1000 fps High-Speed Angiography (HSA) Evaluation of Vortex Flow Characteristics in 3D-printed Cerebral Vascular Aneurysm Phantoms

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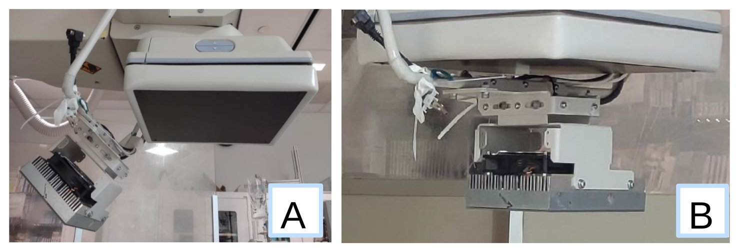
INTRODUCTION

Aneurysms are regions where blood wall weakening causes the blood vessel to expand. Aneurysms present unique geometries which provide flow features non-typical for healthy blood vessels. Quantification of flow features within aneurysms from angiographic x-ray acquisitions provides essential information regarding aneurysm diagnosis, rupture risk, and treatment. Conventional endovascular procedures use angiography acquired at 3-15 fps which is mainly used for morphologic visualization, but its hemodynamic temporal resolution is inadequate for fine flow pattern analysis. For this, high frame rate is essential. In this study, 1000 fps High-Speed Angiography (HSA) is used to visualize detailed hemodynamic patterns, including vortex-flow features.

Figure 1: HSA detector in mounted changer which mechanically rotates in front of the FPD to use the x-ray source of a Canon Infinix Unit (parked position A, and in place B).



METHODS

- 1000 fps high-speed CdTe photon-counting detector (Aries, Varex) with 7.5 x 5 cm field of view and 100 μm pixel pitch (Figure 1)
- Flow loop of 60%/40% Water/Glycerol Mixture to mimic hemodynamic characteristics
- Computer-controlled pump circulating fluid at 245 ml/min for anatomically specific carotid waveform pulsatile flow
- Automatic contrast-injector to inject Omnipaque contrast at a constant 2 ml/s rate
- Two 3D-printed patient-specific Internal Carotid Artery (ICA) aneurysm phantoms
- Optical Flow (OF) method was used in determining velocities[2]

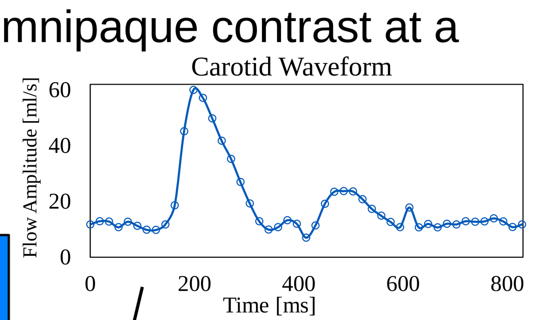
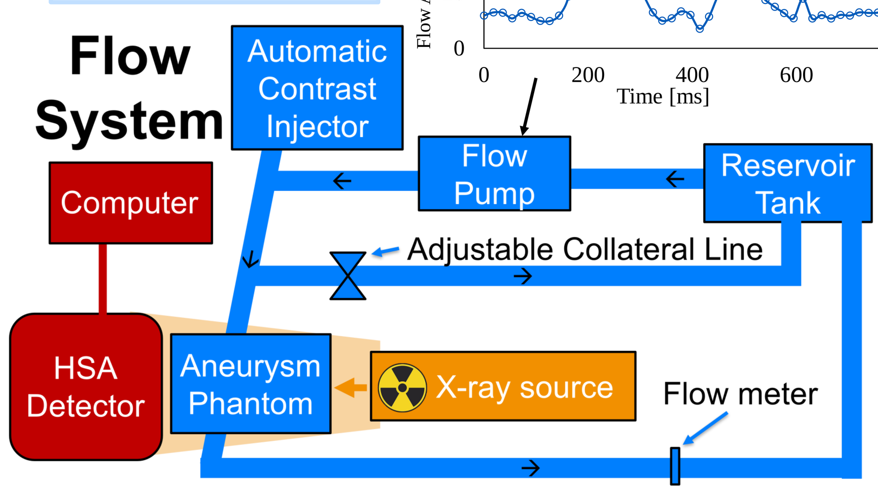


Figure 2: Flow system diagram



PHANTOMS

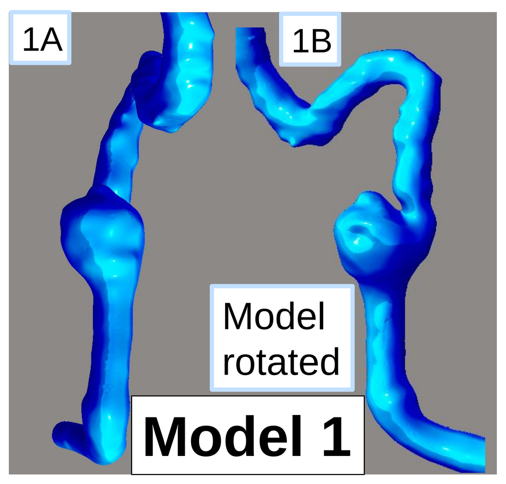
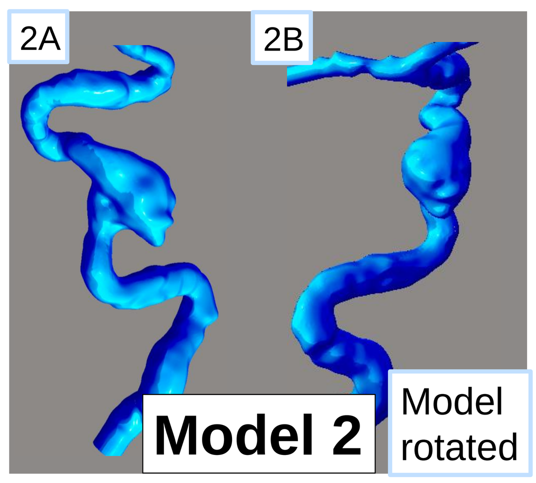


Figure 3: STL files of two ICA patient-specific saccular aneurysm phantoms at two angles (A & B) (Left, Model 1) (Right, Model 2)



CONCLUSION

Measurement of vortex characteristics presents additional quantitative metrics that may assist in the diagnosis and treatment of aneurysms. At 1000 fps, the details of fine fluctuation in vortex formation and core location are observed and enable velocity and vortex characteristics analysis. This detailed analysis of vortex flow phenomena made possible by 1000 fps HSA could provide additional information for evaluation of patient aneurysms and ultimately result in improved patient care.

RESULTS

Model 1

High-Speed Angiography

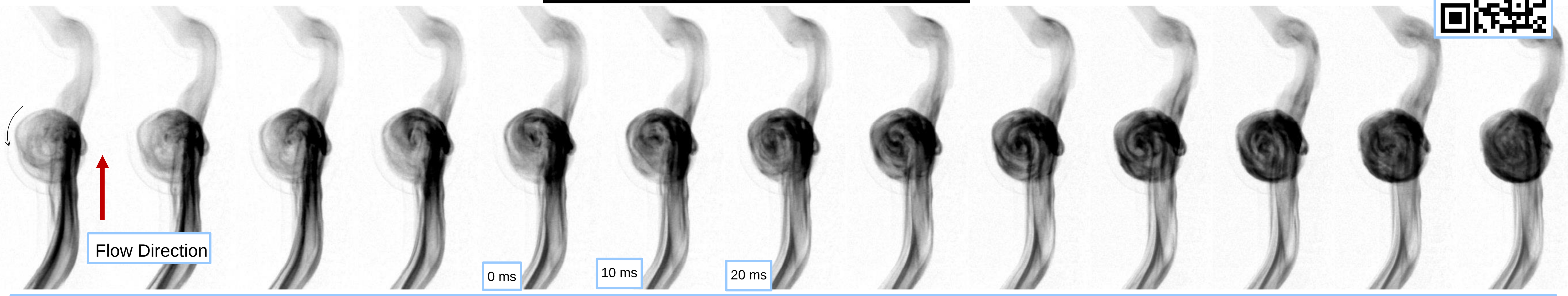


Figure 4: 1000 fps HSA acquisition of model 1 (Figure 3, Model 1A projection), shown with 10 ms intervals between the 1ms images. Flow enters the aneurysm from the bottom and flows to the top of the image (Red arrow shows flow direction). Omnipaque contrast circulates within the aneurysm in a counterclockwise direction. Time labeling on three frames is added for reference to Figure 6. All 1000 fps HSA videos are accessible by the QR code and will be available in the manuscript on the SPIE Digital Library.

Optical Flow Velocities

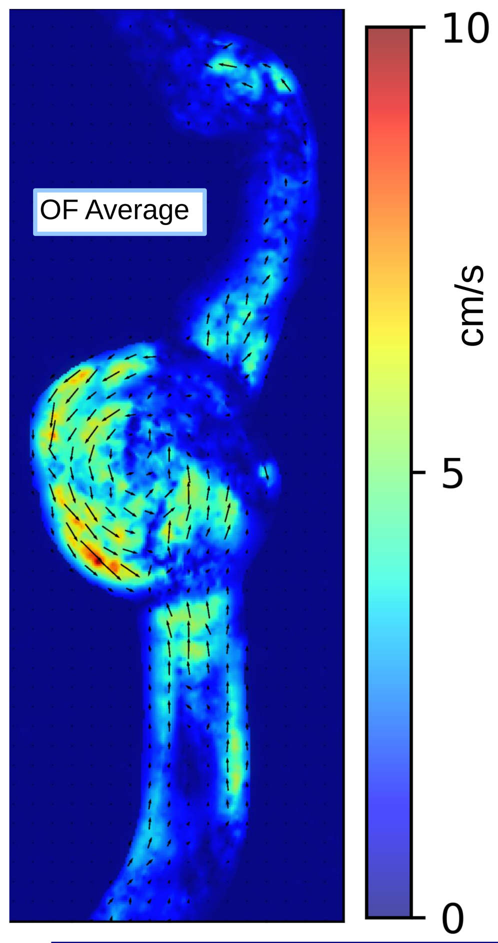


Figure 5: (Left) OF-determined velocity, averaged over 60 ms; velocity direction is shown by the arrows.

RESULTS: Model 1 shows a counter-clockwise vortex within the saccular aneurysm that, while mostly consistent, shows some variation in the vortex core's center. The velocity components in Figure 6 show the vortex motion.

Velocity Components Showing Vortical Flow

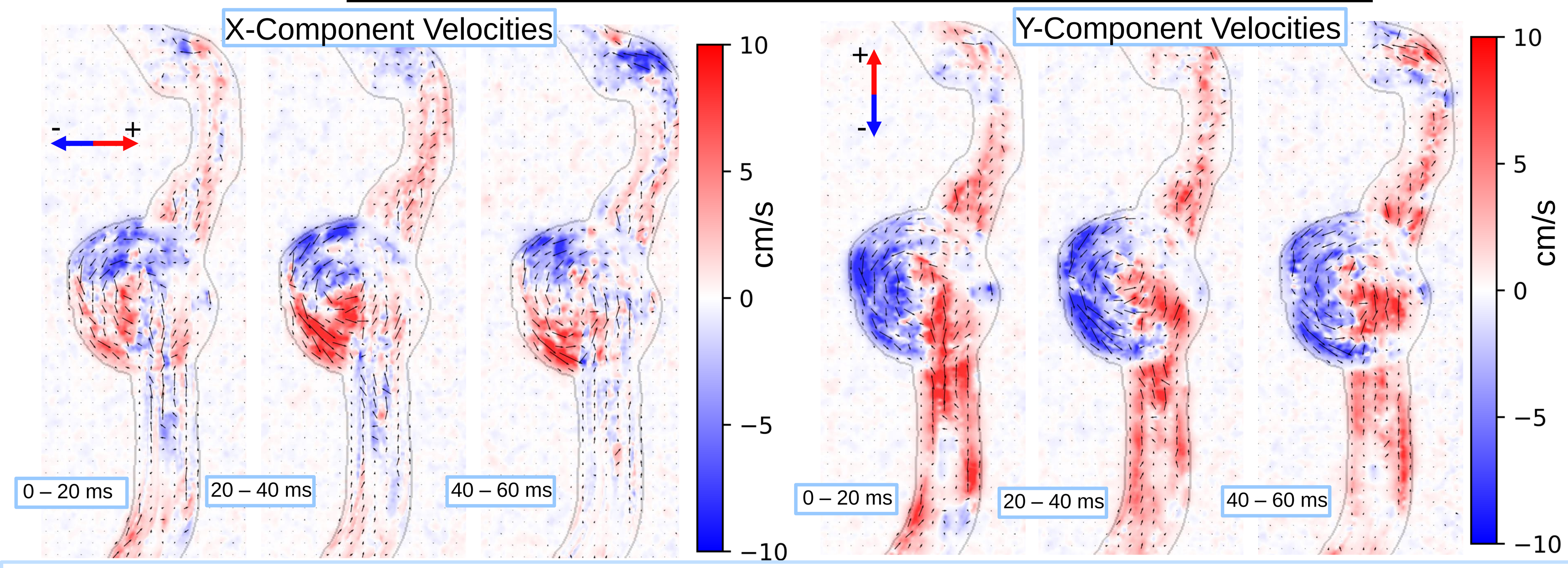


Figure 6: The color-scale shows the magnitude of the velocity components derived from OF for Model 1 with the X-component on the left and the Y-component on the right. The black arrows depict the net velocity magnitude and direction (note: the arrows are identical for each of the respective images shown on the X and Y component images since they represent the net vector sum). Each image is an average over 20 ms. The arrows clearly show a counterclockwise vortex.

Model 2

High-Speed Angiography

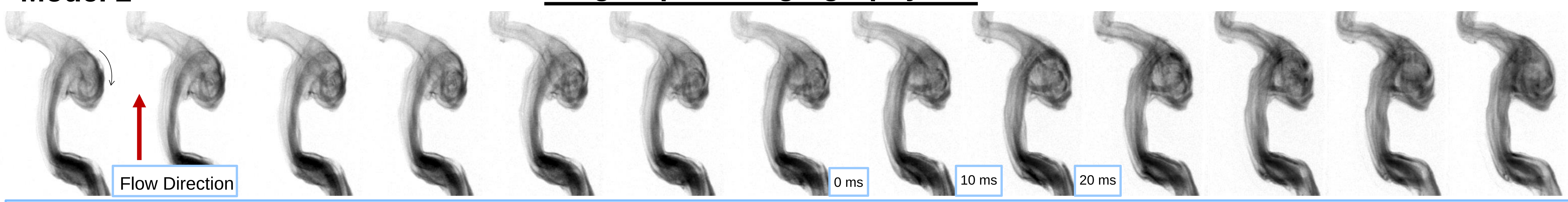


Figure 7: 1000 fps HSA contrast run of model 2, (Figure 3, Model 2A projection), shown with 10 ms intervals between the 1 ms images. For Model 2, as the contrast fills the aneurysm, most of the circulation is clockwise within the aneurysm for this projection, with some flow directed more into the plane. Model 2 shows more complex hemodynamic patterns compared to Model 1; the vortex is more complex and centered more towards the lower region of the aneurysm than for Model 1.

Optical Flow Velocities

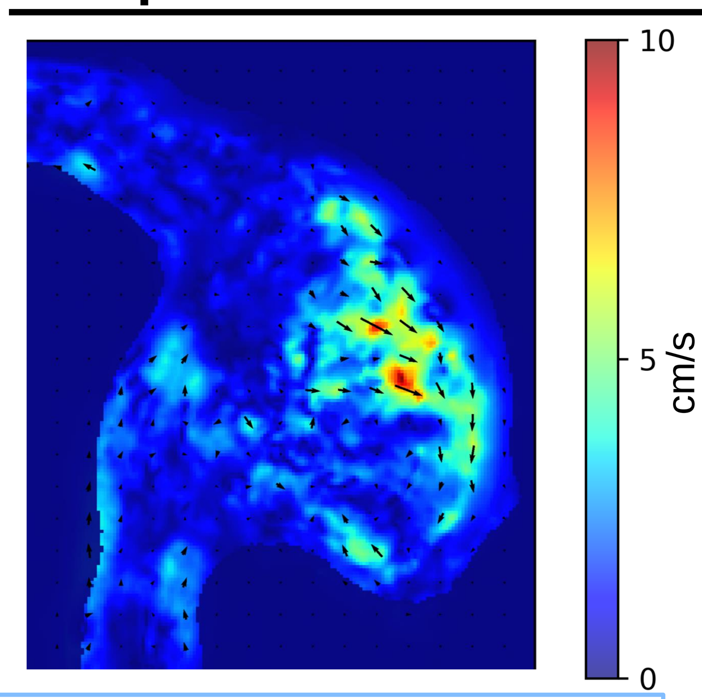


Figure 8: OF Velocity averaged over 60 ms with arrows showing velocity directionality, for the same time period as Figure 9. For this time segment, there is a clockwise flow of the contrast edge entering the aneurysm.

Velocity Components Showing Vortical Flow

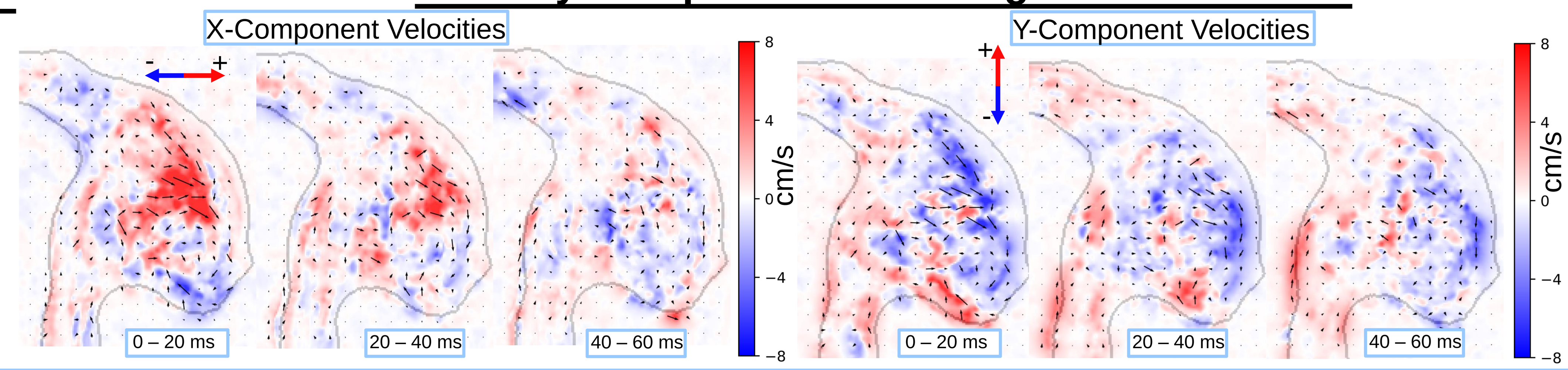


Figure 9: The color-scale shows the magnitude of the velocity components derived from OF for Model 2 with the X-component on the left and the Y-component on the right. The black arrows depict the net velocity magnitude and direction (note: the arrows are identical for each of the respective images shown on the X and Y component images since they represent the net vector sum). Each image is an average over 20 ms. The vortex is more complex and centered more towards the lower region of the aneurysm.

RESULTS: Model 2 shows a dynamic clockwise vortex with larger variation in the vortex core's center. The velocity components illustrate variation in the vortex. Even over 60 ms intervals, fine changes to flow could be observed.

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