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

Activity Report 2011

Project-Team REO

Numerical simulation of biological flows

IN COLLABORATION WITH: Laboratoire Jacques-Louis Lions

RESEARCH CENTER
Paris - Rocquencourt

THEME
Observation, Modeling, and Control for Life Sciences

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Project-Team REO

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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 University (Paris 6) and CNRS (UMR7598). 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 2011

- Marc Thiriet received the Franco-Taiwanese Science Foundation prize 2011 awarded by the French Academy of Sciences and the National Science Council of Taiwan (shared with Tony Wen-Hann Sheu).
- Laurent Boudin defended his habilitation thesis (HDR) on December 8, 2011.

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.

We have proposed over the last few years several efficient fluid-structure interaction algorithms. We are now using these algorithms to address inverse problems in blood flows (for example, estimation of artery wall stiffness from medical imaging).

3.1.2. Aerosol

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

This type of model was first introduced by Williams [61] in the frame of combustion. It was later used to develop the Kiva code [51] at the Los Alamos National Laboratory, or the Hesione code [56], for example. It has a wide range of applications, besides the nuclear setting: diesel engines, rocket engines [54], 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 [57]. The underlying idea consists in coupling different models (3D, 1D or 0D) with a decreasing level of accuracy, which is compensated by their decreasing level of computational complexity.

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

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

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

A long term goal is to achieve 3D simulations of a system including heart and arteries. One of the difficulties of this very challenging task is to model the cardiac valves. To this purpose, we 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 [60], and Biot [52] later gave a description of the mechanical behavior of a porous medium using an elastic formulation for the solid matrix, and Darcy's law for the fluid flow through the matrix. Finite strain poroelastic models have been proposed (see references in [53]), 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. 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.

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

4. Application Domains

4.1. Blood flows

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

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

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

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

4.2. Respiratory tracts

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

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

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

One of the goals of REO team in the ventilation field is to visualize the airways (virtual endoscopy) and simulate flow in image-based 3D models of the upper airways (nose, pharynx, larynx) and the first generations of the tracheobronchial tree (trachea is generation 0), whereas simple models of the small bronchi and alveoli are used (reduced-basis element method, fractal homogenization, multiphysics homogenization, lumped parameter models), in order to provide the flow distribution within the lung segments. 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 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.* [55], [59], [58] 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). We are now working on using our ECG simulator to address the inverse problem of electrocardiology. In collaboration with the Macsproject-team, we are working on the electromechanical coupling in the myocardium. We are also interested in various clinical and industrial issues related to cardiac electrophysiology. In particular, we collaborated with ELA Medical company (pacemaker manufacturer, Sorin group).

5. Software

5.1. LiFE-V library

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

LiFE-V[2] 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, 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).

5.3. FELiScE

Participants: Grégory Arbia, Cesare Corrado, Miguel Ángel Fernández Varela, Justine Fouchet-Incaux, David Froger, Jean-Frédéric Gerbeau [correspondant], Damiano Lombardi, Elisa Schenone, Saverio Smaldone.

FELiScE – standing for "Finite Elements for Life Sciences and Engineering" – is a new finite element code which the MACS and REO project-teams have decided to jointly develop in order to build up on their respective experiences concerning finite element simulations. One specific objective of this code is to provide in a unified software environment all the state-of-the-art tools needed to perform simulations of the complex cardiovascular models considered in the two teams – namely involving fluid and solid mechanics, electrophysiology, and the various associated coupling phenomena. FELISCE is written in C++, and may be later released as an opensource library. https://gforge.inria.fr/projects/felisce/

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

6. New Results

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

Participants: Cristóbal Bertoglio Beltran, Muriel Boulakia, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Jimmy Mullaert.

- Over the last decade, the numerical simulation of incompressible fluid-structure interaction has been a very active research field and the subject of numerous works. In [19], we review some of the coupling schemes recently proposed in the literature. Some numerical results that show the effectiveness of the novel approaches are also presented.
- In [21], we propose a new class of time-marching schemes for the explicit coupling of an incompressible fluid and a general elastic solid (i.e., not necessarily thin [46] and possibly damped). We state a general energy-based stability result and illustrate the accuracy of the different variants in a numerical benchmark.
- [30]: This paper focuses on Eulerian-based algorithms for fluid-structure applications featuring large structural motions and/or deformations in the context of compressible flows. First, it presents a numerical method for treating simultaneously the fluid pressure and velocity conditions on static and dynamic embedded interfaces. This method is based on the exact solution of local, one-dimensional, fluid-structure Riemann problems. Next, it describes two consistent and conservative approaches for computing the flow-induced loads on rigid and flexible embedded structures.
- In [39], we present some issues encountered in fluid-structure interaction simulation (this text is targeted to a non-expert audience).
- In [42], we present a robust and efficient parameter estimation strategy for fluid-structure interaction problems. The method is based on a filtering algorithm restricted to the parameter space, known as the reduced order Unscented Kalman Filter. We illustrate our methodology with the estimation of the artery wall stiffness and the proximal Windkessel resistance.
- [44]: In this paper, we are interested in the three-dimensional coupling between an incompressible fluid and a rigid body. The fluid is modeled by the Navier-Stokes equations, while the solid satisfies the Newton's laws. In the main result of the paper we prove that, with the help of a distributed control, we can drive the fluid and structure velocities to zero and the solid to a reference position provided that the initial velocities are small enough and the initial position of the structure is close to the reference position.
- In [46], we introduce a class of incremental displacement-correction schemes for the explicit coupling of a thin-structure with an incompressible fluid. We provide a general stability and convergence analysis that covers both the incremental and the non-incremental variants, and also the fully implicit case. The incremental variant with first-order extrapolation is unconditionally stable and yields optimal first-order accuracy in time.

6.2. Numerical methods for fluid mechanics and application to blood flows

Participants: Jean-Frédéric Gerbeau, Marc Thiriet, Irène Vignon-Clementel.

- [13]: In this work, a virtual planning of three different surgical Fontan repairs was performed to test the predictive capability of a closed-loop multi-scale model (3D-0D), constructed based on preoperative patient-specific data. Results from this multi-scale approach showed that the preoperative caval flows should not be used as boundary conditions in post-operative simulations. The Y-TCPC repair seemed to perform better than all other TCPC models both at rest and under exercise conditions. Further work is needed to correlate results from these simulations with clinical outcomes.

- [18]: Flow reversal at an outlet, although perfectly physical, can lead to rapid numerical divergence in computational fluid dynamics. Several remedies have been proposed in the literature and are discussed in the present finite element study. The most robust one was found to be a boundary advective stabilization term. The comparison was done on simple examples, as well as realistic three-dimensional multi-branched models of blood flow.
- [22] & [23]: Treatments for coarctation of the aorta (CoA) can alleviate blood pressure gradients, but long-term morbidity still exists that can be explained by altered indices of hemodynamics and biomechanics. These articles present a combination of CFD methods (physiologically realistic boundary conditions and FSI with viscoelastic tissue support) to explore these indices in untreated and treated CoA, comparing them to normal subjects under rest and exercise conditions. These studies showed in particular that CoA disturbs normal patterns of wall shear stress and oscillatory shear index throughout the thoracic aorta (potentially linked to the development of atherosclerosis) and that restoring favorable anatomy may not restore normal hemodynamics.
- [24]: The objective of this work is to address the formulation of an adequate model of the external tissue environment when studying a portion of the arterial tree with fluid-structure interaction. The simulations are quantitatively assessed by detailed comparisons with dynamical medical image sequences, and the model results are shown to be in very good adequacy with the data.
- [26] The wide range of existing viscoelastic wall models may produce significantly different blood flow, pressure, and vessel deformation solutions in cardiovascular simulations. In this paper, we have successfully implemented and verified two viscoelastic wall models in a nonlinear 1D finite element blood flow solver and analyzed differences between these models in various idealized and physiological simulations, including exercise.
- [28]: High-intensity focused ultrasound (HIFU) is used as a thermal ablation process to eliminate tumors in different body's organs. Blood flow has a cooling effect. Conversely, ultrasounds are responsible for acoustic streaming. A three-dimensional acoustics-thermal-fluid coupling model is carried out to compute the temperature field a given hepatic cancerous region.
- [29]: Imaged-based patient-specific models of the multi-branched pulmonary arteries and superior vena cava were built for five cavopulmonary connection (i.e. Glenn) patients prior to their third surgery to alleviate their congenital heart disease. Inflow and outflow boundary conditions for computational blood flow simulations (CFD) were constructed based on an iterative procedure to match available MRI and catheterization clinical data. Common trends and differences emerged from this three-dimensional CFD study; in particular low wall shear stress was found for all subjects, which is potentially deleterious. A sensitivity analysis was performed to investigate the impact of input data (clinical and modeling) to construct boundary conditions on several clinical and mechanical indicators. Among other findings, this study suggests that although 6-10% flow split imprecision seemed reasonable in terms of patient comparison, the common practice of imposing a right pulmonary artery/left pulmonary artery flow split of 55%/45% when performing patient specific simulations should be avoided.
- [31]: A novel Y-shaped baffle has been proposed for the Fontan operation with promising initial results on idealized models or a single patient-specific model. The objective of this study is to comprehensively compare the hemodynamic performance and hepatic blood flow distribution of the Y-graft Fontan baffle with two current designs on multiple patient-specific models. Methods include virtual geometrical design, computational fluid dynamics based on preoperative patient-specific data, particle tracking and sensitivity analysis, including rest and exercise conditions. The Y-graft Fontan design achieves overall superior hemodynamic performance compared with traditional designs. However, the results emphasize that designs should be customized for individual patients before clinical application.

6.3. Numerical methods for cardiac electrophysiology

Participants: Muriel Boulakia, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Vincent Martin, Elisa Schenone.

- [32]: We consider the problem of estimating some parameters of a model of electrocardiograms from the data of the Einthoven leads. The direct model is based on the bidomain equations in the heart and a Poisson equation in the torso. To keep the computational time reasonable, the evaluation of the direct problem is approximated with a reduced order model based on Proper Orthogonal Decomposition.The optimization problem is solved using an evolutionary algorithm. Numerical tests show that, with noisy synthetic data, the proposed procedure allows to recover ionic parameters and initial activation regions with a fair accuracy.
- [34] and [48]: In presence of a high magnetic field, the blood flow in the aorta induces an electrical potential which is responsible for an increase of the T-wave in the electrocardiogram (ECG). This phenomenon may perturb ECG-gated imaging. The aim of this numerical study is to reproduce this experimental observation through computer simulations. The proposed model consists of three components: magnetohydrodynamics (MHD) in the aorta, bidomain equations in the heart and electrical diffusion in the rest of the body. These models are strongly coupled together and solved with finite elements.
- [38]: We present an overview of our works about electrocardiogram numerical simulations.
- [45]: A reduced-order model based on Proper Orthogonal Decomposition is proposed for the bidomain equations of cardiac electrophysiology. Its accuracy is assessed through electrocardiograms in various configurations, including myocardium infarctions and long-time simulations. We show in particular that a restitution curve can efficiently be approximated by this approach. The reduced-order model is then used in an inverse problem solved by an evolutionary algorithm. Some attempts are presented to identify infarction locations from synthetic electrocardiograms.

6.4. Lung and respiration modeling

Participants: Laurent Boudin, Bérénice Grec, Muriel Boulakia, Anne-Claire Egloffe, Céline Grandmont, Ayman Moussa.

- [9]: This paper is concerned with a system that couples the incompressible Navier–Stokes equations to the Vlasov–Fokker–Planck equation. Such a system arises in the modeling of sprays, where a dense phase interacts with a disperse phase. The coupling arises from the Stokes drag force exerted by a phase on the other.
- [25]: We are concerned with the global well-posedness of a two-phase flow system arising in the modelling of fluid-particle interactions. This system consists of the Vlasov-Fokker-Planck equation for the dispersed phase (particles) coupled to the incompressible Euler equations for a dense phase (fluid) through the friction forcing.
- [49]: We obtain the Maxwell-Stefan diffusion model by studying the asymptotic behaviour of a multicomponent kinetic model when the Knudsen number goes to 0.
- [50]: We are concerned here with identifiability, stability properties and estimates for the inverse problem of identifying a Robin coefficient on some non accessible part of the boundary from available data on the other part of boundary corresponding to solutions of the Stokes equations. We first study the identifiability of Robin coefficient and then we establish a stability estimate of logarithm type using Carleman inequality.

6.5. Miscellaneous

Participant: Laurent Boudin.

- [43]: We deal with a kinetic model to describe the evolution of the opinion in a closed group where there are two opposite behaviours: conciliatory and contradictory agents. We provide an existence and uniqueness result for the model and numerically test it in some relevant cases.

7. Partnerships and Cooperations

7.1. National Initiatives

7.1.1. ANR Project "M3RS"

Participants: Laurent Boudin, Muriel Boulakia, Paul Cazeaux, Anne-Claire Egloffe, Céline Grandmont [Principal Investigator], Bérénice Grec, Sébastien Martin.

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: 2008-2011.
This project [3] 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. INRIA Research Collaborative Action "Sirap"

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

Period: 2009-2011.

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. FP7 Projet

7.2.1.1. EUHEART

Participants: Cristóbal Bertoglio Beltran, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau [correspondant], Saverio Smaldone.

Period: 2008-2012

REO is a member of the Integrated Project "euHeart"[4] 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, 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[5].

[3] http://www.endocom.upmc.fr
[4] http://www.vph-noe.eu/vph-projects/74-eu-fp7-vph-projects/44-euheart-ip
[5] http://modelingventricle.clemson.edu/home

7.3.2. INRIA Associate Teams

Participants: Grégory Arbia, Cristóbal Bertoglio Beltran, Miguel Ángel Fernández Varela, Jean-Frédéric Gerbeau, Céline Grandmont, Irène Vignon-Clementel [coordinator].

Period: 2008-2014

CARDIO: 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 colleagues such as Dr. Feinstein, and the project-team REO, through research on cardiovascular and respiratory related topics (boundary conditions for complex flow, patient-specific modeling of congenital heart disease, image-based fluid solid interaction, postprocessing of numerical simulations). The associated team has been extended to other partners: team-project MACS at INRIA, the Marsden group at USCD and the Flow physics group at IIT. CA Figueroa is now at KCL, UK.

7.3.3. Visiting professors

- Francesco Salvarani, Professor, Univ. degli studi di Pavia (Italy), Jannuary 15 - July 13, 2011
- André Garon, Professor, Département Génie Mécanique de l'Ecole Polytechnique de Montréal (Canada) 10-17 may, 2011
- Erik Burman, Professor, University of Sussex, UK, December 12-16, 2011

7.3.4. Internships

- Jessica Oakes, PhD candidate, University of California, San Diego, July 1st - September 30, 2011.

8. Dissemination

8.1. Animation of the scientific community

- Laurent Boudin
  - Hiring committees: Univ. Besançon (MCF position in Numerical analysis), Univ P. & M. Curie (MCF position in Modeling, PDE analysis, numerical analysis, scientific computing).
- Miguel Ángel Fernández Varela
  - Member of the Postdocs Selection Committee, INRIA Paris-Rocquencourt, 2011
- Jean-Frédéric 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 committee: D. Lombardi, Univ. Bordeaux (referee)
  - Hiring committees: Univ Rouen (Professor position), INRIA Bordeaux (CR2 and CR1 positions).
- Céline Grandmont

  - Co-organizer of the *first parity day in mathematic* http://postes.smai.emath.fr/parite/journee/journee_parite.php;
  - Program committee for 4 years of the "forum des jeunes mathématiciennes" (2010–2014);
  - Member of the CNU 26 (2011–2015)
  - Thesis committees: Referee for the Ph.D thesis of E. Schwindt (Univ. of Nancy and Santiago de Chili); Referee for the Ph.D thesis of J. Lequeurre (Toulouse Univ.); Member of the Ph. D. jury of A. Blasselle (Paris 6 Univ.) J. Lequeurre (Toulouse Univ.) and E. Schwindt (Univ. of Nancy and Santiago de Chili).
  - Hiring committee: INSA Lyon.

- Marc Thiriet
  - Editorial board: *Computer Methods in Biomechanics and Biomedical Engineering*.
  - Member of the selection comittee of HPC projects in the framework of HPC-Europa2 – Pan-European Research Infrastructure for High Performance Computing supported by the European Commission Capacities Area - Research Infrastructures Initiative
  - President of thematic comittee CT3 (Biomedical Simulation and Applications to Health) of GENCI (Grand Equipement National de Calcul Intensif – National Large Equipement for Intensive Computation)
  - Thesis committee of K.C. Chang Chien, Telecom & Management Sud Paris and University Pierre et Marie Curie, France, September 2011.

- Irène Vignon-Clémentel
  - Organizing the monthly seminar at INRIA Paris-Rocquencourt on "modeling and scientific computing"
  - 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 21rst to new PhD students
  - Coordinator of the associated team CARDIO between REO and Prof. Taylor's lab at Stanford University, USA and colleagues both at INRIA and in the USA (2008-present)

8.2. Participation in conferences, workshops and seminars

- Cristóbal Bertoglio Beltran
  - Seminar, Université Paris 5, February 11th, 2011, Paris, France.
  - Contributed talk at "2nd International Conference on Computational & Mathematical Biomedical Engineering", March 30th - April 1st, 2011, George Mason University, Washington D.C., USA,
  - Seminar, euHeart's Data Assimilation Workshop, July 1st, 2011, Paris, France
  - Seminar, Department of Biomedical Engineering, King's College of London, November 4th, 2011, London, UK
  - Seminar, INRIA-Rocquencourt, December 20th, Le Chesnay, France

- Laurent Boudin
  - Seminar, Applied Mathematics, Collège de France, January 14, 2011, Paris, France
  - Seminar, Numerical Analysis and PDEs, Univ. Paris-sud, February 3, 2011, Orsay, France

  - Contributed talk at SMAI 2011 Congress, May 23–27, 2011, Guidel, France
  - Invited talk at "Rencontres EDP-Normandie 2011", October 25–26, 2011, Rouen, France

- Muriel Boulakia
  - Meeting Researchers-Industrialists, UPMC Paris 6, June 2011
  - Seminar, University Darmstadt (Germany), May 2011
  - Invited in a minisymposium, 16th International Conference on Finite Elements in Flow problems (FEF2011), Munich (Germany), March 2011
  - Seminar, University Caen, January 2011

- Anne-Claire Egloffe
  - Invited speaker, Lions-Magenes days, Paris 6, december 2011
  - PhD students Seminar, LJLL, Paris 6, may 2011
  - Contributed talk, SMAI 2011, Guidel, mai 2011
  - Contributed talk, Conference of the European GDR control of PDEs, Marseille, novembre 2011
  - CEMRACS, Marseille 17/07-26/08, 2011

- Miguel Ángel Fernández Varela
  - Invited in Mini-symposium. USNCCM-11, July 25-29, 2011, Minneapolis, USA
  - Third Workshop on Generic Solvers for PDES: FreeFem++ and Applications, December 5-7, 2011, Paris
  - Seminar, University of Paris XIII, June 10, 2011
  - Seminar, University of Paris VI, May 23, 2011

- Jean-Frédéric Gerbeau
  - Plenary conference, ECCOMAS Simbio conference, Brussel, Belgium, 2011
  - Plenary conference, ENUMATH, Leicester, United Kingdom, 2011
  - Invited keynote conference, International Conference on Computational & Mathematical Biomedical Engineering (CMBE), Washington D.C., USA, 2011
  - Invited conference, Numerical Methods for PDEs, Heraklion, Greece, 2011
  - Invited conference, Workshop Berkeley Inria Stanford, USA, 2011
  - Invited lecture, Riemann International School of Mathematics, Verbania, Italia, 2011
  - Seminar, Texas A & M university (USA)
  - Seminar, Politecnico di Milano (Italy)
  - Seminar, Agro ParisTech, Paris (France)
  - Invited minisymposium talk, Conference on Mathematics of Medical Imaging, Fields Insitute, Toronto (Canada) 2011
  - Minisymposium talk, ICIAM, Vancouver, Canada, 2011
  - Minisymposium talk, USNCCM, Minneapolis, USA, 2011
  - Journée de la Fédération de Recherche Mathématique Paris Centre
  - Journée de l'Institut Thématique Multi-Organisme (ITMO) Circulation métabolisme nutrition,
  - Journée interaction données - simulation, UPMC

- Céline Grandmont
  - Invited speaker, SIAM PDE, San Diego, nov. 2011;
  - Invited speaker in a minisymposium, Enumath 2011, Leicester, sept. 2011;
  - Invited Lecturer, Summer school *Fluid-Structure for Biomedical Applications*, Prague, sept. 2011;
  - Seminar, Orléans, March 2011;
  - Seminar, Grenoble, January, 2011.
- Bérénice Grec
  - Contributed talk, SMAI 2011, May 23–27th, 2011, Guidel, France.
- Sébastien Martin
  - Invited talk in a minisymposium at MAMERN '11, May 23–26th, 2011, Saïdia, Marocco.
  - Invited talk at "Reaction-Diffusion Systems in Mathematics and the Life Sciences: A conference in honor of Jacques Demongeot and Masayasu Mimura", September 20–22nd, 2011, Montpellier, France.
  - Seminar, Université Blaise Pascal, December 8th, 2011, Clermont-Ferrand, France.
- Vincent Martin
  - Poster, 6th Internat. Conf. on Functional Imaging & Modelling of the Heart (FIMH 2011), May 2011, New York, USA.
  - Seminar, may 2011, Mox, Politecnico di Milano, Milan, Italy.
  - Seminar, june 2011, Inria Paris Rocquencourt.
- Ayman Moussa
  - Invited speaker, 23eme seminaire de mécanique des fluides numériques CEA-GAMNI, IHP, January 24/25 2011, Paris, France
  - Contributed talk at SMAI 2011 Congress, May 23–27, 2011, Guidel, France
  - Seminar, IMATH-ANLM, Univ. Toulon-Var, invited speaker, March 10 2011
- Marc Thiriet
  - Seminar, Warsaw Polytechnique University, April 20 2011, Poland.
  - Invited talk, International Conference VipIMAGE 2011 - III ECCOMAS thematic conference on computational vision and medical image processing. October 11-14, Olhão, Portugal
- Irène Vignon-Clementel
  - Keynote speaker at a minisymposium, FEF2011 conference, March 23-25th, Munich, Germany
  - Invited talk, 2nd International Conference on Engineering Frontiers in Congenital Heart Diseases, March 17th-18th, London, UK
  - Invited talk at a minisymposium, CSMA, May 9th-13th, Giens, France
  - Seminar, Mathematics, Université Montpellier II, June 7th, Montpellier, France
  - Invited talk at a minisymposium, Conference on Mathematics of Medical Imaging, June 19th-22th, Toronto, Canada
  - 2 contributed talks, European Conference on Mathematical and Theoretical Biology, June 27th-July, 2nd, Krakow, Poland

- Evaluation talk, INRIA national days ARC-ADT, November, 16th-17th, 2011, Vincennes, France
- Seminar, Laboratoire Jean Kuntzmann - mathématiques appliquées informatique, November 24th, Grenoble, France
- Invited presentation, "Associated team experience", internal communication for the International Relation Department, February 7th, 2011, Rocquencourt, France
- Mediation and popularization of sciences:
  * Trofemina, finalist in the "sciences, research and technology" category, Spring 2011, Paris, France
  * Invited, lunch debate of the "Magazine Tentation", March 8th, 2011, Paris, France
  * TV interview, NRJ12, April 17th (broacasted on May 7th), 2011, Rocquencourt, France
  * Plenary talk, Journée "Filles et Mathématiques", High-school students, January 27th, 2011, Paris, France
  * Promenade mathématique dans les vaisseaux sanguins, Conference in High school, April 8th, 2011, Mantes La Jolie, France

8.3. Teaching

8.3.1. Licence & Master

- Grégory Arbia

  Licence: LateX CNED, 20h, L2, Universite Pierre et Marie Curie, France.

  Licence: Scilab CNED, 20h, L2, Universite Pierre et Marie Curie, France.

  Licence: Series et Integrales CNED, 25.9h, L2, Universite Pierre et Marie Curie, France.

  Licence: Calcul matriciel numerique, 12h, L3, Universite Pierre et Marie Curie, France.

  Licence: Algebre 1: calcul vectoriel, 36h, L1, Universite Pierre et Marie Curie, France.

- Laurent Boudin

  Supervisor of the bidisciplinary computer science / applied maths licence program and of the joint program UPMC-Brown on computer science / applied maths at the licence level (18h)

  Licence: "Series and integrals" (30h), L2, UPMC.

  Licence: "Functions of several variables and multiple integrals" (36h taught in French), L2, UPMC.

  Licence: "Functions of several variables and multiple integrals" (48h taught in English), joint program UPMC-Brown.

  Licence: "Hilbertian analysis" (16h), L3, Polytech'Paris.

  Licence: "Introduction to numerical analysis" (36h), L3, UPMC.

  Master: "Numerical analysis" (38h), M1, Polytech'Paris.

- Muriel Boulakia

  Licence: Linear optimization and convexity (36h), L3, UPMC, France.

  Licence: Hilbertian analysis (21h), L3, Polytech'Paris, France.

  Licence: Upgrade course (64h), L3, Polytech'Paris, France.

Master: Approximation methods for partial differential equations (72h), M1, UPMC, France.

Master: Supervision of an internship "Use of Freefem++ for simulating the electrical activity of the heart" (5h), M1, UPMC, France.

- Anne-Claire Egloffe

  Licence: Differential calculus, 72h, L2, Pierre and Marie Curie University (Paris 6), France.

  Licence: Sequences, series, integrals , 20h, L2, Pierre and Marie Curie University (Paris 6), France.

- Miguel Ángel Fernández Varela

  Licence: Scientific computing, 30h, level L3, École des Ponts ParisTech, France.

  Master: Numerical methods in bio-fluids, 6h, level M2, University of Vigo, Spain.

  Master: Inverse problems, 44h, level M1, Ecole Supérieure d'Ingénieurs Léonard de Vinci, France.

- Ayman Moussa

  Licence: "Numerical Methods for differential equations" (36h), L3, UPMC.

  Master: "Real Analysis" (72h), M1, UPMC.

  Master:"Numerical analysis" (38h), M1, Polytech'Paris.

- Marc Thiriet

  Master: "Biofluid flows", 12 h, niveau M2, University Pierre et Marie Curie, France.

- Irène Vignon-Clémentel:

  Licence: Mathematics for biology, 64h ETD, L1, Université de Versailles Saint Quentin, France.

  Master: Different types of model for blood flow simulations, within the course "Mathematics modeling for biology", 5h ETD, M1, Ecole Centrale Paris, France.

  Different types of model for blood flow simulations, 1h, "Diplôme universitaire de Médicine" on percutaneous valvular replacement, Paris, France.

8.3.2. PhD & HDR

- HdR [12]: Laurent Boudin, Modélisation cinétique et hydrodynamique pour la physique, la chimie et la santé, analyse mathématique et numérique, Université Pierre et Marie Curie, 8 décembre 2011.
- PhD in progress :
  - Grégory Arbia, *Multi-scale Modeling of Single Ventricle Hearts for Clinical Decision Support*, since October 2010. Supervisors: J-F. Gerbeau & I. Vignon-Clementel.
  - Cristóbal Bertoglio Beltran, *Forward and Inverse problems in fluid-structure interaction. Application in hemodynamics*, since October 2008. Supervisors: J-F. Gerbeau & M.A. Fernández Varela.
  - Paul Cazeaux, *Homogenization and lungs modelling*, since September 2009. Supervisors: C. Grandmont & Y. Maday
  - Anne-Claire Egloffe, *Inverse problems in lungs modelling*, since October 2009. Supervisors: C. Grandmont & M. Boulakia.
  - Justine Fouchet-Incaux, *Mathematical and numerical modeling of the human breathing*, since October 2011. Supervisors: C. Grandmont & B. Maury.

- Stéphane Liwarek, *Air flow in the nasal cavity*, since October 2010. Supervisors: M.A. Fernández & J-F. Gerbeau.
- Jimmy Mullaert, *Fluid-structure interaction*, since September 2009. Supervisors: M.A. Fernández & Y. Maday
- Elisa Schenone, *Inverse problems in electrocardiology*, since October 2011. Supervisors: J-F. Gerbeau & M. Boulakia.
- Saverio Smaldone, *Numerical methods for cardiac hemodynamics*, since October 2010, Supervisors: J-F. Gerbeau & M.A. Fernández.

9. Bibliography

Major publications by the team in recent years

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

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

[3] E. BURMAN, M. A. FERNÁNDEZ VARELA. *Galerkin Finite Element Methods with Symmetric Pressure Stabilization for the Transient Stokes Equations: Stability and Convergence Analysis*, in "SIAM Journal on Numerical Analysis", 2008, vol. 47, n^{o} 1, p. 409–439.

[4] E. BURMAN, M. A. FERNÁNDEZ VARELA. *Stabilization of explicit coupling in fluid-structure interaction involving fluid incompressibility*, in "Comput. Methods Appl. Mech. Engrg.", 2008.

[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^{o} 42-44.

[6] M. A. FERNÁNDEZ VARELA, J.-F. GERBEAU, C. GRANDMONT. *A projection semi-implicit scheme for the coupling of an elastic structure with an incompressible fluid*, in "Internat. J. Numer. Methods Engrg.", 2007, vol. 69, n^{o} 4, p. 794–821.

[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", 2005, vol. 8, p. 279-293.

[8] C. GRANDMONT. *Existence of weak solutions for the unsteady interaction of a viscous fluid with an elastic plate*, in "SIAM J. Math. Anal.", 2008, vol. 40, n^{o} 2, p. 716–737.

[9] A. MOUSSA, T. GOUDON, L. HE, P. ZHANG. *The Navier-Stokes-Vlasov-Fokker-Planck system near equilibrium*, in "SIAM Journal on Mathematical Analysis", September 2010, http://hal.inria.fr/hal-00652341/en.

[10] 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.

[11] I. VIGNON-CLEMENTEL, C. FIGUEROA, K. E. JANSEN, C. A. 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", 2006, vol. 195, p. 3776-3796.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[12] L. BOUDIN. *Modélisation cinétique et hydrodynamique pour la physique, la chimie et la santé, analyse mathématique et numérique*, Université Pierre et Marie Curie - Paris VI, December 2011, Habilitation à Diriger des Recherches, http://hal.inria.fr/tel-00650560/en.

Articles in International Peer-Reviewed Journal

[13] A. BARETTA, C. CORSINI, W. YANG, I. VIGNON-CLEMENTEL, A. MARSDEN, J. FEINSTEIN, T.-Y. HSIA, G. DUBINI, F. MIGLIAVACCA, G. PENNATI, MODELING OF CONGENITAL HEARTS ALLIANCE INVESTIGATORS, MOCHA. *Virtual surgeries in patients with congenital heart disease: a multi-scale modelling test case.*, in "Philosophical Transactions A: Mathematical, Physical and Engineering Sciences", November 2011, vol. 369, n^{o} 1954, p. 4316-30 [*DOI :* 10.1098/RSTA.2011.0130], http://hal.inria.fr/hal-00650838/en.

[14] L. BOUDIN, J. MATHIAUD. *A numerical scheme for the one-dimensional pressureless gases system*, in "Numerical Methods for Partial Differential Equations", August 2011 [*DOI :* 10.1002/NUM.20700], http://hal.inria.fr/hal-00537145/en.

[15] E. BURMAN, M. A. FERNÁNDEZ VARELA. *Analysis of the PSPG method for the transient Stokes' problem*, in "Computer Methods in Applied Mechanics and Engineering", 2011, vol. 200, n^{o} 41-44, p. 2882-2890 [*DOI :* 10.1016/J.CMA.2011.05.001], http://hal.inria.fr/inria-00426777/en.

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[18] M. ESMAILY MOGHADAM, Y. BAZILEVS, T.-Y. HSIA, I. VIGNON-CLEMENTEL, A. MARSDEN, MODELING OF CONGENITAL HEARTS ALLIANCE INVESTIGATORS, MOCHA. *A comparison of outlet boundary treatments for prevention of backflow divergence with relevance to blood flow simulations*, in "Computational Mechanics", September 2011, vol. 48, n^{o} 3, p. 277-291 [*DOI :* 10.1007/S00466-011-0599-0], http://hal.inria.fr/hal-00650986/en.

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[22] J. F. LADISA, R. J. DHOLAKIA, C. FIGUEROA, I. VIGNON-CLEMENTEL, F. P. CHAN, M. M. SAMYN, J. R. CAVA, C. A. TAYLOR, J. FEINSTEIN. *Computational simulations demonstrate altered wall shear stress in aortic coarctation patients treated by resection with end-to-end anastomosis.*, in "Congenital Heart Disease", September 2011, vol. 6, n^{o} 5, p. 432-43 [*DOI :* 10.1111/J.1747-0803.2011.00553.X], http://hal.inria.fr/hal-00651958/en.

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[24] P. MOIREAU, N. XIAO, M. ASTORINO, C. FIGUEROA, D. CHAPELLE, C. A. TAYLOR, J.-F. GERBEAU. *External tissue support and fluid-structure simulation in blood flows*, in "Biomechanics and Modeling in Mechanobiology", 2011 [*DOI :* 10.1007/S10237-011-0289-Z], http://hal.inria.fr/hal-00653231/en.

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[29] G. TROIANOWSKI, C. A. TAYLOR, J. FEINSTEIN, I. VIGNON-CLEMENTEL. *Three-dimensional simulations in Glenn patients: clinically based boundary conditions, hemodynamic results and sensitivity to input data*, in "Journal of Biomechanical Engineering", November 2011, vol. 133, n^{o} 11 [*DOI :* 10.1115/1.4005377], http://hal.inria.fr/hal-00651023/en.

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2011, epub ahead of print - Official Publication of The American Association for Thoracic Surgery and The Western Thoracic Surgical Association [*DOI :* 10.1016/J.JTCVS.2011.06.042], http://hal.inria.fr/hal-00649953/en.

International Conferences with Proceedings

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