3D-real-time visualization of blood flow in cerebral aneurysms by light field particle image velocimetry

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Summary

Particle image velocimetry (PIV) of simulated blood flow within transparent 3D resin models of cerebral aneurysms allows 3D real-time measurement and visualization of the flow-dynamics with and without implants as a new pre-interventional opportunity for endovascular treatment. The purpose of the experiments is to demonstrate the feasibility of a fast and reliable set up for high resolution 3D-flow visualization of particles in small volumes by a monocular camera with micro lens array.

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- **3D:** multi- view stereo + epipolar geometry
- **Real-time visualization:** pulsatile flow 1.2Hz, 60-80 cm/s
- **Blood flow:** glycerin solution + polymer particles 50µm
- **Cerebral aneurysms:** pathologies of brain arteries: vessel size ∅ < 1mm
- **Light field:** plenoptic 2.0 /light field camera (MLA): ∞
- **Particle image velocimetry:** PIV = stereo camera and/or laser triangulation OR PLENOPTIC CAMERA**!**

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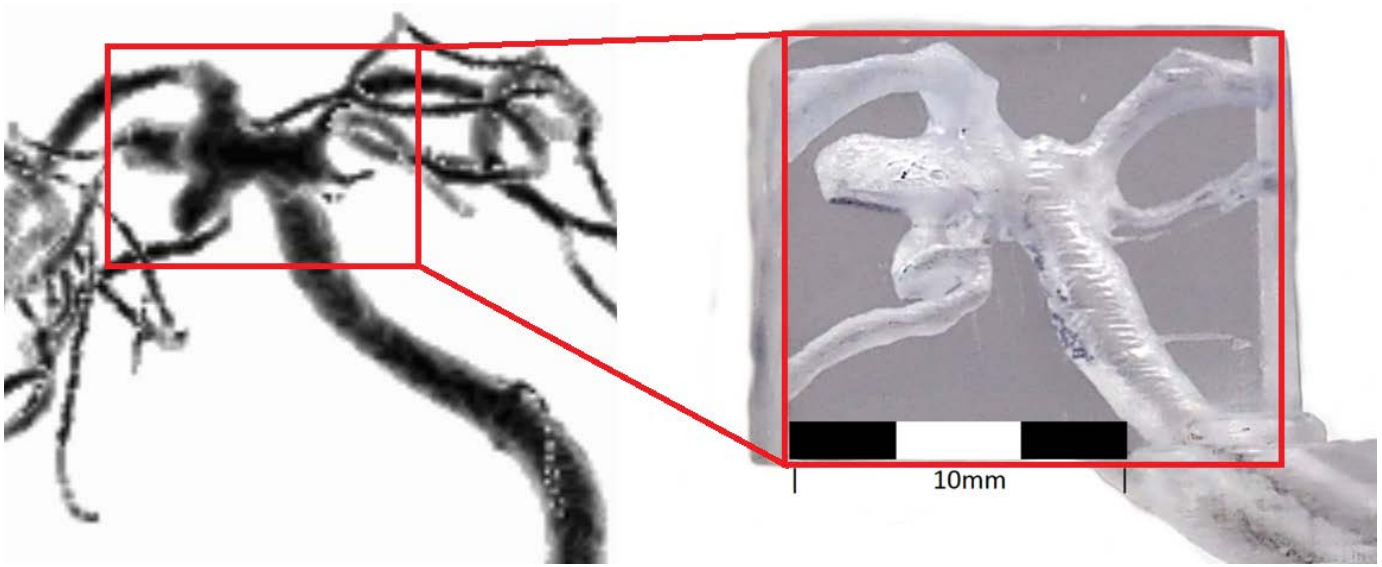
Cerebral aneurysms:

pathologies of brain arteries: vessel ∅ < 1mm



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Real-time visualization:

The concept of "real-time" may be classified into three different categories of conceptual interpretations:

- real-time in the perceptual sense,
- real-time in the software engineering sense and
- real-time in the signal processing sense!

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Real-time visualization:

real-time in the perceptual sense:

- interaction between human and machines
- instantaneous response of the computer to the operator input
- image processing results are available immediately after the input without a perceivable delay
  - applicable to the clinical time frame of patient hospitalization and planning of treatment for elective endovascular embolization of the aneurysm
  - including
    - rotational DSA,
    - image post-processing
    - generation of the 3D-printing data set
    - manufacture of the 3D-aneurysm model by SLA

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Real-time visualization:

real-time in the signal processing sense:

- termination of processing during the time period of subsequent sample values
  - samples of flowing particles
  - their timely detection
  - tracking in subsequently recorded images over time
  - but also across all spatial dimensions!
- flow speed and direction in all 3 space dimensions
  - multi-view stereo epipolar geometry: computing depth from several views
  - concatenation of vector elements
  - assembling a video showing the flow dynamics over time and space

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Blood flow:

- On a microscopic level the real-time constraints are determined by the speed of the blood-flow:
  - 80 to 100 cm/s in the in-going vessel
  - reduced from 60 to 80 cm/s
  - in the smallest vessels/aneurysm 40 cm/s are realistic estimations.

- human blood: highly complex fluid contains erythrocytes ∅ 6-8µm

- tracer particles: ∅ 50µm

- upcoming measurements: smaller but fluorescent particles ∅ 6µm

- >> similar to the real erythrocytes flow!

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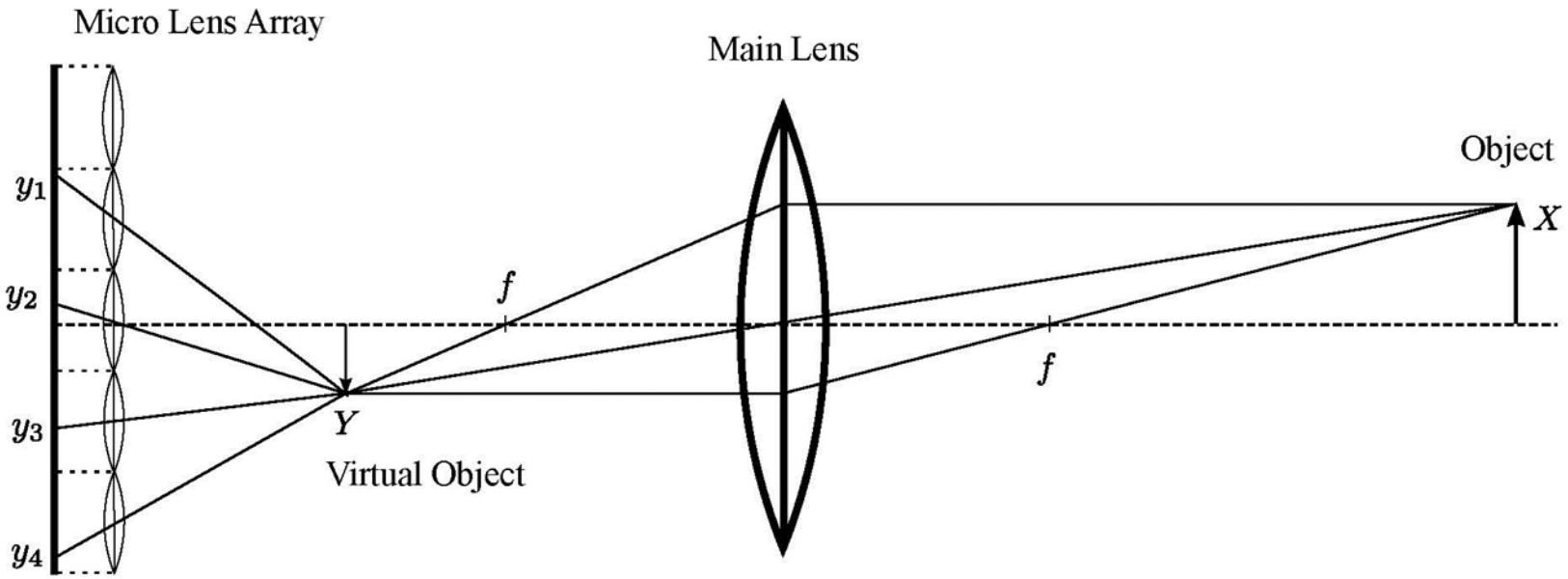
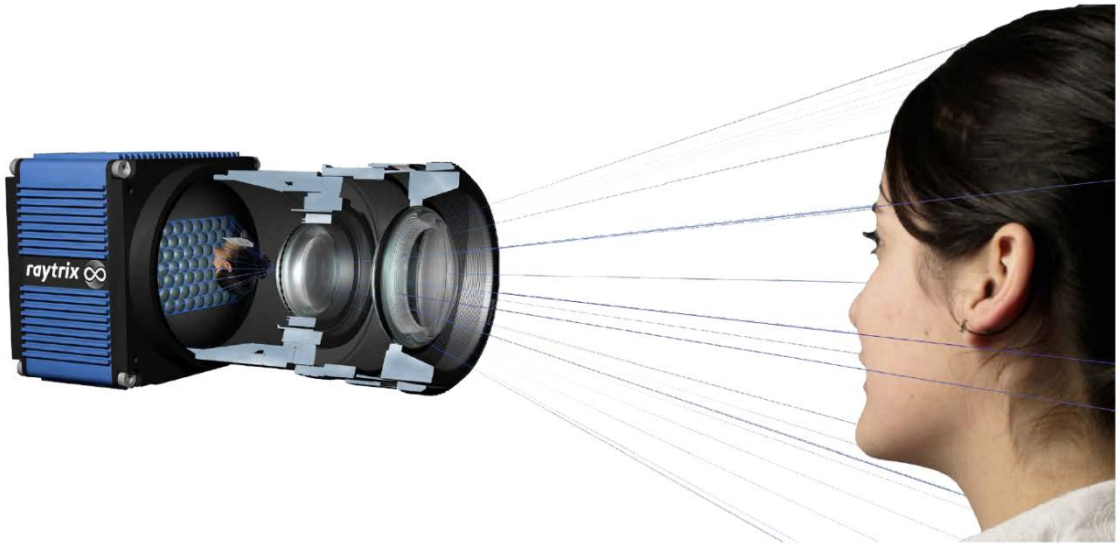
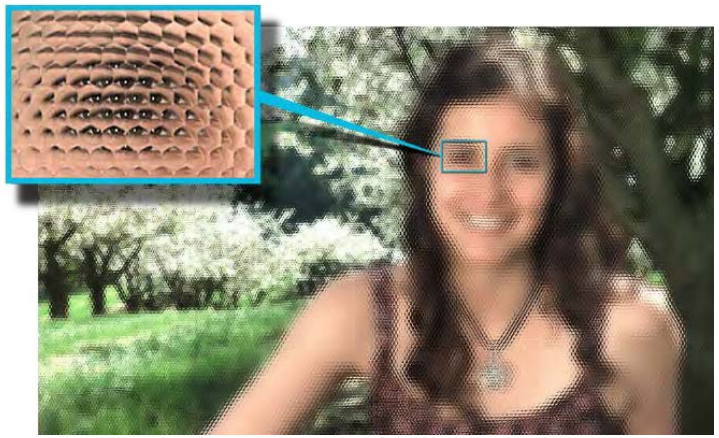
Lightfield Imaging: plenoptic principle

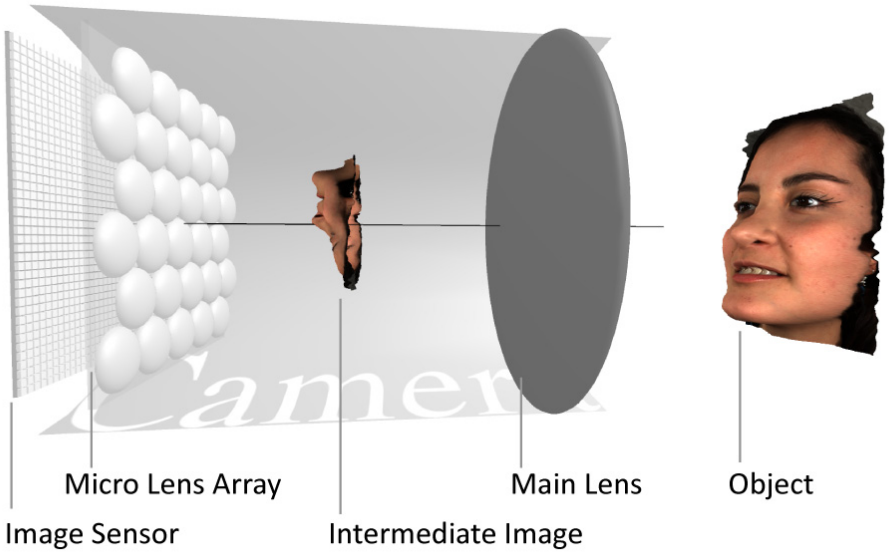


Light field camera with micro lense array

Light field Imaging: plenoptic principle







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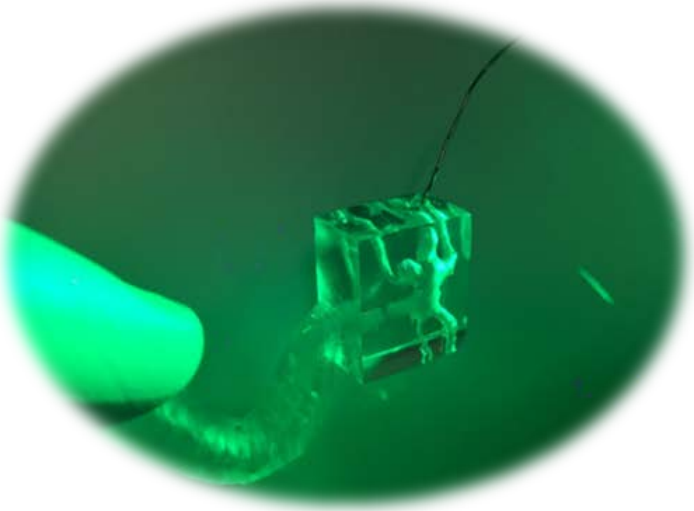
Light field Imaging: plenoptic principle



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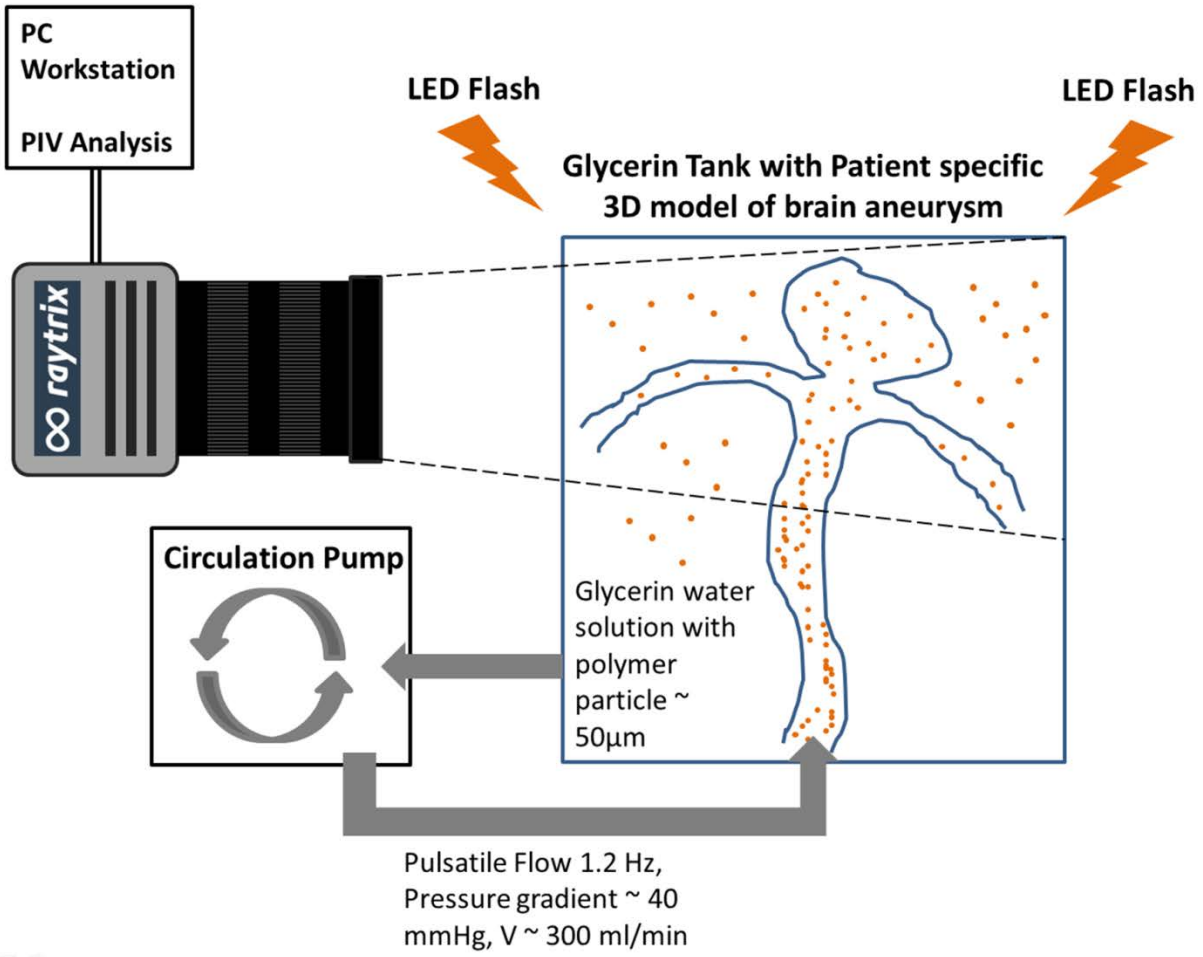
Experimental PIV Set-up:



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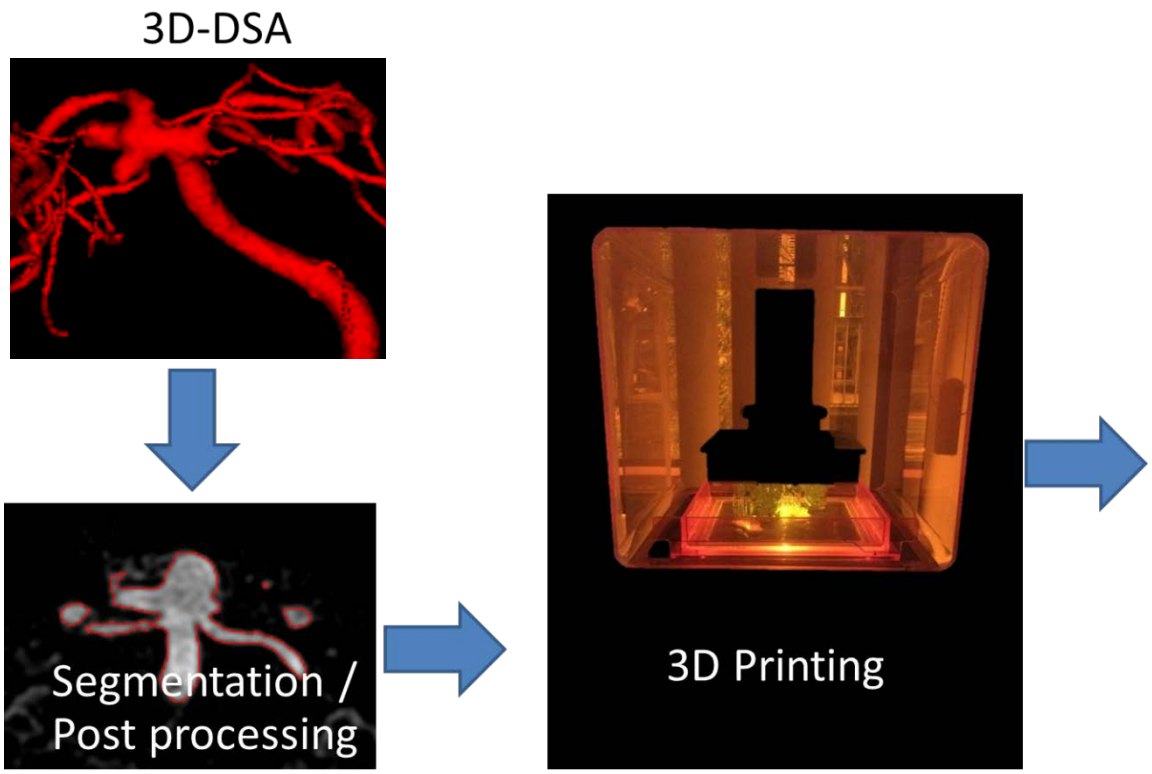
Workflow: from DSA to SLA printed resin models



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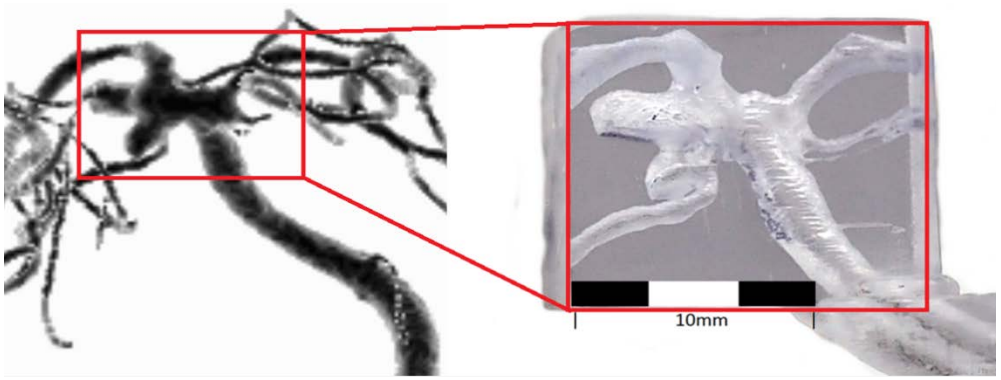
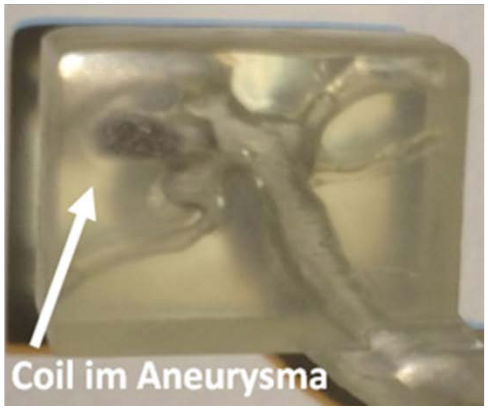
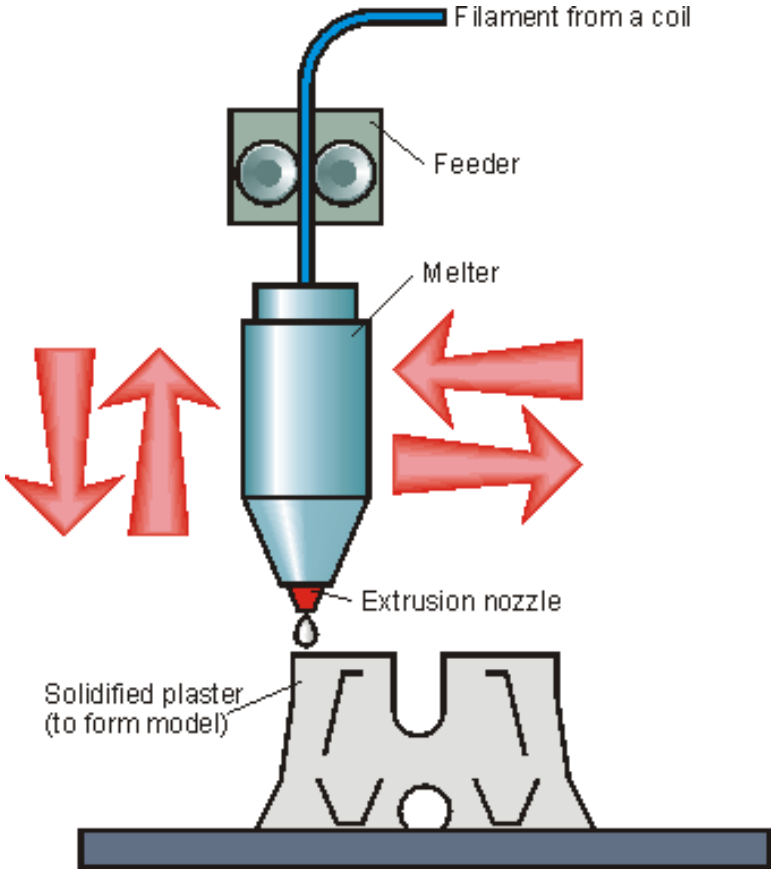
Workflow: from DSA to SLA printed resin models



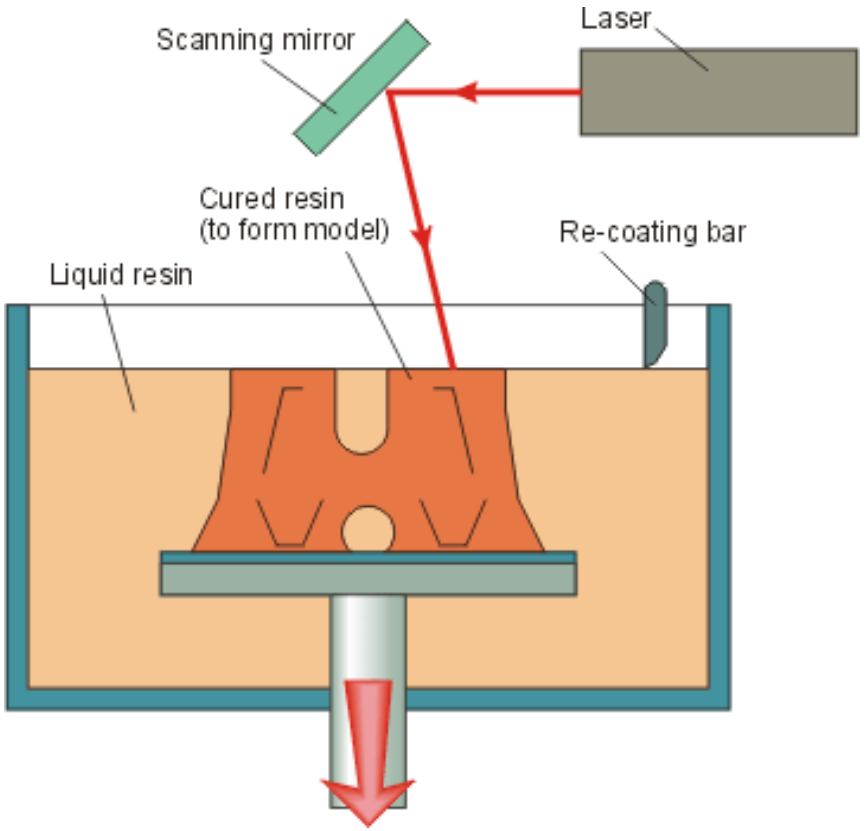


3D Printing techniques

Fused Deposition Modeling (FMD)



Stereolithography (SLA)



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Production

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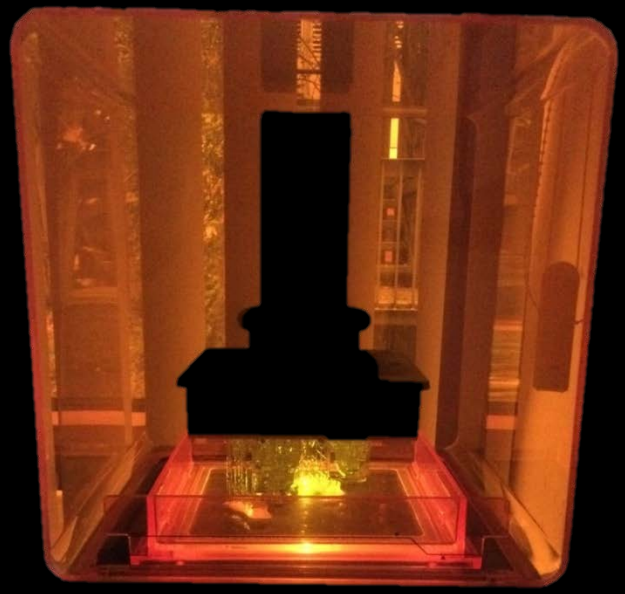

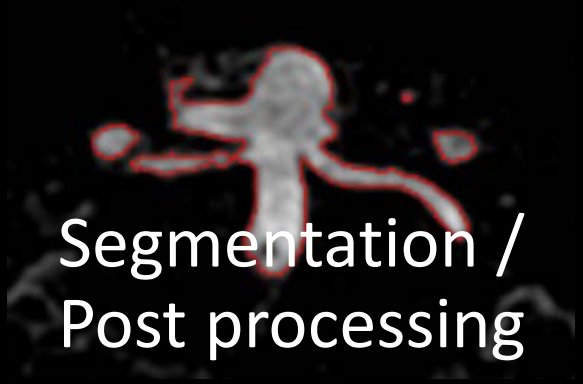

Segmentation /
Post processing

3D Printing

Production

post print preparation

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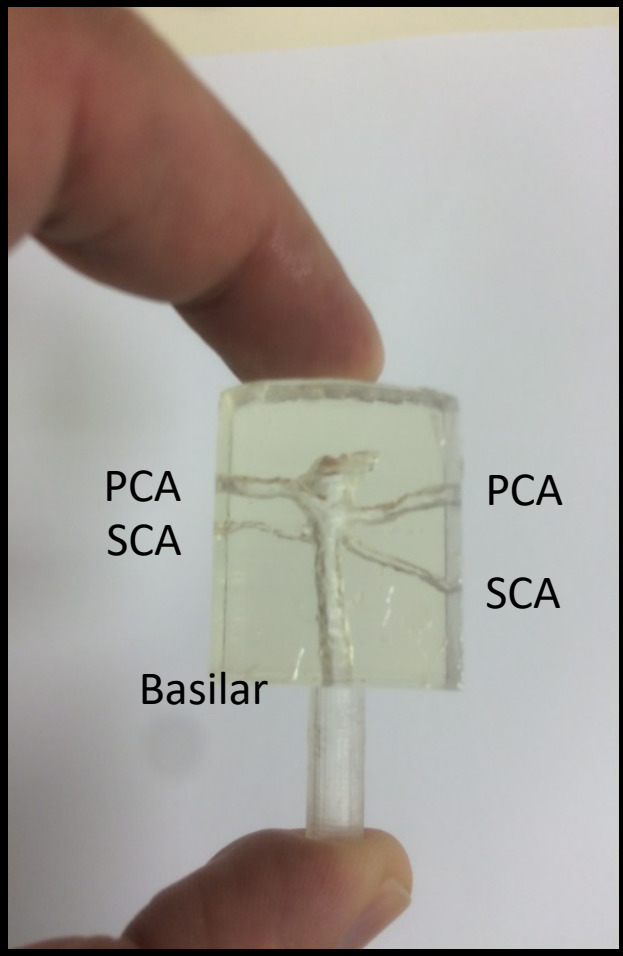
Production

post print preparation



Feasibility of production and precision of 3D Model

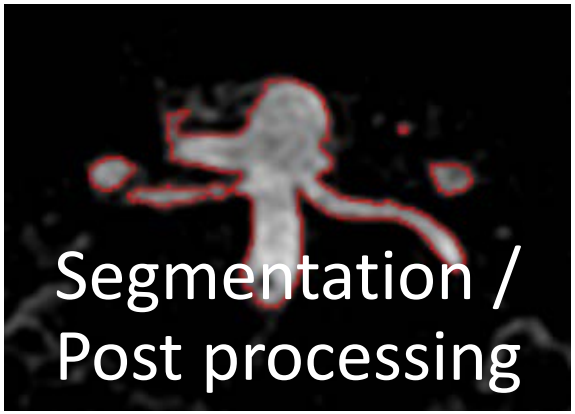
- 5x ACI
- 4x Mediatrifurkation
- 3x Basilariskopf
- 3x ACom

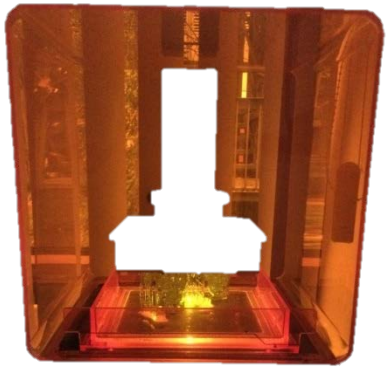
Feasibility of production

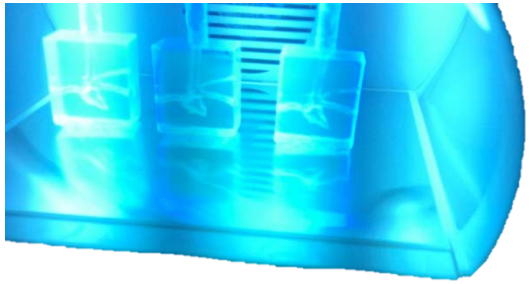
- technically feasible in 15 out of 15 cases

Image preparation
2-3h

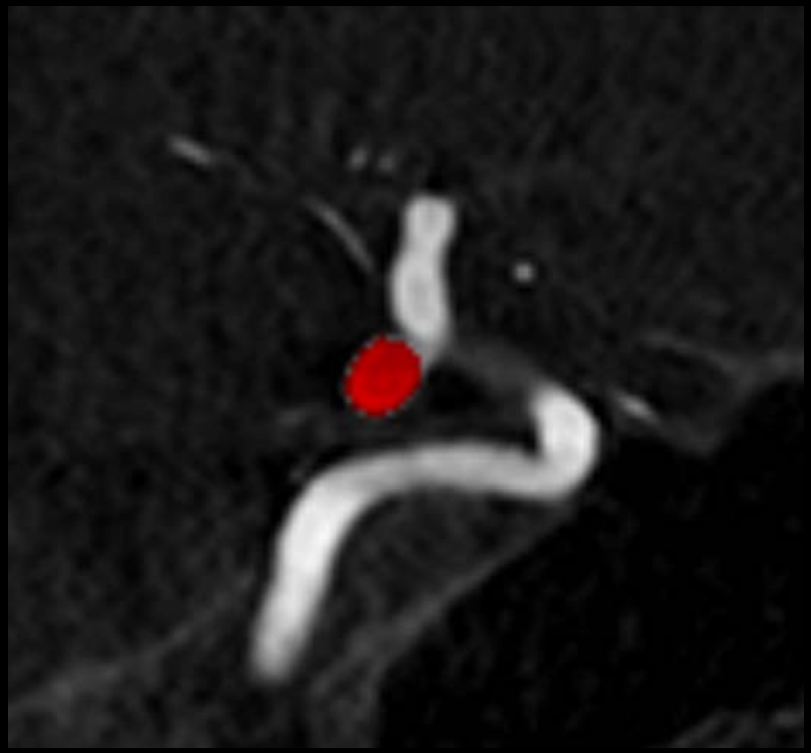
Printing time range 9-15 h



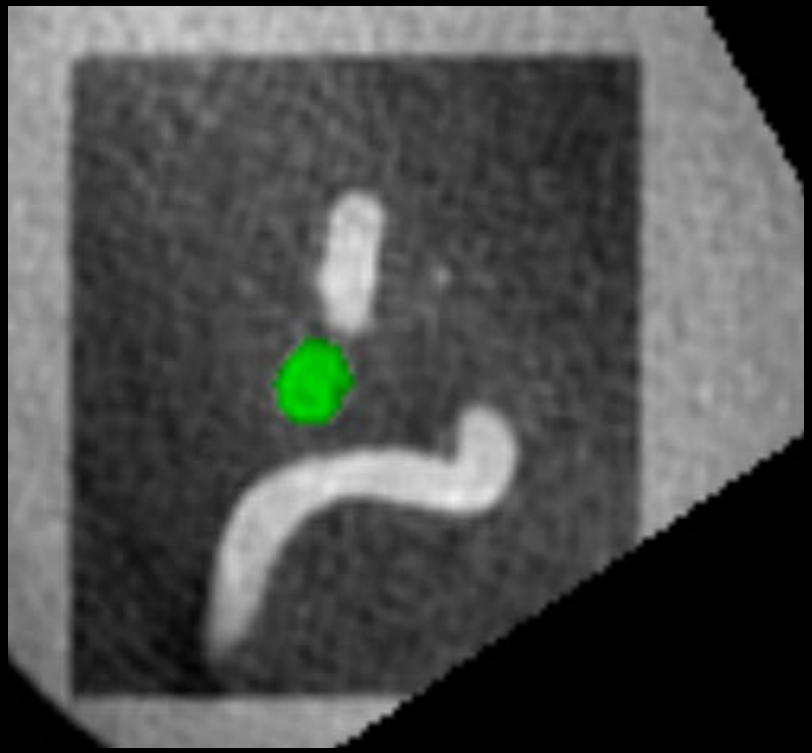




Precision of 3D Model



Original
Volume: 50.23 microliter



3D Model
Volume: 50.48 microliter

DICE Index: 98.1 %
Volume Difference: 0.4 %

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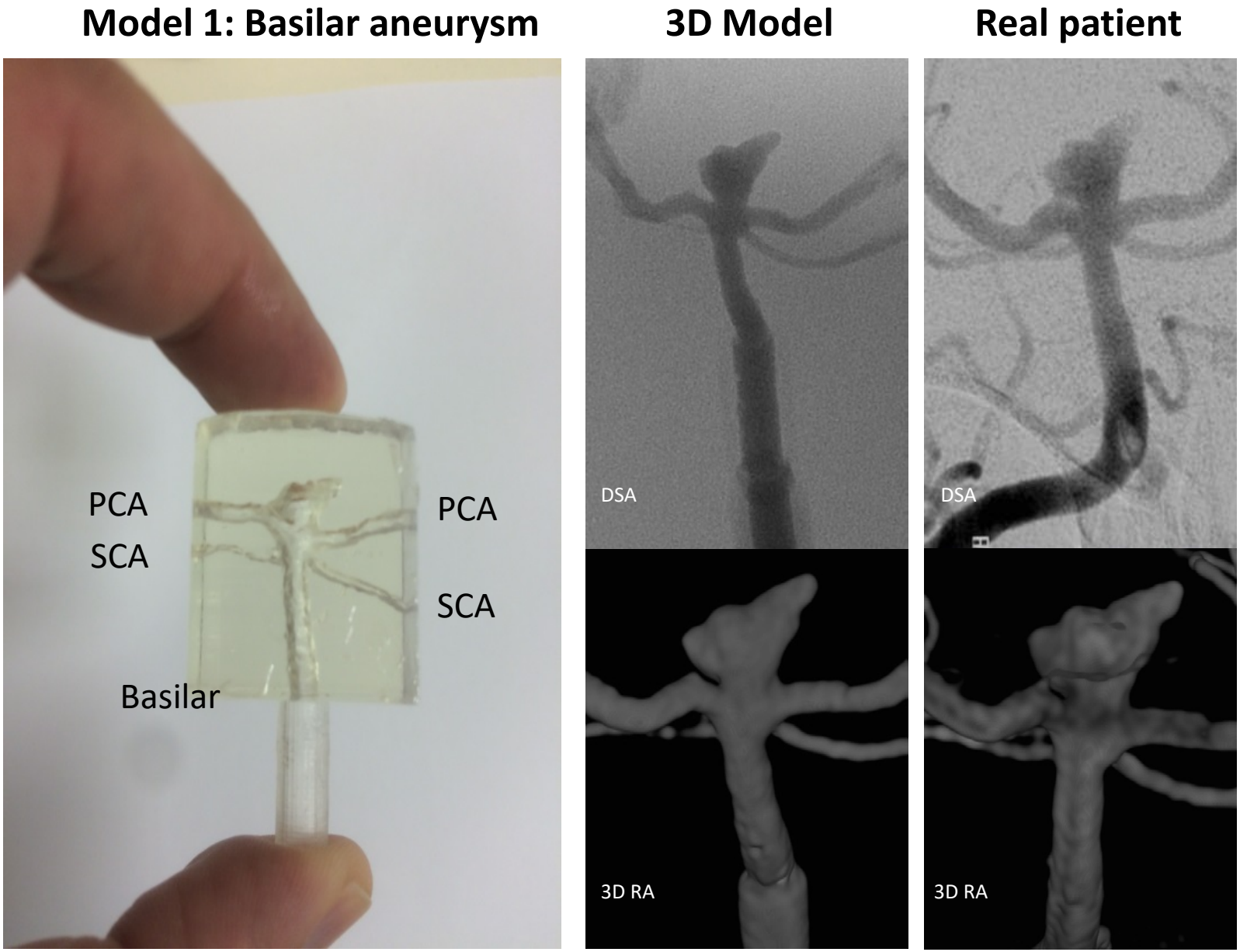

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Dual Mode Target Coil

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How can these printed parts revolutionize the traditional surgical methods?

In vitro device tests for treatment of complex aneurysms of brain arteries (endovascular coils, flow diverters, stents):

- Functional tests of new endovascular devices in high fidelity patient specific models of cerebral aneurysms
- Patient specific treatment planning and simulation: deployment of endovascular devices within anatomy of complex aneurysms
- Risk minimization by early anticipation of expected/foreseeable complications
- Device development: high resolution in vitro measurement of flow dynamics within different patient specific anatomies of aneurysms.
- Proposal to corresponding certification bodies (FDA etc.) as supplementary method for quality assurance and/or device/intervention documentation

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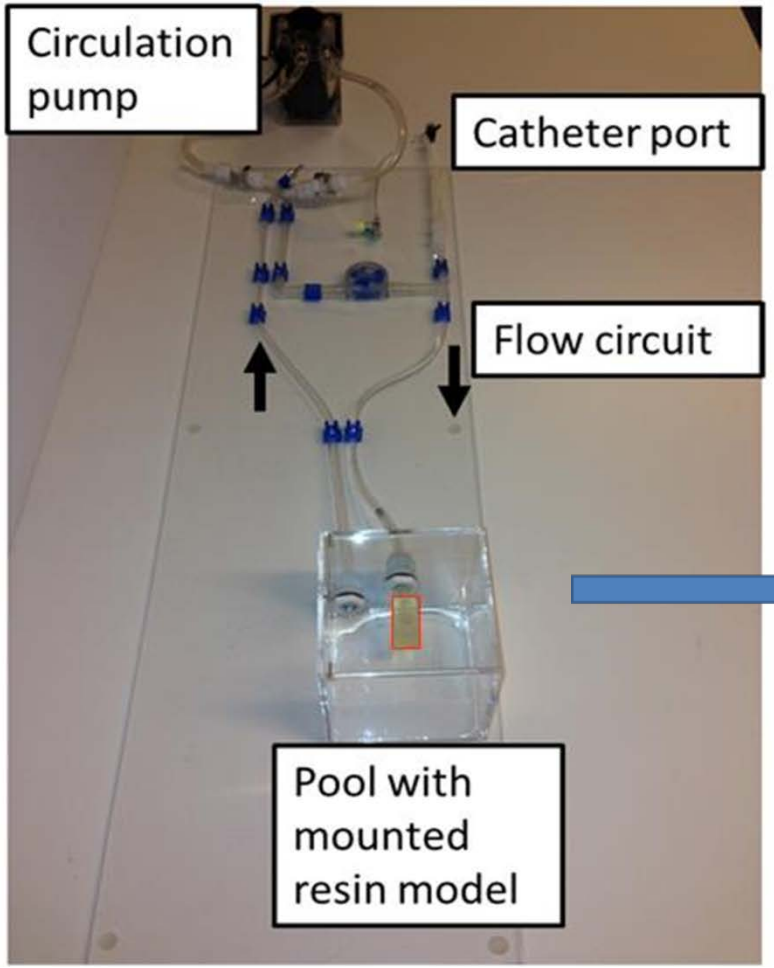

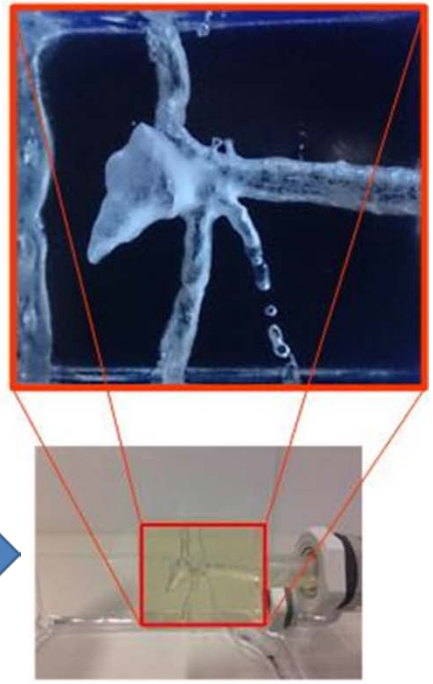

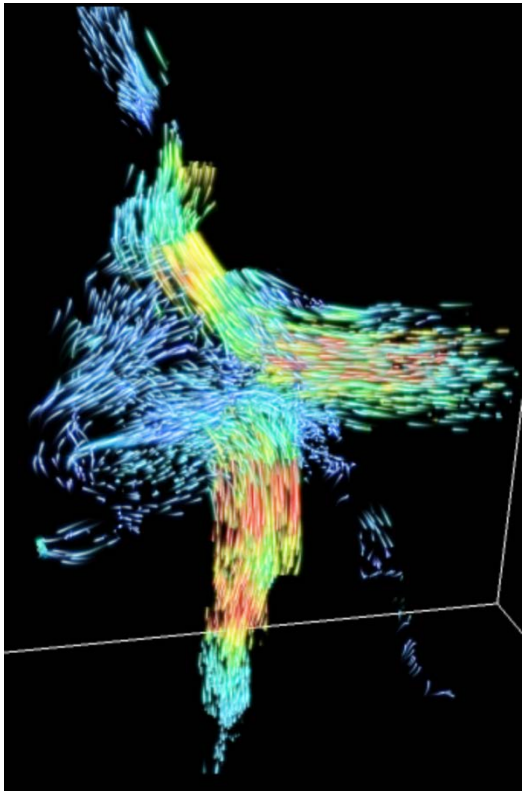

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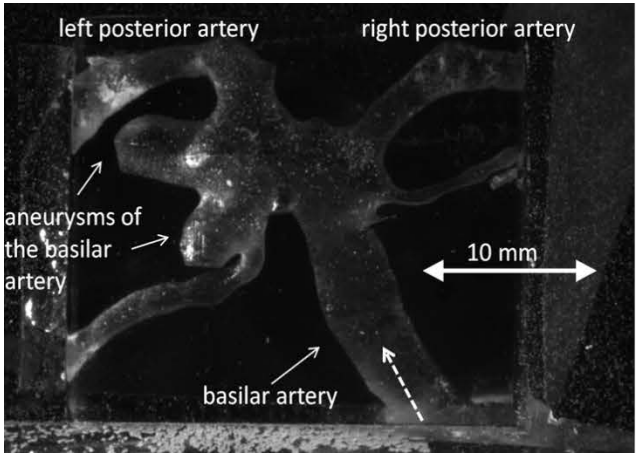
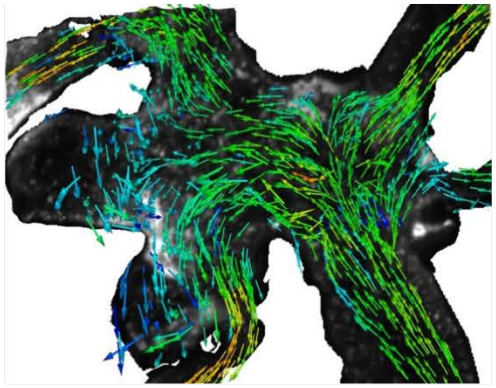
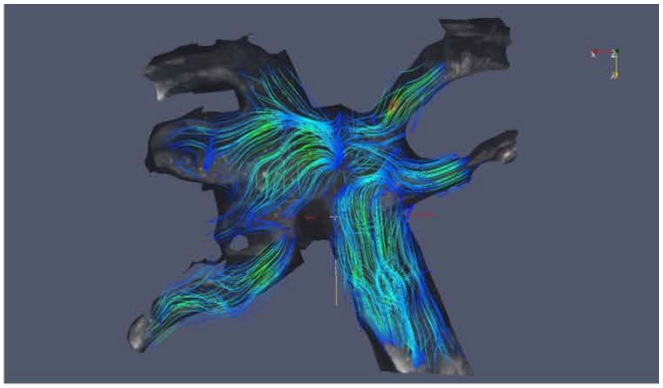
PIV Analysis of patient specific 3D models of brain aneurysms



Aneurysm model I: "all in focus"



Aneurysm model I: vector lines of flow and direction



Aneurysm model I: flow line representation

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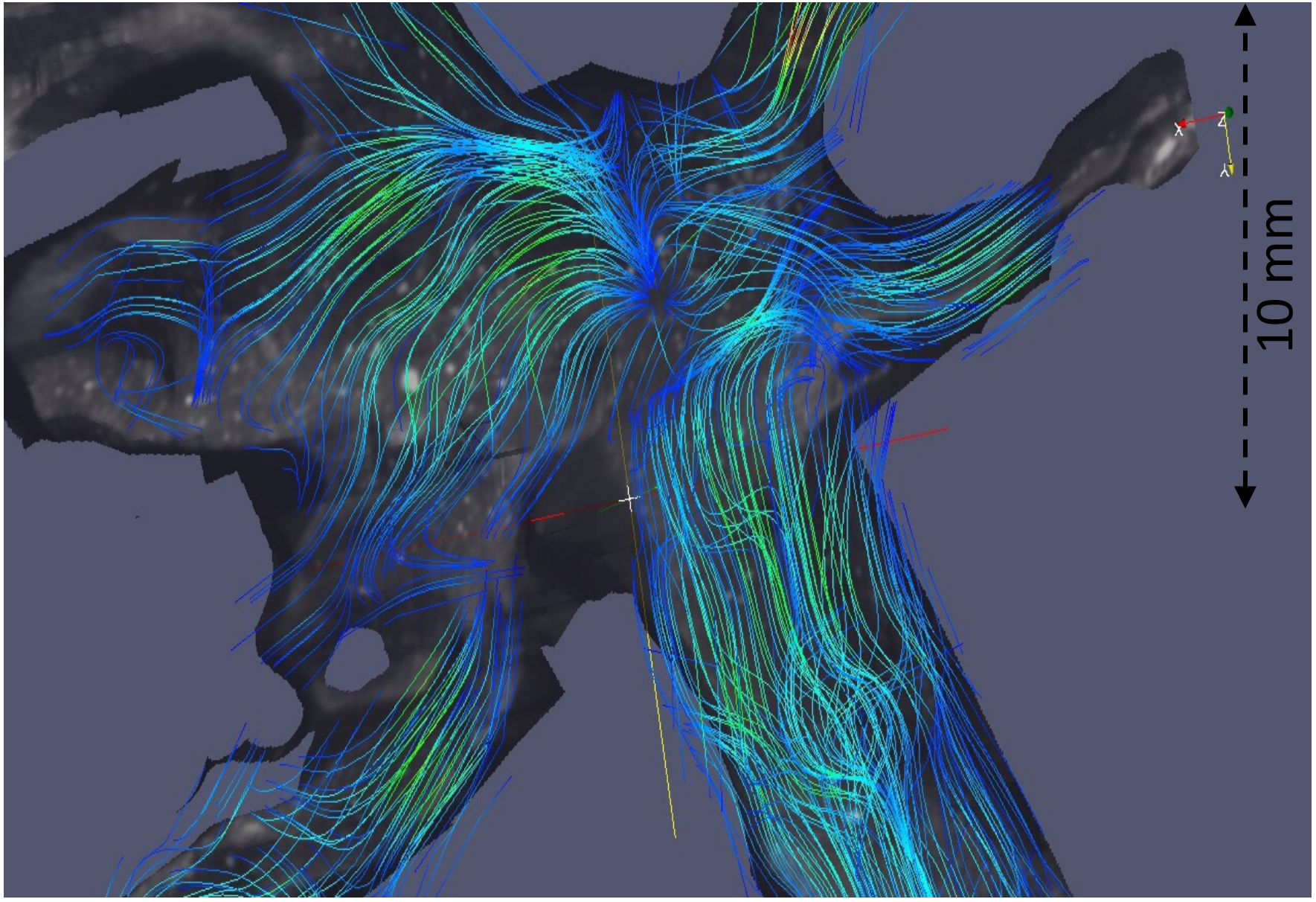
PIV in aneurysm models



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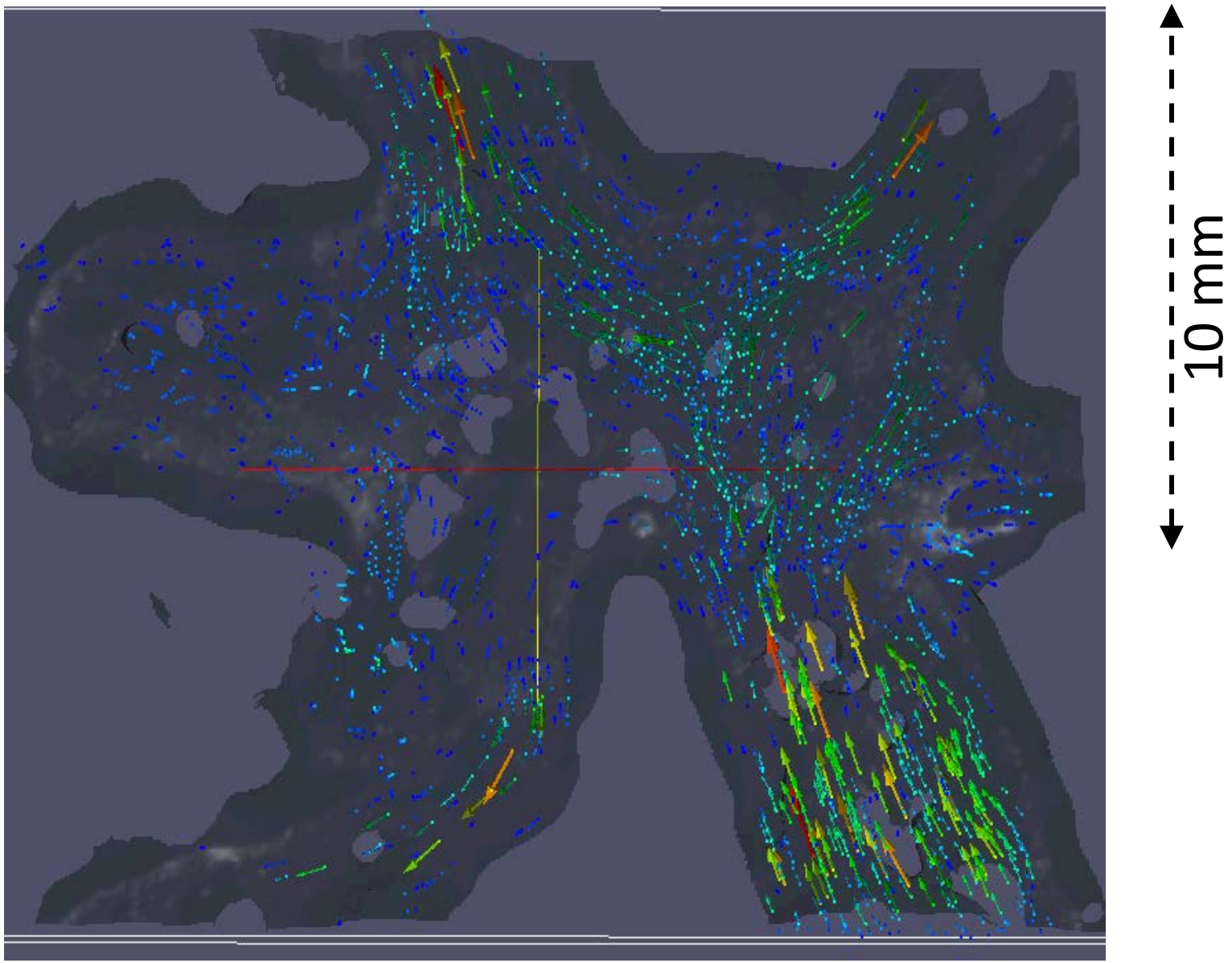
PIV in aneurysm models



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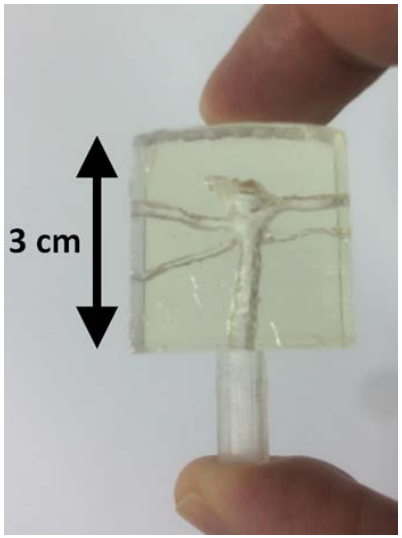
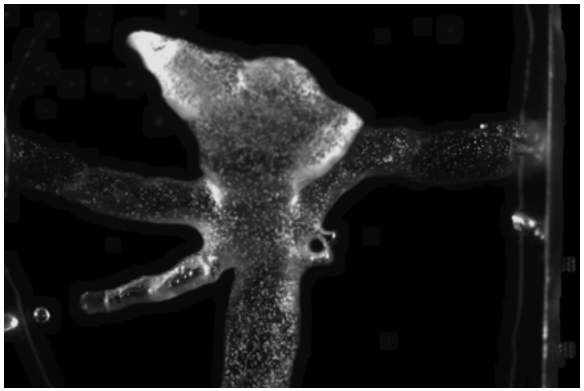
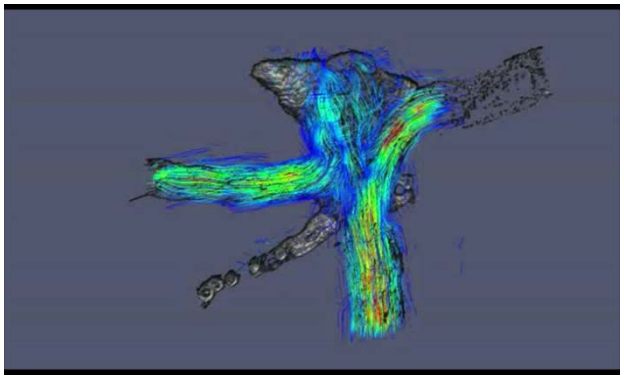
PIV Analysis of patient specific 3D models of brain aneurysms



Aneurysm replica resin model II



Aneurysm model II: “all in focus”



Aneurysm model II: flow line representation

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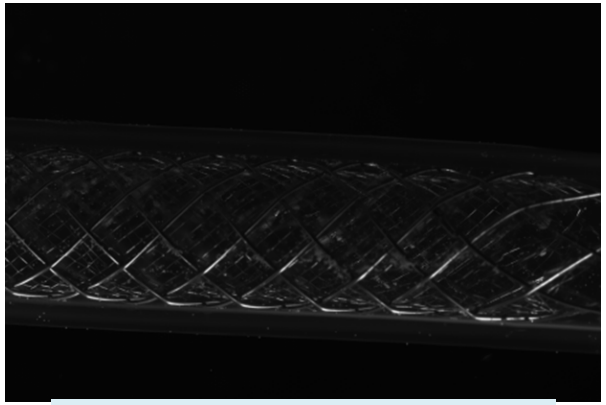
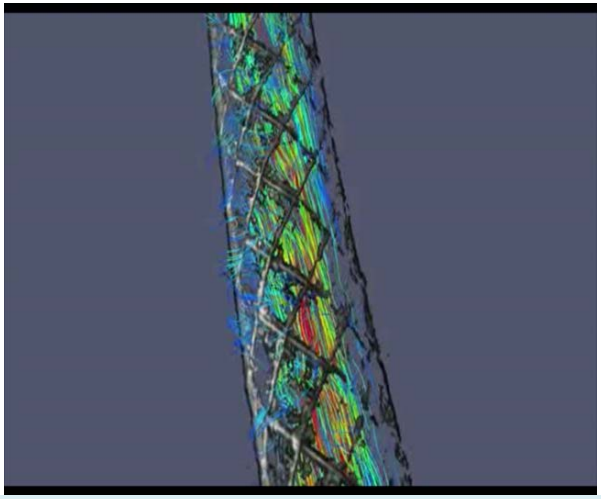
PIV Analysis of carotid stents

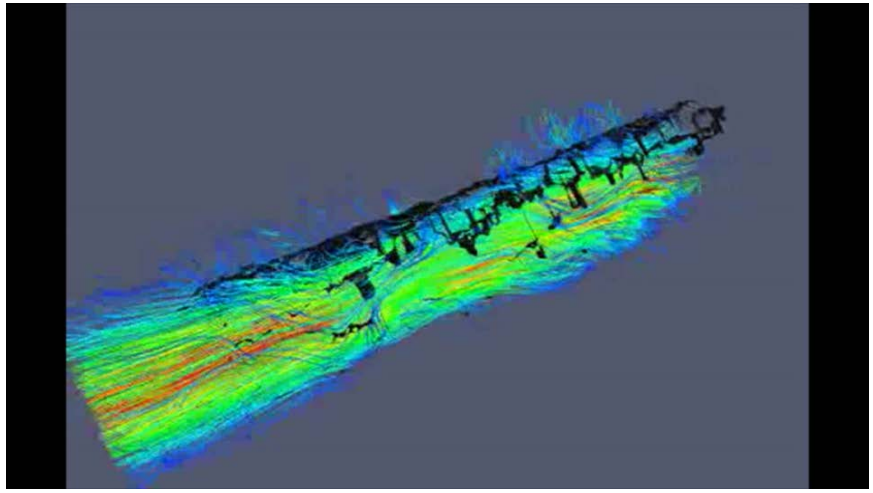


Stent “C”: “all in focus”

Stent “C”: flow speed and directions



Stent “C”: flow line representation



Stent “A”: flow line representation

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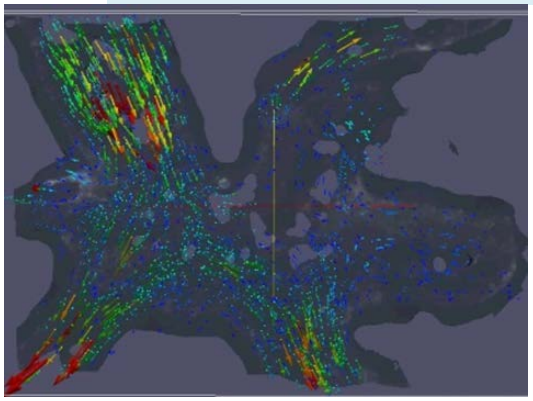
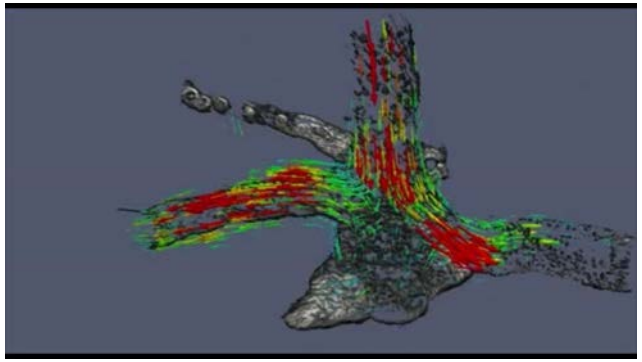
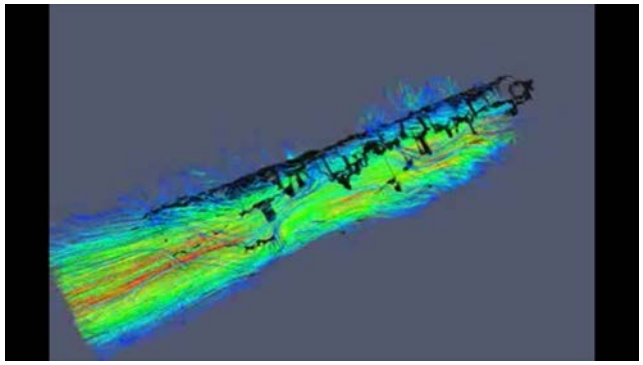
PIV Analysis of carotid stents



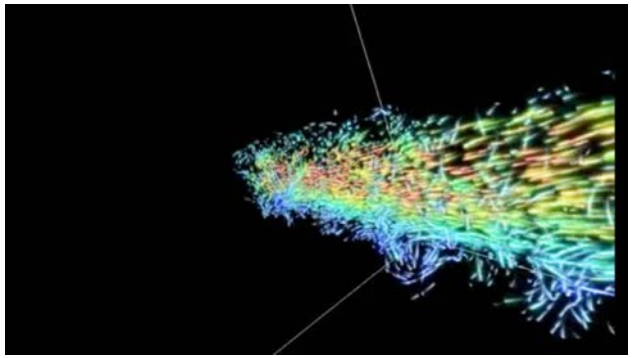
Aneurysma model I: 1ms 200µs



Aneurysma model II: flow presentation by color coded vectors indicating flow directions and speed



Stent “A”: flow line representation



Stent “C”: particle flow representation of average flow speed (red:high, blue:low)

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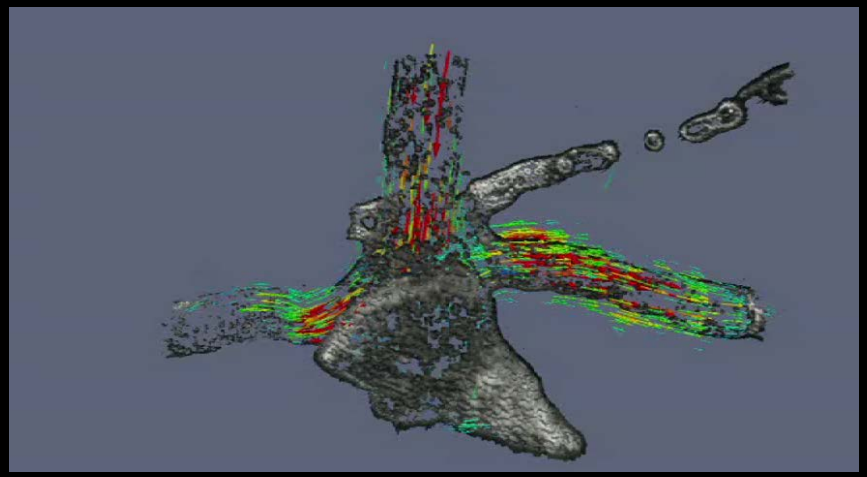
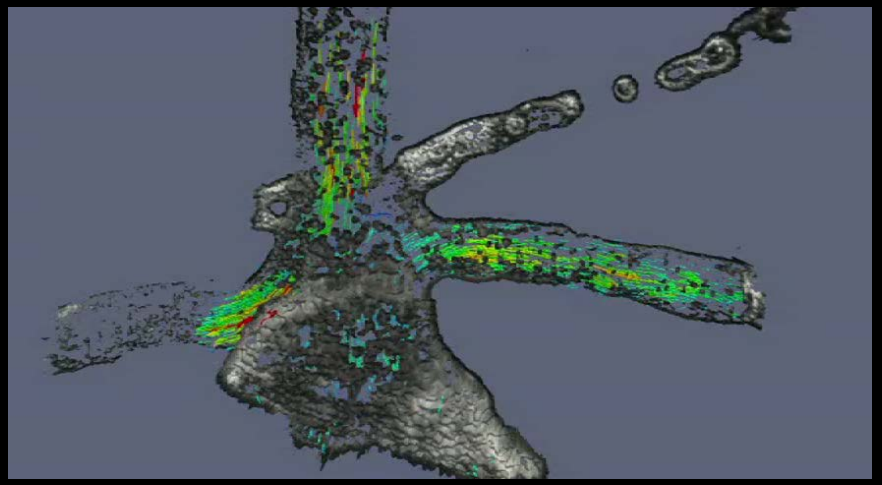
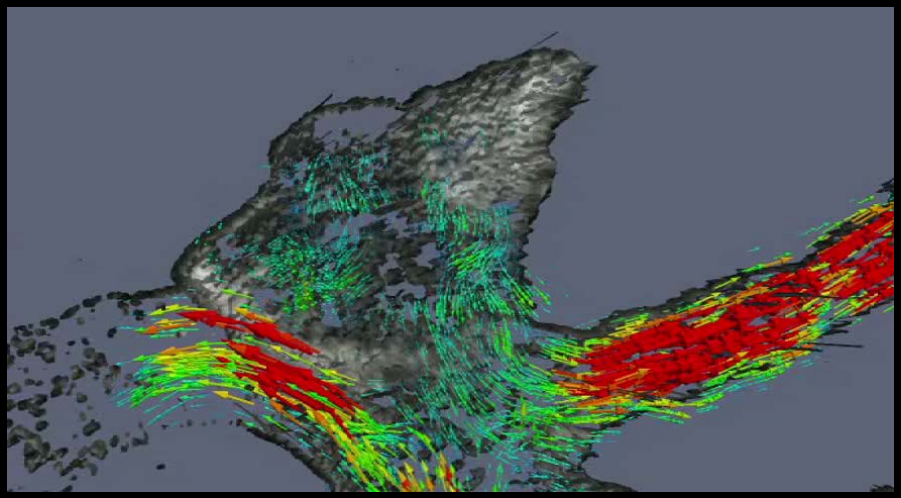
Video 1



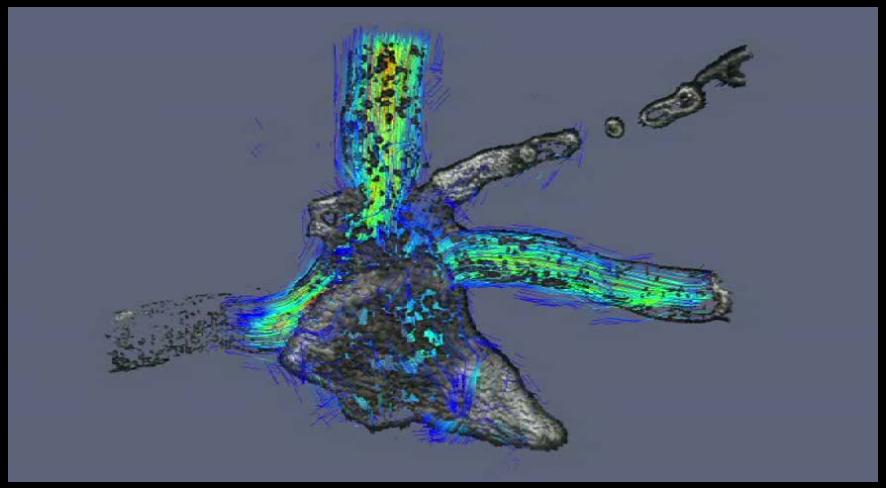
Video 2



Video 3



Video 4



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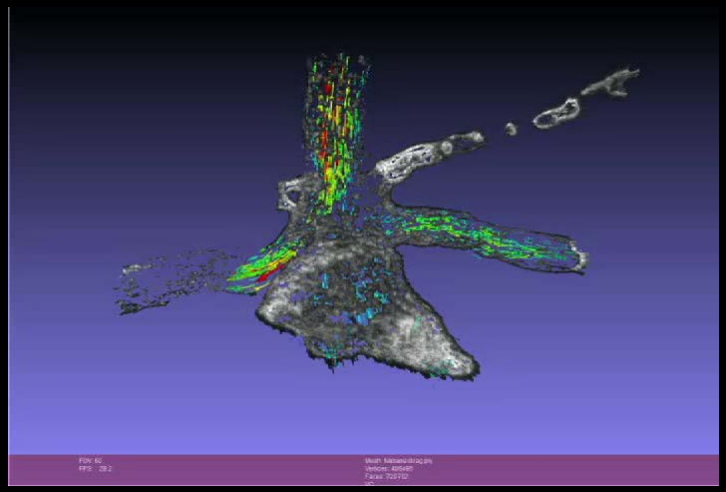
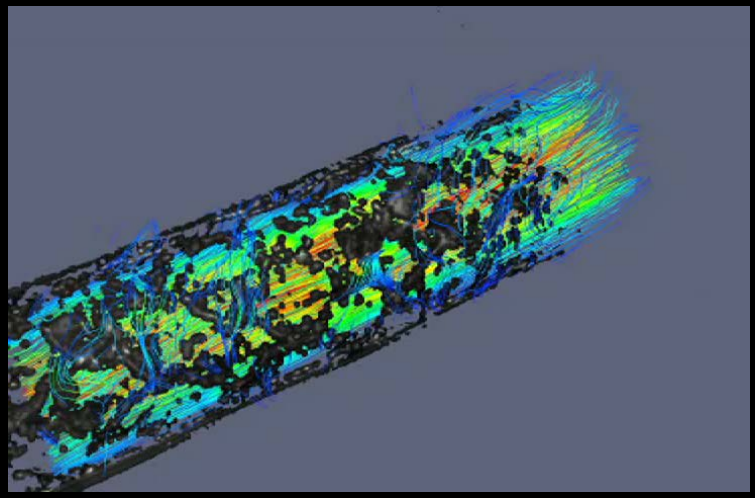
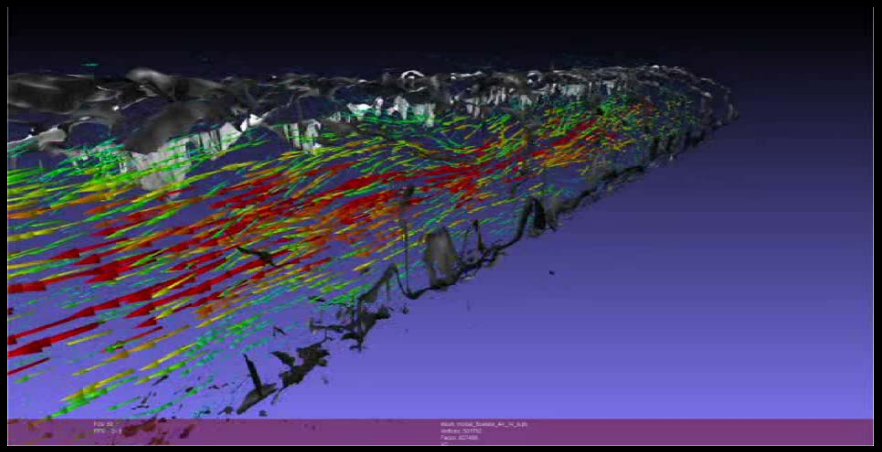
Video 5



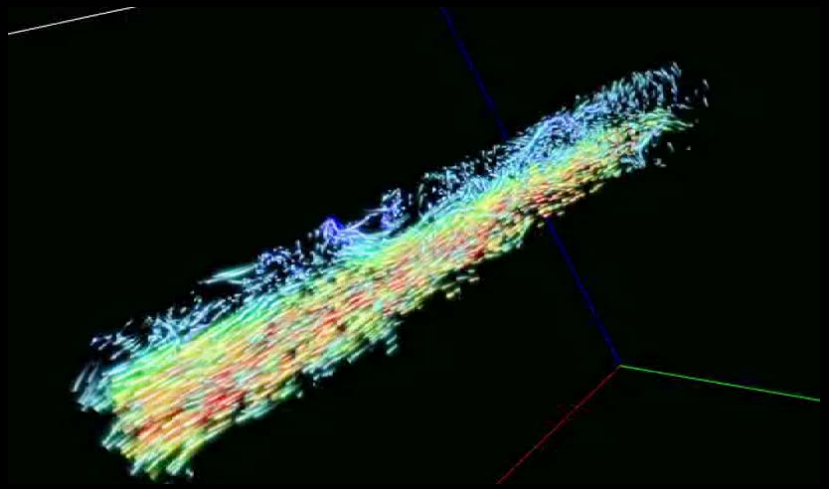
Video 6



Video 7

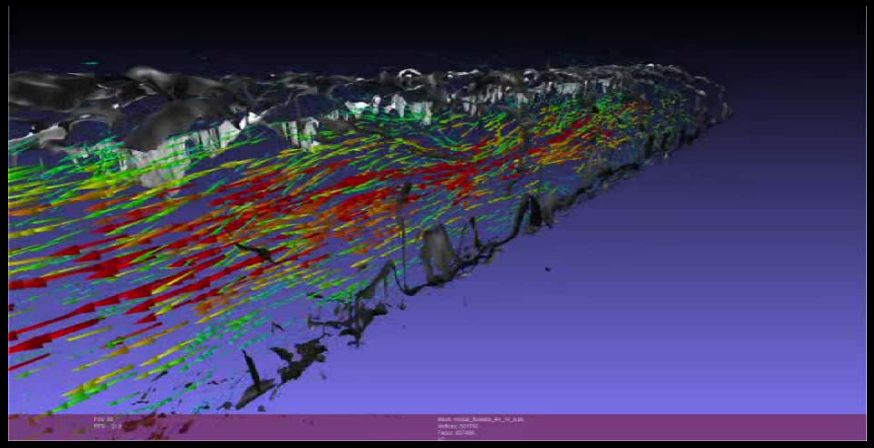


Video 8

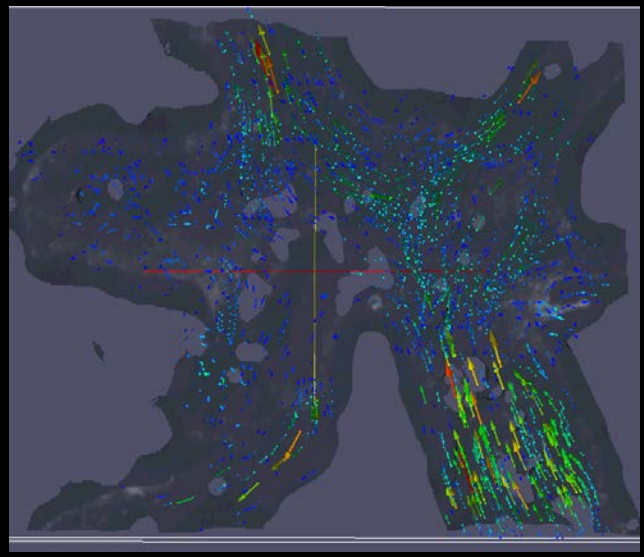


3D-real-time visualization of blood flow in cerebral aneurysms by light field particle image velocimetry

Video 9



Video 10



3D-real-time visualization of blood flow in cerebral aneurysms by light field particle image velocimetry

Conclusion

- This low cost, high resolution and fast set up approach of PIV analyses allows high throughput PIV analysis in patient specific aneurysms.
- A library of 3D aneurysm models combined with fast and high throughput PIV may allow patient specific device design and treatment planning