INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Team reo

Numerical simulation of biological flows

Rocquencourt

THEME BIO

Activity Report

2005

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1. Team

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. Overall Objectives

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

- modeling the flow of biological fluids, more especially blood in large vessels and air in the respiratory tracts, both in normal and pathological states;
- developing and analyzing efficient, robust and reliable numerical methods for the simulation of such flows;
- developing simulation software to guide medical decision and to design more efficient medical devices.

3. Scientific Foundations

3.1. Multiphysics modeling

Keywords: *fluid-structure interaction*, *spray modelling*.

In large vessel 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, particules 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 developped 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 displacement.

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 to the above mentionned difficulties, here 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 succesfully 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 developped and analysed.

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 [44] in the frame of combustion. It was later used to develop the Kiva code [38] at the Los Alamos National Laboratory, or the Hesione code [41], for example. It has a wide range of applications, besides the nuclear setting: diesel engines, rocket engines [39], 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 therapic 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 modelling

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 [42]. 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 generalizes the work reported in [40] 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 travelling waves. Indeed imposing a boundary condition at the begining 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 recently developped in the ICEMA project [43]. 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. Respiratory tract modelling

Work is in progress to develop a multiscale modelling 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 modelled 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 compertment. 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 modelled 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 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 developpement 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) perturbate blood flows and may create local stresses favourable 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 planing.

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 wich 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, in the framework of “R-MOD” (RNTS 2001) and of “le-poumon-vous-dis-je” (ACI Nouvelles Interfaces des Mathématiques, 2003), 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.

5. Software

5.1. LiFE-V library

Keywords: *Finite element library*.

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

LiFE-V[1] 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

6.1.1. Existence results in fluid-structure interaction

Participant: C. Grandmont.

In [14], we study the existence of a solution for an unsteady fluid-structure interaction problem that can be viewed as a really simplified model to describe blow flow through large arteries. We consider a tridimensional viscous incompressible flow, which is modeled by the Navier-Stokes equations. This fluid is interacting with a thin elastic structure located on a part of the fluid boundary. The equations of the structure are the equations modelling a plate in flexion. The fluid equations are set in an unknown domain depending on the structure displacement itself resulting from the fluid force. We prove the existence of at least one weak solution as long as the structure does not touch the rigid part of the fluid boundary. The same result holds aslo for a 2D fluid interacting with a 1D membrane.

In [37], we consider a two–dimensional viscous incompressible fluid governed by the Navier–Stokes equations, interacting with an elastic beam located on one part of the fluid boundary. The purpose of this work is to study the solutions of this unsteady fluid–structure interaction problem, as the coefficient modeling the viscoelasticity (resp. the rotatory inertia) of the beam tends to zero. As a consequence, we obtain the existence

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

of at least one wea k solution for the limit problem (Navier–Stokes equation coupled with Euler–Bernoulli equation) as long as the beam does not touch the bottom of the fluid cavity.

In [21] we present and analyse a dynamical geometrically nonlinear formulation that models the motion of two–dimensional and three–dimensional elastic structures in large displacements–small strains. In a first part we derive the equations describing the motion of the body. In a second part, existence of a weak solution is proven using a Galerkin method. We also prove that the solution is unique.

6.1.2. Numerical methods in fluid-structure interaction

Participants: N. Diniz dos Santos, M.Á. Fernández, J.-F. Gerbeau, A. Gloria, C. Grandmont.

This activity on fluid-structure interaction is done in close collaboration with the MACS project, in particular with M. Vidrascu and P. Le Tallec [23].

M.Á. Fernández, J.-F. Gerbeau and C. Grandmont have proposed a new method to solve fluid-structure interaction problems involving an incompressible viscous fluid. This coupling may be delicate when the so-called added-mass effect is strong. Indeed, in such situations, *implicit* coupling schemes (*i.e.* preserving energy balance), seem to be necessary to avoid numerical instabilities. This leads to very expensive simulations since, at each time step, a lot of resolutions of the fluid and the structure problems have to be performed. Nevertheless, in other situations, *e.g.* when dealing with compressible fluids or with a low added-mass effect, *explicit* coupling schemes (*i.e.* typically requiring only one fluid and structure resolution per time step) prove to be stable.

We introduced and analyzed a partially explicit (or semi-implicit) scheme, which remains stable in test cases for which only fully implicit schemes were known to be stable (to the best of our knowledge). The proposed algorithm, based on the classical Chorin-Temam projection scheme for incompressible flows, is much more efficient than any strongly coupled scheme we are aware of. Moreover, its stability properties, observed in various complex numerical simulations, are confirmed by a theoretical analysis carried out in a simplified configuration. This work has been announced in [18] and reported in [35].

6.1.2.1. Work in progress

A. Gloria investigates in his PhD thesis alternative decomposition domain methods for fluid-structure interaction problems.

6.1.2.2. Work in progress

N. Diniz dos Santos investigates in his PhD thesis fictitious domain approaches for valve simulations. Preliminary results have been published in [31].

6.1.3. Stabilized finite element methods in fluid mechanics

Participant: M.Á. Fernández.

M.Á. Fernández and E. Burman (during a visit in the REO team as an INRIA invited professor), extended the face oriented stabilization method to the time-dependent Navier-Stokes equations in an space semi-discrete formulation. The key issue in this work is that the stabilization allows for estimates that are uniform in the Reynolds number. It is also interesting to note that the present stabilized method allows for a complete decoupling of the analysis for the velocities and pressures. The only requirement for convergence is that the solution is sufficiently smooth. Our analysis is inspired by the one by Hansbo & Szepessy (1990), but our results using face oriented stabilization are sharper. In fact, to control the convective velocity, which is only weakly divergence free, special nonlinear stabilization terms are introduced, leading to a more complex formulation and stronger regularity assumptions on the exact solution are required. In our case, the fact that the stabilization of the velocities is decoupled from the stabilization of the pressure allows us to prove convergence using essentially the stabilization terms of the linear case (previous work for the Oseen equations, in collaboration with E. Burman and P. Hansbo), and under similar regularity assumptions. Moreover, we prove convergence for all polynomial orders, whereas in Hansbo & Szepessy's work the analysis was restricted to piecewise linear approximations in a space-time formulation. This work has been reported in [34].

6.1.4. Optimization algorithms

Participant: L. Dumas.

In [15], we reformulate global optimization problems in terms of boundary value problems. This allows us to introduce a new class of optimization algorithms. Indeed, current optimization methods, including non-deterministic ones, can be seen as discretizations of initial value problems for differential equations or systems of differential equations. This new class of algorithms are applied and compared with a genetic algorithm for the design of multichannel optical filters.

In [17], [16], various global optimization methods are constructed in order to be able to tackle realistic drag reduction problems in the automotive industry. All the methods consist in improving classical genetic algorithms (GA), by coupling them with a fast but approximated evaluation process. The efficiency of these methods is shown, first on analytical test functions, then on a drag reduction problem where the computational time of a GA is highly reduced.

6.2. Respiration tree modelling

6.2.1. Modelling

Participants: C. Grandmont, Y. Maday, B. Maury.

Among all systems in medical modeling, the respiration tree certainly holds a pole position for complexity. It is indeed a place where many exchanges and interactions take place. A numerical lung would certainly be most helpful in the understanding of some of the deceases and a way to guide the intuition for curative gestures. Even though a complete working simulation will not be available soon, it is our goal to start on modeling and simulating this organ. In [22] our interest is, starting from a simple, rather naive, model of the acini, to show how an upstream model can be hooked up and result in a well-posed coupled system that will allow for simulations. After presenting the naive model, we present the global model where between it and the outside and prove that the coupling is pertinent.

We elaborate a model to describe some aspects of the human lung considered as a continuous, deformable, medium. To that purpose, we study the asymptotic behaviour of a spring-mass system with dissipation. The key feature of our approach is the nature of this dissipation phenomena, which is related here to the flow of a viscous fluid through a dyadic tree of pipes (the bronches), each exit of which being connected to an air pocket (alveol) delimited by two successive masses. The first part concentrates on the relation between fluxes and pressures at the outlets of a dyadic tree, assuming the flow within the tree obeys Poiseuille-like laws. In a second part, which contains the main convergence result, we intertwine the outlets of the tree with a spring-mass array. Letting ag ain the number of generations (and therefore the number of masses) go to infinity, we show that the solutions to the finite dimensional p roblems converge to the solution of a wave-like partial differential equation with a non-local dissipative term.

6.2.2. Airway flow

Participants: M. Thiriet, L. Vial.

A computational model of an oscillatory laminar flow of an incompressible Newtonian fluid has been carried out in the proximal part of human tracheobronchial trees, either normal or with a strongly stenosed right main bronchus. After acquisition with a multislice spiral CT, the thoracic images are processed to reconstruct the geometry of the trachea and the six first bronchus generations and to virtually travel inside this duct network. The facetisation associated with the three-dimensional reconstruction of the tracheobronchial tree is improved to get a computation-adapted surface triangulation, which leads to a volumic mesh composed of tetrahedra. The Navier-Stokes equations associated with the classical boundary conditions and different values of the flow dimensionless parameters are solved using the finite element method. The airways are supposed to be rigid during rest breathing. The flow distribution among the set of bronchi is determined during the respiratory cycle. Cycle reproducibility and mesh size effects on the numerical results are examined. Helpful qualitative data are provided rather than accurate quantitative results in the context of multimodelling, from image processing to numerical simulations.

Experimental validation has been performed using magnetic resonance velocimetry with hyperpolarized helium 3. The NMR technique has been itself validated by measurements in planar 180 degree bend of uniform curvature and a summetric bifurcation. The facetisation associated with the three-dimensional reconstruction of a normal tracheobronchial tree has been used for rapid prototyping. Numerical simulations of steady flow have been carried out with the experimental tracheal velocity input. Experimental and numerical results are in qualitative good agreement.

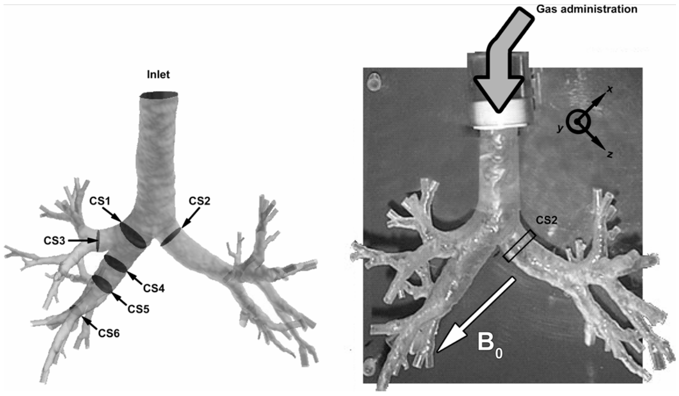

Figure 1.

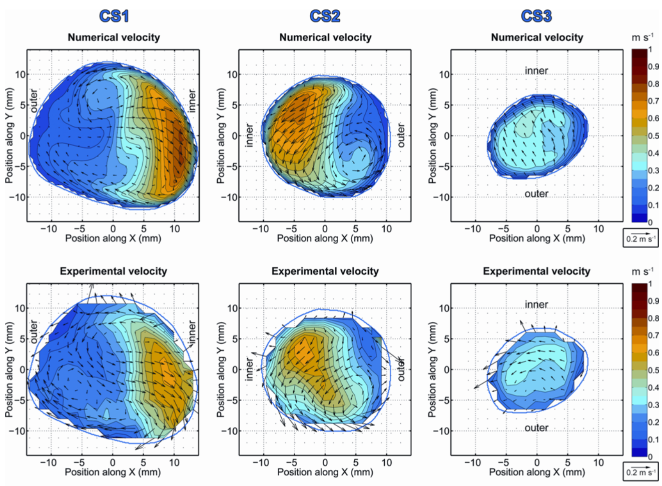

Figure 2.

6.3. Blood flows

6.3.1. Abdominal Aortic Aneurysm

Participant: M.Á. Fernández.

M.Á. Fernández in collaboration with A.-V. Salsac (UTC Compiegne), P. Le Tallec (Ecole Polytechnique) are working on the 3D numerical simulation of the flow in an abdominal aortic aneurysm (AAA). As an AAA develops, large changes occur in the composition and structure of the arterial wall, which result in its stiffening. So far, most studies, whether experimental or numerical, have been conducted assuming the walls to be rigid. A numerical simulation of the fluid-structure interactions, using the numerical methods developed by our team, is performed in different models of aneurysms in order to analyze the effects that the wall compliance might have on the flow topology. Both symmetric and non-symmetric models of aneurysms are considered, all idealistic in shape. In the case of rigid walls, the calculation of the wall shear stresses and pressure compare very well with experimental results (carried out by A.-V. Salsac during her PhD work). Now, the wall mechanical properties are being varied in order to simulate the progressive stiffening of the walls. The spatial and temporal distributions of wall tension are calculated for the different values of the wall elasticity and compared to the results for the rigid walls.

This work has been presented by A.V Salsac at the "58th Annual Meeting of the Division of Fluid Dynamics" November 20 - 22, 2005, Chicago, USA.

6.3.2. Numerical simulation of stents for aneurysms

Participants: M.Á. Fernández, J.-F. Gerbeau, V. Martin.

This study ([36]) is carried on in collaboration with the CARDIATIS company.

In order to reduce the blood flow in a terminal aneurysm, an approach consists in introducing a stent into the artery where the aneurysm develops. This device acts as a resistance to the flow, and can be thought of as a thin porous medium inserted in the flow domain. We propose to model this device as a surface measure added to the classical Navier-Stokes equations. The normal stress is discontinuous at the interface and its jump is proportional to the velocity. The coefficient introduced in the model is a resistance parameter that can be directly determined by experiments. Two slightly different models were derived, according to the heuristic taken. The models are well-posed; one of the two is close to the limit of the plane sieve Stokes problem, obtained by Conca with homogeneity arguments.

To see the physical relevance of the models, they were numerically tested in different configurations and with different spaces of approximation. The models were validated over a stationary flow in a 2D tube. Some 2D and 3D numerical simulations were performed in simplified geometries of aneurysms with realistic flow conditions. Preliminary fluid-structure interaction tests with a resistive term are being studied. Further tests will involve a realistic geometry of a terminal aneurysm.

6.3.3. Parameter estimation for a 1D blood flow model

Participants: J.-F. Gerbeau, V. Martin.

In [33], we use a variational method to identify some of the parameters of one-dimensional models for blood flow in arteries (in collaboration with F. Clément, ESTIME project and A. Decoene, BANG project). These parameters can be fit to approach as much as possible some data coming from experimental measurements or from numerical simulations performed using more complex models.

A nonlinear least squares approach to parameter estimation was taken, based on the optimization of a cost function. The resolution of such an optimization problem generally requires the efficient and accurate computation of the gradient of the cost function with respect to the parameters.

This gradient is computed analytically when the one-dimensional hyperbolic model is discretized with a second order Taylor-Galerkin scheme. An adjoint approach was used.

Some preliminary numerical tests were performed. In these simulations, we mainly focused on determining a parameter that is linked to the mechanical properties of the arterial walls, the compliance. The synthetic data we used to estimate the parameter were obtained from a numerical computation performed with a more accurate model: a three-dimensional fluid-structure interaction model. These first results seem to be promising. In particular, it is worth noticing that the estimated compliance which gives the best fit is quite different from the values that are commonly used in practice.

6.3.4. Electrical activity of the heart (work in progress)

Participants: M. Boulakia, M.Á. Fernández, J.-F. Gerbeau.

We have just started a work whose aim is to couple the cardiac electrical activity with the electrical activity in the thorax. The short term objective is the numerical simulation of electrocardiograms. The long term objective is to develop a simulation tool able to provide some insights in the optimization of multisite stimulations of the myocardium. This work is a part of the CardioSense3D INRIA project and is partially supported by the ELA Medical company.

6.3.5. Simulation of heart perfusion (work in progress)

Participants: J.-F. Gerbeau, L. Janski.

Perfusion is the act of pouring over or through, especially the passage of a fluid through the vessels of a specific organ. In case of the heart, blood passes through: the coronary arteries, arterioles, capillaries, cardiac venules and veins. Perfusion allows for supply of nutrients and oxygen to the myocardial muscle, as well as for recovery of metabolic wastes and carbon dioxide from the myocardial muscle. To model perfusion in an appropriate way, hierarchic structure of the vessel tree must be well described. In the framework of the project, the hierarchic porous medium theory is used to achieve the mentioned aim. The theory takes into account not only the structure of the vessel tree, but also the mechanical response of the vessel walls, as well as the interaction between: the myocardial muscle contraction, the mechanical behaviour of the vessel walls and transported blood. An implementation in the LifeV numerical library of a simplified, rigid variant of the theory is currently in progress.

7. Contracts and Grants with Industry

7.1. ELA Medical

Participants: M. Boulakia, M.Á. Fernández, J.-F. Gerbeau.

ELA Medical, a Sorin Group company, is a manufacturer of pacemakers and implantable diagnostic systems. Our study is devoted to the numerical simulation of the electrical activity of the heart. See section 6.3.4 above.

7.2. Cardiatis

Participants: M.Á. Fernández, J.-F. Gerbeau, V. Martin.

The company CARDIATIS is developing a new generation of stents (wire mesh tube). Our studies is devoted to the numerical simulation of a stent which aims at excluding cerebral aneurysms. See section 6.3.2 above.

7.3. Alcan

Participant: J.-F. Gerbeau.

Industrial contracts with Ecole Nationale des Ponts et Chaussées in the framework of a collaboration with ALCAN (formerly Aluminium Pechiney) on the mathematical modelling of aluminium electrolysis cells (magnetohydrodynamics in presence of free interfaces). The work is done in collaboration with Claude Le Bris, Tony Lelièvre and Antonin Orriols (CERMICS & MicMac project).

8. Other Grants and Activities

8.1. National research program

8.1.1. CARDIOSENSE3D

Participants: M. Boulakia, M.Á Fernández [coordinator], J.-F. Gerbeau, L. Janski.

The REO project is member of the “CardioSense3D project”, an INRIA “Large Initiative Action” aimed at developping an electro-mechanical model of the heart[2].

8.1.2. ACI “le-poumon-vous-dis-je”

Participants: J.-F. Gerbeau, C. Grandmont, Y. Maday, B. Maury [coordinator], M. Thiriet.

This project[3] aims at studying mathematical and numerical issues raised by the modelling of the lungs.

8.2. European research program

8.2.1. Research Training Network “Haemodel”

Participants: N. Diniz dos Santos, M.Á. Fernández, J.-F. Gerbeau [coordinator], C. Grandmont, L. Janski.

The aim of this project[4] is to investigate the main mathematical and numerical problems related to the simulation of the human cardiovascular system. Participants: INRIA, Université Paris 6, Politecnico di Milano (Italy), Imperial College (UK), Ecole Polytechnique Fédéral de Lausanne (Switzerland), Instituto Superior Técnico de Lisboa (Portugal), Technische Universität Graz (Austria).

8.2.2. ERCIM working group “IM2IM”

Participant: Marc Thiriet [coordinator].

The ERCIM Working Group "IM2IM"[5] has been initiated in june 2003 in the context of minimally invasive treatment in medicine and surgery.

9. Dissemination

9.1. Scientific community animation

9.1.1. Various academic responsibilities

- M.Á Fernández, J.-F. Gerbeau and M. Thiriet have organized a CEA-EDF-INRIA school on the numerical simulation of blood flows (december 6-9, 2005)
- L. Dumas
  - *Membre du jury d’entrée au concours commun ENS Cachan-Ecole Polytechnique (PSI).*
  - *Membre du jury du CAPES externe de Mathématiques.*
  - External member of the *Commission de spécialistes* of Paris 13 university.
- L. Boudin

[2] http://www-sop.inria.fr/CardioSense3D/
[3] http://www.insa-rennes.fr/ACINIMpoumon/index.html
[4] http://mox.polimi.it/it/progetti/haemodel/
[5] http://www-rocq1.inria.fr/Marc.Thiriet/Im2im/

  - Scientific coordinator in Mathematics Departement (DSPT 1) of the *Mission Scientifique, Technique et Pédagogique* (MSTP), of the *Ministère de l'Education Nationale, de l'Enseignement Superieur et de la Recherche*.

- J.-F. Gerbeau

  - Scientific coordinator of the CEA-EDF-INRIA schools organized by INRIA.
  - External member of the *Commission de spécialistes* of the Montpellier II University.

- C. Grandmont

  - Co-organizer of the first meeting devoted to the junior researchers and assistant professor in mathematics, 28/01/2005, Institut Henri Poincaré, Paris, http://postes.smai.emath.fr/accueil/index.php

9.2. Teaching

- Laurent Boudin

  - Linear algebra and numerical methods, Licence, Paris 6 University.

- Miguel Á. Fernández

  - "Fluid-structure interaction. Application to blood flows", Master of numerical analysis, Paris 6 University (with J.-F. Gerbeau and Y. Maday)
  - Exercises of "Numerical Optimization". ENSTA.

- Jean-Frédéric Gerbeau

  - Analysis and scientific computing courses, Ecole Nationale des Ponts et Chaussées.
  - "Fluid-structure interaction. Application to blood flows", Master of numerical analysis, Paris 6 University (with M. Á. Fernández and Y. Maday)
  - Master in mathematical engineering, Ecole Polytechnique de Tunisie.

- Marc Thiriet

  - Montréal, Ecole de printemps, Centre de Recherches Mathématiques de l'Université de Montréal, may 2005.

9.3. Participation in conferences, workshops and seminars

- Muriel Boulakia
  - International congress "Nonlinear parabolic problems", Helsinki, Finland (october 2005).
- Nuno Diniz dos Santos
  - Sesimbra (Portugal) - april 2005 - Modelling Physiological Flows 2005
  - Evian - 23-27 may 2005 - Congrés SMAI 2005 (*poster*)
  - INRIA - 23 september 2005 - Journée C.A. Taylor
  - Mulhouse - 17-18 november 2005 - Workshop: “Fluid-Structure” (*invited seminar*)
- Laurent Dumas
  - 1ère Journées Méditerranéennes de Mathématiques Appliquées, Tozeur, 24/03/2005.
  - workhop on PDE constrained optimization, Tomar, 27/07/2005 *(invited talk)*.
  - ICCSA 2005, Singapour, 11/05/2005.
  - Indian Institute of Technology, Bombay, 19/10/2005 *(invited seminar)*
  - Tata Institue of Fundamental Research, Bangalore (27/10 and 03/11, *invited seminars*)
- Miguel Ángel Fernández
  - ENUMATH2005, July 18 - 22, 2005, Santiago de Compostela, Spain.
  - Modelling Physiological Flows, MPF2005, March 30 - April 2, 2005, Sesimbra, Portugal.
  - “Groupe de Biomécanique et Génie Biomédicale”, February 14, 2005, UTC Compiègne, France *(invited seminar)*.
  - Institut de Mathématiques Appliquées de Grenoble, December 15, 2005, Grenoble, France *(invited seminar)*.
  - CEA-INRIA-EDF & HaeMOdel School on *Numerical Simulations of Blood Flows*, December 6 - 9, 2005, Rocquencourt, France *(lecturer)*.
  - Spring School *Mini-invasive procedures in medecine and surgery: mathematical and numerical challenges*, May 16 - 27, 2005, Montreal, Canada *(lecturer)*.
- Jean-Frédéric Gerbeau
  - 5th International Conference on Computation of Shell and Spatial Structures, june 1-4, 2005, Salzburg, Austria *(keynote speaker)*
  - Modelling Physiological Flows (MPF 2005), March 30 - April 2, 2005, Sesimbra, Portugal *(keynote speaker)*
  - Third M.I.T. Conference on Computational Fluid and Solid Mechanics, june 2005, Boston, USA *(minisymposium organizer)*.
  - LATP (Université de Provence), *(invited seminar)*.
  - MAPMO(Université d’Orléans), *(invited seminar)*.
  - GT “Méthodes numériques” Université Paris 6, *(invited seminar)*.

- Céline Grandmont
  - Third M.I.T. Conference on Computational Fluid and Solid Mechanics, june 2005, Boston, USA.
  - Congres SMAI 2005, Evian
- Vincent Martin
  - Sesimbra (Portugal) - april 2005 - Modelling Physiological Flows 2005
- Marc Thiriet
  - Hong Kong, october 2005.
  - Taiwan, National Taiwan University et National Health Research Institutes, november 2005

10. 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.", vol. 1, n° 4, 2003, p. 657–669.

[2] 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.", vol. 194, n° 42-44, 2005.

[3] L. DUMAS, F. GOLSE. *Homogenization of transport equations*, in "SIAM J. Appl. Math.", vol. 60, n° 4, 2000, p. 1447–1470.

[4] M. A. FERNÁNDEZ, P. LE TALLEC. *Linear stability analysis in fluid-structure interaction with transpiration. II. Numerical analysis and applications*, in "Comput. Methods Appl. Mech. Engrg.", vol. 192, n° 43, 2003, p. 4837–4873.

[5] M. A. FERNÁNDEZ, P. LE TALLEC. *Linear stability analysis in fluid-structure interaction with transpiration. I. Formulation and mathematical analysis*, in "Comput. Methods Appl. Mech. Engrg.", vol. 192, n° 43, 2003, p. 4805–4835.

[6] L. FORMAGGIA, J.-F. GERBEAU, F. NOBILE, A. QUARTERONI. *On the Coupling of 3D and 1D Navier-Stokes equations for Flow Problems in Compliant Vessels*, in "Comp. Meth. Appl. Mech. Engrg.", vol. 191, n° 6-7, 2001, p. 561-582.

[7] J. GERBEAU, M. VIDRASCU. *A quasi-Newton algorithm based on a reduced model for fluid-structure interactions problems in blood flows*, in "Math. Model. Num. Anal.", vol. 37, n° 4, 2003, p. 631-648.

[8] M. THIRIET, R. ISSA, J. M. R. GRAHAM. *A pulsatile developing flow in a bend*, in "J. Phys. III", vol. 2, 1992, p. 995-1013.

Books and Monographs

[9] M. THIRIET. *Biology and Mechanics of Blood Flows*, CRM Series in Mathematical Physics, to appear, Springer.

Articles in refereed journals and book chapters

[10] J.-D. BOISSONNAT, R. CHAINE, P. FREY, G. MALANDAIN, S. SALMON, E. SALTEL, M. THIRIET. *From arteriographies to computational flow in saccular aneurisms: the INRIA experience*, in "Medical Image Analysis (MedIA)", vol. 9, n^o 2, 2005, p. 133-143.

[11] M. BOULAKIA. *Existence of weak solutions for the three dimensional motion of an elastic structure in an incompressible fluid*, in "J. Math. Fluid Mech.", to appear.

[12] M. BOULAKIA. *Existence of weak solutions for an interaction problem between an elastic structure and a compressible viscous fluid*, in "J. Math. Pures et Appliquées", vol. 84, 2005, p. 1515-1554.

[13] 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.", vol. 194, n^o 42-44, 2005.

[14] A. CHAMBOLLE, B. DESJARDINS, M. J. ESTEBAN, C. GRANDMONT. *Existence of weak solutions for the unsteady interaction of a viscous fluid with an elastic plate*, in "J. Math. Fluid Mech.", vol. 7, n^o 3, 2005, p. 368–404.

[15] L. DUMAS, O. DURAND, B. IVORRA, B. MOHAMMADI. *A semi-deteminist method : Multi-level shooting algorithm . Application to the synthesis of high-channel-count multichannel filters based on sampled fiber Bragg grating, results comparison with a genetic algorithm*, in "IJCSE", to appear.

[16] L. DUMAS, V. HERBERT, F. MUYL. *Comparison of global optimization methods for drag reduction in the automotive industry*, Lecture Notes in Computer Science 3483, 2005, p. 948-957.

[17] L. DUMAS, V. HERBERT, F. MUYL. *Optimisation de forme en aérodynamique automobile*, in "Mécanique et Industrie", vol. 6, n^o 3, 2005.

[18] M. FERNÁNDEZ, J.-F. GERBEAU, C. GRANDMONT. *A projection algorithm for fluid-structure interaction problems with strong added-mass effect*, in "C. R. Acad. Sci. Paris, Mathématiques", to appear.

[19] C. FETITA, S. MANCINI, D. PERCHET, F. PRÊTEUX, M. THIRIET, L. VIAL. *An image-based computational model of oscillatory flow in the proximal part of tracheobronchial trees*, in "Computer Methods in Biomechanics and Biomedical Engineering", vol. 8, n^o 3, 2005, p. 1-15.

[20] J.-F. GERBEAU, M. VIDRASCU, P. FREY. *Fluid-Structure Interaction in Blood Flows on Geometries based on Medical Imaging*, in "Comp. & Struct.", vol. 83, n^o 2-3, 2005, p. 155-165.

[21] C. GRANDMONT, Y. MADAY, P. METIER. *Modeling and analysis of an elastic problem in large displacements and small strain*, Submitted.

[22] C. GRANDMONT, B. MAURY, N. MEUNIER. *A Viscoelastic Model with Non-local Damping: Application to the Human Lungs*, in "M2AN", to appear.

[23] P. LE TALLEC, P. HAURET, J.-F. GERBEAU, M. VIDRASCU. *Structure Interaction Problems in Large Deformations*, in "C. R. Acad. Sci. Paris, Mécanique", vol. 333, nº 12, 2005, p. 910-922.

[24] S. NAILI, M. THIRIET. *Pressure field in flow through uniform straight pipes with varying wall cross curvature*, in "Computers in Biology and Medicine", vol. 35, nº 8, 2005, p. 645-663.

[25] S. NAILI, M. THIRIET, C. RIBREAU. *Wall shear stress in a laminar flow through a collapsed tube with wall contact*, in "Eur. Phys. J. – Applied Physics", to appear.

[26] S. NAILI, M. THIRIET, C. RIBREAU. *Developing steady laminar flow through uniform straight tubes with varying wall cross curvature*, in "Computer Methods in Biomechanics and Biomedical Engineering", vol. 7, nº 6, 2004, p. 319-330.

[27] D. PERCHET, C. FETITA, L. VIAL, F. PRETEUX, G. CAILLIBOTTE, G. SBIRLEA-APIOU, M. THIRIET. *Virtual investigation of pulmonary airways in volumetric computed tomography*, in "Comput. Anim. Virtual Worlds", vol. 15, nº 3-4, 2004, p. 361-376.

[28] M. THIRIET. *Modeling of Biological Materials*, Modeling and Simulation in Sciences, Engineering, and Technology, to appear, chap. Biochemical and Biomechanical Aspects of Blood Flow, Birkhauser.

[29] L. VIAL, D. PERCHET, R. FODIL, G. CAILLIBOTTE, C. FETITA, F. PRÊTEUX, C. BEIGELMAN-AUBRY, P. GRENIER, M. THIRIET, D. ISABEY, G. SBIRLEA-APIOU. *Airflow modeling of steady inspiration in two realistic proximal airway trees reconstructed from human thoracic tomodensitometric images*, in "Computer Methods in Biomechanics and Biomedical Engineering", to appear.

Publications in Conferences and Workshops

[30] C. BARANGER, L. BOUDIN, P.-E. JABIN, S. MANCINI. *A modeling of biospray for the upper airways*, in "CEMRACS 2004 - Mathematics and applications to biology and medicine", ESAIM: Proceedings, vol. 14, September 2005, p. 41–47.

[31] P. CAUSIN, N. DINIZ DOS SANTOS, J. GERBEAU, C. GUIVIER, P. METIER. *An embedded surface method for valve simulation. Application to stenotic aortic valve estimation*, in "CEMRACS 2004 - Mathematics and applications to biology and medicine", ESAIM: Proceedings, vol. 14, September 2005, p. 48–62.

[32] C. GRANDMONT, Y. MADAY, B. MAURY. *A multiscale/multimodel approach of the respiration tree*, in "Proceedings of the International Conference, "New Trends in Continuum Mechanics", 8-12 September 2003, Constantza, Romania Theta Foundation Publications, Bucharest", 2005.

[33] V. MARTIN, F. CLÉMENT, A. DECOENE, J.-F. GERBEAU. *Parameter identification for a one-dimensional blood flow model*, in "CEMRACS 2004 - Mathematics and applications to biology and medicine", ESAIM: Proceedings, vol. 14, September 2005, p. 174–200.

Internal Reports

[34] E. BURMAN, M. FERNÁNDEZ. *A finite element method with edge oriented stabilization for the time-dependent Navier-Stokes equations: space discretization and convergence*, Technical report, INRIA RR-5630, 2005, http://www.inria.fr/rrrt/rr-5630.html.

[35] M. FERNÁNDEZ, J.-F. GERBEAU, C. GRANDMONT. *A projection semi-implicit scheme for the coupling of an elastic structure with an incompressible fluid*, Technical report, INRIA RR-5700, 2005, http://www.inria.fr/rrrt/rr-5700.html.

Miscellaneous

[36] M. FERNÁNDEZ, J.-F. GERBEAU, V. MARTIN. *Modelling of a stent in blood flow as a resistive interface*, In preparation.

[37] C. GRANDMONT. *Existence of weak solutions for an unsteady fluid–beam interaction problem*, Submitted.

Bibliography in notes

[38] A. AMSDEN, P. O'ROURKE, T. BUTLER. *A computer program for chemically reactive flows with sprays*, Technical report, n^o LA-11560-MS, Los Alamos National Laboratory, 1989.

[39] J. DUPAYS, Y. FABIGNON, P. VILLEDIEU, G. LAVERGNE, G. ESTIVALEZES. *Some aspects of two phase flows in solid propellant rocket motors*, *in Solid propellant chemistry, combustion and interior ballistics*, in "Progress in Astronautics and Aeronautics", V. YANG, T. BRILL, W. PEN (editors). , vol. 185, 2000.

[40] L. FORMAGGIA, J. F. GERBEAU, F. NOBILE, A. QUARTERONI. *On the coupling of 3D and 1D Navier-Stokes equations for flow problems in compliant vessels*, in "Comput. Methods Appl. Mech. Engrg.", vol. 191, n^o 6-7, 2001, p. 561–582.

[41] R. MOTTE. *A numerical method for solving particle-fluid equations*, in "Trends in numerical and physical modeling for industrial multiphase flows, Cargèse, France", 2000.

[42] A. QUARTERONI, S. RAGNI, A. VENEZIANI. *Coupling between lumped and distributed models for blood flow problems*, in "Comput. Visual Sci.", vol. 4, 2001, p. 111–124.

[43] M. SERMESANT, Y. COUDIÈRE, H. DELINGETTE, N. AYACHE, J. SAINTE-MARIE, D. CHAPELLE, F. CLÉMENT, M. SORINE. *Progress towards model-based estimation of the cardiac electromechanical activity from ECG signals and 4D images*, in "ESAIM-Proceedings", vol. 12, 2003, p. 153-161.

[44] F. WILLIAMS. *Combustion theory*, 2nd, Benjamin Cummings, 1985.