Mathematics of electrical imaging: modeling, theory and implementation

Rapport sur les contributions

https://indico.math.cnrs.fr/e/9272

ID de Contribution: **1** Type: **Non spécifié**

Electrocardiology modeling after pulsed field ablation relying on asymptotic analysis

lundi 12 juin 2023 16:00 (1 heure)

In healthy hearts, the propagation of electrical waves follows a predictable pattern, whereas in people suffering from arrhythmia, the electrical waves can become chaotic and directly affect the pumping function of the heart. One of the main treatments for these arrhythmias is catheter ablation, which destroys small areas of heart tissue to isolate or eliminate the cause of the rapid and irregular heartbeats. Most catheter ablation therapies are performed thermally through the application of a radiofrequency electromagnetic field (RFA). Some limitations and disadvantages are observed in clinical application, such as damage to adjacent structures.
In this work, we focus on the study of a novel and mainly non-thermal ablation technique: pulsed electric field ablation (PFA), which takes advantage of irreversible electroporation, a complex phenomenon of cell membrane rupture that occurs when biological tissue is exposed to very intense electric pulses. This technique has been used in oncology for more than a decade, but it is still in its infancy in cardiology. Preclinical evaluations of PFA in atrial fibrillation and ventricular ablation in large animal studies show successful results with possible transmural lesions. Despite these promising results, the application of PFA in routine clinical practice still presents some difficulties because of the technical complexity of this novel approach. Mathematical models and numerical strategies could be developed to improve the understanding of PFA on the cardiac signal and to develop numerical criteria for treatment assessment based on clinical data. The aim of this work is to derive a cardiac electrophysiological model of a cardiac domain containing a region ablated by PFA. In doing so, we start from the following three points: (1) the electroporated region is small compared with the entire domain, (2) the intra-cellular conductivity within the electroporated zone is also very small, and (3) a linearization of the ionic current is assumed in the electroporated region. The last two assumptions can be explained by the fact that the ablated tissue contains few cells and the gap junctions connecting the cells are severely compromised. This leads to a model that depends on a small parameter which could lead to numerical problems. To address this, an asymptotic analysis is performed in a static context and convergence analysis is explored. The strategy allows to determine the transmission conditions at the interface between the two regions, yielding a suitable model of a cardiac domain containing an ablation region by PFA. Well-designed Schwarz algorithms are developed to numerically solve the obtained PDE system.

Orateur: COLLIN, Annabelle

ID de Contribution: **2** Type: **Non spécifié**

Addressing Challenges in Modeling Human Head Anatomy for Stroke Monitoring with EIT

lundi 12 juin 2023 15:00 (30 minutes)

In this talk, we explore the challenges encountered while implementing a computational framework for stroke monitoring using Electrical Impedance Tomography (EIT). Our focus is on accurately modeling human head anatomy based on a library of MRI scans and integrating real-world data obtained from physical experiments.

Accurately representing anatomical surfaces, such as the brain, skull, and scalp, presents significant challenges in stroke monitoring with EIT. We discuss the complexities involved in capturing the intricate geometry of these surfaces and present meshing techniques that ensure faithful representation of the underlying anatomy.

An important milestone in our project is the successful reconstruction of real-world data acquired from physical experiments, assuming prior knowledge of the geometry. This proof of concept demonstrates the effectiveness of our computational framework in stroke monitoring.

By addressing these challenges, our project contributes to advancing the field of stroke monitoring with EIT, with the ultimate goal of improving early detection and treatment outcomes. In this talk, we discuss insights into the implementation aspects of modeling human head anatomy and utilizing real-world data, underscoring the potential of EIT as a tool for stroke monitoring.

Orateur: VAVILOV, Anton

ID de Contribution: **3** Type: **Non spécifié**

Subspace surrogates for the parametric diffusion equation

lundi 12 juin 2023 14:00 (1 heure)

In this talk, I consider efficient solution of the parametric diffusion equation for several parameter values. First, I study the dependency of the solution u from the parameter and establish that u can be approximated by low-dimensional subspace for any admissible parameter value. Then I propose an efficient method for approximately computing this subspace. I conclude with numerical examples investigating the performance of the proposed method.

Orateur: HANNUKAINEN, Antti

ID de Contribution: **4** Type: **Non spécifié**

EEG source localisation and cortical mapping

lundi 12 juin 2023 17:00 (30 minutes)

We present a theoretical and numerical framework for performing source localisation and cortical mapping using EEG data with various source models. This framework is built on the idea that the problems of source localisation and cortical mapping are different aspects of the same inverse problem rather than independent inverse problems. This approach promises to improve numerical accuracy and to provide context to the numerical results obtained both for source localisation and cortical mapping. We provide theoretical results which allow the sources to be modelled as vector-fields from a wide range of functional and distributional spaces. The study of the various source models in motivated by a need to take advantage of advances in medical imaging such as diffusion MRI. This opens the possibility to restrict the support of the sources to anatomical structures of the brain that we now have access to thanks to these advances. We present numerical results to demonstrate the proposed alternating minimisation algorithm for solving the source location and cortical mapping problems simultaneously. Such an alternating minimisation procedure provides practical advantages especially in computer memory usage.

Orateur: NEMAIRE, Masimba

ID de Contribution: **5** Type: **Non spécifié**

Liver tumor ablation by electroporation: mathematical modeling for clinical applications

mardi 13 juin 2023 09:15 (1 heure)

Electropermeabilization (also called electroporation–EP) is a significant increase in the electrical conductivity and permeability of the cell membrane that occurs when pulses of large amplitude (a few hundred volts per centimeter) are applied to the cells: due to the electric field, the cell membrane is permeabilized. If the pulse duration is sufficiently short (a few milliseconds or a few microseconds, depending on the pulse amplitude), the cell membrane reseals within several tens of minutes: reversible EP, preserves the cell viability and is used in electrochemotherapy to vectorize the drugs until the cell inside. If the pulses are too long, too numerous or if their amplitude is too high, the cell membrane is irreversibly destroyed and the cells are killed. Irreversible EP provides thus a novel non thermal and minimally invasive ablation therapy.
In this talk I will present some recent results of the Inria Team MONC on the mathematical EP modeling combining PDE models and image registration techniques, in order to help interventional radiologists in their practice of percutaneous liver tumor ablation by irreversible electroporation.

Orateur: POIGNARD, Clair (INRIA & Université de Bordeaux)

ID de Contribution: **6** Type: **Non spécifié**

EIT reconstruction using virtual X-rays and machine learning

mardi 13 juin 2023 10:15 (30 minutes)

We introduce a new reconstruction algorithm for EIT, which provides a connection between EIT and traditional X-ray tomography, based on the idea of "virtual X-rays". We divide the exponentially ill-posed and nonlinear inverse problem of EIT into separate steps. We start by mathematically calculating so-called virtual X-ray projection data from the DN map. Then, we perform explicit algebraic operations and one-dimensional integration, ending up with a blurry and nonlinearly transformed Radon sinogram. We use a neural network to learn the nonlinear deconvolution-like operation. Finally, we can compute a reconstruction of the conductivity using the inverse Radon transform. We demonstrate the method with simulated data examples.

This is a joint work with Samuli Siltanen, Matti Lassas, Rashmi Murthy, Fernando Silva de Moura, Juan Pablo Agnelli, and Melody Alsaker.

Orateur: RAUTIO, Siiri

ID de Contribution: **7** Type: **Non spécifié**

Experimental Validation and Clinical Applications of ECGI

mardi 13 juin 2023 11:15 (1 heure)

Cardiac electrical diseases are a major cause of mortality in the world today. Many individuals are not identified as at risk, or incorrectly identified for treatment. These suboptimal results are mostly due to the limitations of current clinical methods to detect cardiac electrical activity. Real-time and panoramic images of cardiac electrical activity can be noninvasively reconstructed through electrocardiographic imaging (ECGI) This modality fills the gap between the noninvasive (low-resolution) 12-lead ECG and invasive (high-resolution) electrophysiology studies. Much progress has been made to establish ECGI meaning today it is available for use in a clinical setting. This presentation will demonstrate the capabilities and limitations of current clinical ECGI methods through experimental validation studies, and present the latest clinical findings using ECGI to understand the mechanisms underlying unexplained sudden cardiac death.

Orateur: BEAR, Laura

ID de Contribution: **8** Type: **Non spécifié**

Numerical resolution of the inverse source problem for EEG

mardi 13 juin 2023 14:00 (1 heure)

In the talk, I will present a numerical method for solving the EEG inverse source problem which is able to take into account the heterogeneity of the head tissues. One of the applications is to consider fontanels in the skull layer for neonates. The approach consists in firstly transmitting the recorded data from the scalp to the cortex using the
quasi-reversibility method. The second stage solves the inverse source problem within the brain by applying the method developed in the software tool FindSources3D.

Orateur: DARBAS, Marion

ID de Contribution: **9** Type: **Non spécifié**

Immersed boundary method for electrical impedance tomography in the frame of Electrocardiography.

mardi 13 juin 2023 15:00 (30 minutes)

Orateur: NASR, Niami

ID de Contribution: **10** Type: **Non spécifié**

Reconstruction of inclusions and cracks in Calderón's inverse conductivity problem

mercredi 14 juin 2023 09:15 (1 heure)

I will talk about the exact reconstruction of general inclusions in Calderón's inverse conductivity problem from boundary electrical measurements in the form of a local Neumann-to-Dirichlet map. Here "inclusion" means the support of perturbations to a known conductivity coefficient.

I will briefly cover the cases on open sets, where the perturbed coefficient can have finite positive and negative perturbations, can have perfectly conducting parts and have perfectly insulating parts, and may also have parts given as restrictions of Muckenhoupt coefficients with singular and degenerate behavior (enabling continuous growth to infinity or decay to zero).

I will give a more detailed account of new results on reconstructing general cracks given as unions of Lipschitz hypersurfaces, including both perfectly conducting and perfectly insulating cracks.

Orateur: GARDE, Henrik

ID de Contribution: **11** Type: **Non spécifié**

Some remarks on the quadratic nature of the matching to data operator

mercredi 14 juin 2023 11:15 (1 heure)

We study the inverse problem of the reconstruction of an obstacle in an media from boundary measurements. We assume that the data is noised and that a statistical model for the data is at hand. We propose and study a reconstruction algorithm based a weighted combination of the first two moments of the Kohn-Vogelius criterion. By numerical results in dimension two, the applicability and feasibility of our approach is demonstrated.

Orateur: DAMBRINE, Marc

ID de Contribution: **12** Type: **Non spécifié**

Monitoring of hemorrhagic stroke using electrical impedance tomography

mardi 13 juin 2023 16:00 (1 heure)

Orateur: KOLEHMAINEN, Ville

ID de Contribution: **13** Type: **Non spécifié**

Multimodal analysis and inverse problems for brain imaging

mercredi 14 juin 2023 10:15 (30 minutes)

The deeper understanding of brain activity is a major challenge for clinical and mathematical research. In case of neurological disease, such as epilepsy, the main objective is to better understand and diagnose the origin of the crisis in order to propose a proper treatment for each patient. Among the non-invasive imaging methods used to study these pathologies, we are interested in the coupling of two of them : the electroencephalography (EEG) and the diffuse optical tomography (DOT). On one hand, the EEG measures the electrical potential generated by the neuronal activity. On the other hand, the DOT measures the absorption and diffusion of the light in the near-infrared spectrum by biological tissues, attesting of a change in the concentrations of oxyhemoglobin and deoxyhemoglobin.

EEG measures the electric potential difference between a reference electrode and electrodes placed on the scalp. There can be up to 128 electrods, arranged on a head cap placed on the head of the patient. Regarding the DOT, it is an imaging technique based on the absorption and diffusion of the light by the tissues. A head cap equiped with transmitters and receivers is placed on the head of the patient. A transmitter sends out light which is measured by the receptors after passing through the various layers of the head. Thanks to these measurements, it is then possible to reconstruct the optical parameters of the tissues in the head. Co-registration already exists for these two modalities, which represents a source of motivation for the mathematical modeling of this coupling.

In this communication, we present a time-dependent model for the acquisition of coupled measurements of these two modalities. Indeed, time is an important component of the neurovascular coupling. On the one hand, EEG measures the neural activity and on the other hand, the DOT highlights the change of optical parameters of brain tissues induced by the local increase in blood volume during cerebral activity. We will also present the inverse problems associated with these two imaging modalities, the inverse problem of the EEG being a source localization problem whearas the DOT problem is a parameter identification problem. Finally, we will explain how these modalities can be used together to improve the resolution of the inverse problems from a numerical point of view.

Orateur: SULIS, Benjamin

ID de Contribution: **14** Type: **Non spécifié**

Parameter estimation in the eikonal equation

mardi 13 juin 2023 17:00 (1 heure)

Electrical waves propagate at the surface of the heart, the simplest modelling is to describe them as a front propagating according to the eikonal equation. The propagation velocity is anisotropic since it occurs along fibers. For medical diagnosis purposes, we aim at finding the source location and the parameters of the velocity, either from measurements directly on the surface of the heart, or through an observation operator that models an electrocardiogram. The parameters to be recovered are thus a point x on a manifold and a small number of scalar quantities. We implemented a least squares minimization using Gauss-Newton algorithm on a manifold. It is necessary to obtain Exp_x the exponential map based at x on the manifold (or more precisely its reciprocal Log_x). This quantity can be efficiently computed using techniques borrowed from the field of image synthesis. We illustrate our approach using sunthetic data.

Orateur: FEHRENBACH, Jérôme (IMT)