# Investigating Flow-Structure Interactions in Cerebral Aneurysms

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**ABSTRACT**

Modeling flow-structure interaction (FSI) in biological systems, where elastic tissues and fluids have almost identical density (low mass ratio problem), is one of the most challenging problems in computational mechanics. One of the major challenges in FSI simulations at low mass ratio is the stability of semi-implicit coupled fluid-structure solvers. Based on our recent advances in developing stable numerical algorithms we have developed a solver capable of tackling problems with mass ratios approaching zero, enabling high-resolution FSI simulations of biological systems, such as blood flow in compliant arteries. Our coupled solver, NekTar, is based on high-order spectral/*hp* element discretization and iterative coupling between the fluid and structure (solid) domains.

Realistic FSI simulations produce very large and complex data sets, yielding the need for parallel data processing and visualization. Here we present our recent advancements in developing an interactive visualization tool which now enables the visualization of such FSI simulation data. Specifically, we present a ParaView-NekTar interface that couples the ParaView visualization engine with NekTar's parallel libraries, which are employed for the calculation of derived fields in both the fluid and solid domains with spectral accuracy. This interface allows the flexibility of independently choosing the resolution for visualizing both the volume data and the surface data from each of the solid and fluid domains, which significantly facilitates the visualization of complex structures under large deformations.

The animation of the fluid and structure data is synchronized in time, while the ParaView-NekTar interface enables the visualization of different fields to be superimposed, e.g. fluid jet and structural stress, to better understand the interactions in this multi-physics environment.

**Index Terms:** J.2 [Computer Applications]: Physical Sciences and Engineering—Physics; I.6 [Computing Methodologies]: Simulation and Modeling—applications, simulation output analysis; I.3.8 [Computer Applications]: Computer Graphics—Applications

## 1 INTRODUCTION

The cardiovascular system of the human body is the envy of every engineer. In just one minute the average heart beats about 70 times, pumping the entire blood supply of 5 liters through 62,000 miles of vessels. That is one-fourth the distance between the Moon and the Earth. The brain, in particular, although less than 2% of a human's body weight, receives about 20% of the resting cardiac output of blood and 25% of the body's oxygen supply.

Interactions of blood flow in the human brain occur between different scales, determined by flow features in the large arteries (diameter of 0.5 mm or larger), the smaller arteries and arterioles ($500\mu m$ to $10\mu m$), and the capillaries (mean diameter of $5\mu m$) all being coupled to cellular and sub-cellular biological processes. While many biological aspects have been studied systematically, surprisingly less effort has been put into studying blood flow patterns within the brain; a matter of particular relevance to the clinical evolution of life threatening conditions such as cerebral aneurysms.

Cerebral aneurysms (CAs) [7] occur in up to 5% of the general population, leading to strokes for over 40,000 Americans each year. They are manifested as a pathological dilation of the vascular wall, due to the congenital or acquired structural weakening of the wall media. A potential rupture of a CA can cause subarachnoid hemorrhage, a devastating event that leaves over 60% of the afflicted patients dead or disabled, with less than 50% of survivors being able to return to their former jobs or level of activity.

Currently, there exists no formal framework towards the diagnosis of CAs, and most cerebral aneurysms go unnoticed until they rupture or are detected by brain imaging that may have been obtained for another condition. Moreover, assessing the risk of a potential rupture of a diagnosed CA is mostly empirical as the biomechanics governing the time-evolution of CAs is far from being fully understood. However, it is believed that factors such as location, geometry, blood flow patterns and resulting mechanical stresses within the aneurysm play a prominent role.

Recent advances in computational science now allow for high-fidelity numerical simulations of flow-structure interactions in compliant CAs. The ability to simulate and visualize such cases enables us to study in-detail the flow patterns and the resulting mechanical stress field in the aneurysm, shedding new light on the conditions for its eventual rupture. Here, we demonstrate the potential of this pipeline by presenting visualization results for flow-structure interactions in a patient-specific aneurysm. The aneurysm is located in the cavernous segment of the right internal carotid artery and its detailed geometry was extracted using Magnetic Resonance Imaging (MRI). The fluid mesh (artery and aneurysm) consists of 42,065 tetrahedral spectral elements, while its solid counterpart (arterial wall), contains 16, 912 prismatic spectral elements (see Figure 1).

In the subsequent section we will briefly describe the multi-physics FSI computational framework. This is followed by discussion of the visualization components that were developed to enable the interactive visual exploration of the resulting FSI data. This comprises a custom ParaView-NekTar plug-in for parallel data processing and visualization. ParaView is leveraged for performing standard parallel visualization algorithms and rendering. The key contribution here is reading the NekTar data in its native simulation format, applying transformations for visualizing moving unstructured meshes subject to large displacements and calculating derived quantities of high-order volume data, such as the stress tensor inside solid domains.

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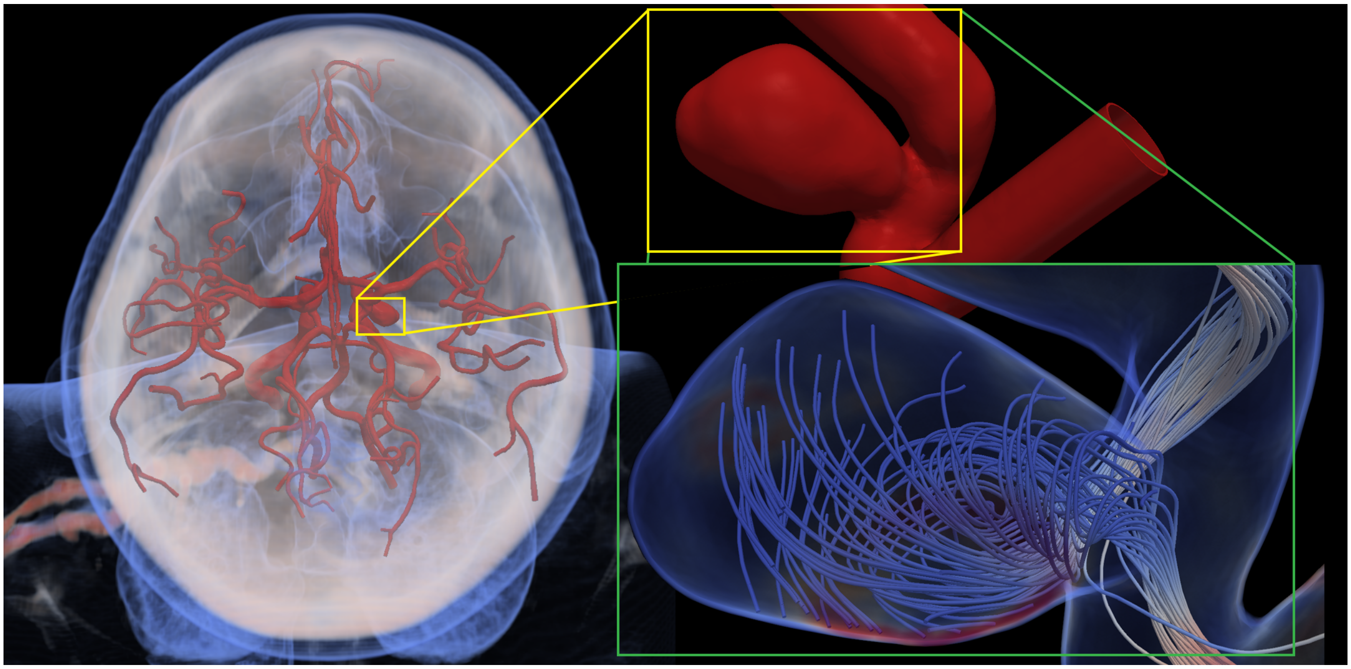

Figure 1: Flow-structure interactions in an aneurysm. Shown on the left is the patient-specific cranial arterial network where the spectral element equations are solved. Shown in the inset (*top*) is the structure domain representing the elastic tissue of the aneurysm wall. Shown in the inset (*bottom*) is the local stress field in the aneurysm wall due to interactions with recirculating blood flow.

## 2 FSI SIMULATION MODELING

Here, we follow a partitioned strategy in which the FSI solver is based on coupling the open source parallel codes NekTar [5] and StressNekTar [2, 9]. The main challenge here is to tackle cases where the fluid and structure densities are close and convergence of the coupled solver becomes problematic due to the so-called added mass effect [10].

The fluid domain governed by the Navier-Stokes equations is assumed to be incompressible and Newtonian. The response of the solid domain is described by the elastodynamics equations [1]. To account for moving boundaries we employ the Arbitrary Lagrangian-Eulerian framework (ALE). The strong coupling of the two models is achieved by using a sub-iterative approach with convergence accelerated by Aitken relaxation [1]. Finally, the formulation is closed by appropriate boundary, initial and fluid-solid interface coupling conditions [1, 10].

Both domains are discretized in space using the spectral/*hp* element method (SEM) [5], according to which, the computational domain is decomposed into a set of polymorphic non-overlapping elements. Within each element, the solution is approximated as a linear combination of hierarchical, mixed-order, semi-orthogonal Jacobi polynomial expansions. This hierarchical structure consists of separated vertex (linear term), edge, face and interior (or bubble) modes. The solution computed by NekTar is saved in modal space. The polynomial expansion representing the solution in each spectral element is exploited by the visualization software to obtain the solution (or derived quantities) on a given number of points (vertices) within each spectral element.

## 3 PARAVIEW - NEKTAR INTERFACE

Leveraging ParaView's plug-in interface, and building on previous work reported in [4], we enable the visualization of fluid-structure interaction data with high-order spectral accuracy.

NekTar's geometry and solution data are stored separately in *mesh* and *solution* files, respectively. The *mesh* file contains the initial coordinates of elements on the continuum mesh, the connectivity of the elements, boundary condition information, as well as information on the curved boundaries. The *solution* files contain the calculated values, which can be used both for restart and also for data analysis. The size of the *mesh* and *solution* files depends on the number of elements in the mesh, spectral resolution and number of field variables considered in the computation, i.e., fluid velocity, pressure, mesh displacement, etc. There is a separate *mesh* and set of *solution* files for each fluid and solid portion of the domain.

### 3.1 Plugin Overview

Processing of NekTar's data is accomplished in two steps. In the *first step* the *mesh* data (a connected list of polymorphic elements) is read and the computational domain is partitioned across processes using METIS [8].

The plugin analyzes the *solution* file to see what field variables are included in the data and populates the ParaView GUI based on this information. Along with the variables present in the *solution* file, interfaces for calculating derived fields (with high-order accuracy) from the stored variables are added. These will be specific interfaces for solid and fluid domains.

In the *second step* each process reads and stores the solution corresponding to the elements included in its partition. The modal values of the solution are cached in memory, and are used to transform the solution from modal to physical space. These two steps are applied to process the data for each domain. The second step is repeated for each time step. The task of loading field variables, transforming the solution from modal to physical space, computing derived properties and interpolating data on vertices of linear elements representing the visualization mesh is performed independently in each partition. Processing of NekTar's data is performed with the custom reader using the functionality provided by the NekTar library. Finally, the data is passed on to the ParaView pipeline where all of the standard visualization algorithms can be applied to it.

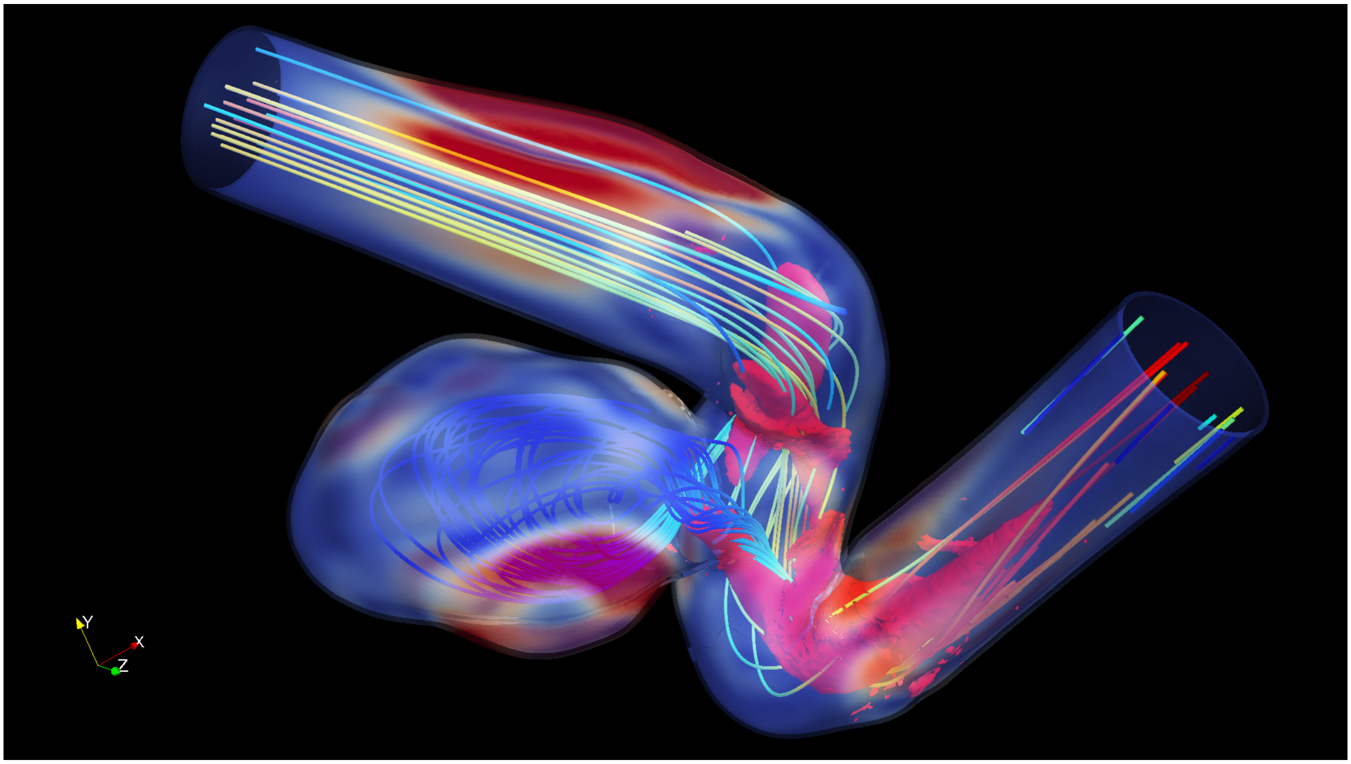


Figure 2: Blood flow in a compliant cerebral aneurysm containing blood flow streamlines (colored by fluid velocity magnitude), blood vortex structures (colored by pressure), and stress magnitude in the flexible arterial wall.

### 3.2 Processing high-order spectral element data from NekTar

In computing derived quantities it is important to take into account that high spatial resolution achieved by P-refinement (i.e. using higher polynomial order) allows for the use of relatively large elements, thus using high-order operators for computing derived quantities is more appropriate.

The data computed by NekTar are processed with high-order spectral accuracy, i.e., the interpolation, integration and differentiation are performed on the quadrature grid consistent with the simulation resolution. The plugin uses NekTar methods for calculating vorticity and Lambda2 for the fluid mesh, and to extract the boundary surface from the mesh and calculate the wall shear stress (WSS). For solid mesh solutions that contain the solid mesh displacement, the stress tensor can also be calculated.

### 3.3 Visualizing Fluid-Structure Interactions

The FSI calculations we consider here include deformation of the elements of the mesh over time. These are stored in the *solution* files as displacement values for each coordinate of the mesh. For each time step the mesh displacement values from the *solution* file are used to update the coordinates of the continuum mesh. The coordinates are then interpolated onto the requested element resolution and used to update the data passed to ParaView. The results of this process can be seen in Figure 3. Tile A) shows the original mesh while B) shows the same structure with the deformation applied. In tile C) we display both the original mesh in white together with the deformed mesh in gold to highlight the differences. In cases where the displacements are small the differences can be accentuated by applying a scaling factor. This is illustrated in tile D) of Figure 3, where the deformation is exaggerated to illustrate the effects of the fluid on the structure.

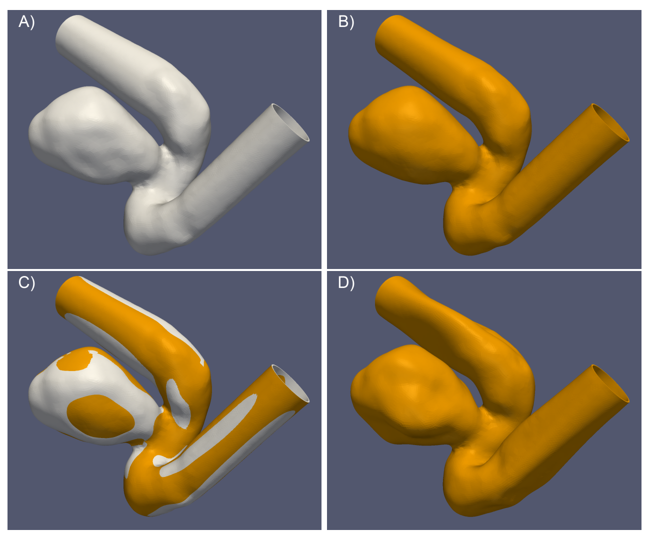


Figure 3: Illustrations of the application of mesh displacement. A) shows the original mesh. B) shows the deformed mesh due to fluid flow. C) shows both meshes together to highlight their differences. In tile D) the values of the displacement have been scaled to accentuate the effect.

## 4 Aneurysm Case Study

We present here visualization results for fluid-structure interactions in the patient-specific aneurysm introduced earlier. The data output of the coupled NekTar solver comprises of the corresponding solution fields for the fluid and structure domains. We employed $2^{nd}$ order accurate time integration schemes and $3^{rd}$ order polynomial expansions, resulting to about 30 million degrees of freedom. The simulation output consists of thousands of files with approximately 100Gb of data, while the computation of two cardiac cycles took about 24hrs on 1,024 cores of a Cray XK7. This is a mid-sized, yet state-of-the-art FSI problem, with larger more complex simulations planned for the future.

The results loaded into ParaView contain the fluid velocity and pressure, as well as the mesh displacement, velocity and acceleration in each of the domains. Using the ParaView-NekTar interface we compute the fluid vorticity, wall shear stress on the arterial wall boundary surface, and the full volume representation of the stress tensor in the arterial wall.

Visualization of the blood flow streamlines and vorticity isocontours can reveal the complex flow patterns in the aneurysm, while rendering the stress tensor on the arterial walls highlights the local stresses in the aneurysm due to the multi-physics, flow-structure interactions. Looping though animation frames offers invaluable information of the evolving dynamics in a global setting, such as tracing and tracking possible hydrodynamic instabilities, detecting oscillatory responses, and identifying the effective dimensionality of the system. Furthermore, in a local setting, visualization allows researchers to zoom in and extract high-resolution spatio-temporal analytics of the flow field and derived quantities that may be of vital importance to the medical practitioner. For instance, visual identification and monitoring of the location of maximum wall shear stress within the aneurysm sack during a full heartbeat could ultimately provide clearcut evidence towards the assessment of a potential treatment.

Although visualization offers a flexible platform for debugging, post-processing, and data analytics, its true power lies in the fact that it can often transform a perplexing simulation into a lucid story, accessible by a very broad audience. In the particular case of studying CAs, visualization can deliver content of both educational and practical value, with the audience ranging from aspiring biomedical engineers to seasoned neurosurgeons.

A manifestation of the capabilities and functionality of the ParaView-NekTar plugin is presented in Figure 2. The frame depicts the blood streamlines and vortical structures at the systolic peak of the cardiac cycle. The blood velocity streamlines are colored by the velocity magnitude and vorticity iso-surfaces are colored by pressure, the gradient of which is the driving force of the flow. Swirling flow inside the aneurysm sack induces deformation of the arterial wall due to mechanical stress. By rendering the derived stress tensor data we can provide a clear visual identification of the regions of high stress, hence the regions of susceptible rupture. The visualization clearly establishes the correlation between complex flow patterns and stress on the vascular wall and provides insight on this fundamental biomechanical interplay.

## 5 Discussion

Computational resources follow an ever-increasing path, while developments in sophisticated models and algorithms create new directions to elucidating the mechanisms that drive many physical and biological systems. This promising loop has been increasingly drawing the interest of scientists and engineers across a broad range of disciplines, leading to an unprecedented volume of simulation data output. Designing efficient, application-driven tools for accurately analyzing, visualizing and interacting with these complex datasets is of crucial importance for gaining a better understanding of the underlying processes [6, 3].

We presented visualization results using a new NekTar reader plug-in designed to process and visualize fluid-structure interaction data computed by a coupled high-order spectral/*hp* element solver. The software was used to study the interaction between unsteady blood flow and the resulting stresses in the elastic tissue of a brain aneurysm, revealing the intricate interactions within this pathology.


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