Scalable simulations of hemodynamics in intracranial aneurysms

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Intracranial Aneurysm

- Localized dilation of blood vessel
- Rupture (SAH) can be lethal
- Risk Factors:
  - Smoking, Narcotics like Cocaine
  - Family History, High Blood Pressure
- Symptoms:
  - Localized Headache
  - Dilated Pupils
  - Pain above and behind eye
- Statistics:
  - Suffering: 1 in 50 people
  - Ruptures: 8-10 per 100,000 who suffer
- Treatment Options:
  - Surgical Clipping
  - Endovascular Coiling
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- Intracranial stenting:
  - Flow diversion to increase clotting
  - Optimal control of flow by stent configuration

Scalable simulations of hemodynamics in intracranial aneurysms
Outline

• The APES Simulation Framework
• Scaling on SuperMUC
• Simulation Results
• Conclusions and on-going research
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The APES Simulation Framework

- End-to-end parallel simulations
- Mesh generator, flow solvers, post processor
- Flexible, Scriptable, Portable
- Efficient Parallel I/O
- Flow solvers:
  - DG solver for Conservation equations: Ateles
  - LBM Solver: Musubi

https://bitbucket.org/apesteam/musubi
The APES Simulation Framework

• Musubi:
  • Lattice Boltzmann Solver
  • Highly suitable for flow in aneurysms
  • Multispecies flow
  • Passive scalar transport
  • Complex boundaries
  • Local grid refinement
  • Open Source:
    
    https://bitbucket.org/apesteam/musubi

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Musubi on SuperMUC: Performance Map

Figure 1: Performance map of Musubi on SuperMUC on up to 4 islands.

- The parallel efficiency is represented in reference to a single node with 16 processes. The efficiency on 4 islands is above 90% in this scenario. Interestingly, the major drop in performance happens on a full island (512 nodes) while the run on multiple islands maintains the same efficiency as a single island.

Figure 3 shows the strong scaling behavior of Musubi with the parallel efficiency over the number of nodes. This scaling uses the performance on 16 nodes as reference, as this is the smallest partition on which this large test case was computed. The increased efficiency is due to the caching effects that are also nicely seen in the performance map of Figure 1.

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Musubi on SuperMUC: Weak Scaling (~2M cells/node)

![Graph of parallel efficiency vs number of nodes](image)

**Figure 2:** Weak scaling of Musubi with 2097152 elements per node on up to 4 islands of SuperMUC.

**Figure 3:** Strong scaling of Musubi for 134217728 elements on up to 4 islands of SuperMUC.

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Musubi on SuperMUC: Strong Scaling (~134 M cells)

![Graph showing strong scaling of Musubi on SuperMUC](image)

- **Number of nodes:** 1, 8, 64, 512, 2048
- **Parallel efficiency:** 1.0, 0.8, 0.6, 0.4, 0.2
- **Elements per node:** $8^9$

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Aneurysm simulations

A patient specific aneurysm deployed with highly porous stent

A patient specific aneurysm deployed with less porous stent

Geometries provided by THROMBUS project partners

Scalable simulations of hemodynamics in intracranial aneurysms
Aneurysm simulations

Details:

• Non-uniform mesh of 15 and 7.5 µm with local refinement around stent

• ~ 500 million elements

• 4 cardiac cycles (4 seconds) are usually simulated on 16000 SuperMUC cores for flow quantification
The need for HPC

Resolving the thin wires of the stent:

Details:

- Non-uniform mesh of 15 and 7.5 µm with local refinement around stent
- ~ 500 million elements
- 4 cardiac cycles (4 seconds) are usually simulated on 16000 SuperMUC cores for flow quantification

Cross section of the stent which opens towards the aneurysmal sac
The need for HPC

Resolving the thin wires of the stent:

Details:

- Uniform mesh of 30 µm
- \( \sim \) 60 million elements
- 4 cardiac cycles (4 seconds) are usually simulated on 16000 SuperMUC cores for flow quantification

The coarse computational mesh on the top of stent

CFD: Computational Fluid Dynamics
Or
Confounding Factor Dissemination

American Journal of Neuroradiology
David F. Kallmes, MD
The need for HPC

Resolving the thin wires of the stent:

Details:

- Uniform mesh of 15 µm
- ~ 470 million elements
- 4 cardiac cycles (4 seconds) are usually simulated on 16000 SuperMUC cores for flow quantification

The fine computational mesh on the top of stent
The need for HPC

Resolving the thin wires of the stent:

Details:

• Non-uniform mesh of 15 and 7.5 µm with local refinement around stent
• ~500 million elements
• 4 cardiac cycles (4 seconds) are usually simulated on 16000 SuperMUC cores for flow quantification

The FINAL computational mesh on the top of stent
Flow profile inside aneurysm

Velocity streamlines in non-stented aneurysm at peak systole

Velocity streamlines in aneurysm with highly porous stent at peak systole

Velocity streamlines in aneurysm with less porous stent at peak systole
Flow profile inside aneurysm

- Aneurysmal flow reduction by stents:
  - 35% by highly porous stent
  - 50% by less porous stent
- Both stent causes some reflection in the parent artery
- Stent increases *residence time* of blood, which increases clotting

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Conclusions and on-going Research

- Present results elucidate grid requirements for simulations in stented aneurysms and quantify flow reduction to predict stent induced thrombosis.

- Improvements in the sustained simulation performance of APES.

- Dynamic Load Balancing for complex cases like local grid refinement.

- Quantification of high frequency flow fluctuations in bifurcation aneurysms:
  - *A space-time refinement study at extreme scale with up to 1 billion cells and 9 million time steps per second is under review.*

- Modeling of cyclic Cerebrospinal Fluid (CSF) and Chiari I malformation.
Conclusions and on-going Research

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Thank You Very Much for your Attention!

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