Activity Report 2011

Project-Team ATHENA

Computational Imaging of the Central Nervous System

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THEME
Computational Medicine and Neuro-sciences

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Project-Team ATHENA

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2. Overall Objectives

2.1. Presentation

The main objective of ATHENA is to develop rigorous mathematical models and computational tools for analyzing and modeling the complex Central Nervous System (brain and spinal cord) anatomy and function. These models and tools will help to better understand the architecture and the functioning of human Central Nervous System (CNS) and address pressing and challenging clinical and neuroscience questions. Exploring new directions to solve these challenging problems will push forward the state-of-the-art in Anatomical and Functional Computational Imaging of the CNS.

The relationship between CNS structure and function is fundamental in neuroscience. Developing computational models and techniques that recover the anatomical connectivity and the function of the CNS in vivo is thus of utmost importance: it will definitely improve the understanding of the CNS and its mechanisms. On the basis of our expertise and contributions to the field of Computational Imaging of the CNS and in order to have an impact on this field, our research focusses mainly on the Anatomical and Functional Imaging of the CNS with a particular emphasis on signal and image recording from Diffusion Magnetic Resonance Imaging (dMRI), Magneto-Encephalography (MEG) and Electro-Encephalography (EEG).

In order to further increase the impact of our research, we also aim to push our contributions towards some applications related to CNS diseases with characteristic abnormalities in the micro-structure of brain tissues that are not apparent and cannot be revealed reliably by standard imaging techniques. Diffusion MRI, a recent imaging modality based on the measurement of the random thermal movement (diffusion) of water molecules within samples can make visible these co-lateral damages to the fibers of the CNS white matter that connect different brain regions. This is why in our research, Diffusion MRI is the major anatomical imaging modality that will be considered to recover the CNS connectivity.

Connectivity represents the network infrastructure of the CNS. Electric activity corresponds to communications over this network. MEG and EEG (jointly as M/EEG) reveal part of the cortical electric activity. M/EEG are also instrumental in diagnosing diseases linked to anomalous brain function - that in some cases anatomical or functional MR images do not reveal. In some CNS injuries (medullar injuries, strokes, AMS), the peripheral nervous system may not be able to execute commands that are issued by the brain.

Brain Computer Interfaces (BCI) is an application of EEG that has been proposed as a means to translate in real-time the electrical activity of the brain in commands to control devices. While BCI had been advocated as a means to communicate and help restore mobility or autonomy for very severe cases of disabled patients, it is more realistically a tool for a new interactive probing and training of the human brain.

These considerations support the need to do research on new models and computational tools to analyse CNS signals and imaging data. Our main objective is to push forward the state-of-the-art in our research domain to better understand the architecture and function of the CNS and help address pressing and challenging clinical and neuroscience questions. This better understanding of the CNS will help the development of new biomarkers related to the progression of certain types of neurodegenerative diseases and will also help improving BCI systems with the goal of better interactive probing and training of the human brain. These long term and ambitious applications, if successful, will help us make true our dream to effectively contribute reducing the number of people suffering from CNS diseases.

In order to tackle these challenging objectives, our strategy is based on the following road map:

- Develop rigorous mathematical and computational tools for the analysis and interpretation of Diffusion MRI and M/EEG data.
- Improve acquisition and processing techniques and push forward the state-of-the-art in Computational CNS imaging.
- Use our expertise to address with collaborators clinical and neuroscience questions.

This is implemented through:

- Publications in international conferences and journals dedicated to promoting advances in computational methods for Diffusion MRI and M/EEG analysis and/or use of Diffusion MRI and M/EEG in clinical and neuroscience applications.
- A dense network of collaborations with national as well as international neuroimaging laboratories through which we have access equipment and data and with whom we will jointly contribute to solve common crucial problems of interest.
- Software packages developed to be used in a first stage by our national and international collaborators and then made available to other partners.

2.2. Highlights

- Rachid Deriche: *Most Influential Paper over the Decade Award* for the article *Dense Disparity Map Estimation Respecting Image Discontinuities: A PDE and Scale-Space Based Approach* co-authored with L. Alvarez, J. Sanchez & J. Weickert (14 June, 2011 - Nara Centennial Hall - Nara, Japan- 12th IAPR Conference on Machine Vision Applications.
- The Athena EEG Lab received the agreement as a laboratory to conduct biomedical research from *Agence Régionale de Santé PACA* for the period from 2011 to 2015.

3. Scientific Foundations

3.1. Computational Diffusion MRI

Diffusion MRI (dMRI) provides a non-invasive way of estimating in-vivo CNS fiber structures using the average random thermal movement (diffusion) of water molecules as a probe. It's a recent field of research with a history of roughly three decades. It was introduced in the mid 80's by Le Bihan et al [51], Merboldt et al [55] and Taylor et al [62]. As of today, it is the unique non-invasive technique capable of describing the neural connectivity in vivo by quantifying the anisotropic diffusion of water molecules in biological tissues. The great success of dMRI comes from its ability to accurately describe the geometry of the underlying microstructure and probe the structure of the biological tissue at scales much smaller than the imaging resolution.

The diffusion of water molecules is Brownian in an isotropic medium and under normal unhindered conditions, but in fibrous structure such as white matter, the diffusion is very often directionally biased or anisotropic and water molecules tend to diffuse along fibers. For example, a molecule inside the axon of a neuron has a low probability to cross a myelin membrane. Therefore the molecule will move principally along the axis of the neural fiber. Conversely if we know that molecules locally diffuse principally in one direction, we can make the assumption that this corresponds to a set of fibers.

Diffusion Tensor Imaging

Shortly after the first acquisitions of diffusion-weighted images (DWI) were made in vivo [56], [58], Basser et al [42], [41] proposed the rigorous formalism of the second order Diffusion Tensor Imaging model (DTI). DTI describes the three-dimensional (3D) nature of anisotropy in tissues by assuming that the average diffusion of water molecules follows a Gaussian distribution. It encapsulates the diffusion properties of water molecules in biological tissues (inside a typical 1-3 mm^3 sized voxel) as an effective self-diffusion tensor given by a 3×3 symmetric positive definite tensor $\mathbf{D}$ [42], [41]. Diffusion tensor imaging (DTI) thus produces a three-dimensional image containing, at each voxel, the estimated tensor $\mathbf{D}$. This requires the acquisition of at least six Diffusion Weighted Images (DWI) S_k in several non-coplanar encoding directions as well as an unweighted image S_0. Because of the signal attenuation, the image noise will affect the measurements and it is therefore important to take into account the nature and the strength of this noise in all the pre-processing steps. From the diffusion tensor $\mathbf{D}$, a neural fiber direction can be inferred from the tensor's main eigenvector while various diffusion anisotropy measures, such as the Fractional Anisotropy (FA), can be computed using the associated eigenvalues to quantify anisotropy, thus describing the inequality of diffusion values among particular directions.

DTI has now proved to be extremely useful to study the normal and pathological human brain [52], [47]. It has led to many applications in clinical diagnosis of neurological diseases and disorder, neurosciences applications in assessing connectivity of different brain regions, and more recently, therapeutic applications, primarily in neurosurgical planning. An important and very successful application of diffusion MRI has been brain ischemia, following the discovery that water diffusion drops immediately after the onset of an ischemic event, when brain cells undergo swelling through cytotoxic edema.

The increasing clinical importance of diffusion imaging has drived our interest to develop new processing tools for Diffusion MRI. Because of the complexity of the data, this imaging modality raises a large amount of mathematical and computational challenges. We have therefore started to develop original and efficient algorithms relying on Riemannian geometry, differential geometry, partial differential equations and front propagation techniques to correctly and efficiently estimate, regularize, segment and process Diffusion Tensor MRI (DT-MRI) (see [54], [8] and [53]).

High Angular Resolution Diffusion Imaging

In DTI, the Gaussian assumption over-simplifies the diffusion of water molecules. While it is adequate for voxels in which there is only a single fiber orientation (or none), it breaks for voxels in which there are more complex internal structures. This is an important limitation, since resolution of DTI acquisition is between 1mm^3 and 3mm^3 while the physical diameter of fibers can be between 1μm and 30 μm [60], [43]. Research groups currently agree that there is complex fiber architecture in most fiber regions of the brain [59]. In fact, it is currently thought that between one third to two thirds of imaging voxels in the human brain white matter contain multiple fiber bundle crossings [44]. This has led to the development of various High Angular Resolution Diffusion Imaging (HARDI) techniques [64] such as Q-Ball Imaging (QBI) or Diffusion Spectrum Imaging (DSI) [65], [66], [71] to explore more precisely the microstructure of biological tissues.

HARDI samples q-space along as many directions as possible in order to reconstruct estimates of the true diffusion probability density function (PDF) – also referred as the Ensemble Average Propagator (EAP) – of water molecules. This true diffusion PDF is model-free and can recover the diffusion of water molecules in any underlying fiber population. HARDI depends on the number of measurements N and the gradient strength (b-value), which will directly affect acquisition time and signal to noise ratio in the signal.

Typically, there are two strategies used in HARDI: 1) sampling of the whole q-space 3D Cartesian grid and estimation of the EAP by inverse Fourier transformation or 2) single shell spherical sampling and estimation of fiber distributions from the diffusion/fiber ODF (QBI), Persistent Angular Structure [50] or Diffusion Orientation Transform [76]. In the first case, a large number of q-space points are taken over the discrete grid ($N > 200$) and the inverse Fourier transform of the measured Diffusion Weighted Imaging (DWI) signal is taken to obtain an estimate of the diffusion PDF. This is Diffusion Spectrum Imaging (DSI) [71], [65], [66]. The method requires very strong imaging gradients ($500 \leq b \leq 20000$ s/mm^2) and a long time for acquisition (15-60 minutes) depending on the number of sampling directions. To infer fiber directions of the diffusion PDF at every voxel, people take an isosurface of the diffusion PDF for a certain radius. Alternatively, they can use the second strategy known as Q-Ball imaging (QBI) i.e just a single shell HARDI acquisition to compute the diffusion orientation distribution function (ODF). With QBI, model-free mathematical approaches can be developed to reconstruct the angular profile of the diffusion displacement probability density function (PDF) of water molecules such as the ODF function which is fundamental in tractography due to the fact that it contains the full angular information of the diffusion PDF and has its maxima aligned with the underlying fiber directions at every voxel.

QBI and the diffusion ODF play a central role in our work related to the development of a robust and linear spherical harmonic estimation of the HARDI signal and to our development of a regularized, fast and robust analytical QBI solution that outperforms the state-of-the-art ODF numerical technique available. Those contributions are fundamental and have already started to impact on the Diffusion MRI, HARDI and Q-Ball Imaging community. They are at the core of our probabilistic and deterministic tractography algorithms devised to best exploit the full distribution of the fiber ODF (see [45], [3] and [46],[4]).

High Order Tensors

Other High Order Tensors (HOT) models to estimate the diffusion function while overcoming the shortcomings of the 2nd order tensor model have also been recently proposed such as the Generalized Diffusion Tensor Imaging (G-DTI) model developed by Ozarslan et al [74], [77] or 4th order Tensor Model [40]. For more details, we refer the reader to our recent article in [48] where we review HOT models and to our article in [7], co-authored with some of our close collaborators, where we review recent mathematical models and

computational methods for the processing of Diffusion Magnetic Resonance Images, including state-of-the-art reconstruction of diffusion models, cerebral white matter connectivity analysis, and segmentation techniques.

All these powerful techniques are of utmost importance to acquire a better understanding of the CNS mechanisms and have helped to efficiently tackle and solve a number of important and challenging problems. They have also opened up a landscape of extremely exciting research fields for medicine and neuroscience. Hence, due to the complexity of the CNS data and as the magnetic field strength of scanners increase, as the strength and speed of gradients increase and as new acquisition techniques appear [2], these imaging modalities raise a large amount of mathematical and computational challenges at the core of the research we develop at ATHENA.

3.2. MEG and EEG

Electroencephalography (EEG) and Magnetoencephalography (MEG) are two non-invasive techniques for measuring (part of) the electrical activity of the brain. While EEG is an old technique (Hans Berger, a German neuropsychiatrist, measured the first human EEG in 1929), MEG is a rather new one: the first measures of the magnetic field generated by the electrophysiological activity of the brain have been done in 1968 at MIT by D. Cohen. Nowadays, EEG is relatively inexpensive and used routinely to detect and qualify neural activities (epilepsy detection and characterisation, neural disorder qualification, BCI, ...). MEG is, comparatively, much more expensive as SQUIDS only operate under very challenging conditions (at liquid helium temperature) and as a specially shielded room must be used to separate the signal of interest from the ambient noise. However, as it reveals a complementary vision to that of EEG and as it is less sensitive to the head structure, it also bears great hopes and an increasing number of MEG machines are being installed throughout the world. INRIA and ODYSSÉE/ATHENA have participated in the acquisition of one such machine installed in the hospital "La Timone" in Marseille.

MEG and EEG can be measured simultaneously (M/EEG) and reveal complementary properties of the electrical fields. The two techniques have temporal resolutions of about the millisecond, which is the typical granularity of the measurable electrical phenomena that arise within the brain. This high temporal resolution makes MEG and EEG attractive for the functional study of the brain. The spatial resolution, on the contrary, is somewhat poor as only a few hundreds of simultaneous data points can be acquired simultaneously (about 300-400 for MEG and up to 256 for EEG). MEG and EEG are somewhat complementary with fMRI and SPECT in that those provide a very good spatial resolution but a rather poor temporal resolution (of the order of a second for fMRI and a minute for SPECT). Contrarily to fMRI, which “only” measures an haemodynamic response linked to the metabolic demand, MEG and EEG also measure a direct consequence of the electrical activity of the brain: it is acknowledged that the signals measured by MEG and EEG correspond to the variations of the post-synaptic potentials of the pyramidal cells in the cortex. Pyramidal neurons compose approximately 80% of the neurons of the cortex, and it requires at least about 50,000 active such neurons to generate some measurable signal.

While the few hundreds of temporal curves obtained using M/EEG have a clear clinical interest, they only provide partial information on the localisation of the sources of the activity (as the measurements are made on or outside of the head). Thus the practical use of M/EEG data raises various problems that are at the core of the ATHENA research in this topic:

- First, as acquisition is continuous and is run at a rate up to 1kHz, the amount of data generated by each experiment is huge. Data selection and reduction (finding relevant time blocks or frequency bands) and pre-processing (removing artifacts, enhancing the signal to noise ratio, ...) are largely done manually at present. Making a better and more systematic use of the measurements is an important step to optimally exploit the M/EEG data [1].
- With a proper model of the head and of the sources of brain electromagnetic activity, it is possible to simulate the electrical propagation and reconstruct sources that can explain the measured signal. Proposing better models [6], [9] and means to calibrate them [67] so as to have better reconstructions are other important aims of our work.

- Finally, we wish to exploit the temporal resolution of M/EEG and to apply the various methods we have developed to better understand some aspects of the brain functioning, and/or to extract more subtle information out of the measurements. This is of interest not only as a cognitive goal, but it also serves the purpose of validating our algorithms and can lead to the use of such methods in the field of Brain Computer Interfaces. To be able to conduct such kind of experiments, an EEG lab is currently being set up at Athena.

4. Application Domains

4.1. Applications of Diffusion MRI

Various examples of CNS diseases as Alzheimer's and Parkinson's diseases and others like multiple sclerosis, traumatic brain injury and schizophrenia have characteristic abnormalities in the micro-structure of brain tissues that are not apparent and cannot be revealed reliably by standard imaging techniques. Diffusion MRI can make visible these co-lateral damages to the fibers of the CNS white matter that connect different brain regions. This is why in our research, Diffusion MRI is the major anatomical imaging modality that will be considered to recover the CNS connectivity.

- **Clinical domain: Diagnosis of neurological disorder**
  - *Parkinson's and Alzheimer's diseases* are among the most important CNS diseases. Six million patients (among which 850.000 in France) are suffering from Alzheimer's, making it the most important neurodegenerative disease in Europe. Over 85 years of age, 1 woman in 4 and 1 man in 5 are affected in Europe. In France, the number of Alzheimer's patients is expected to reach at least 2 million in 2025 and will probably double in 2050, with the increasing age of the population. Parkinson's disease is the second most important neurodegenerative disease. There are six and a half million patients in the world and roughly 150.000 patients in France, among which 10% are under 40 and 50% over 58. Together with our partners from NeuroSpin (Saclay), Inserm U678 and CENIR (CHUPS, Paris), we are involved in the ANR project NucleiPark which is about high field MRI of the braintem, the deep nuclei and their connections in the Parkinsonian syndromes.
  - *Spinal Cord Injury* (SCI) has a significant impact on the quality of life since it can lead to motor deficits (paralysis) and sensory deficits. In the world, about 2.5 million people live with SCI (http://www.campaignforcure.org). To date, there is no consensus for full rehabilitative cure in SCI, although many therapeutic approaches have shown benefits [61], [63]. It is thus of great importance to develop tools that will improve the characterization of spinal lesions as well as the integrity of remaining spinal tracts to eventually establish better prognosis after spinal injury. We have already started to be active in this domain with our collaborators at Inserm U678 (H. Benali) and CRSN/Faculté de médecine Université de Montréal (Pr. S. Rossignol).

4.2. Applications of M/EEG

Applications of EEG and MEG cover:

- **Clinical domain:** diagnosis of neurological disorders such as
  - Diagnosis of neurological disorders such as epilepsy, schizophrenia, tinnitus, ...
  - Presurgical planning of brain surgery.
- **Cognitive research** aims at better understanding the brain spatio-temporal organisation.
- **Brain Computer Interfaces** look at allowing a direct control of the world using brain signal such as EEG signals. Those can be considered both as an application of EEG processing techniques and as a tool for fundamental and applied research as it opens the way for more dynamical and active brain cognitive protocols.

The dream of all M/EEG researchers is to alleviate the need for invasive recordings (electrocorticograms or intracerebral electrodes), which are often necessary prior to brain surgery, in order to precisely locate both pathological and vital functional areas. We are involved in this quest, particularly through our collaboration with the La Timone hospital in Marseille. M/EEG are also used in **cognitive research**, and we collaborate with the *Laboratory for Neurobiology of Cognition* in order to develop methods that suit their needs for sophisticated data analysis.

5. Software

5.1. OpenMEEG

Participants: Théodore Papadopoulo, Maureen Clerc, Emmanuel Olivi, Alexandre Gramfort [Parietal project-team].

OpenMEEG provides state-of-the art tools for low-frequency bio-electromagnetism, notably solving forward problems related to EEG and MEG [5]. It implements the symmetric BEM, thus providing excellent accuracy. OpenMEEG is a free open software written in C++. It can be accessed either through a command line interface or through Python/Matlab interfaces.

OpenMEEG is multiplatform (Linux, MacOS, Windows) and it is distributed under the French opensource license CeCILL-B. See also the web page http://www-sop.inria.fr/athena/software/OpenMEEG/.

5.2. Diffusion MRI

Participants: Aurobrata Ghosh, Rachid Deriche.

The algorithms previously developed within the ODYSSÉE Project team and related to the Diffusion Tensor and Q-Ball imaging are available upon request from the INRIA source forge (https://gforge.inria.fr). One can use all the estimation and visualization tools developed, ranging from estimation, regularization, segmentation to Q-ball estimation, fiber ODF estimation and tractography algorithms. New visualization tools for Q-Ball images represented by spherical harmonic decomposition have also been developed.

The software library comprises geometric and variational methods devised to estimate, regularize, segment and perform tractography in DT (Diffusion Tensor) and HARDI (High Angular Resolution) MRI images. The library is multi-platform (Linux, Windows and OS X) ans is embedded into two open-source high level languages, TCL and Python.

Thanks to the *ADT MedInria-NT*, this library is in the process to be partly integrated within the interactive medical imaging platform MedINRIA.

6. New Results

6.1. Computational Diffusion MRI

This sub-theme is dedicated to describe our various contributions performed within the framework of Computational Diffusion MRI. In 6.1.1, we start by presenting our contributions to improving dMRI signal and optimize dMRI acquisition schemes. Then, we present our modeling contributions related to the problem of reconstructing and characterizing important Diffusion MRI features such as the Orientation Distribution Function (ODF) and the Ensemble Average Propagator (EAP) in 6.1.2, including contributions of the compressed sensing theory to dMRI and contributions to on line motion detection. Finally, we end up, in 6.1.3, with some general applications such as tractography, clustering and microstructures recovery with pore size distribution estimation.

6.1.1. Improving dMRI Signal and Acquisitions

6.1.1.1. Optimal Design of Multiple Q-shells experiments for Diffusion MRI

Participants: Rachid Deriche, Emmanuel Caruyer, Iman Aganj [Department of Electrical and Computer Engineering, University of Minnesota], Christophe Lenglet [Department of Electrical and Computer Engineering, University of Minnesota], Guillermo Sapiro [Department of Electrical and Computer Engineering, University of Minnesota], Jian Cheng [ATHENA and LIAMA, China], Jiang Tianzi [LIAMA, China].

This work was partly supported by the CD-MRI Associate Team.

Recent advances in diffusion MRI make use of the diffusion signal sampled on the whole Q-space, rather than on a single sphere. While much effort has been done to design uniform sampling schemes for single shell experiment, it is yet not clear how to build a strategy to sample the diffusion signal in the whole Fourier domain. In this work, we proposed a method to generate acquisition schemes for multiple Q-shells experiment in diffusion MRI. The acquisition protocols we designed are incremental, which means they remain approximately optimal when truncated before the acquisition is complete. Our method is fast, incremental, and we can generate diffusion gradients schemes for any number of acquisitions, any number of shells, and any number of points per shell. The samples arranged on different shells do not share the same directions. The method has been tested for Spherical Polar Fourier reconstruction of the diffusion signal, and is based on Monte-Carlo simulations. Several prefered acquisition parameters are identified.

This work has been published in [20].

6.1.1.2. Incremental gradient table for multiple Q-shells diffusion MRI

Participants: Rachid Deriche, Emmanuel Caruyer, Iman Aganj [Department of Electrical and Computer Engineering, University of Minnesota], Christophe Lenglet [Department of Electrical and Computer Engineering, University of Minnesota], Guillermo Sapiro [Department of Electrical and Computer Engineering, University of Minnesota].

This work was partly supported by the CD-MRI Associate Team.

Most studies on sampling optimality for diffusion MRI deal with single Q-shell acquisition. For single Q-shell acquisition, incremental gradient table has proved useful in clinical setup, where the subject is likely to move, or for online reconstruction. In this work, we proposed a generalization of the electrostatic repulsion to generate gradient tables for multiple Q-shells acquisitions, designed for incremental reconstruction or processing of data prematurely aborted.

This work has been published in [21].

6.1.1.3. Impact of radial and angular sampling on multiple shells acquisition in diffusion MRI

Participants: Rachid Deriche, Sylvain Merlet, Emmanuel Caruyer.

In this work, we evaluated the impact of radial and angular sampling on multiple shells (MS) acquisition in diffusion MRI. The validation of our results is based on a new and efficient method to accurately reconstruct the Ensemble Average Propagator (EAP) in term of the Spherical Polar Fourier (SPF) basis from very few diffusion weighted magnetic resonance images (DW-MRI). This approach nicely exploited the duality between SPF and a closely related basis in which one can respectively represent the EAP and the diffusion signal using the same coefficients. We efficiently combined this relation to the recent acquisition and reconstruction technique called Compressed Sensing (CS). Based on results of multi-tensors models reconstruction, we showed how to construct a robust acquisition scheme for both neural fibre orientation detection and attenuation signal/EAP reconstruction.

This work has been published in [32].

6.1.1.4. Simultaneous Smoothing and Estimation of DTI via Robust Variational Non-local Means

Participants: Rachid Deriche, Meizhu Liu [Department of CISE, University of Florida, Gainesville, USA], Baba Vemuri [Department of CISE, University of Florida, Gainesville, USA].

Regularized diffusion tensor estimation is an essential step in DTI analysis. There are many methods proposed in literature for this task but most of them are neither statistically robust nor feature preserving denoising techniques that can simultaneously estimate symmetric positive definite (SPD) diffusion tensors from diffusion MRI. One of the most popular techniques in recent times for feature preserving scalar-valued image denoising is the non-local means filtering method that has recently been generalized to the case of diffusion MRI denoising. However, these techniques denoise the multi-gradient volumes first and then estimate the tensors rather than achieving it simultaneously in a unified approach. Moreover, some of them do not guarantee the positive definiteness of the estimated diffusion tensors. In this work, we proposed a novel and robust variational framework for the simultaneous smoothing and estimation of diffusion tensors from diffusion MRI. Our variational principle makes use of a recently introduced total Kullback-Leibler (tKL) divergence, which is a statistically robust similarity measure between diffusion tensors, weighted by a non-local factor adapted from the traditional non-local means filters. For the data fidelity, we use the nonlinear least-squares term derived from the Stejskal-Tanner model. We have performed experimental results depicting the positive performance of our method in comparison to competing methods on synthetic and real data examples.

This work has been published in [31].

6.1.1.5. Anisotropic LMMSE denoising of MRI based on statistitcal tissue models

Participants: Rachid Deriche, Gonzalo Vegas-Sánchez-Ferrero [Universidad de Valladolid, Spain], Santiago Aja Fernández [Universidad de Valladolid, Spain].

Linear Minimum Mean Squared Error Estimation (LMMSE) is a simple, yet powerful denoising technique within MRI. It is based on the computation of the mean and variance of the data being filtered according to a noise model assumed, which is usually accomplished by calculating local moments over squared neighborhoods. When these neighborhoods are centered in pixels corresponding to image contours, the estimation is not accurate due to the presence of two or more tissues with different statistical properties. In this work, we overcome this limitation by introducing an anisotropic LMMSE scheme: the grey levels of each tissue in the MRI volume are modeled as a Gamma-mixture, such that we can discriminate between the different matters to construct anisotropic neighborhoods containing only one kind of tissue. The potential of the Gamma distribution relies on its ability to fit both the Rician distribution traditionally used to model the noise in MRI and the non-central Chi noise found in modern parallel MRI systems.

This work is currently under submission.

6.1.2. Modeling in Diffusion MRI

6.1.2.1. Multiple q-Shell Diffusion Propagator Imaging.

Participants: Rachid Deriche, Maxime Descoteaux [Sherbrooke University, Quebec], Denis Le Bihan [NeuroSpin, IFR 49 CEA Saclay], Jean-François Mangin [NeuroSpin, IFR 49 CEA Saclay], Cyril Poupon [NeuroSpin, IFR 49 CEA Saclay].

This work was partly supported by the Association France Parkinson and the ANR NucleiPark project.

Many recent high angular resolution diffusion imaging (HARDI) reconstruction techniques have been introduced to infer an orientation distribution function (ODF) of the underlying tissue structure. These methods are more often based on a single-shell (one b-value) acquisition and can only recover angular structure information contained in the ensemble average propagator (EAP) describing the three-dimensional (3D) average diffusion process of water molecules. The EAP can thus provide richer information about complex tissue microstructure properties than the ODF by also considering the radial part of the diffusion signal. In this work, we presented a novel technique for analytical EAP reconstruction from multiple q-shell acquisitions. The solution is based on a Laplace equation by part estimation between the diffusion signal for each shell acquisition. This simplifies greatly the Fourier integral relating diffusion signal and EAP, which leads to an analytical, linear and compact EAP reconstruction. An important part of this work is dedicated to validate the diffusion signal estimation and EAP reconstruction on real datasets from ex vivo phantoms. We also illustrated multiple q-shell diffusion propagator imaging (mq-DPI) on a real in vivo human brain and performed a qualitative comparison against

state-of-the-art diffusion spectrum imaging (DSI) on the same subject. mq-DPI is shown to reconstruct robust EAP from only several different b-value shells and less diffusion measurements than DSI. This opens interesting perspectives for new q-space sampling schemes and tissue microstructure investigation.

This work has been published in [13].

6.1.2.2. A Riemannian Framework for Ensemble Average Propagator Computing

Participants: Rachid Deriche, Jian Cheng [ATHENA and LIAMA, China], Aurobrata Ghosh, Jiang Tianzi [LIAMA, China].

This work was partly supported by the Association France Parkinson and the ANR NucleiPark project.

In Diffusion Tensor Imaging (DTI), Riemannian framework (RF) has been proposed for processing tensors, which is based on Information Geometry theory. Many papers have shown that RF is useful in tensor estimation, interpolation, smoothing, regularization, segmentation and so on. Recently RF also has been proposed for Orientation Distribution Function (ODF) computing and it is applicable to any Probability Density Function (PDF) based on any orthonormal basis representation. Spherical Polar Fourier Imaging (SPFI) was proposed recently to fast and robustly estimate the ODF and Ensemble Average Propagator (EAP) from arbitrary sampled DWI signals. In this work, we proposed the RF for EAPs and implemented it via SPFI. We proved that the RF for EAPs is diffeomorphism invariant, which is the natural extension of affine invariant RF for tensors. It could avoid the so-called swelling effect for interpolating EAPs, just like the RF for tensors. We also proposed the Log-Euclidean framework (LEF), Affine-Euclidean framework (AEF), for fast processing EAPs, and Geometric Anisotropy (GA) for measuring the anisotropy of EAPs, which are all the extensions of previous concepts in RM for tensors respectively.

This work has been published in [22].

6.1.2.3. Diffeomorphism Invariant Riemannian Framework for Ensemble Average Propagator Computing

Participants: Rachid Deriche, Jian Cheng [ATHENA and LIAMA, China], Aurobrata Ghosh, Jiang Tianzi [LIAMA, China].

This work was partly supported by the Association France Parkinson and the ANR NucleiPark project.

In Diffusion Tensor Imaging (DTI), Riemannian framework based on Information Geometry theory has been proposed for processing tensors on estimation, interpolation, smoothing, regularization, segmentation, statistical test and so on. Recently Riemannian framework has been generalized to Orientation Distribution Function (ODF) and it is applicable to any Probability Density Function (PDF) under orthonormal basis representation. Spherical Polar Fourier Imaging (SPFI) was proposed for ODF and Ensemble Average Propagator (EAP) estimation from arbitrary sampled signals without any assumption. Tensors only can represent Gaussian EAP and ODF is the radial integration of EAP, while EAP has full information for diffusion process. To our knowledge, so far there is no work on how to process EAP data. In this work, we presented a Riemannian framework as a mathematical tool for such task. We proposed a state-of-the-art Riemannian framework for EAPs by representing the square root of EAP, called wavefunction based on quantum mechanics, with the Fourier dual Spherical Polar Fourier (dSPF) basis. In this framework, the exponential map, logarithmic map and geodesic have closed forms, and weighted Riemannian mean and median uniquely exist. We analyzed theoretically the similarities and differences between Riemannian frameworks for EAPs and for ODFs and tensors. The Riemannian metric for EAPs is diffeomorphism invariant, which is the natural extension of the affine-invariant metric for tensors. We proposed Log-Euclidean framework to fast process EAPs, and Geodesic Anisotropy (GA) to measure the anisotropy of EAPs. With this framework, many important data processing operations, such as interpolation, smoothing, atlas estimation, Principal Geodesic Analysis (PGA), can be performed on EAP data. The proposed Riemannian framework was validated in synthetic data for interpolation, smoothing, PGA and in real data for GA and atlas estimation. Riemannian median is much robust for atlas estimation.

This work has been published in [23].

6.1.2.4. Theoretical Analysis and Practical Insights on EAP Estimation via a Unified HARDI Framework

Participants: Rachid Deriche, Jian Cheng [ATHENA and LIAMA, China], Jiang Tianzi [LIAMA, China].

This work was partly supported by the Association France Parkinson and the ANR NucleiPark project.

Since Diffusion Tensor Imaging (DTI) cannot describe complex non-Gaussian diffusion process, many techniques, called as single shell High Angular Resolution Diffusion Imaging (sHARDI) methods, reconstruct the Ensemble Average Propagator (EAP) or its feature Orientation Distribution Function (ODF) from diffusion weighted signals only in single shell. Q-Ball Imaging (QBI) and Diffusion Orientation Transform (DOT) are two famous sHARDI methods. However, these sHARDI methods have some intrinsic modeling errors or need some unreal assumptions. Moreover they are hard to deal with signals from different q-shells. Most recently several novel multiple shell HARDI (mHARDI) methods, including Diffusion Propagator Imaging (DPI), Spherical Polar Fourier Imaging (SPFI) and Simple Harmonic Oscillator based Reconstruction and Estimation (SHORE), were proposed to analytically estimate EAP or ODF from multiple shell (or arbitrarily sampled) signals. These three methods all represent diffusion signal with some basis functions in spherical coordinate and use plane wave formula to analytically solve the Fourier transform. To our knowledge, there is no theoretical analysis and practical comparison among these sHARDI and mHARDI methods. In this work, we proposed a unified computational framework, named Analytical Fourier Transform in Spherical Coordinate (AFT-SC), to perform such theoretical analysis and practical comparison among all these five state-of-the-art diffusion MRI methods. We compared these five methods in both theoretical and experimental aspects. With respect to the theoretical aspect, some criteria are proposed for evaluation and some differences together with some similarities among the methods are highlighted. Regarding the experimental aspect, all the methods were compared in synthetic, phantom and real data. The shortcomings and advantages of each method were highlighted from which SPFI appears to be among the best because it uses an orthonormal basis that completely separates the spherical and radial information.

This work has been published in [24].

6.1.2.5. Compressive Sensing Ensemble Average Propagator Estimation via L1 Spherical Polar Fourier Imaging

Participants: Rachid Deriche, Sylvain Merlet, Emmanuel Caruyer, Jian Cheng [ATHENA and LIAMA, China], Jiang Tianzi [LIAMA, China].

In diffusion MRI (dMRI) domain, many High Angular Resolution Diffusion Imaging (HARDI) methods were proposed to estimate Ensemble Average Propagator (EAP) and Orientation Distribution Function (ODF). They normally need many samples, which limits their applications. Some Compressive Sensing (CS) based methods were proposed to estimate ODF in Q-Ball Imaging (QBI) from limited samples. However EAP estimation is much more difficult than ODF in QBI. Recently Spherical Polar Fourier Imaging (SPFI) was proposed to represent diffusion signal using Spherical Polar Fourier (SPF) basis without specific assumption on diffusion signals and analytically obtain EAP and ODF via the Fourier dual SPF (dSPF) basis from arbitrarily sampled signal. Normally the coefficients of SPF basis are estimated via Least Square with weighted L2 norm regularization (L2-SPFI). However, L2-SPFI needs a truncated basis to avoid overfitting, which brings some estimation errors. By considering the Fourier relationship between EAP and signal and the Fourier basis pair provided in SPFI, we proposed a novel EAP estimation method, named L1-SPFI, to estimate EAP from limited samples using CS technique, and favorably compared it to the classical L2-SPFI method. L1-SPFI estimates the coefficients in SPFI using least square with weighted L1 norm regularization. The weights are designed to enhance the sparsity. L1-SPFI significantly accelerates the ordinary CS based Fourier reconstruction method. This is performed by using SPF basis pair in CS estimation process which avoids the numerical Fourier transform in each iteration step. By considering high order basis in L1 optimization, L1-SPFI improves EAP reconstruction especially for the angular resolution. The proposed L1-SPFI was validated by synthetic, phantom and real data. The CS EAP and ODF estimations are discussed in detail and we showed that recovering the angular information from CS EAP requires much less samples than exact CS EAP reconstruction. Various experiments on synthetic, phantom and real data validate the fact that SPF basis can sparsely represent DW-MRI signals and L1-SPFI largely improves the CS EAP reconstruction especially the angular resolution.

This work has been published in [25], [26].

6.1.2.6. Spherical Polar Fourier EAP and ODF Reconstruction via Compressed Sensing in Diffusion MRI

Participants: Rachid Deriche, Sylvain Merlet, Aurobrata Ghosh, Jian Cheng [ATHENA and LIAMA, China].

In diffusion magnetic resonance imaging (dMRI), the Ensemble Average Propagator (EAP), also known as the propagator, describes completely the water molecule diffusion in the brain white matter without any prior knowledge about the tissue shape. In this work, we described a new and efficient method to accurately reconstruct the EAP in terms of the Spherical Polar Fourier (SPF) basis from very few diffusion weighted magnetic resonance images (DW-MRI). This approach exploits the duality between SPF and a closely related basis in which one can respectively represent the EAP and the diffusion signal using the same coefficients, and efficiently combines it to the recent acquisition and reconstruction technique called Compressed Sensing. Our work provides an efficient analytical solution to estimate, from few measurements, the diffusion propagator at any radius. We also provide a new analytical solution to extract an important feature characterising the tissue microstructure: the Orientation Distribution Function (ODF). We illustrate and prove the effectiveness of our method in reconstructing the propagator and the ODF on both noisy multiple q-shell synthetic and phantom data.

This work has been published in [33].

6.1.2.7. On Line Reconstruction and Motion Detection in HARDI

Participants: Rachid Deriche, Emmanuel Caruyer, Iman Aganj [Department of Electrical and Computer Engineering, University of Minnesota], Christophe Lenglet [Department of Electrical and Computer Engineering, University of Minnesota], Guillermo Sapiro [Department of Electrical and Computer Engineering, University of Minnesota].

This work was partly supported by the CD-MRI Associate Team.

With acquisition protocols such as high angular resolution diffusion imaging, head motion can become an issue. Although the misalignment between diffusion-weighted images (DWIs) can be corrected in a post-processing step, this might increase partial volume effects, because of the relatively low spatial resolution of DWIs and interpolation in the registration procedure. If able to detect motion online, the scanner technician could be issued a warning and make a decision accordingly. Orientation distribution functions (ODF) can be reconstructed online using a Kalman filter (KF). In this work, we presented three contributions related to the problem of online ODF reconstruction and motion detection in HARDI. First, we developed a proper error propagation accounting for the non-linear transform on the diffusion signal. Next, we developed two motion detection algorithms, based on the monitoring of residuals, and compared them using synthetic data.

This work has been published in [18].

6.1.2.8. Online Motion Detection in High Angular Resolution Diffusion Imaging

Participants: Rachid Deriche, Emmanuel Caruyer, Iman Aganj [Department of Electrical and Computer Engineering, University of Minnesota], Christophe Lenglet [Department of Electrical and Computer Engineering, University of Minnesota], Guillermo Sapiro [Department of Electrical and Computer Engineering, University of Minnesota].

This work was partly supported by the CD-MRI Associate Team.

The orientation distribution function (ODF) can be reconstructed online incrementally from diffusion-weighted MRI with a Kalman filtering framework. This online reconstruction can provide real-time feedback to the practitioner, especially appreciated for long acquisition protocols typical in Q-ball imaging. On top of the Kalman filter, we proposed a method to evaluate online the reconstruction accuracy of the estimated ODF in constant solid angle. In addition, monitoring the residuals of the Kalman filter, we designed, based on statistical tests, two algorithms for online detection of subject motion. The proposed techniques, tested on real and synthetic data under various experimental conditions, can detect rotation by angle less than 3°.

This work has been published in [19].

6.1.3. From DW-MRI to Fiber Pathways and Microstructures Recovery

6.1.3.1. A Polynomial Approach for Maxima Extraction and Its Application to Tractography in HARDI

Participants: Rachid Deriche, Aurobrata Ghosh, Demian Wassermann [Harvard Medical School].

A number of non-parametrically represented High Angular Resolution Diffusion Imaging (HARDI) spherical diffusion functions have been proposed to infer more and more accurately the heterogeneous and complex tissue microarchitecture of the cerebral white-matter. These spherical functions overcome the limitation of Diffusion Tensor Imaging (DTI) at discerning crossing, merging and fanning axonal fiber bundle configurations inside a voxel. Tractography graphically reconstructs the axonal connectivity of the cerebral white-matter in vivo and non-invasively, by integrating along the direction indicated by the local geometry of the spherical diffusion functions. Tractography is acutely sensitive to the local geometry and its correct estimation. In this work, we first proposed a polynomial approach for analytically bracketing and numerically refining with high precision all the maxima, or fiber directions, of any spherical diffusion function represented non-parametrically. This permits an accurate inference of the fiber layout from the spherical diffusion function. Then we proposed an extension of the deterministic Streamline tractography to HARDI diffusion functions that clearly discern fiber crossings. We also extended the Tensorline algorithm to these HARDI functions, to improve on the extended Streamline tractography. We illustrated our proposed methods using the Solid Angle diffusion Orientation Distribution Function (ODF-SA). We presented results on multi-tensor synthetic data, and real in vivo data of the cerebral white-matter that show markedly improved tractography results.

This work has been published in [30].

6.1.3.2. Tract-based statistical analyzes in dMRI in autism spectrum disorder

Participants: Rachid Deriche, Anne-Charlotte Philippe, Demian Wassermann [Harvard Medical School, Boston, MA], Pablo Barttfeld [Integrative Neuroscience Laboratory, Physics Dept. University of Buenos Aires, Buenos Aires, Argentina], Jorge Calvar [Fundación parala Luchacontralas Enfermedades Neurológicasdela Infancia, Buenos Aires, Argentina], Ramon Leiguarda [Fundación para la Lucha contra las Enfermedades Neurológicasdela Infancia, Buenos Aires, Argentina], Bruno Wicker [INCM CNRS, Marseille, France], Mariano Sigman [Integrative Neuroscience Laboratory, Physics Dept. University of Buenos Aires, Buenos Aires, Argentina].

This work was partly supported by the ECOS-Sud grant.

Abnormal face processing is one of the hallmark features of social impairments in autism spectrum disorder (ASD). Previous neuroimaging studies showed that the fusiform gyrus is involved in face perception and is not or abnormally activated in autistic subjects. The aim of this study was to quantify potential anatomical differences in the white matter tracts that traverse the fusiform gyrus, the prefrontal cortex and the superior temporal gyrus, and correlate them with ADOS scores in ASD subjects. We used Diffusion Tensor MRI (DT) images to assess the integrity of automatically segmented white matter bundles connecting these brain areas. Then, we performed statistical analysis on these fiber bundles using diffusivity measures calculated from DT to characterize tissue microstructure changes and correlate these changes with ADOS scores. 7 adults with high functioning autism or Asperger syndrome and 11 typical adults participated in the study. We found several clusters with dissimilarities between ASD and control subjects in FA measures on tracts traversing the fusiform gyrus in both hemispheres of the brain. We observed a significant reduction of FA values in a cluster on a bundle joining the superior temporal gyrus to the prefrontal.

This work has been published in [37]. A related work on large-scale network analysis reflecting big-world characteristics in ASD has been published in [35].

6.1.3.3. Unsupervised automatic white matter fiber clustering using a Gaussian mixture model

Participants: Rachid Deriche, Meizhu Liu [Department of CISE, University of Florida, Gainesville, USA], Baba Vemuri [Department of CISE, University of Florida, Gainesville, USA].

Fiber tracking from diffusion tensor images is an essential step in numerous clinical applications. There is a growing demand for an accurate and efficient framework to perform quantitative analysis of white matter fiber bundles. In this work, we proposed a robust framework for fiber clustering. This framework is composed of two parts: accessible fiber representation, and a statistically robust divergence measure for comparing fibers. Each fiber is represented using a Gaussian mixture model (GMM), which is the linear combination of Gaussian distributions. The dissimilarity between two fibers is measured using the total square loss function between their corresponding GMMs (which is statistically robust). Finally, we performed the hierarchical total

Bregman soft clustering algorithm on the GMMs, yielding clustered fiber bundles. Further, our method is able to determine the number of clusters automatically. We performed experimental results depicting favorable performance of our method on both synthetic and real data examples.

This work is currently under submission.

6.1.3.4. Riemannian geometry based brain white matter fiber clustering

Participants: Rachid Deriche, Ali Demir [Sabanci University, Istanbul, Turkey], Gozde Unal [Sabanci University, Istanbul, Turkey].

This work was partly supported by the PHC Bosphore grant.

Clustering of reconstructed brain white matter fibers into meaningful anatomical bundles becomes an important tool for detailed analysis of brain white matter diseases via diffusion MRI. In this work we developed a Riemannian geometry based geodesic distance measure between fiber pairs, which is then utilized in fiber clustering. A second contribution is a fiber selection algorithm, which compresses the dataset and speed up the computation time. We demonstrated methods on synthetic kissing fibers dataset, and validated on a brain white matter atlas.

This work is currently under submission.

6.1.3.5. White Matter Clustering Revisited

Participants: Rachid Deriche, Alvaro-Alejandro Sanchez-Moscosa.

This work was partly supported by the Association France Parkinson and the ANR NucleiPark project.

In [70], we have introduced an interesting hierarchical agglomerative based algorithm that represents and clusters white matter bundles under a Gaussian Process framework. In this work, a new implementation which drastically improves the performance of the clustering algorithm before mentioned is proposed and validated. This implementation notably improves the performance of the clustering algorithm [70] and has been validated on real data. This approach has the advantage of running in a lower abstraction level, which leads to lowered memory requirements, shorter running times and ultimately provides the possibility to process more densely seeded tractographies. The new implementation is then used to process densely seeded streamline tractographies which provide more localized fiber bundles. Additionally, as Parkinson's Disease is believed to induce changes in the axonal bundles, tract-based statistical analysis is performed on interesting fiber tracts to find significant differences in diffusion scalar measures.

6.1.3.6. Using Radial NMR Profiles to Characterize Pore Size Distributions

Participants: Rachid Deriche, John Treilhard [Queen's University, CA].

Extracting information about axon diameter distributions in the brain is a challenging task which provides useful information for medical purposes; for example, the ability to characterize and monitor axon diameters would be useful in diagnosing and investigating diseases like amyotrophic lateral sclerosis (ALS) or autism. In [75], three families of operators are defined, whose action upon an NMR attenuation signal extracts the moments of the pore size distribution of the ensemble under consideration; also a numerical method is proposed to continuously reconstruct a discretely sampled attenuation profile using the eigenfunctions of the simple harmonic oscillator Hamiltonian – the SHORE basis. The work we have performed here extends this method to other bases that can offer a better description of attenuation signal behaviour – in particular, we proposed the use of the radial Spherical Polar Fourier (SPF) basis. Testing is performed to contrast the efficacy of the radial SPF basis and SHORE basis in practical attenuation signal reconstruction. The robustness of the method to additive noise is tested and analyzed. We demonstrated that a low-order attenuation signal reconstruction outperforms a higher-order reconstruction in subsequent moment estimation under noisy conditions. We proposed the simulated annealing algorithm for basis function scale parameter estimation. Finally, analytic expressions are derived and presented for the action of the operators on the radial SPF basis (obviating the need for numerical integration, thus avoiding a spectrum of possible sources of error).

This work is currently under submission.

6.2. Brain functional imaging using MEG/EEG

6.2.1. EEG forward problem

6.2.1.1. OpenMEEG software library

Participants: Maureen Clerc, Emmanuel Olivi, Alexandre Gramfort, Théodore Papadopoulo.

This work was partly supported by the Regional Council of Provence Alpes Cote d'Azur and the ANR ViMAGINE.

To recover the sources giving rise to electro- and magnetoencephalography in individual measurements, realistic physiological modeling is required, and accurate numerical solutions must be computed. The OpenMEEG software library solves the electromagnetic forward problem in the quasistatic regime, for head models with piecewise constant conductivity. The core of OpenMEEG consists of the symmetric Boundary Element Method, which is based on an extended Green Representation theorem. OpenMEEG is able to provide lead fields for four different electromagnetic forward problems: Electroencephalography (EEG), Magnetoencephalography (MEG), Electrical Impedance Tomography (EIT), and intracranial electric potentials (IPs). OpenMEEG is open source and multiplatform. It can be used from Python and Matlab in conjunction with toolboxes that solve the inverse problem; its integration within FieldTrip is operational since release 2.0.

Some new developments have concerned the organization of the computations to compute the lead fields. A lead-field matrix is obtained by concatenating the forward fields computed for thousands of sources characterized by their positions, orientations and strengths. A line of this lead-field matrix represents the physical quantity (potential for EEG, or some components of the magnetic field for MEG) at a sensor for each source. The number of sources largely exceeds the number of sensors (up to 256 electrodes for EEG, and less than 600 squids for MEG). When solving the forward problem with a BEM (Boundary Element Method), the lead-field matrix is generally computed column-by-column, i.e. source by source, which represents nsources resolutions of the forward problem. Using the adjoint operator of the forward problem, one can reduce the computations to sensors resolutions. Some previous works [72], [73] have used similar techniques for efficient computation of the lead-fields using finite element methods. The adjoint method [69] generalizes the Helmholtz reciprocity theorem and here is proposed its implementation using the BEM provided by the open-source software OpenMEEG

This work has been published in [15] and [36].

6.2.1.2. Conductivity calibration for the EEG forward problem

Participants: Maureen Clerc, Emmanuel Olivi, Alexandre Gramfort, Théodore Papadopoulo, Jean-Michel Badier [INSERM U751, La Timone, Marseille], Martine Gavaret [INSERM U751, La Timone, Marseille], Laurent Koessler [CRAN Nancy].

This work was partly supported by the Regional Council of Provence Alpes Cote d'Azur and the ANR ViMAGINE.

Bioelectric phenomena at low temporal frequency can be described by the electrostatic Poisson equation

$$\text{div } \sigma \nabla V = \text{div } J^p \ ,$$

where J^p are primary current sources and $\sigma \nabla V$ the Ohmic current. Appropriate boundary conditions (b.c.) must be set on the domain boundary, typically imposing the potential (Dirichlet b.c.) or the normal current (Neumann b.c.).

Solving this electrostatics equation for the electric potential is a problem common to different fields such as electroencephalograhy (EEG), electrocardiography (ECG), functional electrical stimulation. The main difficulty of the model concerns the conductivity field, which is not homogeneous, and whose values depend on the tissue type. Although the tissue structure can be revealed by imaging methods such as CT, Magnetic Resonance Imaging, diffusion Magnetic Resonance Imaging, conductivity values must nevertheless be assigned to the different tissues. In order to calibrate conductivity, injected current Electrical Impedance Tomography (EIT) can be used: it consists of injecting current on the outer boundary, and measuring the associated electric potential.

The thrust of OpenMEEG is to propose accurate forward problems, in several instances, including electro- and magneto-encephalography (EEG-MEG) and Electrical Impedance Tomography (EIT). OpenMEEG allows to compute the electric potential and magnetic fields due to boundary current injection or to sources within the compartments.

We apply this methodology to conductivity calibration in the context of high-density EEG pre-surgical epileptic exploration. High-density EEG measurements may be used to solve the inverse problem of source localization, in order to localize the foci of the epileptic activity within the brain. The solution of the inverse problem relies on a forward problem, linking sources to measurements. In turn, this forward problem is dependent on the conductivity of the head tissues.

Prior work has shown that the scalp-to-skull conductivity ratio is a sensitive parameter for source localization, because it has an influence on the depth of the estimated dipoles [68]. There have been several studies demonstrating the feasibility of injected-current Electrical Impedance Tomography to calibrate the scalp-to-skull conductivity ratio [57], [49]. We are currently collaborating with our partners from La Timone in Marseille in a clinical assessment of the use of injected current Electrical Impedance Tomography to calibrate the scalp-to-skull conductivity ratio.

This work has been presented at the international conference on Electrical Impedance Tomography, see [27] and [28].

6.2.1.3. Coupling numerical methods for the forward problem

Participants: Maureen Clerc, Emmanuel Olivi, Théodore Papadopoulo, Mariette Yvinec [Geometrica Project-Team, INRIA Sophia Antipolis Méditerranée].

This work was partly supported by the ANR grant ViMAGINE.

Electroencephalography (EEG) and magnetoencephalography (MEG) are two modalities that aim at measuring brain activity. Source localization from external data such EEG or MEG, requires a good understanding of the electromagnetic behavior of the patient head. Several models can been used, representing more or less complex geometrical shapes, and conductivity profiles. Different numerical methods allow to cope with different types of models: the Finite Element Method (FEM) can handle very general conductivity models, whereas the Boundary Element Method (BEM) is limited to piecewise constant conductivity. On the other hand, BEM is more capable than FEM to accurately represent sources in isotropic media.

Using a domain decomposition approach, we propose to independently use BEM or FEM in different subdomains. In the EEG forward problem considered, the BEM is limited to the domain where the sources lie (the brain) while the other tissues are handled with the FEM. This leads to an accurate description of the sources while allowing for inhomogeneous and anisotropic conductivity. The proposed method is first validated against analytical solutions in multi-sphere models. Results of the forward problem are presented for a four-layer realistic head-model incorporating a burr-hole in the skull. Convergence of the iterative algorithm is analyzed numerically. The domain decomposition framework provides a way of taking the best advantage of both methods, thus significantly improving the accuracy in the resolution of the forward EEG problem, as well as time and memory consumption.

This work is part of Emmanuel Olivi's PhD thesis [11], and a journal article is under submission.

6.2.1.4. White matter anisotropy

Participants: Maureen Clerc, Emmanuel Olivi, Alexandre Gramfort, Théodore Papadopoulo.

This work was partly supported by the ANR grant ViMAGINE.

Conductivity of tissues in the vicinity of the sources is especially influential on the MEG and EEG forward fields. Those tissues include white matter, whose conductivity is anisotropic because of its fiber structure. While white matter anisotropy can be measured thanks to Diffusion-Weighted MRI, it is rarely incorporated in MEG and EEG head models. Boundary Element Methods can only deal with piecewise constant conductivities, therefore ruling out white matter anisotropy that has a complex structure, and Finite Element Methods have been developed to deal with anisotropic conductivity, but require very fine meshes, thus huge linear systems. We have extended the BEM framework to incorporate white matter anisotropy by treating anisotropic conductivity as a perturbation of an isotropic one. With this extension we have been able to compute the influence of a fiber within the brain white matter on the electric potential, and to validate the restults by comparison with a Finite Element Method.

This work has been published in [34].

6.2.2. Inverse problems in MEG and EEG

6.2.2.1. Rational Approximations

Participants: Maureen Clerc, Théodore Papadopoulo, Juliette Leblond [APICS Project Team, INRIA Sophia Antipolis Méditerranée], Jean-Paul Marmorat [Centre de Mathématiques Appliquées, Ecole des Mines].

In functional neuroimaging, a crucial problem is to localize active sources within the brain non-invasively, from the knowledge of the electromagnetic measurements outside the head. Identification of point sources from boundary measurements is an ill-posed inverse problem. In the case of electroencephalography (EEG), measurements are only available at electrode positions, the number of sources is not known in advance, and the medium within the head is inhomogeneous. We pursue our ongoing work on EEG source localization, based on rational approximation techniques in the complex plane. The method is used in the context of a nested sphere head model, in combination with a cortical mapping procedure. Results on simulated data prove the applicability of the method in the context of realistic measurement configurations.

This work has been submitted to a journal and published as a Research Report in [38].

6.2.3. Brain Computer Interfaces

6.2.3.1. New features for Motor Imagery

Participants: Maureen Clerc, Joan Fruitet, Théodore Papadopoulo, Eoin Thomas.

This work was partly supported by ANR grant CoAdapt.

Our goal is to build a training free BCI based on beta rebound detection and discrimination during the first stage of use, while the learning of the conventional sensorimotor rhythms is done. We show in this preliminary study that it is possible to use the beta rebound to discriminate, real and imagined, right versus left hand movement with either no or very little training.

This work has been published in [14].

6.2.3.2. A bandit algorithm for exploring mental imagery

Participants: Maureen Clerc, Joan Fruitet, Alexandra Carpentier [Sequel Project Team, INRIA Lille Nord Europe], Rémi Munos [Sequel Project Team, INRIA Lille Nord Europe].

This work was partly supported by ANR grant Co-Adapt.

This study presents a new procedure to automatically select a discriminant motor task for an asynchronous brain-controlled button. This type of control pertains to Brain Computer Interfaces (BCI). When using sensorimotor rythms in a BCI, several motor tasks, such as moving the right or left hand, the feet or the tongue, can be considered as candidates for the control. This report presents a method to select as fast as possible the most promising task. We develop for this purpose an adaptive algorithm UCB-classif based on the stochastic bandit theory and build an EEG experiment to test our method. By not wasting time on inefficient tasks, our algorithm can focus on the most promising ones, resulting in a faster task selection and a more efficient use of the BCI training session. This leads to better classi cation rates for a xed time budget, compared to a standard task selection.

This work has been published in [39] and is currently under submission to a journal.

6.3. Multi-Imaging Modalities

6.3.1. Coupling neuronal and haemodynamic models

6.3.1.1. Modeling of the neurovascular coupling in epileptic discharges

Participants: Maureen Clerc, Théodore Papadopoulo, Nicole Voges [former Athena postdoc], Christian Bénar [INSERM U751 Marseille], Solenna Blanchard [INSERM U642 Rennes], Fabrice Wendling [INSERM U642 Rennes], Habib Benali [INSERM U678 Paris], Olivier David [INSERM U594 Grenoble].

This work was partly supported by ANR MultiModel.

Despite the interest in simultaneous EEG-fMRI studies of epileptic spikes, the link between epileptic discharges and their corresponding hemodynamic responses is poorly understood. In this context, biophysical models are promising tools for investigating the mechanisms underlying observed signals. We have applied a metabolic-hemodynamic model to simulated epileptic discharges, in part generated by a neural mass model. We analyzed the effect of features specific to epileptic neuronal activity on the blood oxygen level dependent (BOLD) response, focusing on the issues of linearity in neurovascular coupling and on the origin of negative BOLD signals. We found both sub- and supra-linearity in simulated BOLD signals, depending on whether one observes the early or the late part of the BOLD response. The size of these non-linear effects is determined by the spike frequency, as well as by the amplitude of the excitatory activity. Our results additionally indicate a minor deviation from linearity at the neuronal level. According to a phase space analysis, the possibility to obtain a negative BOLD response to an epileptic spike depends on the existence of a long and strong excitatory undershoot. Moreover, we strongly suggest that a combined EEG-fMRI modeling approach should include spatial assumptions. The present study is a step towards an increased understanding of the link between epileptic spikes and their BOLD responses, aiming to improve the interpretation of simultaneous EEG-fMRI recordings in epilepsy.

This work has been published in [17].

6.3.1.2. A nested cortex parcellation combining analysis of MEG forward problem and diffusion MRI tractography

Participants: Anne-Charlotte Philippe, Maureen Clerc, Théodore Papadopoulo, Rachid Deriche.

Understanding the relationship between structure and function is a major challenge in neuroscience. Diffusion MRI (dMRI) in the only non-invasive modality allowing to have access to the neural structure. Magnetoencephalography (MEG) is another non-invasive modality that allows a direct access to the temporal succession of cognitive processes. Functional cortex parcellation being one of the most important ways to understanding structure-function relationship, we propose an innovative method merging MEG and dMRI to parcellate the cortex. The combination of MEG forward problem and connectivity information reveals cortical areas generating a similar magnetic field at sensors while having a similar connectivity. Results show suitable clusters that forecast interesting studies for inter- and intra- subjects comparisons of the cortex parcellations. The automatic nested cortex parcellation we propose could be a first step to analyse sources that are seeds of long or short range connectivity and to differentiate these connectivities in the white matter

This work is currently under submission.

6.3.1.3. Improved computer-aided detection of small polyps in CT colonography using interpolation for curvature estimation

Participants: Rachid Deriche, Jiamin Liu [Imaging Biomarkers and Computer-Aided Diagnosis Laboratory, Radiology and Imaging Sciences, Clinical Center, National Institutes of Health, Bethesda], Suraj Kabadi [Imaging Biomarkers and Computer-Aided Diagnosis Laboratory, Radiology and Imaging Sciences, Clinical Center, National Institutes of Health, Bethesda], Robert Van Uitert [Imaging Biomarkers and Computer-Aided Diagnosis Laboratory, Radiology and Imaging Sciences, Clinical Center, National Institutes of Health, Bethesda], Nicholas Petrick [Center for Devices and Radiological Health, U.S. Food and Drug Administration, Maryland], Ronald M. Summers [Imaging Biomarkers and Computer-Aided Diagnosis Laboratory, Radiology and Imaging Sciences, Clinical Center, National Institutes of Health, Bethesda].

Surface curvatures are important geometric features for the computer-aided analysis and detection of polyps in CT colonography (CTC). However, the general kernel approach for curvature computation can yield erroneous results for small polyps and for polyps that lie on haustral folds. Those erroneous curvatures will reduce the performance of polyp detection. This work presents an analysis of interpolation's effect on curvature estimation for thin structures and its application on computer-aided detection of small polyps in CTC. In this work, we demonstrated that a simple technique, image interpolation, can improve the accuracy of curvature estimation for thin structures and thus significantly improve the sensitivity of small polyp detection in CTC. Our experiments showed that the merits of interpolating included more accurate curvature values for simulated data, and isolation of polyps near folds for clinical data. After testing on a large clinical data set, it was observed that sensitivities with linear, quadratic B-spline and cubic B-spline interpolations significantly improved the sensitivity for small polyp detection. In conclusion, the image interpolation can improve the accuracy of curvature estimation for thin structures and thus improve the computer-aided detection of small polyps in CTC.

This work has been published in [16]

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. CPER TELIUS

Duration: *2007–2013*

This grant, funded by regional and National support, covers 3 areas: an experimental platform for research on telecomnumication networks, a software and informatics platform (including a virtual reality environment, a medical imaging platform, and a peer-to-peer computing grid), and a experimental platform on the usage of information systems. Athena is being funded through the medical imaging platform, to develop its electro-encephalography laboratory.

7.2. National Initiatives

7.2.1. ANR ViMAGINE

Participants: Maureen Clerc, Rachid Deriche, Alexandre Gramfort [Parietal project-team], Emmanuel Olivi, Théodore Papadopoulo, Anne-Charlotte Philippe.

Duration: *July 2008 to July 2012*

The partners of this project are Athena, the LENA (CHU Pitié-Salpétrière), and the Parietal project-team at INRIA Futurs and Neurospin-Saclay.

This project takes a new challenge on the non invasive exploration of the Human visual system in vivo. Beyond the basic mechanisms of visual perception – which have already been investigated at multiple scales and through a large variety of modalities – we are primarily interested in proposing and exploring innovative solutions to the investigation of dynamic neural activations and interactions at the systems level. Bridging the elements involved in this endeavour requires that we are capable of observing, modelling and predicting the interplay between the anatomical/functional architecture of the brain systems and some identified timing properties of neural processes. The overall framework in which this project will be conducted is a federation of partners who will be bringing complementary expertise to this multidisciplinary research. The collaborators include experts in (1) electromagnetic and magnetic resonance brain imaging methods, (2) computational models of neural systems and (3) the neuroscience of vision. A central asset of our group is the easy access to state-of-the-art imaging platforms (e.g. high-density MEG and EEG arrays; 3T and 7T MR scanners) that will ensure the acquisition of quality experimental data.

7.2.2. ANR CO-ADAPT

Participants: Maureen Clerc, Dieter Devlaminck, Joan Fruitet, Sebastian Hitziger, Théodore Papadopoulo, Eoin Thomas, Romain Trachel.

Duration: *September 2009 to December 2013*

The partners of this projects are the INSERM U821 laboratory of Bron, the "laboratoire de Neurologie de la cognition" UMR6155 CNRS of Marseille, The INRIA Lille Sequel project-team and the "Laboratoire d'Analyse Topologie et Probabilités UMR6632/CNRS of Université de Provence, Marseille.

Brain Computer Interfaces (BCI) provide a direct communication channel from the brain to a computer, bypassing traditional interfaces such as keyboard or mouse, and also providing a feedback to the user, through a sensory modality (visual, auditory or haptic). A target application of BCI is to restore mobility or autonomy to severely disabled patients, but more generally BCI opens up many new opportunities for better understanding the brain at work, for enhancing Human Computer Interaction, and for developing new therapies for mental illnesses.

In BCI, new modes of perception and interaction come into play, and a new user must learn to operate a BCI, as an infant learns to explore his/her sensorimotor system. Central to BCI operation are the notions of feedback and of reward, which we believe should hold a more central position in BCI research.

The goal of this project is to study the co-adaptation between a user and a BCI system in the course of training and operation. The quality of the interface will be judged according to several criteria (reliability, learning curve, error correction, bit rate). BCI will be considered under a joint perspective: the user's and the system's. From the user's brain activity, features must be extracted, and translated into commands to drive the BCI system. Feature extraction from data, and classification issues, are very active research topics in BCI. However, additional markers may also be extracted to modulate the system's behavior. It is for instance possible to monitor the brain's reaction to the BCI outcome, compared to the user's expectations. This type of information we refer to as meta-data because it is not directly related to the command, and it may be qualitative rather than quantitative. To our knowledge, there is so far no BCI system that integrates such meta-data from the user's brain. From the point of view of the system, it is important to devise adaptive learning strategies, because the brain activity is not stable in time. How to adapt the features in the course of BCI operation is a difficult and important topic of research. A Machine Learning method known as Reinforcement Learning (RL) may prove very relevant to address the above questions. Indeed, it is an adaptive learning method that explicitly incorporates a reward signal, which may be qualitative (hence allowing meta-data integration). The aim of CO-ADAPT is to propose new directions for BCI design, by modeling explicitly the co-adaptation taking place between the user and the system (web site http://coadapt.inria.fr).

7.2.3. ANR NucleiPark

Participants: Rachid Deriche, Aurobrata Ghosh, Anne-Charlotte Philippe, Emmanuel Caruyer, Jian Cheng, Alvaro-Alejandro Sanchez-Moscosa, Demian Wassermann.

Duration: *September 2009 to December 2012*

This project is about High field MR imaging (7T and 3T) of the brainstem, the deep nuclei and their connections in the parkinsonian syndromes with applications to prognosis, pathophysiology and improvement of therapeutic strategies. It involves three partners: The NeuroSpin team including C. Poupon and D. Le Bihan, the INRIA with our project as well as the VISAGES project-team and the UPMC (University Pierre and Marie Curie, Paris) including INSERM U678 (H. Benali) and the CENIR (S. Lehericy).

The goal of the project is to find new neuroimaging markers of deep brain nuclei in neurodegenerative diseases that can be used for the diagnosis of Parkinsonian syndromes at the early stage. In addition, the goal is the characterization of lesions of deep brain structures and the detection of biomarkers of neuronal lesions in PD that can be related to clinical signs, such as gait disorders. Biomarkers of Parkinsonian syndromes could be used to create a diagnostic tool of the pathology and to correlate the identified markers with clinical signs. We will perform tractography of small fibre bundles using our HARDI techniques and Diffusion markers

(anisotropy, apparent diffusion coefficient, fibre density, curvature, average diameter) will be collected along the reconstructed bundles.

Complementary parts of these objectives directly related to the acquisitions protocols have been accepted within the framework of another proposal submitted by the same partners and accepted for grant for two years (2009 & 2010) by the *France-Parkinson Association*

7.2.4. ANR MULTIMODEL

Participants: Théodore Papadopoulo, Maureen Clerc, Sebastian Hitziger.

Duration: *December 2010 to March 2014*

The general objectives of the MULTIMODEL project are twofold:

- Develop computational models at the level of neuronal systems that will help interpreting neuroimaging data in terms of excitation-, inhibition- and synchronization-related processes.
- Acquire multimodal datasets, obtained in rats and humans under physiological and epileptogenic conditions, which will be used to develop the biophysical models and to test their face validity and predictability.

Specifically, during this 3-year project, the following questions will be dealt with:

- How can models be integrated in order to link data from different modalities (electro/magneto-encephalography, optical imaging, functional MRI)?
- What is the influence of hidden parameters on the observed signals (e.g. ratio of excitation/inhibition and synchronization degree across regions)?
- To what extent can biophysical modelling bring valuable insights on physiological and pathological brain activity ?

We will operate at the level of population of cell, i.e. at a scale compatible with the resolution of neuroimaging tools (at the level of the mm). A novel model structure will be investigated. It will include astrocytes at this "mesoscopic" level and will operate in networks of connected regions. Moreover, models in physiological and pathological conditions will be compared, which will be a step towards a better understanding of mechanisms underlying epileptic condition.

The MULTIMODEL project stems from a conjoint INSERM-INRIA scientific initiative launched in December 2008 and ended in 2010. It involves 5 partners (Inserm U751 in Marseille, U678 in Paris, U836 in Grenoble, U642 in Rennes and INRIA Athena project-team).

7.2.5. ADT Immersive BCI

Participants: Théodore Papadopoulo, Maureen Clerc, Nicolas Servant, Joan Fruitet.

Duration: *December 2009 to December 2011*

The goal of this technical project, funded by INRIA for 2 years, is to facilitate the use of EEG within a new immersive environment at INRIA Sophia Antipolis Méditerranée, in order to make it possible to perform BCI or cognitive experiments within this environment. Using a BCI within an immersive environment will open up new possibilities for scientific research, both in BCI and in Virtual Reality. All development linked to this project will take place within an integrative software platform. This development will include electrode localization and real-time EEG processing with feedback to the user.

7.2.6. ADT MedInria-NT

Participants: Théodore Papadopoulo, Maureen Clerc, Rachid Deriche.

Duration: *December 2010 to December 2012*

The goal of this technical project, funded by INRIA for 2 years, is to introduce some tools developed at ODYSSÉE/ATHENA into the MedINRIA platform. There are basically two such facilities:

- Integrate the tools developed for the statistical characterization of brain white matter fiber bundles.
- Develop an interface for M/EEG data within MedINRIA. This will focus on two main goals:
  - Create a facility to read and visualize M/EEG signals.
  - Integrate M/EEG forward problem tools.

7.3. International Initiatives

7.3.1. INRIA Associate Teams

7.3.1.1. CDMRI

Title: Computational Diffusion MRI

INRIA principal investigator: Rachid Deriche

International Partner:

Institution: University of Minnesota (United States)

Laboratory: Department of Electrical and Computer Engineering at University of Minnesota, Center for Magnetic Resonance Research

Researchers: Guillermo Sapiro & Christophe Lenglet

International Partner:

Institution: National Institute of Child Health and Human Development (Bethesta, MD) (United States)

Laboratory: Section on Tissue Biophysics and Biomimetics

Researcher: Peter Basser

Duration: 2009 - 2011

See also: http://www-sop.inria.fr/teams/odyssee/contracts/Computational-Diffusion-MRI/

The CD-MRI Associate Team was created to bring each partner's expertise together in the field of Diffusion Magnetic Resonance Imaging with the objective to help in making significant contributions to the processing and analysis of diffusion weighted imaging data, a task well known to be extremely challenging due to the complex underlying properties of the tissue being imaged and the structure of the data

The rational behind this project was to benefit from the complementarity and the synergy of our expertise and to combine our efforts and ideas to succeed achieving this exciting and challenging objective. Indeed, our groups at Inria, NICHD and the University of Minnesota have great and complementary expertise in Diffusion MRI.

ATHENA Project Team has greatly contributed during the last years to develop original and efficient algorithms relying on Riemannian geometry, differential geometry, partial differential equations and front propagation techniques to correctly and efficiently process Diffusion MRI data. The group of Peter Basser at NICHD had pioneered the so-called diffusion tensor imaging in the mid 90's, and since then has developed numerous and important applications to clinical research. The Center for Magnetic Resonance Research at University of Minnesota is a research lab, unique in the domain of high field MRI, with no less than six high field magnets; and the group of Guillermo Sapiro in the department of Electrical and Computer Engineering is one of the best worldwide dedicated to research in imaging sciences.

Therefore, the CD-MRI started in 2009 with the following main objectives:

- Develop rigorous mathematical and computational tools for the analysis of Diffusion MRI data.
- Improve acquisition techniques for High Angular Resolution Diffusion Imaging,
- Write joint publications and help address challenging clinical applications.

Through an extensive exchange program involving PhD's as well Post-Docs's and senior scientists between all the partners, our Associate Team has been able to tackle these challenging objectives without the need to relocate any of them.

Indeed, we have contributed to advance the state-of-the-art in Computational Diffusion MRI, we have been very successful to initiate and pursue research on optimal diffusion gradient schemes (single, multi-shell), online ODF reconstruction and motion detection, optimal reconstruction of the propagator and decoding axon diameter distribution information encrypted in radial NMR attenuation signals. We proposed new Kalman based acquisition and sampling techniques particularly well adapted to process HARDI data and make it clinically feasible, and wrote several joint publications in international conferences, some of which are or will be submitted to journals.

7.3.2. Visits of International Scientists

7.3.2.1. Internships

John TREILHARD (from May 2011 until Aug 2011)

Subject: Using Radial NMR Profiles to Characterize Pore Size Distributions.

Institution: Queen's University, Kingston Ontario (Canada).

Supervisor: R. Deriche.

Alvaro Alejandro SANCHEZ MOSCOSA (from April 2011 until Sept. 2011)

Subject: White Matter Clustering Revisited.

Institution: Royal Institute of Technology, KTH STH (Sweden).

Karthikeyan GANESAN (from March 2011 until June 2011)

Subject: Modélisation multimodale de données fonctionnelles cérébrales.

Institution: Delft University of Technology (Netherlands).

Supervisor: T. Papadopoulo and M. Clerc.

Meizhu Liu (from May 2011 until July 2011)

Subject: A Variational based Approach for Diffusion MRI Régularization and its Applications.

Institution: University of Florida (United States).

Supervisor: R. Deriche.

Gonzalo Vegas-Sánchez-Ferrero (from May 2011 until July 2011)

Subject: Anisotropic LMMSE denoising of MRI based on statistitcal tissue models

Institution: University of Valladolid (Spain).

Supervisor: R. Deriche.

7.3.3. Participation In International Programs

We have initiated a collaboration entitled *Computational Brain Imaging Through Diffusion MRI* with the Computer Vision and Pattern Analysis Laboratory led by Pr. Gozde Unal at the Faculty of Engineering and Natural Sciences, Sabanci University, Istanbul (Turkey). Our main objectif in this *PHC Bosphore 2010* project is focused on automating the tractography process for white matter fibers. Building on the expertise of the two teams at INRIA and Sabanci University (SU), we will develop novel computational techniques for processing Diffusion Tensor-MRI (DTI), and study specific pathways for their analysis and visualization using new mathematical models. This project started in January 2010 and is granted for 2 years.

We have also a collaboration within the framework ECOS-Sud on a project based on Diffusion MRI and Autism with Prof. Mariano Sigman (Integrative Neuroscience Laboratory, Physics Dept. University of Buenos Aires, Buenos Aires, Argentina) and B. Wicker (INCM UMR 6193 CNRS, Université de la Méditerranée, Marseille, France) and O. Coulon (LSIS/ESIL UMR 6168). This project started in Sept. 2009 and is granted for 2 years.

We have also a collaboration within the framework STIC-Algerie on a project based on Diffusion MRI with Prof. D. Cherifi and L. Boumghar from USTHB, Algiers. This project started in July. 2011 and is granted for 2 years.

8. Dissemination

8.1. Animation of the scientific community

- R. Deriche is Assistant Director at the Doctoral School EDSTIC (http://edstic.i3s.unice.fr/index.html), member of the Scientific Council of the ITMO ITS (Institut des Technologies pour la Santé) and member of the Administration Council of the GRETSI.
- R. Deriche is Associate Editor of SIAM Journal on Imaging Sciences (SIIMS) and editorial board member at Springer for the book series entitled Computational Imaging and Vision.
- Rachid Deriche gave plenary invited talks at Centro de Investigation en Matematicas (CIMAT, Guanajuato), Mexico (18-22 October 2011); Séminaire LIRIS, Villeurbanne (11 October, 2011); Centre des Techniques Avancées, Algiers (26-30 June, 2011); Brain Science Awareness Workshop 2011, Bangalore (14-15 March, 2011); Séminaire du groupe Signal et Image du Laboratoire IMS (Intégration du Matériau au Système), ENITAB, Université de Bordeaux (10 March, 2011);
- R. Deriche has served as a member of the EADS Foundation PhD Award Committee and has been president, reviewer and examiner in the jury committee of a number of PhD and HDR thesis among which two in Netherlands (N. Sepasian, Eindhoven University of Technology, Sept. 2011 and O.Dzyubachyk, Dept. of Medical Informatics, Rotterdam, April 13 & 14).
- R. Deriche was in charge of the coordination and oral presentation of the research activities carried ou within the framework of *Domaine 5: Stic pour les Sciences du Vivant et de l'Environnement* during the AERES evaluation seminar of Inria Sophia Antipolis - Méditerranée Research Center (7 & 8 feb. 2011). Domaine 5 has been awarded the grade **A+**.
- R. Deriche has served for many years as area-chair and/or as program committee member for International Conferences as ICCV, MICCAI, ECCV, CVPR, ISBI and national conferences as AFRIF-AFIA RFIA and serves several international journals and conferences (NeuroImage, IEEE Transactions on Medical Imaging, Magnetic Resonance in Medicine, JMIV, Medical Image Analysis Journal, ISBI, ISMRM, HBM..).
- M. Clerc serves on the Editorial Board of the journal BioMedical Engineering OnLine. She serves as reviewer of many international conferences and journals (NeuroImage, Physics in Medicine and Biology, Inverse Problems, to name a few).

- M. Clerc is the coordinator of the ANR grant Co-Adapt, and is part of the organizing committee of the Biomag conference to be held in Paris in August 2012.
- M. Clerc gave invited talks at INSERM Lyon U1028, at the Séminaire Image Paris 6, at the Séminaire Probas Stats Laboratoire Jean-Alexandre Dieudonné, Nice, at the Biomedical Institute Seminar at EPFL, and in the Computational Neurosciences Workshop in Marseille.
- M. Clerc was part of several thesis committees (referee for D. Kandaswamy, EPFL, and mid-term reviews for A. Baratchant in Grenoble and M. Perrin in Lyon).
- M. Clerc gave a course in the Neurocomp Autumn School on Brain Computer Interfaces, in Nancy.
- T. Papadopoulo served as a referee for the international conferences ICCV 2011, CVPR 2011 and NER 2011. He is also area chair for the national conference GRETSI 2011. In 2011, he has been reviewer for the journals SIAM Journal on Imaging Sciences, International Journal of Computer Vision, Pattern Recognition Letters, Transactions on Image Processing, Numerical Methods for Partial Differential Equations, Journal of Mathematical Imaging and Vision, Physics in Medicine and Biology and Mathematics and Computers in Simulation.
- Since September 2011, T. Papadopoulo is the coordinator of the Master of Science in Computational Biology and Biomedicine from Université Nice Sophia Antipolis (Website: http://cbb.unice.fr). The scientific goal of this program is to focus on the human being from different perspectives (understanding and modeling functional aspects or interpreting biomedical signals from various devices) and at different scales (from molecules to organs and the whole organism).
- T. Papadopoulo is a member of the local (Sophia Antipolis) committees for software development (CDT) and for Sustainable development.
- T. Papadopoulo is the coordinator of the ADT "Immersive BCI" and the Athena contact for the ADT MedINRIA-NT and the ANR MULTIMODEL.

8.2. Teaching

- Maureen Clerc:

  Licence: *Mathematics for Engineers* (24H), L3, MAM option at Polytechnic Engineering School, University Nice Sophia Antipolis, France.

  Master: *Inverse problems for brain functional imaging* (12H), Master 2 Computational Biology and Biomedicine, University Nice Sophia Antipolis, France.

- Rachid Deriche:

  Master: *Variational approaches and Geometrical Flows for Brain Imaging* (24H), Master 2 Computational Biology and Biomedicine, University Nice Sophia Antipolis, France.

  Master: *Computational Vision and Image Processing* (12H), 3rd year Engineering School, Institut TELECOM / TELECOM SudParis, Evry, France.

- Théo Papadopoulo:

  Master: *3D Computer Vision* (21H), M2, VIM option at Polytechnic Engineering School, University Nice Sophia Antipolis, France.

  Master: *Inverse problems for brain functional imaging* (12H), M2 Computational Biology and Biomedicine, University Nice Sophia Antipolis, France.

  Master: *Inverse problems for brain functional imaging* (16H), M2 Mathématiques, Vision et Apprentissage, ENS Cachan, France.

PhD & HdR:

HdR: Théo Papadopoulo, Contributions and perspectives to computer vision, image processing and EEG/MEG data analysis, Nice Sophia Antipolis University, Defended on May 9, 2011.

PhD: Aurobrata Ghosh, High Order Models in Diffusion MRI and Applications, Nice Sophia Antipolis University. Defended on April 11, 2011. Advisor: Rachid Deriche

PhD: Emmanuel Olivi, Coupling of numerical methods for the forward problem in Magneto- and Electro-EncephaloGraphy, Defended on December 14, 2011. Advisor: Maureen Clerc

PhD in progress: Emmanuel Caruyer: « Optimal dMRI Acquisition Schemes », Started Oct. 2009. Advisor: Rachid Deriche

PhD in progress: Jian Cheng: « A Riemanian Framework for HARDI », Started Sept. 2009. Advisor: Rachid Deriche & Tianzi Jiang (CASIA-LIAMA).

PhD in progress: Joan Fruitet: « Interfaces Cerveau Ordinateur, méthodes inverses et sélection de sources », Started Oct. 2009. Advisor: Maureen Clerc

PhD in progress: Sebastian Hitziger: « Modeling the variability of Brain Electrical Activity», Started Nov. 2011. Advisors: Théo Papadopoulo & Maureen Clerc

PhD in progress: Sylvain Merlet: « Compressed Sensing & Diffusion MRI », StaRted Sept. 2010. Advisor: Rachid Deriche

PhD in progress: Anne-Charlotte Philippe: « dMRI & MEEG Fusion », Started Sept. 2010. Advisors: Maureen Clerc & Rachid Deriche

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