

Work in progress

M. Fernández and C. Bertoglio, in collaboration with Ph. Moireau (project-team MACS), have started to address the problem of personalizing a simplified linear fluid-structure interaction (FSI) model (of blood flow in a compliant artery) based on the coupling of the Stokes and the linear elasticity equations. They propose to estimate the (initial) state and parameters (e.g. wall Young modulus), from partial observations of the FSI system state (fluid velocity and pressure, solid velocity and displacement). Two different approaches have been considered: variational and sequential.

6.3.4. Perfusion of the myocardium and blood flows in coronaries

Participants: Jean-Frédéric Gerbeau, Thomas Vareschi, Irène Vignon-Clementel.

This activity on perfusion is done in close collaboration with the MACS project-team, in particular with D. Chapelle, Ph. Moireau and J. Sainte-Marie, in the framework of the CardioSense3D INRIA project.

To model the perfusion of the myocardium, a strategy has been developed to couple a Lagrangian nonlinear solid mechanics model to an Eulerian Darcy solver. The latter was first modified to take into account the deformation of the underlying porous media skeleton. The coupling was then successfully verified on simple test cases. Simulations have then been run on an analytical “ventricular” geometry with fibers assuming almost physiological conditions and taking into account the displacement of the heart structure. Results were presented at the CMBBE conference [27], showing the large influence of contraction on perfusion of the medium. However, the parametrization of the system to achieve physiological curves proved to be a difficult task. Current work consists in taking into account the compressibility of the heart tissue to hopefully address this issue.

In coronary perfusion, blood is delivered first to the larger arteries, which lie on the heart and are thus subject to a large strain at each heart beat. The geometry of these vessels - accessible by conventional clinical imaging method - and the flow are highly three dimensional. Yet, so far, few simulations of blood flow in the large coronary arteries have used three dimensional methods taking into account the movement of the artery wall due to the heart and rarely in realistic multi-branched vessels. In this work, we consider initial geometries for the arteries and the heart that come from medical image processing and are therefore not necessarily matching. This necessitates the projection of the heart mesh onto the artery mesh and the imposition of kinematic conditions from the heart to the artery walls. These kinematic conditions can come from a simulation of the heart mechanics or from medical dynamic imaging. On the fluid side, they are imposed through the Arbitrary Lagrangian Eulerian (ALE) formulation. The algorithm was first tested on a simple problem to verify the code (transmission of kinematic conditions) and to explore the influence of movement of the artery wall on the flow inside one vessel. There were significant changes of the velocity profile compared to the rigid case. Simulations were also performed on realistic geometries of the left coronary artery tree. In particular, the influence of the heart movement on hemodynamics is being investigated. Further developments are however necessary to improve the physiological relevance of the results. In particular, this development should be integrated with previous work on the coupling of blood flow in these large coronary arteries with a simplified representation of the downstream vasculature in the myocardium [26].

6.4. Electrophysiology

Keywords: *cardiovascular system modelling*, *electrocardiograms*, *electrophysiology*, *pacemaker*, *simulation for medicine*.

6.4.1. Numerical simulation of the electrical activity of the heart

Participants: Muriel Boulakia, Géraldine Ebrard, Miguel Ángel Fernández, Jean-Frédéric Gerbeau, Elsie Phé, Nejib Zemzemi.

M. Boulakia, M.A. Fernández, J.-F. Gerbeau and N. Zemzemi have been working with Dr. S. Cazeau (Hôpital Saint-Joseph, Paris) on the numerical simulations of electrocardiograms. In [40], they presented a model which allows to obtain realistic electrocardiograms (see Fig. 2). They investigated the sensitivity of the ECG to the model parameters and proposed a procedure for the estimation of the torso conductivity parameters. Some of these results have been reported in [15].

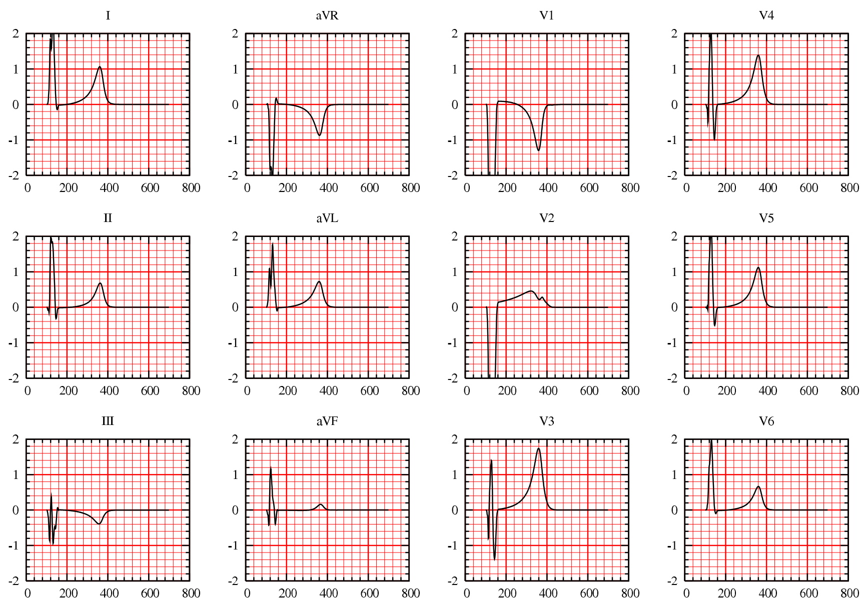

Figure 2. A computational electrocardiogram ([40])

In collaboration with the MACS project-team (D. Chapelle, Ph. Moireau and J. Sainte-Marie), M.A. Fernández, J.-F. Gerbeau and N. Zemzemi simulated the electromechanical activity of the heart with an integrated three-dimensional mathematical model of cardiac electrophysiology and mechanics. Typical medical indicators – such as pressures, volumes and ECGs – show physiological values in a healthy case (see Fig. 3). The predictive capabilities of the model have been illustrated with numerical simulations of different pathological conditions. The resulting medical indicators provided physiological values, by a simple recalibration of the model parameters directly affected by the pathology. A conference paper summarizing this results has been submitted [43].

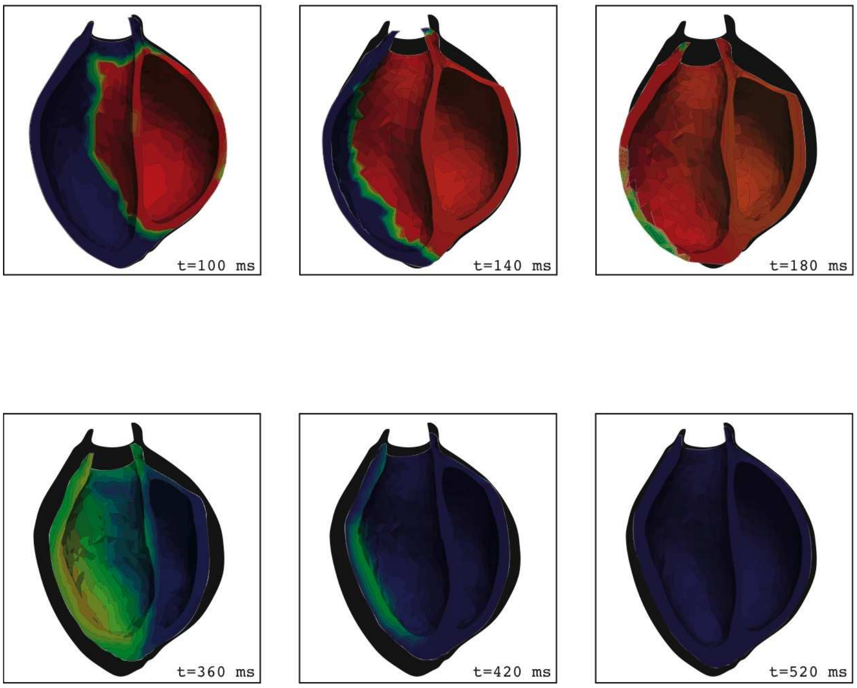

Figure 3. An electromechnical simulation of a Left Bundle Branch Block. The colors represent the electrical potential ([43])).

In collaboration with Fabrice Rossi (Telecom ParisTech), M.A. Fernández, G. Ebrard, J.-F. Gerbeau and N. Zemzemi have addressed the problem of building a standard electrocardiogram (ECG) from the electrical potential provided by a pacemaker in a few points of the heart (electrogram). They used a 3D mathematical model of the heart and the torso electrical activity, able to generate "computational ECG", and a "metamodel" based on a kernel ridge regression. The input of the metamodel is the electrogram, its output is the ECG. The 3D model is used to train and test the metamodel. They illustrated the performance of the proposed strategy on bundle branch blocks of various severities. A conference paper summarizing this results has been submitted [45]. This work has been done in collaboration with the ELA Medical company.

6.4.2. Mathematical analysis of the electrical activity of the heart

Participants: Muriel Boulakia, Céline Grandmont.

M. Boulakia and C. Grandmont have been working with A. Osses (University of Chili, Santiago) on the parameter identification problem for the Allen-Cahn or bistable equation which can be viewed as a simplified model in cardiac electrophysiology. In [41], with the help of suitable Carleman estimates, they recover model parameters from volume or surface measurements and they obtain Lipschitz stability results.

7. Contracts and Grants with Industry

7.1. ELA Medical

Participants: Géraldine Ebrard, Miguel Ángel Fernández, Jean-Frédéric Gerbeau, Nejib Zemzemi.

Industrial contract. Period: september 2007-august 2008.

ELA Medical is a company producing pacemakers. The purpose of this contract was to devise an algorithm to reconstruct electrocardiograms from electrograms. This project mixed numerical simulation and machine learning techniques. For further details, see section 6.4 and [45].

7.2. Alcan

Participant: J.-F. Gerbeau.

Industrial contract. Period: september 2007-august 2008.
Contract with Ecole Nationale des Ponts et Chaussées (ENPC) in the framework of a collaboration with ALCAN-Rio Tinto (formerly Aluminium Pechiney) on the mathematical modeling of aluminium electrolysis cells (magnetohydrodynamics in presence of free interfaces). The project is done in collaboration with Claude Le Bris and Tony Lelièvre (ENPC & project-team MicMac). A book on magnetohydrodynamics of liquid metal has been published [58] in 2006. The focus in 2008 was the boundary condition on the contact line of two-fluid flows. For further details, see Section 6.1.4 and [22].

8. Other Grants and Activities

8.1. National research program

8.1.1. ANR Project "M3RS"

Participants: Laurent Boudin, Céline Grandmont [correspondant].

Period: 2008-2013.
This project aims at studying mathematical and numerical issues raised by the modelling of the lungs.

8.1.2. ANR Project "Endocom"

Participants: Miguel Ángel Fernández, Jean-Frédéric Gerbeau [correspondant].

Period: 2008-2012.
This project [6] is funded by the TECSAN call (health technology) of the ANR. It aims at developing a pressure sensor embedded on an endoprosthesis.

8.1.3. ANR Project "PITAC"

Participants: Franz Chouly, Miguel Ángel Fernández [correspondant], Jean-Frédéric Gerbeau.

Period: 2007-2011.
This project [7] 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.

[6] http://www.endocom.upmc.fr
[7] http://www.ann.jussieu.fr/PITAC/

8.1.4. CARDIOSENSE3D (INRIA Large Initiative Action)

Participants: Matteo Astorino, Miguel Ángel Fernández [correspondant], Jean-Frédéric Gerbeau, Thomas Vareschi, Irène Vignon-Clementel, Nejib Zemzemi.

Period: 2005-2009.

The REO project is a member of the "CardioSense3D project", an INRIA "Large Initiative Action" aimed at developing an electro-mechanical model of the heart[8].

8.1.5. Other grants

- The post-doc of Alfonso Caiazzo (Dec. 2008- Nov. 2009) is funded by an ERCIM grant.
- REO is a member of the following GDR CNRS:
  - *Math-Bio* coordinated by Emmanuel Grenier and Didier Bresch
  - *Fluid-structure interaction in blood flows* coordinated by V. Deplano
  - *Fluid-structure interaction* coordinated by Mhamed Souli

8.2. European research program

8.2.1. European Integrated Project "euHeart"

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

Period: 2008-2012
REO is a member of the Integrated Project "euHeart"[9] 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.

8.3. Bilateral international relations

8.3.1. France-Stanford Center fund

Participant: Irène Vignon-Clementel.

Period: 2007-2008.
The aim of this project is to develop computational simulations as a tool to aid in understanding and predicting post-intervention hemodynamics for congenital interventions.

8.3.2. Foreign Associated Team "Cardio" (INRIA/Stanford)

Participants: Matteo Astorino, Miguel Ángel Fernández, Jean-Frédéric Gerbeau, I. Vignon-Clementel [correspondant], Guillaume Troianowski.

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 Univ.) and the project-team REO, through research on cardiovascular related topics.

8.3.3. Foreign Associated Team "CFT" (INRIA/Centre de Recherche Mathématiques, Canada and SCCS, National Taiwan University)

Participant: Marc Thiriet.

The aim of this project is to perform numerical simulations and experimental measures of various biomechanical systems (aortic valve, carotid, liver,...).

[8] http://www-sop.inria.fr/CardioSense3D/
[9] http://www.euheart.eu/

8.4. Visiting professors and invited researchers

- J.-F. Gerbeau has been a visiting professor at Stanford University since September 2008 (sabbatical leave).
- E. Burman (University of Sussex, UK) was a visiting professor in the project-team in September 2008 (see 6.1.3).
- C.A. Taylor and C.A. Figueroa (Stanford Univ., USA) came for a strategic meeting of the associated team with Stanford University.
- C.A. Figueroa, H.J. Kim and S. Shadden (Stanford Univ., USA) visited the project-team in July to work on boundary conditions for complex flows, imaged-based fluid-structure interaction and post-processing of numerical simulations.

9. Dissemination

9.1. Scientific community animation

9.1.1. Various academic responsibilities

- L. Boudin
  - co-editor with C. Grandmont, Y. Maday (Univ. Paris 6), B. Maury (Univ. Orsay), B. Sapoval (Polytechnique) and J.-F. Gerbeau of ESAIM: Proc., 2008, Vol. 23, entitled *Mathematical and numerical modelling of the human lung*
  - elected member of Paris-6 “Commission de specialistes” (CSE) and external member of ENS Cachan CSE (26th Section : applied math.), till july 2008
  - co-organizer with J.-B. Apoung Kamga (Orsay), M. Ismaïl (Grenoble), S. Martin (Orsay), B. Maury (Orsay), C. Misbah (Grenoble), T. Takahashi (Nancy), of Cemracs 2008 *Modelling and Numerical Simulation of Complex Fluids*, a six week long scientific event (summer school + research projects)
- L. Dumas
  - Jury member of *Agrégation de Mathématiques*.
  - External member of the *Commission de spécialistes* of Paris 13 university.
- M.A. Fernández
  - Coordination of CardioSense3D (with H. Delingette, Asclepios team).
  - Co-organizer of the monthly colloquium of INRIA Paris-Rocquencourt.
  - PhD thesis committees (reviewer): Francisco Calvo (Polytechnic University of Madrid, Spain), Annalisa Quaini (EPFL, Switzerland)
- J.-F. Gerbeau
  - Editor-in-chief of *ESAIM Proceedings* (with E. Cancés and P. del Moral).
  - Member of the editorial board of *Mathematical Modelling and Numerical Analysis* (M2AN).
  - Scientific coordinator of the CEA-EDF-INRIA schools organized by INRIA.
  - PhD thesis committees (reviewer): Fabien Huvelin (Univ. Lille 1 / EDF).
  - Organizer of a CEA-EDF-INRIA summer school on model reduction (2 weeks, 40 participants).

- C. Grandmont
  - co-editor with L. Boudin, Y. Maday (Univ. Paris 6), B. Maury (Univ. Orsay), B. Sapoval (Polytechnique) and J.-F. Gerbeau of ESAIM: Proc., 2008, Vol. 23, entitled Mathematical and numerical modelling of the human lung
  - external member of the Commission de spécialistes of Paris 6, Besançon and Saint-Etienne universities (section 26).
  - member of the “admissibility” selection comity for CR2 recruitment at INRIA Paris - Rocquencourt.
  - member of the “Faites de la science” selection comity.
  - member of the reflexion comity RTRA sciences mathématiques / INRIA Paris - Rocquencourt.
- M. Thiriet
  - coordination of working group ERCIM “IM2IM”
  - coordination of associated INRIA team “CFT”.
  - member of editorial board of Computer Methods in Biomechanics and Biomedical Engineering
  - president of thematic committee 3 “Biomedical simulation and applications to health” for access to national means of intensive computation.
  - member of permanent expert committee of european project “HPCE2” (7FP) Transnational Access Programme for access to some of the biggest supercomputers in Europe under an I3 action
- I. Vignon-Clémentel
  - Organizing the monthly seminar at INRIA Paris-Rocquencourt on “modeling and scientific computing” since January 2008.
  - Organized an international workshop at INRIA on “blood and air flow modeling in complex geometries” with J.F. Gerbeau and the CVBRL from Stanford University, USA. INRIA Paris-Rocquencourt, France, March, 5-6th, 2008. http://www-rocq.inria.fr/bloodairflow. 18 speakers/60 participants.
  - 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 since October 2007.
  - 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) since December 2007.
  - Mediator between PhD students and their supervisors for INRIA Paris-Rocquencourt since October 2007.
  - Participant in an interdisciplinary systems biology group at INRIA to promote research in life sciences modeling. Focus is on collaborations with medical research institutions such as IGR and INSERM.
  - Interviewed by the newspaper Libération as part of an article on researchers in France (published May 27th 2008) - cited as a consequence of this article in the morning pressreview of program TeleMatin on the TV broadcast France2 the following day.
  - Lecture given at Villaroy High School (Terminales/ A level) in Guyancourt on March 13th, “Numerical simulations of the cardiovascular system: synergies between mathematicians and doctors”

9.2. Teaching

- Muriel Boulakia
  - Analysis and numerical methods, Licence, Univ. Paris 6 and Ecole Polytechnique Universitaire Paris 6.
- Laurent Boudin
  - Analysis and numerical methods, Licence, Univ. Paris 6
- Laurent Dumas
  - Master course “Introduction to Fluent and Gambit”, Univ. Paris 6.
- Céline Grandmont
  - “Fluid-structure interaction. Application to blood flows”, Master of numerical analysis, Univ. Paris 6 (with M. Fernández and Y. Maday)
- Miguel Á. Fernández
  - "Numerical methods in bio-fluids”, Master of Mathematical Methods and Numerical Simulation in Engineering and Applied Sciences, University of Vigo, Spain
  - “Fluid-structure interaction. Application to blood flows”, Master of numerical analysis, Univ. Paris 6 (with C. Grandmont and Y. Maday)
  - “Inverse problems”, Ecole Supérieure d’Ingénieurs Léonard de Vinci
  - “Scientific computing”, École Nationale des Ponts et Chaussées
- Jean-Frédéric Gerbeau
  - Associate professor (“professeur chargé de cours”, part-time), Ecole Polytechnique.
  - Functional analysis, Ecole Nationale des Ponts et Chaussées.
- Marc Thiriet
  - Master 2, Master of Sciences & Technologies, Mention Mathematics & Applications, Programs in Mathematical Modeling (10h).
  - Modeling and simulations of physiological flows (36 h) Taida Institute of Mathematical Science (TIMS), Department of Mathematics, National Taiwan University, May 27–June 17, 2008
- Irene Vignon-Clémentel
  - Blood flow, a graduate level class (18 hours) as part of the “life sciences” section of the applied mathematics major at the Ecole Centrale Paris (Winter 2008).

9.3. Participation in conferences, workshops and seminars

- Matteo Astorino
  - Seminar, GTN (Groupe de Travail Numérique), Université Paris 11, November 5th, 2008, Orsay, France.
  - Seminar, GTT (Groupe de Travail de Thésards), Université Paris 6, October 28th, 2008, Paris, France.
  - Seminar, summer school CEMRACS 2008, August 19th, 2008, Marseille, France.
  - Keynote lecture of a Mini-symposium at WCCM8/ECCOMAS 2008, June 30th – July 4th, 2008, Venice, Italy.

  - Talk at Workshop on Finite Element Methods for Fluids and Fluid-Structure Interaction, June 4–5th, 2008, Simula Laboratory, Oslo, Norway.
  - Invited at First CRM-INRIA-MITACS Meeting, May 5-9, 2008, Montreal.
- Laurent Boudin
  - Seminar in Lille (November 2008)
  - Invited talk to the conference *Kinetic modelling for socio-economic and related problems*, Vigevano, Italy (November 2008).
- Muriel Boulakia
  - Seminar of applied mathematics, Clermont-Ferrand, march 2008
  - Workshop Global dynamics of differential systems, Paris 6, april 2008
- Franz Chouly
  - Seminars ANR Pitac, Laboratoire Jacques-Louis-Lions, Université Paris 6, April 3 and July 3 2008, Paris, France.
- Laurent Dumas
  - Contributed talk at ENGOPT2008, June 4th, 2008, Rio, Brasil.
  - Contributed talk at GECCO 2008, July 12th, 2008, Atlanta, USA.
  - Invited talk at IBM-HPC half day workshop, September 18th, 2008, Univ. Paris 6.
  - Invited talk at HPC application workshop, September 29th, 2008, Santiago de Compostella, Spain.
  - Invited talk at an half day workshop on atherosclerosis, October 23th, 2008, Univ. Paris 5.
- Miguel Ángel Fernández
  - Invited to a Mini-symposium of the 8th World Congress on Computational Mechanics (WCCM8) and 5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008), June 30th – July 4th, Venice, Italy.
  - Invited to a Mini-symposium of the Second Canada-France Congress of Mathematics, June 1sth–6th, Montreal, Canada. .
  - Seminar at the Mathematics Department of the University of Sussex, Brighton, UK, May 21th.
  - Seminar at CEMAT, University of Lisbonne, Portugal, April 4th.
  - Seminar at the Chair of Computational Mechanics of the Technical University of Munich, Germany, February 5th.
- Jean-Frédéric Gerbeau
  - Plenary speaker Dutch-Flemish Numerical Analysis Conference (WSC), Woudschoten, October 2008.
  - Invited speaker, IPAM (UCLA) Workshop “Optimal Transport in the Human Body”, Los Angeles, USA, May 19 - 23, 2008
  - Invited speaker, 1st school of Physics applied to life sciences, Univ. Oran, Algeria, 2008
  - Invited speaker, *Journées EDP de Metz*, Université Paul Verlaine, 2008
  - Seminar, Institut Camille Jordan, Université Lyon 1, 2008
  - *Forum d’innovation* GRAVIT, Grenoble, July 8-9, 2008
  - Second France-Canada Congress of Mathematics, Canada, June 1-5, 2008

- Céline Grandmont
  - CEMRACS summer school (july-august), Marseille.
  - Seminars in France (Univ. Paris 6: 02/08, 04/08, 12/08).
  - Invited at First CRM-INRIA-MITACS Meeting, May 5-9, 2008, Montreal.
  - Invited speaker, IPAM (UCLA) Workshop “Optimal Transport in the Human Body”, Los Angeles, USA, May 19 - 23, 2008
- Marc Thiriet
  - Invited at 8th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering (CMBBE’08) Porto, Portugal, 27th February-1st March 2008.
  - Invited at *Journées EDP de Metz* 2008 “PDE and variational methods in life sciences”, April 10–12 2008.
  - Invited at First CRM-INRIA-MITACS Meeting, May 5-9, 2008, Montreal.
  - Invited at Mini-symposium 193 “Composite materials and multiscale modeling in engineering and medicine” of the World Conference on Computational Mechanics (WCCM VIII) and European Congress on Computational Methods in Applied Science and Engineering (ECCOMAS V), Venice, June 30–July 5, 2008.
  - Seminar, Département de Mathématique, Université de Technologie de Compiègne, 18 mars 2008
  - Seminar, Department Bioengineering and Robotics, Tohoku University, Sendai, Japan, october 28, 2008
  - Seminar, School of Computing, National University of Singapore November 4, 2008
  - Seminar, A*STAR, Institute of High Performance Computing, Singapore November 6, 2008
  - Invited speaker at Meditech Workshop Imaging and Measurements in Biomechanics and Medical Engineering, Paris, 2–3 October, 2008
  - Seminar, Department of Applied Physiology, Polish Academy of Sciences, december 21, 2008
- Irène Vignon-Clementel
  - Invited talk, CMBBE conference, Porto, Portugal, February 28th.
  - Poster at the American College of Cardiology 57th Annual Scientific Session, March 29-April 1, 2008, in Chicago, Illinois, USA.
  - Talk at the Fifth International Biofluids Symposium and Workshop, Pasadena, USA, Mar. 28-30.
  - Invited at First CRM-INRIA-MITACS Meeting, May 5-9, 2008, Montreal.
  - Invited keynote, World Congress of Computational Mechanics, Venice, Italy, June.
  - Invited talk, presented in front of medical doctors and researchers in engineering in La Corona, Spain, March 3rd.
  - Talk at “Rencontres de Modélisation en Physiopathologie”, Cachan, France, June 16-17.
  - Talk for the Internship Research Grand Prize in Applied Mathematics, Ecole Polytechnique, France, November.
- Nejib Zemzemi
  - PhD student seminar, LJLL, Univ. Paris 6. December 2nd 2008, Paris, France.
  - Open Bang Seminar. November , 4th 2008, Paris, France

– International Conference of Numerical Analysis and Applied Mathematics 2008 (ICNAAM 2008). September 14th–20th, Kos , Greece.
– Invited at First CRM-INRIA-MITACS Meeting, May 5-9, 2008, Montreal.
– International Conference of Partial Differential Equations and Applications. March 25-29, 2008, Hammamet, Tunisia.

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[7] C. FETITA, S. MANCINI, D. PERCHET, F. PRÊTEUX, M. THIRIET, L. VIAL. *Computational model of oscillatory flow in the proximal part of tracheobronchial trees*, in "Computer Methods in Biomechanics and Biomedical Engineering", vol. 8, 2005, p. 279-293.

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[9] M. THIRIET. *Biology and Mechanics of Blood Flows, part I: Biology of Blood Flows (652 p.), part II: Mechanics and Medical Aspects of Blood Flows (464 p.)*, CRM Series in Mathematical Physics, Springer, 2008.

[10] I. VIGNON-CLEMENTEL, C. FIGUEROA, K. JANSEN, C. TAYLOR. *Outflow Boundary Conditions for Three-dimensional Finite Element Modeling of Blood Flow and Pressure in Arteries*, in "Computer Methods in Applied Mechanics and Engineering", vol. 195, 2006, p. 3776-3796.

Year Publications

Doctoral Dissertations and Habilitation Theses

[11] L. DUMAS. *From particle trajectories to global optimization under PDE constraints*, Habilitation à Diriger des Recherches, Université Paris 6 Pierre et Marie Curie, 2008.

Articles in International Peer-Reviewed Journal

[12] M. ASTORINO, J.-F. GERBEAU, O. PANTZ, K. TRAORÉ. *Fluid-structure interaction and multi-body contact. Application to aortic valves*, in "Comp. Meth. Appl. Mech. Engng.", doi:10.1016/j.cma.2008.09.012, 2008.

[13] L. BAFFICO, C. GRANDMONT, Y. MADAY, A. OSSES. *Homogenization of elastic media with gaseous inclusions*, in "SIAM Multiscale Model. Simul.", vol. 7, n^o 1, 2008, p. 432–465, http://hal.inria.fr/inria-00180307/en/.

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