From Real MRA to Virtual MRA: Towards an Open-Source Framework

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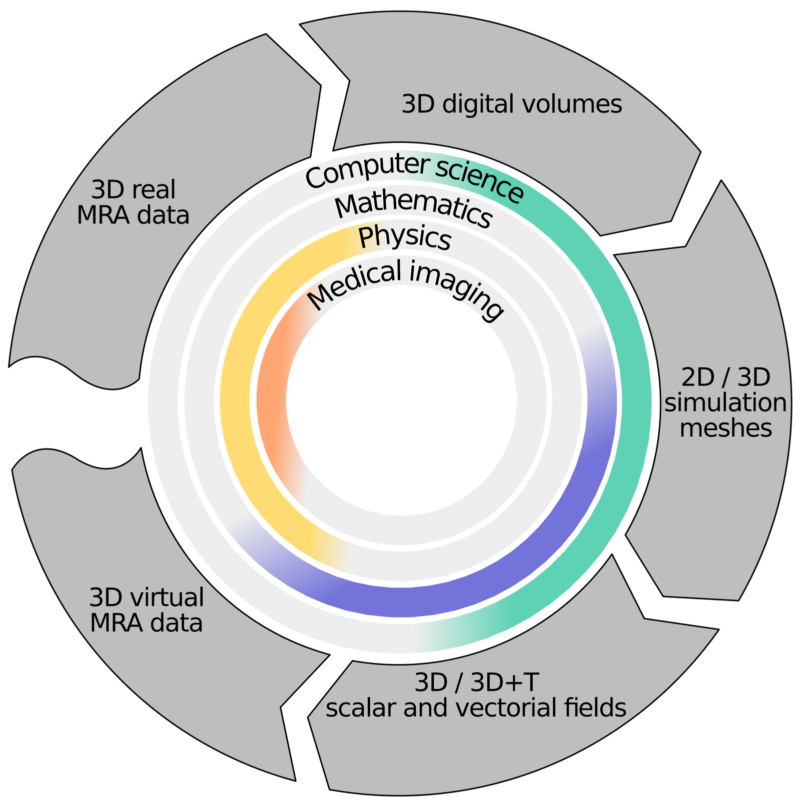
Introduction

Angiographic imaging is a crucial domain of medical imaging. In particular, Magnetic Resonance Angiography (MRA) is used for both clinical and research purposes. This article presents the first framework designed for the production of virtual MRA images from real MRA images. It relies on a pipeline that involves image processing, vascular modeling, computational fluid dynamics and MR image simulation, with several purposes. It aims to provide to the whole scientific community with (1) software tools for MRA analysis and blood flow simulation; and with (2) data (computational meshes, virtual MRAs with associated ground truth), in an open-source / open-data paradigm. Beyond these purposes, it constitutes a versatile tool for progress in the understanding of vascular networks, especially in the brain, and the associated imaging technologies.

Overview of the framework

Our pipeline composed of 5 steps, going from real MRA to virtual MRA:

- MRA acquisition.
- Segmenting vascular volumes to further define mixed 2D/3D computational meshes.
- Designing a vascular model (modeling anatomical and physiological features).
- Simulating the flowing blood (velocity and pressure fields).
- Generating MRA images.

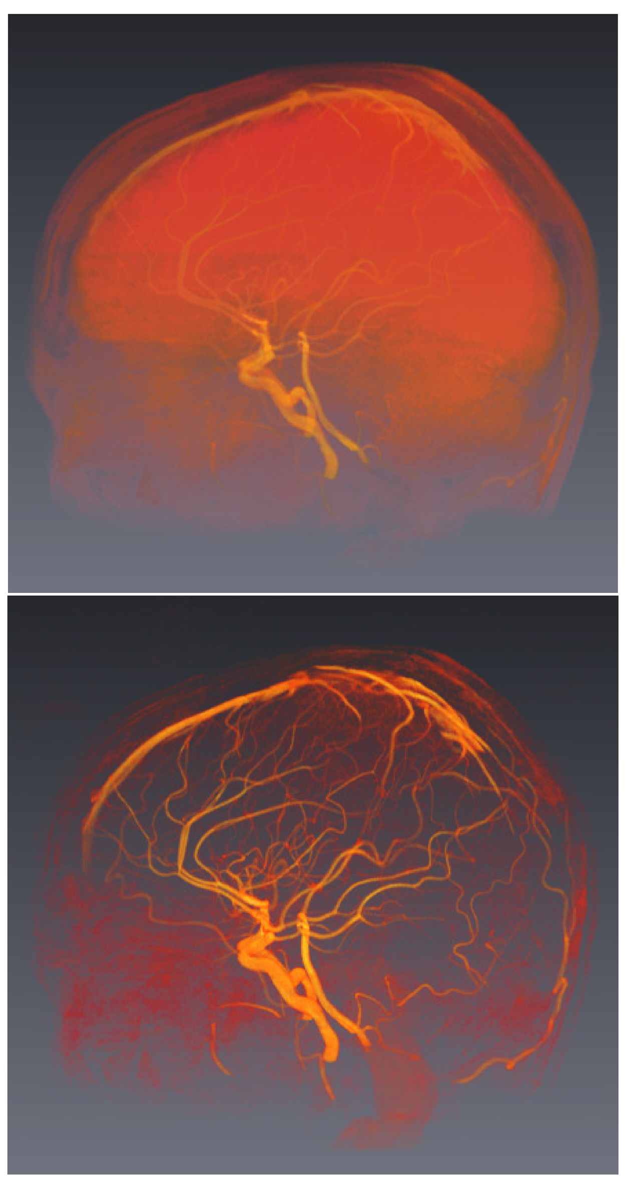


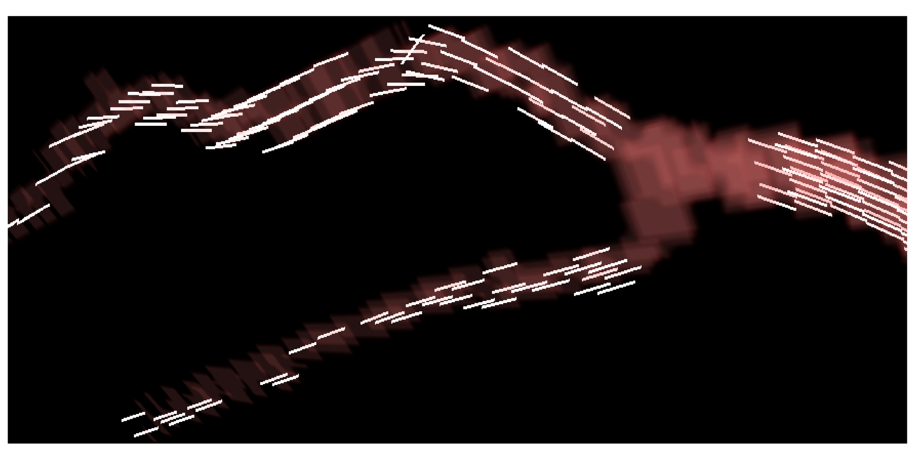
Software

This methodological pipeline is materialized by a software framework, namely AngioTk, which can embed plug-ins implementing some of the above methodological steps. In particular, AngioTk relies on several software tools in a open-source paradigm: VMTK, Gmsh, Feel++, ParaView, JEMRIS, . . .
The next sections of this poster provide some of the most impacting contributions within this framework, in image processing, CFD, and MRI simulation.

A new vessel analysis operator: RORPO

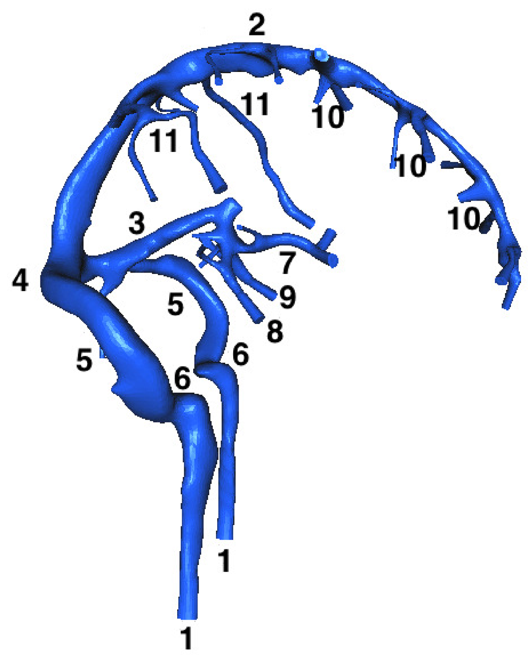
RORPO is a new non-linear, non-local, path-based, antiextensive filtering for tubular detection, developed in the framework of mathematical morphology. It relies on the pointwise ranking of Robust Path Operators, allowing for both the removal of non-curvilinear structures (in particular, blob-like and plane-like structures) and the estimation of linear structure orientations.
https://github.com/path-openings/RORPO





Blood flow simulation example: the cerebral venous network

At the macroscopic scale, the cerebral venous network is composed by input veins (7–11) draining the blood into sinuses (2,3) until their confluence (4). The blood then passes into lateral sinuses (5,6) and reaches an extracranial area, composed of the internal jugular veins (1). The cranium is modeled by a rigid closed box, and the brain tissues and cerebrospinal fluid contain mainly water, thus constituting an incompressible tissue. We then assume that vessel walls are rigid.

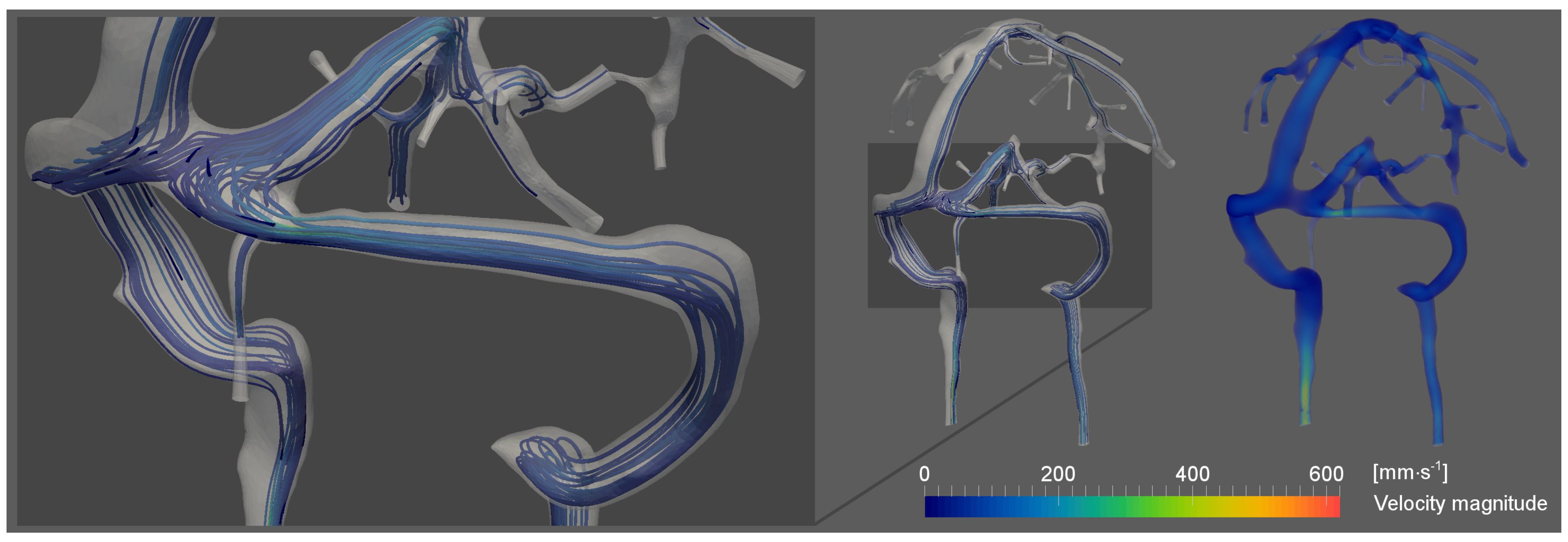


Modelling of the venous blood flow dynamics: Navier-Stokes (NS) equations

$$\begin{cases} \rho(\partial_t \mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u}) - \mu\Delta\mathbf{u} + \nabla p = \mathbf{f} & \text{in } \Omega\times[0,T] \\ \operatorname{div}\mathbf{u} = 0 & \text{in } \Omega\times[0,T] \\ \mathbf{u}|_{t=0} = \mathbf{u_0} & \text{in } \Omega \end{cases}$$

For NS resolution, two numerical methods based in finite elements, are considered (FreeFem++ / Feel++).

- FreeFem++: characteristics method to handle the non-linear term
- Feel++: Oseen linearization



MRA simulation

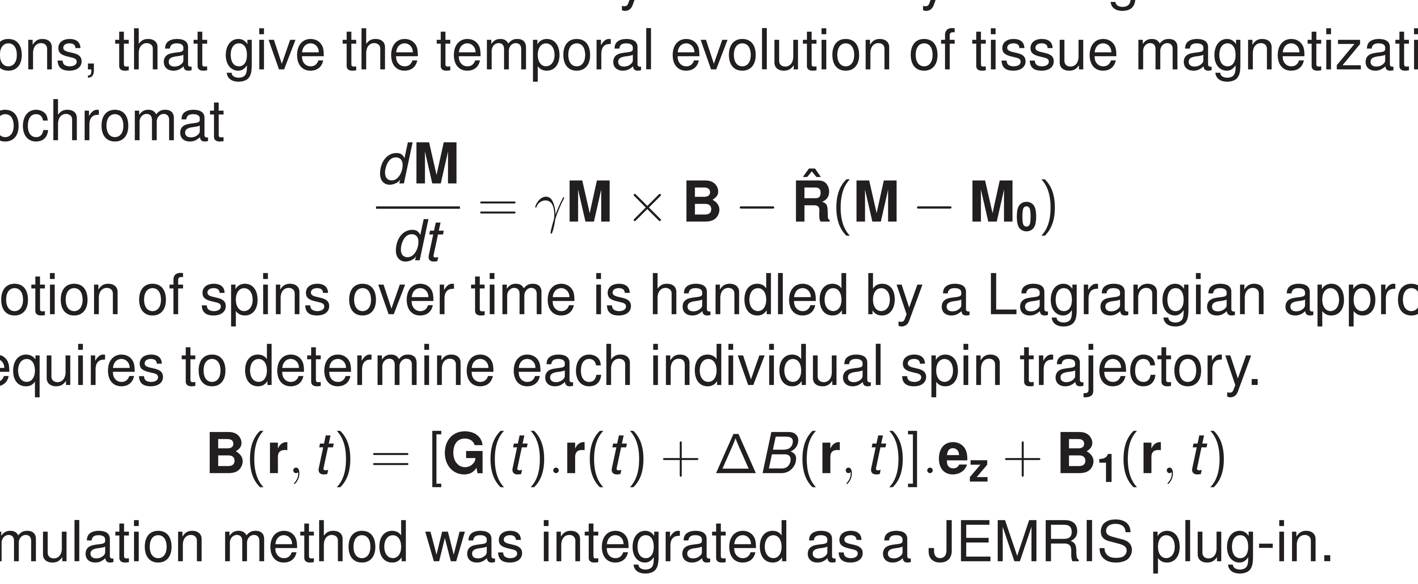
MRA simulation is carried out by numerically solving the Bloch equations, that give the temporal evolution of tissue magnetization for one isochromat

$$\frac{d\mathbf{M}}{dt} = \gamma\mathbf{M}\times\mathbf{B} - \hat{\mathbf{R}}(\mathbf{M}-\mathbf{M_0}) \quad (1)$$

The motion of spins over time is handled by a Lagrangian approach. This requires to determine each individual spin trajectory.

$$\mathbf{B}(\mathbf{r},t) = [\mathbf{G}(t).\mathbf{r}(t) + \Delta B(\mathbf{r},t)].\mathbf{e_z} + \mathbf{B_1}(\mathbf{r},t) \quad (2)$$

The simulation method was integrated as a JEMRIS plug-in.
First, MRA images were computed for two physical phantoms, and compared to real images in order to assess the accuracy of this synthetic MR simulation step.
Second, MRA images were computed for CFD outputs in realistic geometries, which constitutes a final output of the whole pipeline.



This pipeline provides various software components for image processing, CFD and MR simulation. It is also an open-source and versatile framework, made available to the scientific community, that can be enriched by any further contribution.

VIVABRAIN Project (ANR-12-MONU-0010)
Virtual angiography simulation from 3D and 3D+t brain vascular models

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