International workshop on Mathematical Modeling in Hemo-dynamics

Saint-Étienne, December 3rd-5th, 2024

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1 Schedule

All the talks will take place in room L212 of Centre Ingéniérie et Santé (Campus Santé Innovation, 10 Rue de la Marandière, 42270 Saint-Priest-en-Jarez. More information is provided at the end of this document).

Tuesday, December 3rd:

- 1:00 PM: Coffee and registration
- 1:45 PM: Opening session
- 2:00 PM: **Timo Koch**
  Meso-scale mixed-dimensional models of transport in brain tissue
  Abstract page 5
- 2:45 PM: **Youcef Mammeri**
  Influence of environmental and social characteristics in SIR epidemic models
  Abstract page 6
- 3:30 PM: Coffee break
- 4:00 PM: **Maha Reda**
  Modeling the effects of elastic compression on fluid dynamics in lower limb lymphedema
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- 4:45 PM: **Adélia Sequeira**
  Cardiovascular modelling and simulations. Applications to image-based clinical studies.
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Wedneday, December 4th:

- 9:00 AM: **Grigori Panasenko**

  Partial dimension reduction in tube structures

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- 9:45 AM: **Miroslav Kuchta**

  Robust solvers for the Stokes problem in computational hemodynamics

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- 10:30 AM: Coffee break

- 11:00 AM: **Luca Dede'**

  Mathematical Models and Methods in Computational Cardiac Medicine

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- 11:45 AM: **Niami Nasr**

  Immersed boundary numerical methods for the inverse problem of electrical impedance tomography.

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- 12:30 AM: Lunch for registered participants

A social dinner will be held at Escargot d'or (5 cours Victor Hugo, Saint-Étienne) for registered participants.

Thursday, December 4th:

- 9:00 AM: **Oscar Flores Arias**

  Hemodynamics Affects Factor XI/XII Anticoagulation Efficacy in Patient-Derived Left Atrial Models

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- 9:45 AM: **Alexandra Vallet**

  Dispersion effect on solute transport within the perivascular spaces of the brain

  Abstract page 9

- 10:30 AM: Coffee break

- 11:00 AM: **Frédéric Chardard**

  Persistence and speed of a cooperation pulse when cooperators are more mobile than cheaters

  Abstract page 3

- 11:45 AM: End of the talks

A lunch for registered participants will be held at La Taverne, near Chateaucreux railway station.

2 Abstracts

Persistence and Speed of a Cooperation Pulse When Cooperators Are More Mobile Than Cheaters

Frédéric Chardard

Institut Camille Jordan, Université Jean Monnet

frederic.chardard@univ-st-etienne.fr

Abstract:
We consider the spatial dynamics of a population structured by a trait governing both the diffusion speed and the level of cooperation and that is subject to density dependent competition. The reproduction rate increases with the local average level of cooperation, while it decreases with the individual level of cooperation, such that a spatially homogeneous population cannot grow due to the rapid predominance of cheaters.
Numerical simulations indicate that a pulse (a localized wave) can propagate, with a population of cooperators growing at the front, while cheaters become dominant and lead to a population decline at the rear. To predict for which parameter values this phenomenon can occur, as well as the propagation speed, we study, within the framework of a deterministic model, the dispersion relation and the weak diffusion limit, which is a Hamilton-Jacobi equation with a non-convex Hamiltonian. The observed pulses cannot correspond to viscosity solutions of the limiting equation. This leads us to propose a new heuristic, which allows us to find the speed that is actually observed. To justify this, we study the effect of a perturbation on an exponential-type solution for the model without competition

Mathematical Models and Methods in Computational Cardiac Medicine

Luca Dede'

Politecnico di Milano

luca.dede@polimi.it

Abstract:
This talk explores the crucial role of mathematical modeling and scientific computing in advancing healthcare, with a specific focus on cardiac medicine. We begin by discussing the foundational concepts of scientific computing, emphasizing its importance in accurately solving complex problems and managing computational costs across various fields of science and engineering. Through real-world examples, we demonstrate how mathematical models, equations, and algorithms are transforming healthcare, particularly in the areas of computational and precision medicine. We focus on the application of these tools to simulate the human heart's physiology, enhancing our understanding of its function and aiding in the treatment of cardiac diseases. Furthermore, we highlight several instances where personalized heart simulations have led to more precise surgical interventions and improved clinical outcomes for patients with cardiac pathologies. We also introduce the emerging field of Scientific Machine Learning, which integrates physics-based models with data-driven approaches to create digital twins—virtual replicas of the human heart. Finally, we explore how Machine Learning and Deep Learning algorithms are revolutionizing the development of cardiac digital twins, paving the way for more accurate diagnoses, treatment plans, and personalized healthcare solutions.

Hemodynamics Affects Factor XI/XII Anticoagulation Efficacy in Patient-Derived Left Atrial Models

Oscar Flores

Universidad Carlos III de Madrid

oflores@ing.uc3m.es

Abstract:
Atrial fibrillation (AF) is a common arrhythmia that disrupts blood circulation in the left atrium (LA), resulting in relative stasis in the left atrial appendage (LAA) and, thus, increasing thromboembolic risk. Consequently, anticoagulation therapies are indicated for patients considered to be at sufficiently high risk. The benefits of anticoagulation in patients with high-risk of thrombogenesis needs to be measured against the increased risk of bleeding, driven by the fact that currently used agents target the common pathway, central to the coagulation cascade. Novel anticoagulants under development, such as factor XI/XII inhibitors, that target the initial phase of the intrinsic pathway, may be associated with a lower bleeding risk. However, their efficacy in preventing thrombosis is not fully understood.
In this work, we hypothesize that patient-specific flow patterns in the LA and LAA not only influence the risk of thrombosis but also the effectiveness of anticoagulation agents. We test this hypothesis by simulating blood flow and the intrinsic coagulation pathway in patient-specific LA anatomies, with and without factor XI/XII inhibition. We analyze an heterogeneous cohort of thirteen patients, some in sinus rhythm and others in AF, four of whom had an LAA thrombus or a history of transient ischemic attacks. Coagulation metrics based on peak LAA thrombin dynamics suggest that patients could be classified as having no, moderate or high thromboembolic risk. High-risk patients had slower flows and higher residence times in the LAA than those with moderate thromboembolic risk and they required stronger factor XI/XII inhibition to prevent thrombin growth. These data suggest that the anticoagulation effect was also related to the LAA hemodynamics.
The methodology outlined in this study has the potential to enable personalized assessments of coagulation risk and to tailor anticoagulation therapy by analyzing flow dynamics in patient-derived LA models, representing a significant step towards advancing the application of digital twins in cardiovascular medicine.

Meso-scale mixed-dimensional models of transport in brain tissue

Timo Koch

University of Oslo

timokoch@uio.no

Abstract:
In biological tissue, vascular systems have the crucial function to supply nutrients and support homeostasis. Microvessels form well-connected networks that enhance transport, for example in the brain, an organ with an enormous oxygen demand (A $1mm^3$ gray matter tissue samples contains about 20'000 blood vessels). But microvessels also exchange fluids or help regulate temperature. Our hypothesis is that microvascular function is directly connected to the network architecture and its three-dimensional embedding in the surrounding (extra-vascular) tissue.
In this talk, I will present a mixed-dimensional (1d-3d) mathematical model (or model framework) that allows to simulate exchange processes between microvessels and extra-vascular tissue while discretely resolving individual vessel segments and thus the network connectivity. For example, applied to an advection-diffusion setting, these models allow to simulate MRI tracer transport within an MRI voxel or oxygen transport in a $1mm^3$ tissue sample.
I give an overview and motivate the underlying assumptions to construct such models and discuss several alternatives.
Finally, I will then show applications of this type of model to different problems of clinical or biological interest.

Robust solvers for the Stokes problem in computational hemodynamics

Miroslav Kuchta

Simula Research Laboratory

miroslav@simula.no

Abstract:
In this talk we discuss efficient preconditioners for Stokes problem with non-standard boundary conditions [Bertoluzza et al., CMAME 2017]. To obtain robustness with respect to viscosity we apply fractional solvers on the boundary. We then discuss the challenge that the model geometry, namely the aspect ratio of the domain, presents for performance of the proposed solver. To address the issue we consider a simplified 1d network model which is shown to be uniformly stable in the geometric parameters using suitably weighted norms.

Influence of environmental and social characteristics in SIR epidemic models

Youcef Mammeri

Institut Camille Jordan, Université Jean Monnet

youcef.mammeri@univ-st-etienne.fr

Abstract:
The covid-19 epidemic has highlighted the importance of mathematical modeling. Models have been used quite heavily to attempt to predict the state of the epidemic, and to implement strategies to contain the disease, with more or less success.
In this talk, we question the environmental and social underpinnings of these epidemic models by introducing the weight of social and space. A new SEIR metapopulation model will be discussed. We will show that this model can simulate successive waves, and then what are the socially differentiated reactions of the population according to their environment and social characteristics.

Immersed boundary numerical methods for the inverse problem of electrical impedance tomography.

Niami Nasr

Institut Camille Jordan, Université Jean Monnet

niami.nasr@univ-st-etienne.fr

Abstract:
We propose an immersed boundary scheme for the numerical resolution of the Complete Electrode Model in Electrical Impedance Tomography, that we use as a main ingredient in the resolution of inverse problems in medical imaging.
Such method allows to use a Cartesian mesh without accurate discretization of the boundary, which is useful in situations where the boundary is complicated and/or changing. We prove the convergence of our method, and illustrate its efficiency with two dimensional direct and inverse problems.

Partial dimension reduction in tube structures

Grigory Panasenko

Institute Camille Jordan UMR CNRS 5208, University Jean Monnet, Saint-Etienne, France and
Institute of Applied Mathematics, Vilnius University, Lithuania

grigori.panansenko@univ-st-etienne.fr

Abstract:
The talk briefly presents the results on asymptotic analysis for viscous flows in thin tube structures. These domains are idealized geometrical models for networks of thin blood vessels, tubes in catalytic converters, pipelines etc. The asymptotic analysis of the flows in these structures allowed to introduce the hybrid dimension models. They combine one-dimensional and multidimensional description of the flow with asymptotically exact coupling conditions between 3D and 1D parts of the model (see [1, 2] and a recent monograph [3]). Another approach for junction of models of different dimensions for blood flow in arteries was proposed in [4, 5]. Thus, hybrid dimension models provide the one-dimensional description in the main part of the domain and make small full-dimensional zooms. These zooms give detailed description of the flow in the zones of interest such as the bifurcations of vessels, zones of blood clot formation, stents and so on. The hybrid dimension models allow substantially accelerate computations without loss of accuracy. They are justified via asymptotic analysis of the full-dimensional problem in the whole domain of the flow and the proof of estimates for the difference between the exact solution of the full-dimensional problem and the solution to the hybrid dimension model. The classical method of asymptotic decomposition of the domain [2] deals with coupled problems in the zoomed parts of the domain. The new method of partial asymptotic dimension reduction [6] allows the parallelization of the computations in the zoomed parts solving some special problem on the graph of the network.

1. G. Panasenko, Asymptotic expansion of the solution of Navier-Stokes equation in a tube structure, C.R. Acad. Sci. Paris, 326, IIb, 1998, 867—872
2. G. Panasenko, Partial asymptotic decomposition of domain: Navier-Stokes equation in tube structure, C.R. Acad. Sci. Paris, 326, IIb, 1998, 893—898
3. G. Panasenko, K. Pileckas, Multiscale Analysis of Viscoous Flows in Thin Tube Structures, Birkhauser, Springer Nature Switzerland AG, 2024
4. L. Formaggia, A. Veneziani, Reduced and Multiscale Models for the Human Cardiovascular System. Lecture Notes, VKI, Brussels, 2003
5. L. Formaggia, A. Moura, F. Nobile, On the stability of the coupling of 3D and 1D fluid-structure interaction models for blood flow simulations, M2AN, 2007, 743-769.
6. G. Panasenko, K. Pileckas, Partial asymptotic dimension reduction for steady state non-Newtonian flow with strain rate dependent viscosity in thin tube structure, J.Math. Fluid. Mech., 25:11, 2023.

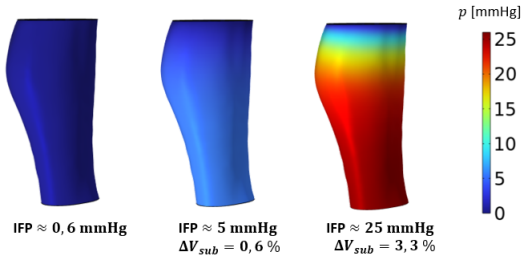
Modeling the effects of elastic compression on fluid dynamics in lower limb lymphedema

Maha Reda

École des mines Saint-Étienne

maha.reda@emse.fr

Abstract:
Under normal conditions, interstitial fluid (IF) pressure in the lower leg is maintained at or slightly below atmospheric levels, thanks to a delicate balance between fluid filtration from blood capillaries and reabsorption by the lymphatic vessels. However, factors such as increased capillary pressure or venous insufficiency can lead to lymphedema, a condition characterized by IF accumulation in the tissue space. In the early stages of lymphedema, fluid accumulates primarily within the subcutaneous space. This accumulation inhibits the natural pumping mechanisms present in healthy lymphatic vessels, resulting in inefficient fluid drainage. To this end, compression therapy stands as one of the primary treatments for early stages lymphedema. To better understand fluid dynamics in lymphedematous tissues and under therapeutic compression, computational modeling has been widely used. However, due to the complexity of the lymphatic system and the multifactorial nature of the disease, modeling the whole network of lymphatic vessels remains challenging. In this study, we developed a patient-specific three-dimensional finite element model of the lower limb. We adopted a continuum approach based on poroelasticity where the subcutaneous tissue of the lower limb was modeled as a biphasic medium comprising a solid matrix and a fluid phase representing, respectively, the tissue components and the interstitial fluid. The model allowed for an analysis of fluid flow, fluid pressure and tissue deformation under varying lymphedematous conditions. Additionally, it provided the tracking of IF pressure and volume change of the lower limb under compression therapy accompanied or not by physical activity. In this workshop we will present the model's components and the preliminary results that were derived from simulations. We will show how these results can offer insights on the effects of compression therapy and how they can be used to deepen our understanding on lower limb lymphedema development and its management.



IFP and volume change for different capillary pressure values

Cardiovascular modelling and simulations. Applications to image-based clinical studies.

Adélia Sequeira

Department of Mathematics and CEMAT, Instituto Superior Técnico, ULisboa, Portugal

adelia.sequeira@tecnico.ulisboa.pt

Abstract:
Mathematical modelling and simulations of the human circulatory system is a challenging and complex multidisciplinary research field that has seen a tremendous growth in the last few years. This field, with a strong socio-economic impact, is rapidly progressing motivated by the fact that cardiovascular diseases are a major cause of death in developed countries.
In this talk we consider some mathematical models and simulations of the cardiovascular system and comment on their significance to yield realistic and accurate numerical results, using reliable and efficient computational methods. Results on the simulation of some image-based patient-specific clinical cases will be presented, including studies of the significant role of hemodynamics in the progress of intracranial aneurysms and in the development of the inflammatory processes of atherosclerosis.

Dispersion effect on solute transport within the perivascular spaces of the brain

Alexandra Vallet

Sainbiose, Mines Saint Etienne

alexandra.vallet@emse.fr

Abstract:
Cerebral pulsations, driven by volumetric fluctuations in blood vessels, play an important role in solute transport within the brain. These pulsations drive cerebrospinal fluid (CSF) flow through interconnected compartments, including the ventricular system, the subarachnoid space (SAS), and the perivascular spaces (PVS). The PVS, directly exchanging with the brain's interstitial fluid (ISF), has been identified as a critical pathway for solute transport. While experimental evidence highlights vessel pulsations as a key driver of solute transport in the PVS, the precise mechanisms underlying this process remain unclear.
This presentation will focus on how mathematical and physical modeling has been employed to unravel the role of cerebral pulsations in solute transport. A mathematical homogenization method, simplifying the 3D advection-diffusion equation into a 1D representation, will be introduced, enabling the analysis of transport efficiency under different pulsation conditions. The model provides insight into how the amplitude and frequency of pulsations influence dispersion effects, which critically impact solute distribution. Comparisons with 2D axisymmetric simulations are used to validate the approach. An application to a full brain-scale network of PVS will be presented. Last, the modulation of pulsatile dynamics during sleep, a state that significantly alters cerebrovascular dynamics, will be discussed, shedding light on its implications for brain clearance and neurodegenerative diseases.

3 Access information

Access to Centre Ingénierie Santé:

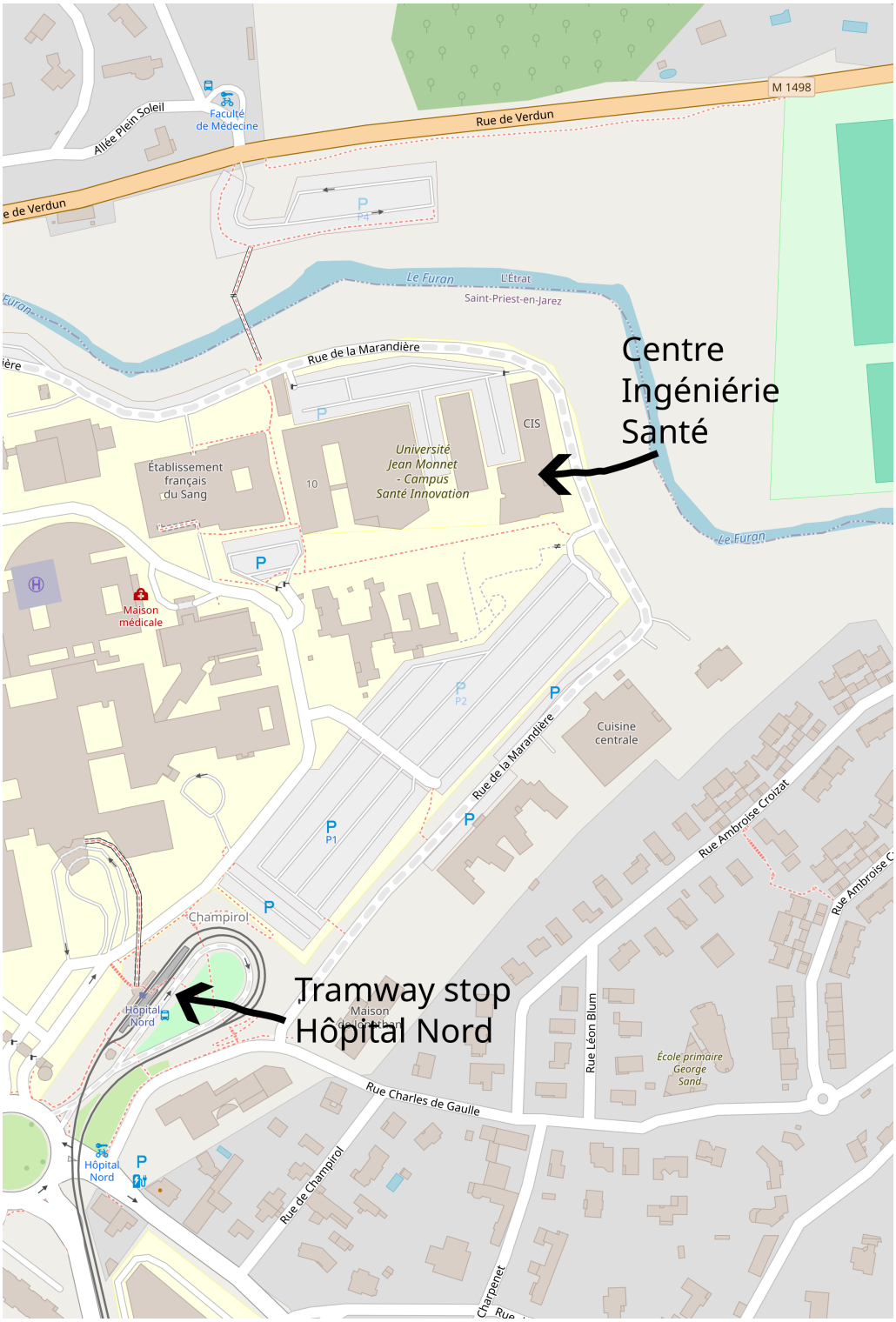
- From Saint-Étienne Chateaucreux Railway station: Tram T3 until Hôpital Nord (last stop).
- From Les Forges 2 (Institut Camille Jordan) : Tram T1 until Hôpital Nord (last stop)

The public transportation company STAS has an application called Moovizy and a website. `https://www.reseau-stas.fr/fr/itineraires/4/JourneyPlanner`.
Regarding tickets, they can be bought at the machines close to the Tramway stops. You might also use your credit card to pay in the tramway, but the university won't be able to reimburse you in this case.
From the airport of Lyon Saint-Exupéry, two options are available to go to Saint-Étienne:

- Rhonexpress Shuttle (Airport to Lyon Part-Dieu) `https://www.rhonexpress.fr/` and TER (Lyon Part-Dieu to Saint-Étienne Chateaucreux) `https://www.sncf-connect.com/`
- Totoom bus shuttle `https://www.totoom.fr/`

Hotel Ibis is located in the immediate vicinity of Saint-Étienne Chateaucreux Railway station.

3.1 Map near Centre Ingénierie Santé



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3.2 Map near Chateaucreux railway station