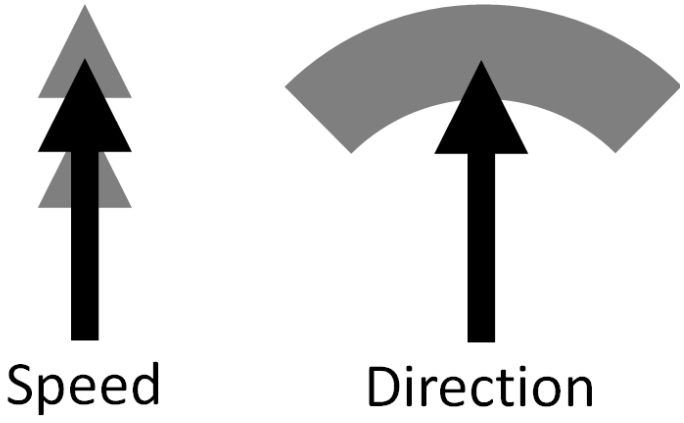
Below is the user study regarding the uncertainty visualization. For this study only domain experts, cardiovascular PC-MRI researchers, were invited.
The user study was conducted in two phases.
The first group of domain experts were involved in determining the initial requirements for the framework. After they completed the questionnaire changes were made to improve the user study by adding additional questions. The additional elements in the user study are indicated using underlining. The updated questionnaire was presented to experts that were not involved in the project in any way before filling in the questionnaire.

Uncertainty visualization of 4D PC-MRI data

Uncertainty

Like any measurement of physical behavior, PC-MRI measurements are prone to noise which can influence both the measured speed and direction of the flow. This means that this noise also alters any visualization of the flow.

By modeling the noise we can determine all the possible speeds and directions of the actual underlying flow. In the images below, this is presented schematically. Here, the black arrow represents the measured velocity vector, while the grey area gives a probability range in which the vector could also fall given the uncertainty caused by measurement noise.



An abstract representation of the influence of noise on a flow vector

Visualizing uncertainty in 4D flow

Below we present some examples of our visualizations. Here, the influence of noise on a flow visualization is shown using our visualization. The visualization here mimics the use of smoke or contrast

agent injected in the flow. Various amounts of noise were injected here to demonstrate how the noise affects the visualization in comparison to a reference, where no noise is injected. Note that the visualization makes uncertain regions more fuzzy or blurry. Furthermore, the amount of deviation from the (noisy) measured data is represented by the brightness of the color(s), the brighter the color, the more it deviates. Visualizing 4D flow phenomena is difficult, the seeding position and time should be chosen with care to visualize important flow features and to avoid occlusion. This makes uncertainty visualization challenging since more information should be displayed.

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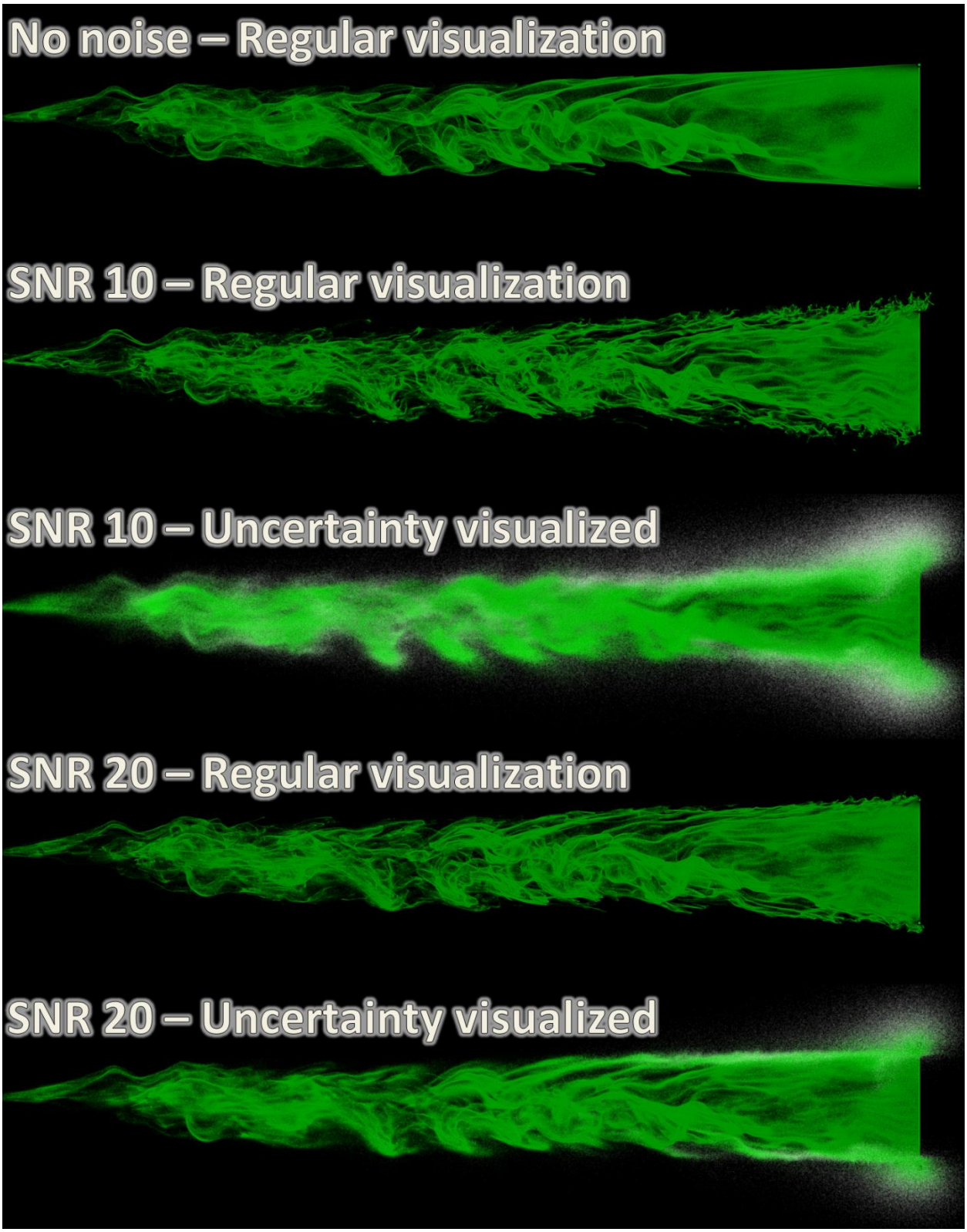
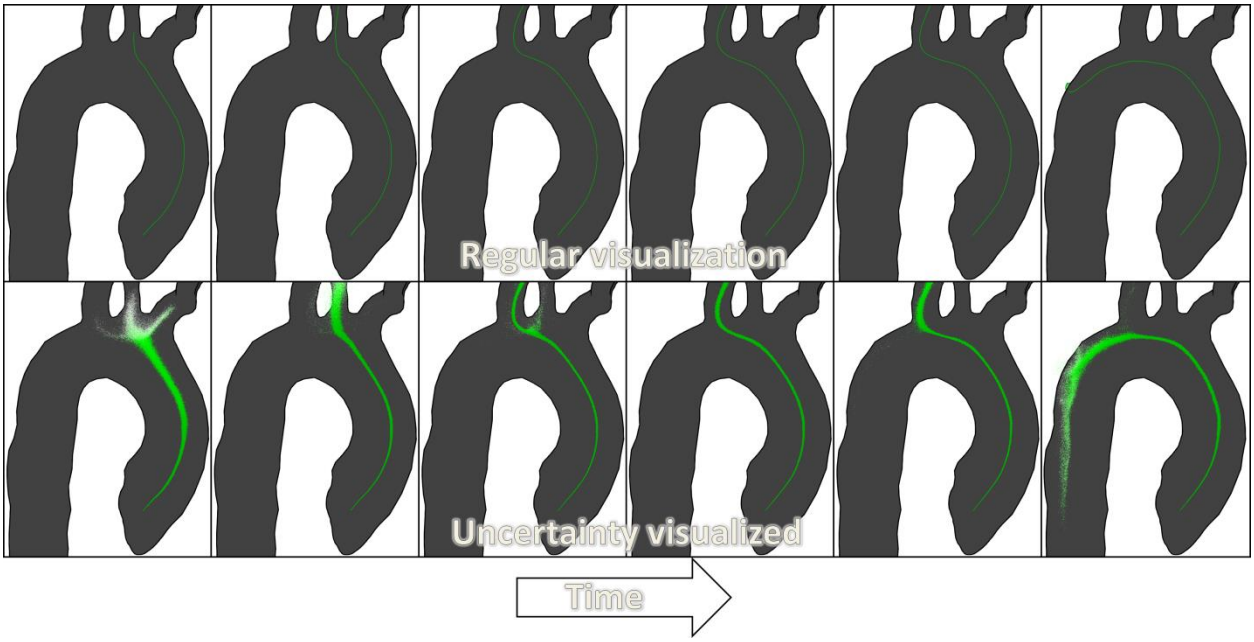

No noise – Regular visualization
SNR 10 – Regular visualization
SNR 10 – Uncertainty visualized
SNR 20 – Regular visualization
SNR 20 – Uncertainty visualized

An example of our visualization using artificial data

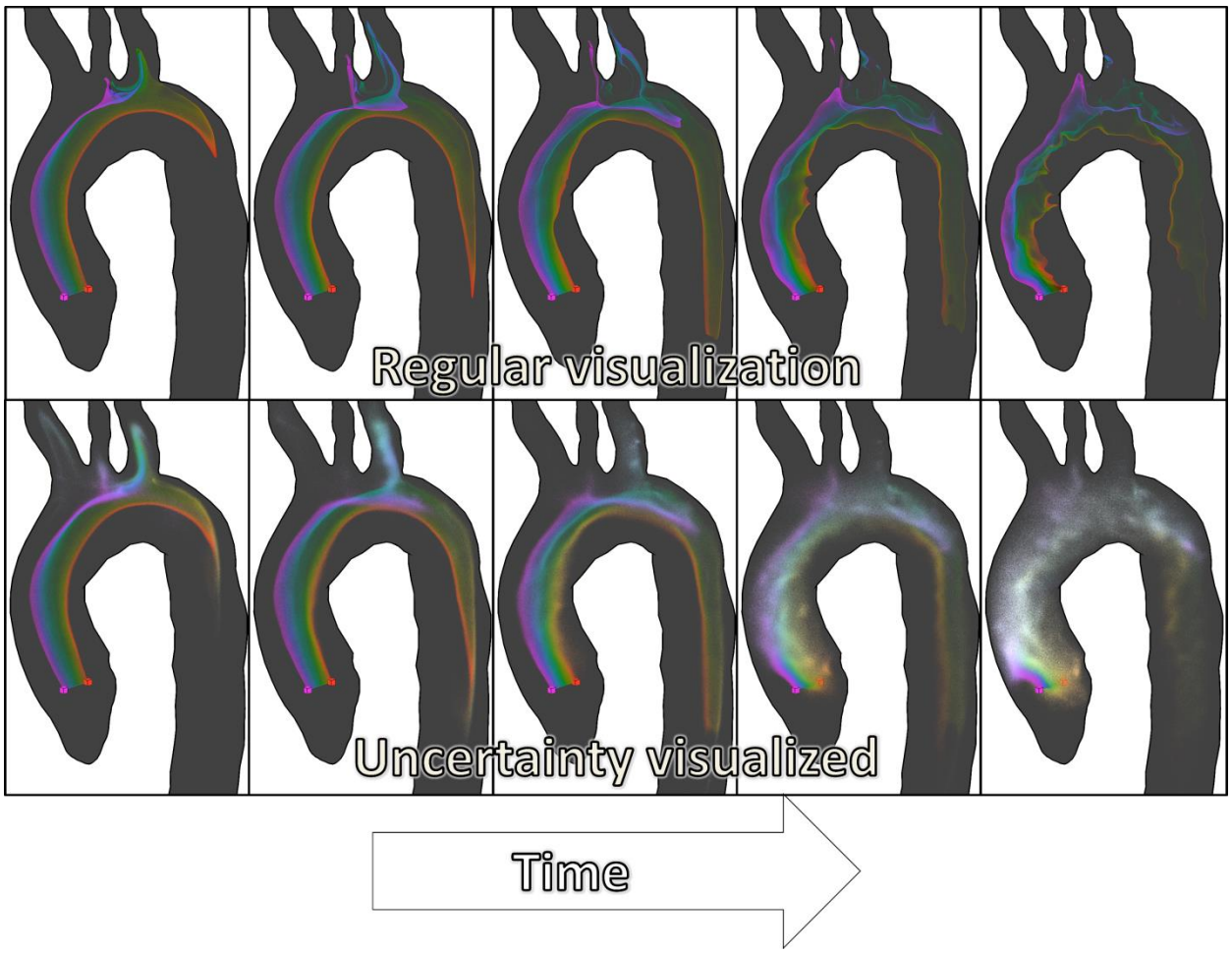
In the next section some examples of our uncertainty visualization are compared with regular flow visualization (without considering the uncertainty).

These images are followed by some questions.

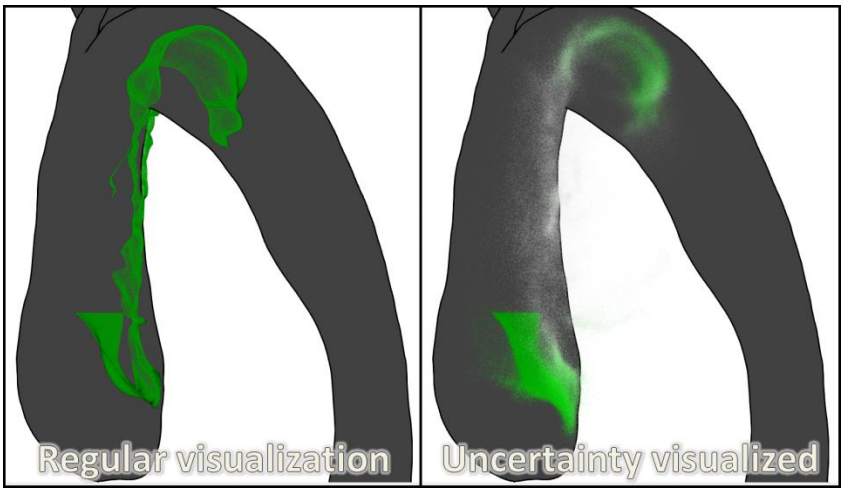
Questionnaire



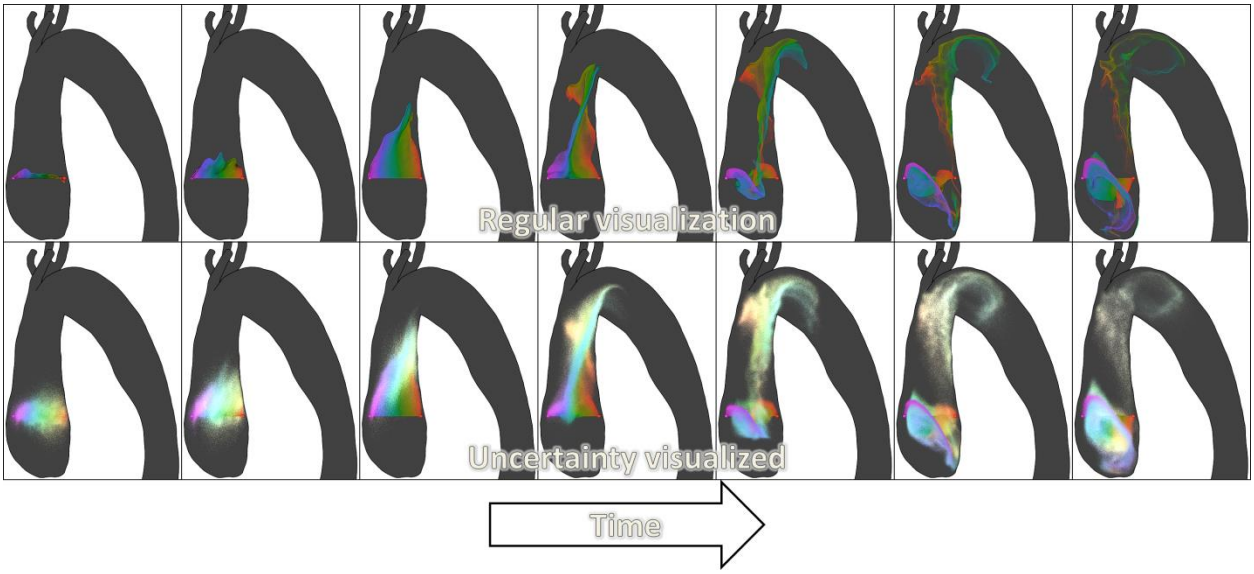
Healthy volunteer data



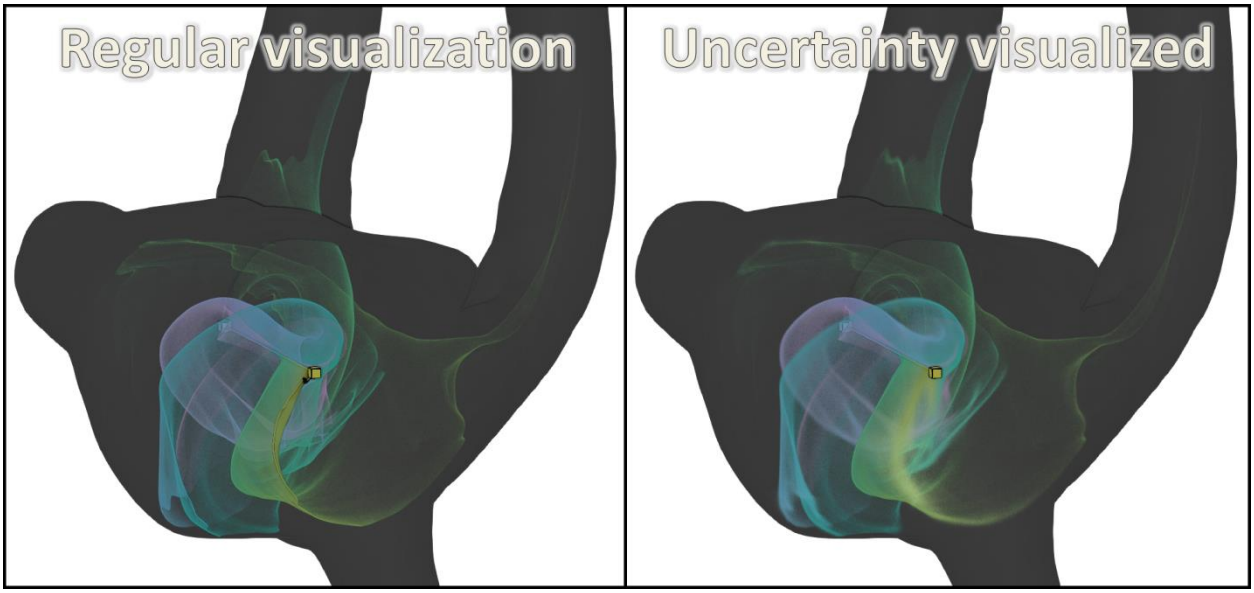
Healthy volunteer data



Patient data with a dissection



Patient data with a dissection



Aneurysm phantom data

Do you think visualization, in general, helps the analysis of blood-flow?

	1	2	3	4	5	6	7	
It does not help at all	○	○	○	○	○	○	○	It helps a lot

Do you think uncertainty visualization is helpful for the analysis of blood-flow?

	1	2	3	4	5	6	7	
It does not help at all	○	○	○	○	○	○	○	It helps a lot

Do you understand what the uncertainty visualization represents?

	1	2	3	4	5	6	7	
It do not understand it	○	○	○	○	○	○	○	I fully understand it

Given the presence of noise in the data, does the uncertainty visualization contribute to your confidence in your analysis?

	1	2	3	4	5	6	7	
I am less confident	○	○	○	○	○	○	○	I am more confident

How does the uncertainty visualization influence your confidence?

Type your answer

Can you perceive the various amounts of measurement noise present in the data using the above visualizations?

	1	2	3	4	5	6	7	
No, not at all	○	○	○	○	○	○	○	Yes, easily

Would you use this uncertainty visualization?

	1	2	3	4	5	6	7	
I would not use it	○	○	○	○	○	○	○	I would use it often

For what type of analysis, if any, would you use the uncertainty visualization?

Type your answer

Uncertainty selection

Having knowledge of the uncertainty also allows for selectively visualizing only the most certain flow patterns.

For example, when seeding from random positions throughout the vessel it is possible to rank each seeding position based on how much the particles deviate from each other.

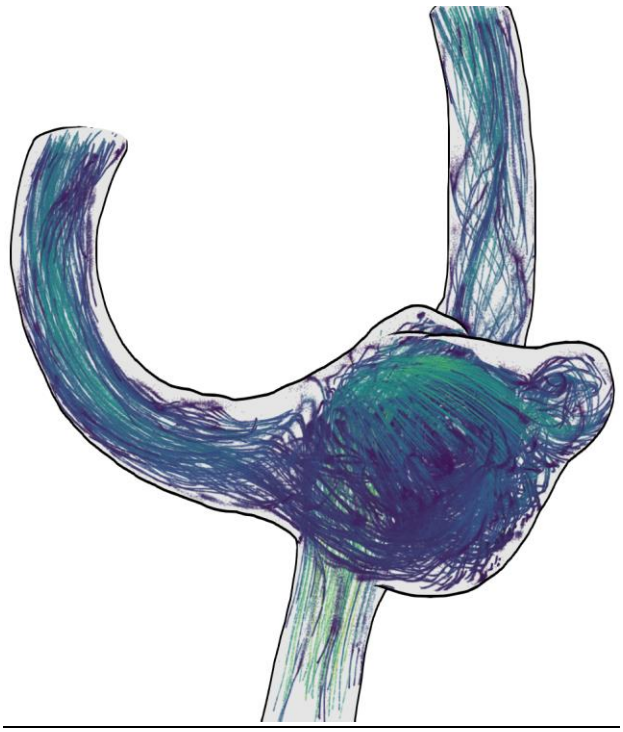
When only a given percentage of the most certain seeding positions are used the less reliable data will be filtered away.

Moreover, by removing uncertain seeding positions, the amount of clutter caused by the uncertainty visualization can be reduced.

Below are some examples of this filtering.

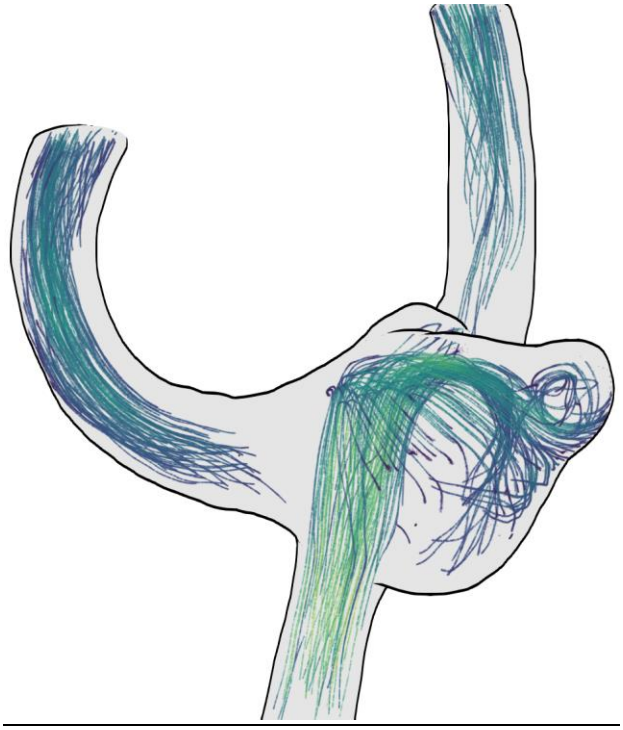
Note that the coloring is used to encode the local speed.

100% of seeding positions used



75% of the most certain seeding positions used

50% of the most certain seeding positions used



25% of the most certain seeding positions used

Do you think this type of filtering can be helpful?

	1	2	3	4	5	6	7	
It does not help at all	○	○	○	○	○	○	○	It helps a lot

Would this type of selection influence your trust in the visualization?

	1	2	3	4	5	6	7	
I do not trust the visualization	○	○	○	○	○	○	○	I think the visualized lines are very reliable

Do you believe this type of filtering will improve your overall analyses?

	1	2	3	4	5	6	7	
I do not think it will	○	○	○	○	○	○	○	I am certain it will

How do you think the filtering could influence your analyses/conclusions?

Type your answer