Optimization of Flow Diverter Treatment for a Patient-specific Giant Aneurysm Using STAR-CCM+

László Daróczy, Philipp Berg, Gábor Janiga
Introduction

• Definition of aneurysm: „permanent and locally limited dilatation of the arterial vessel wall layers“

• Places of occurrence: cerebral/abdominal

• Aneurysm types: fusiform/saccular

• 1 in 50 people have an unruptured brain aneurysm

• Rupture of brain aneurysms is in 40% lethal, 66% of the survivors suffer from permanent neurological deficit

• There are almost 500,000 deaths worldwide each year caused by brain aneurysms (~1/minute)

¹Brain Aneurysm Foundation (http://www.bafound.org)
Aneurysm treatment

- Clipping
  - Open skull surgery
  - Small metallic clip is placed along the neck of the aneurysm
  - Skull bone will heal in 6-12 months

- Coiling
  - Less invasive, performed with a catheter
  - Platinum coils are placed in the aneurysm and detached through electrical current

- Stenting
  - Less invasive, performed with a catheter
  - High density -> flow diverter stent

1Brain Aneurysm Foundation (http://www.bafound.org)
Optimization process

- Completely automatic stent treatment is not (yet) possible
  - Location of stent deployment is decided on a case by case basis by a medical expert
  - Quality of acquired images of the vessel geometry can be very different (post-processing and user expertise is needed)
  - Many different factors contribute to the efficacy of the treatment -> expertise is needed
- How is a fast & efficient patient specific treatment possible?

  → Expert-driven Computer Aided Stent Evaluation (ECASE)

  - Important medical decisions (location of stent deployment, type of stent) are made by a medical expert
  - All other operations (mesh generation, CFD simulation, evaluation) are performed by the computer automatically
  - If needed, the expert (CFD/medical) can have an influence on the process
  - An optimization software tries to find the most efficient solution with the given freedom
Optimization process

- 3D blood vessel reconstruction
- Virtual stent implantation
- Detailed blood flow simulation
- Automatic evaluation

Drastic speed-up

Patient specific treatment
Optimization - Step 1

- Preparation of the geometry
  - image acquisition (angiography, e.g. Siemens Healthcare GmbH)
  - segmentation (e.g., MeVis Medical Solutions AG, Bremen, Germany)
  - preparation of vessel surface (e.g., VMTK)
- Virtual stent deployment based on
  - Finite Element Model, e.g.¹
  - Geometrical considerations, e.g., ²

Optimization - Step 2

- (Automatic) Mesh generation with STAR-CCM+
  - Surface Wrapper enables extraction of volume between vessel & stent surfaces without the need to create volume models in CAD
  - Polyhedral mesh enables automatic generation with STAR-CCM+
  - How to determine mesh size automatically?

- Script-in-Script (SiS) approach
  - Intelligent JAVA script tries to perform mesh generation, where necessary, asks the expert
  - The script remembers the decisions
  - In the upcoming executions no user intervention is necessary
  - Throughout the optimization the recorded values are slightly varied for each case to test multiple meshes -> mesh quality optimization
Optimization - Step 3

- Setup & computation is carried out by a JAVA script with STAR-CCM+
  - Many different options are available based on available time & information
    - Steady/Transient
    - Newtonian/Non-newtonian
    - Laminar/Turbulent/Transitional
    - Rigid walls/Flexible walls

- Post-processing
  - Reports & figures are prepared either with STAR-CCM+ or Ensight
  - Results are not always clear to be interpreted
    - What is optimal mass flow into the aneurysm?
    - Is Wall Shear Stress dominant?
    - What is the maximal velocity in the aneurysm?
Optimization - Workflow

Angiography → 3D vessel reconstruction → choosing parameters: stent deployment → choosing parameters: mesh and CFD

- segmented image
- STL file
- parameter space
- mesh setup

- stent deployment
- mesh setup/optimization
- CFD
- Post-processing

- Optimization software
  - node1
  - node2
  - nodeN

- Database

- Evaluation

**Benefits**
- More designs are tested
- Necessary human resources do not increase

**Optimization methods**
- Design-Of-Experiment
- Genetic optimization
- Uncertainty Quantification
- OPAL++
  - OPtimization Algorithm Library++
Case study

- 53 year old female patient was examined due to acute headache in the emergency department of the University Hospital Magdeburg.

- CT-angiography confirmed the presence of a giant aneurysm of the right internal carotid artery.

- Flow diverter (*Silk, Balt, France*) was implanted (3.5 x 30mm) to reduce blood flow into the sac.

- Patient complained of double vision following the treatment, but symptoms resolved in 4 weeks following a corticoid treatment.

- MRI performed 6 months later indicated complete resolution of the aneurysm.
Example 1

- Effect of compression was investigated
- Stent with 50 µm strut diameter was tested
- Following cases were analyzed
  - untreated (UN)
  - no compression (NC)
  - with 7 different compression locations (C1-7)
  - with high compression rate (HC)
- List of configurations was given to OPAL++
- Geometries were prepared using the batch mode of an in-house stent deployment software
- Mesh generation & steady-state laminar configurations were computed with STAR-CCM+

Example 1 - Results

- The optimization process was performed in parallel on a small Linux cluster (10 workstations)
  - The whole process did not require more than 4 days
- Results have indicated that the stent is able to efficiently reduce the mass flow into the aneurysm sac
- Different locations of the compression had a large influence on the mass flow
  - Optimal placement was not in the middle!
- Wall shear stress, streamlines, velocities & mass flow rates were analyzed for each case automatically with STAR-CCM+
isosurface (0.04 m/s)  NC  isosurface (0.04 m/s)  C1  isosurface (0.04 m/s)  C2
isosurface (0.04 m/s)  C3  isosurface (0.04 m/s)  C4  isosurface (0.04 m/s)  C5
isosurface (0.04 m/s)  C6  isosurface (0.04 m/s)  C7  isosurface (0.04 m/s)  HC
Example 2

- Effect of stent geometry was analyzed
- Stent with 30 µm strut diameter was tested
- Following variations were performed
  - 20×2, 24×2 and 28×2 struts were simulated
  - Interwire distance was varied (14 and 19.2 mm/wires)
- List of configurations was given to OPAL++
- Geometries were prepared using the batch mode of an in-house stent deployment software (previously shown)
- Mesh generation & steady-state laminar configurations were computed with STAR-CCM+
- Mesh optimization was not performed for the present test case
Example 2 - Results

- The optimization process was performed in parallel on a small Linux cluster (8 workstations)
  - The whole process did not require more than 48 hours
- Results have indicated, that the stent is able to efficiently reduce the mass flow into the aneurysm sac
- Different geometries resulted in very different results
- Wall shear stress, streamlines & velocities were analyzed for each case automatically with STAR-CCM+
Future improvements

- The optimization was performed as a proof-of-concept with steady, laminar CFD simulations using Newtonian fluid and rigid walls

  - Pulsatile, transient flow simulations could be performed (very easy to implement, only longer computational time)

  - Non-Newtonian model could be adapted

  - Rigid bodies could be replaced with flexible walls (medical imaging should deliver information on wall properties!)

  - Uncertainties could be analyzed (UQ - Uncertainty Quantification)
Summary

• An automatic workflow for optimization of flow diverter geometries was presented.

• The method expects as input the geometry of the vessel (STL) and the design space (parameter space for optimization).
  
  • Virtual stent deployment is **automatically** performed using an in-house code.

  • Calibration of the mesh setup is performed by recording the choices made by the expert for a sample case (**Script-in-Script**).

  • Mesh generation is performed with the help of **Surface Wrapper** & **Polyhedral Mesher** automatically with an intelligent JAVA script in **STAR-CCM+**.

  • Configurations are automatically computed in parallel on a Linux cluster with **STAR-CCM+**.

  • The whole optimization process is controlled by an in-house optimization software (**OPAL++**).

• The efficacy of the method was presented for **two sample cases**.
Thank you for your attention!