4D magnetic resonance velocimetry and numerical simulations for studying helical flows in cerebral blood vessels

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Study of blood flow

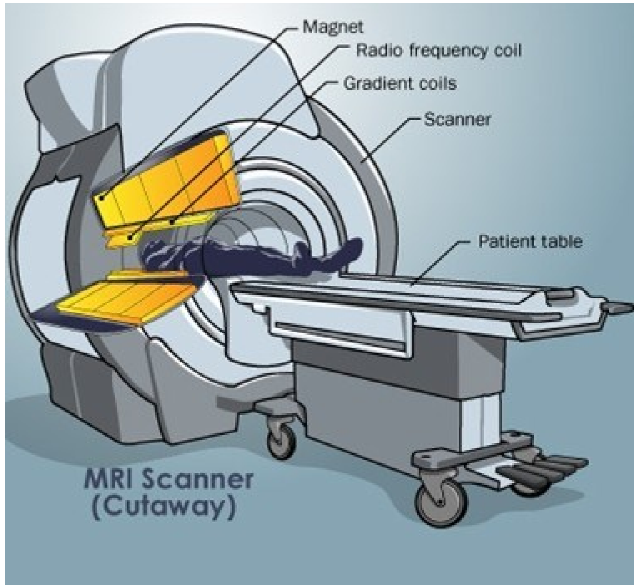
- Non-invasive methods:
  - Doppler ultrasonography
  - Computed tomography (CT)
  - Magnetic resonance imaging (MRI)
- MRI — heart
  - L. A. Bokeria, et al., 2013
- MRI — aorta
  - A. Frydrychowicz, et al., 2009
  - M. Markl, et al., 2010
- Ultrasonography — CCA bifurcation
  - V. P. Kulikov, R. I. Kirsanov, 2013
  - A. D. Yukhnev, Ya. A. Gataulin, et al., 2015

Aim

- Investigation of the velocity field of physiological flows with MRI:
  - Development of the research protocol
  - Development of the post-processing software

  - Study of flood flow helicity in cerebral vessels
  - Study of blood and cerebrospinal fluid flows

Experimental setup



3-tesla MR scanner Philips Ingenia 3T

Programmable pump CompuFlow 1000MR
(Shelley Medical Imaging Technologies)

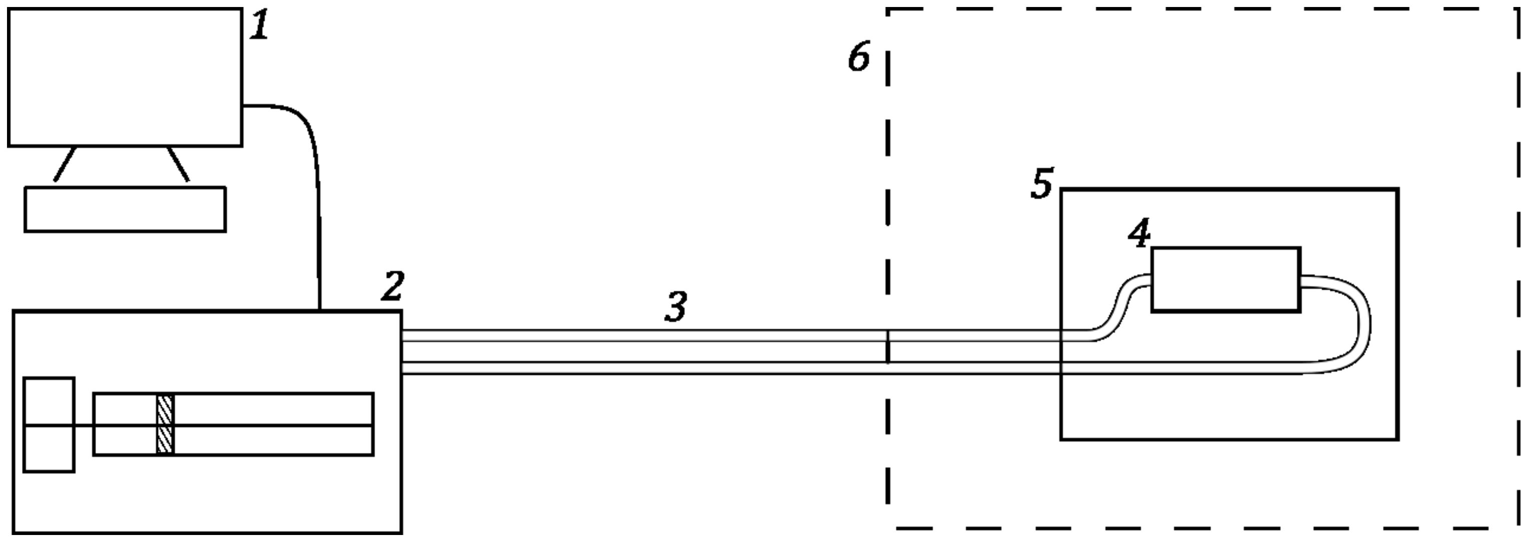
Giant aneurysm on internal carotid artery (Shelley Medical Imaging Technologies)

Common carotid artery bifurcation
(Shelley Medical Imaging Technologies)

Blood mimicking liquid: glycerol solution
(density 1000 kg/m³, viscosity 0,004 Pa·s)

https://science.howstuffworks.com/mri1.htm

Experimental setup

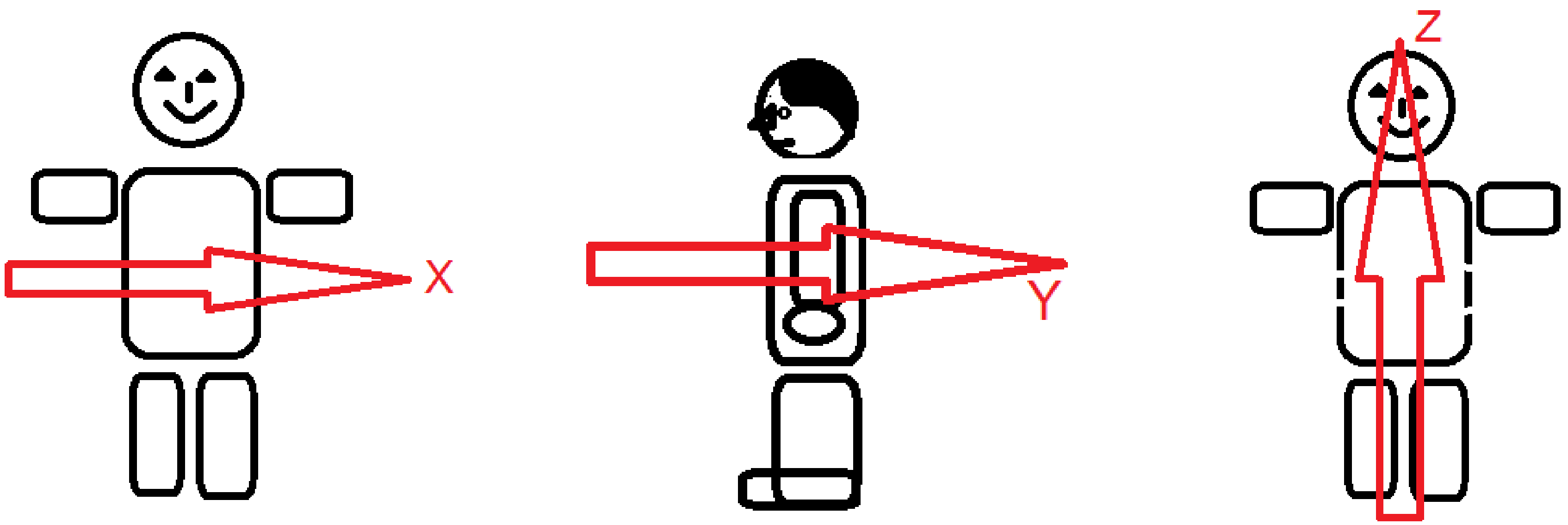


1 — computer
2 — programmable pump
3 — connecting tubes

4 — vessel model
5 — MR scanner
6 — shield (Faraday cage)

Reconstruction of the velocity field (4D Qflow)

- Each measurement in 4D Qflow results in 4 series of DICOM images
  - PCA/P-RL — x PCA/P-AP — y PCA/P-FH — z

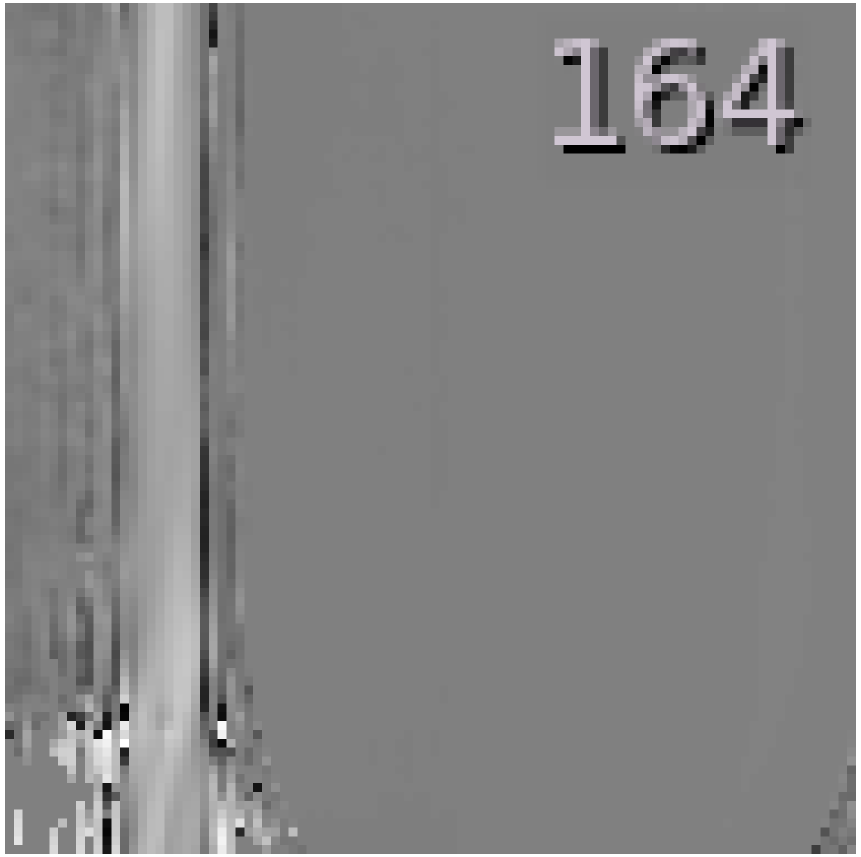


- Metadata: image position, image orientation, spacing between slices, pixel spacing, time step number, trigger time
- ImageOrientation — rotation matrix

https://dicomiseasy.blogspot.ru/2013/06/getting-oriented-using-image-plane.html

DICOM images

Fluid (proton) density image



Velocity component
(three Cartesian components)

Comparison of the measurements*

Philips Achieva 1.5 T

Medical MR scanner

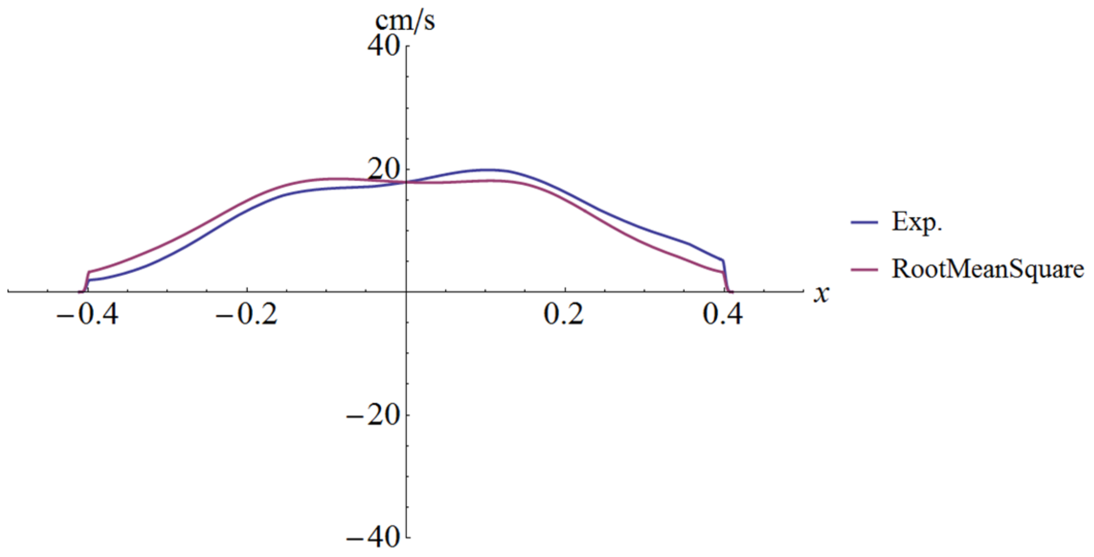
Bruker BioSpec 117/16 USR 11.7 T

Research MR scanner

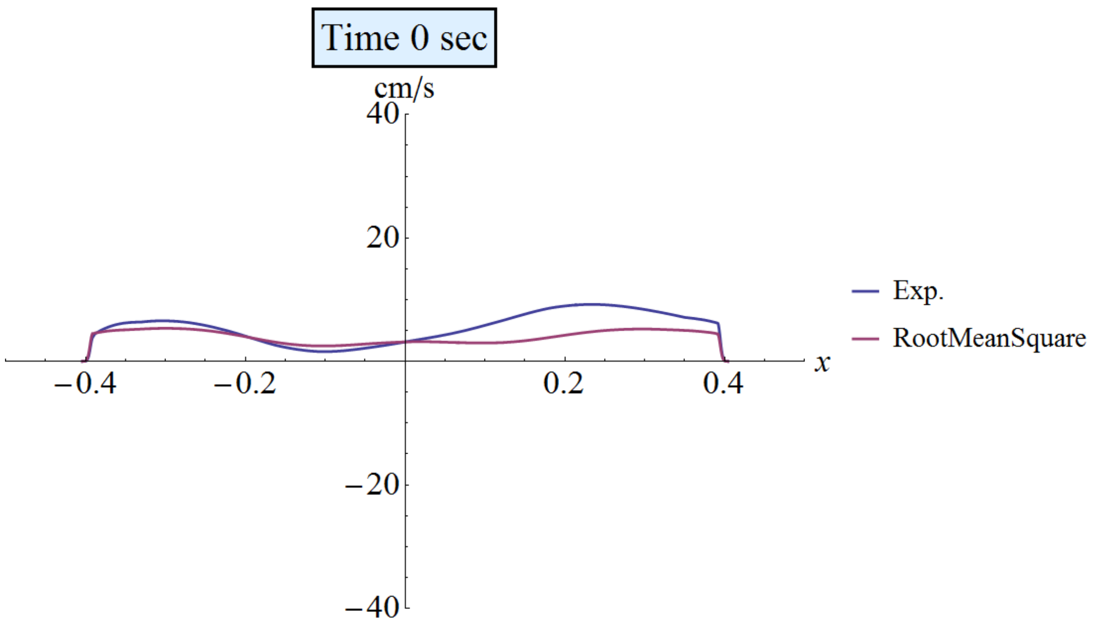
* A. V. Boiko et al. J Appl Mech Tech Phy (2017)

Velocity profile (Philips 1.5 T)

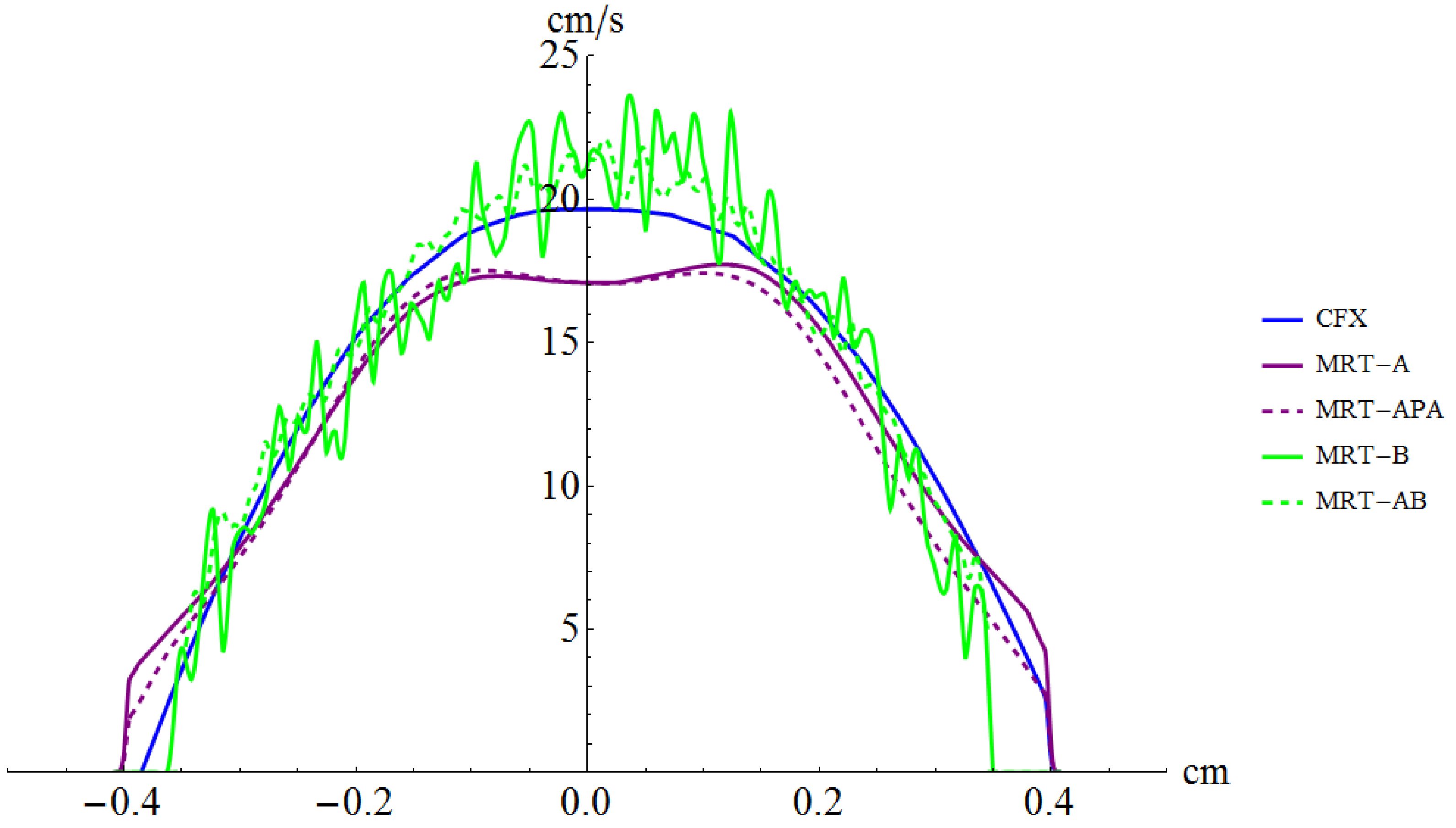
Stationary flow 5 ml/s



Non-stationary flow 0.1 + 10 sin(πt)



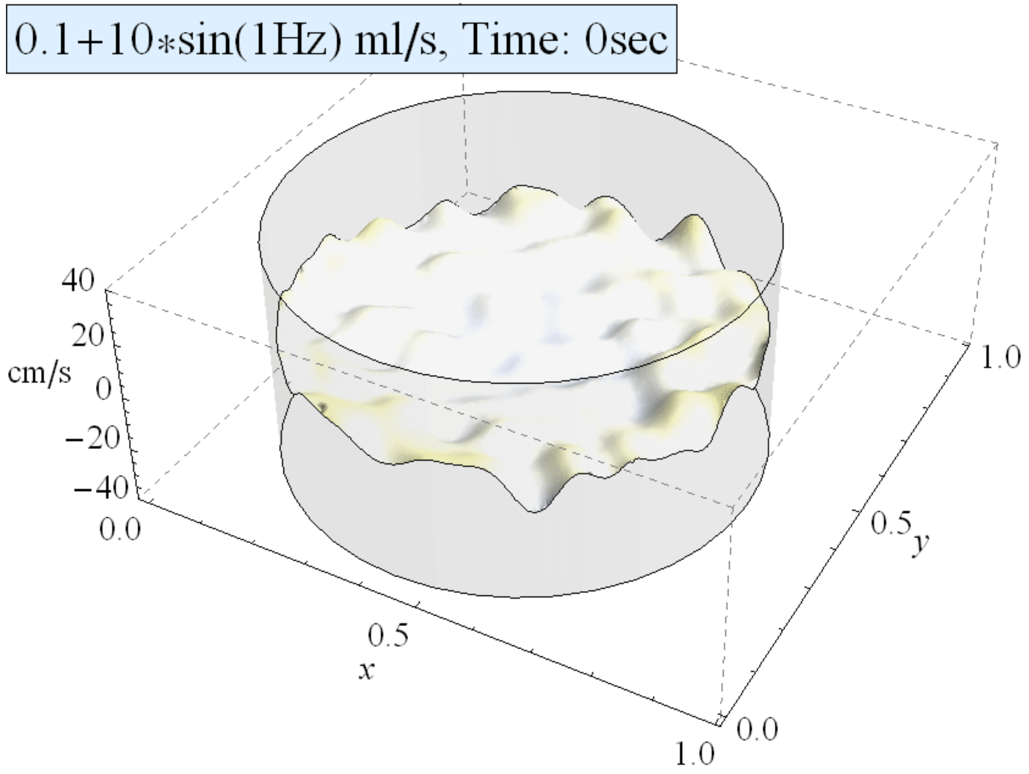
Stationary flow, 5 ml/s



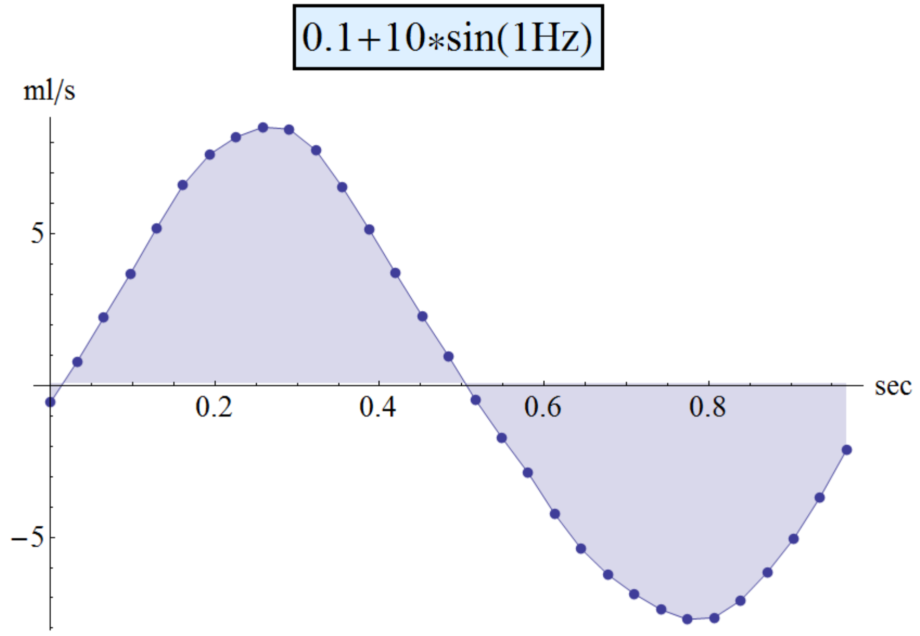
Comparison of the results obtained by numerical simulation and MRI: **violet** – **Philips**, **green** – **Bruker**.

Non-stationary flow (Philips 1.5 T)

Velocity profile

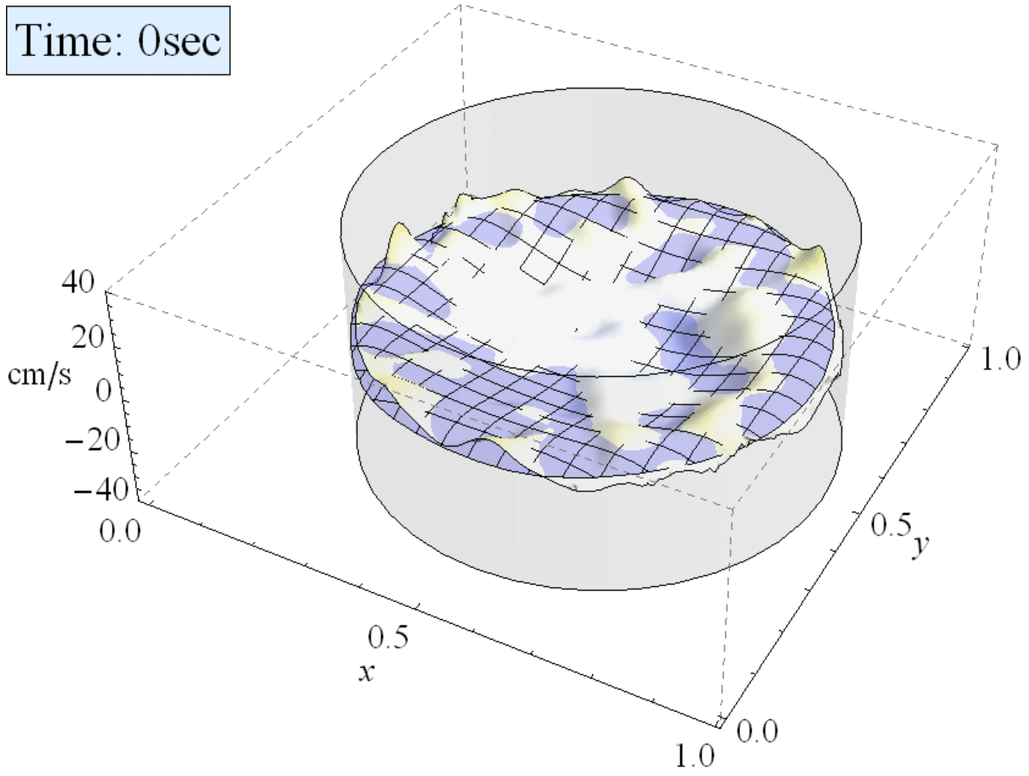


Flow rate

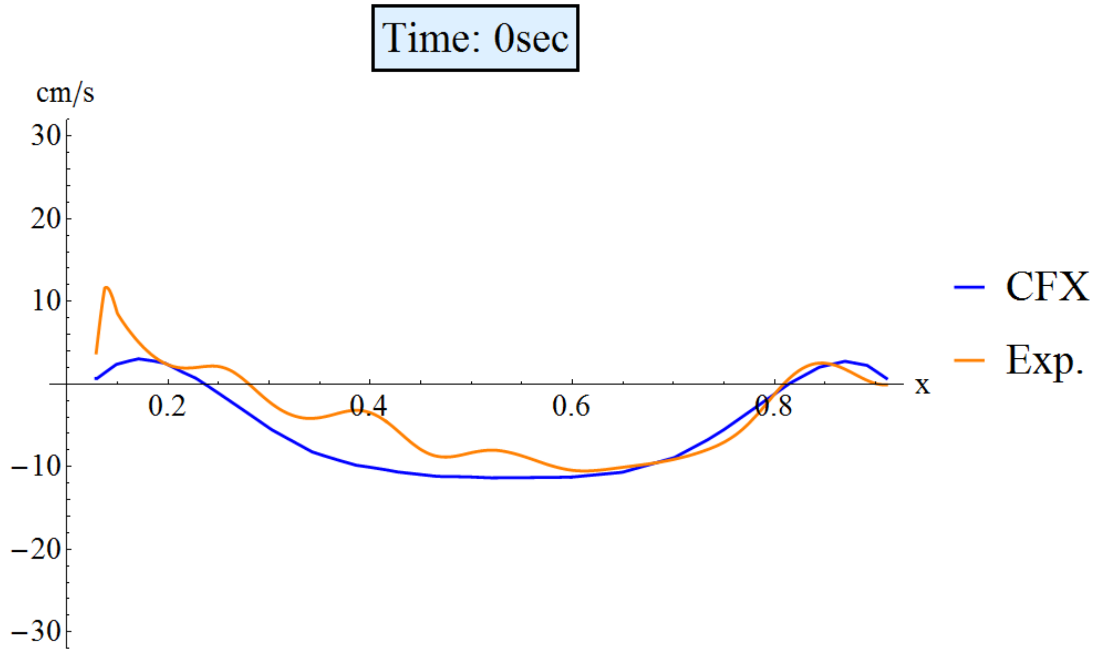


Non-stationary flow 0.1 + 10 sin(πt) ml/s

Velocity profile

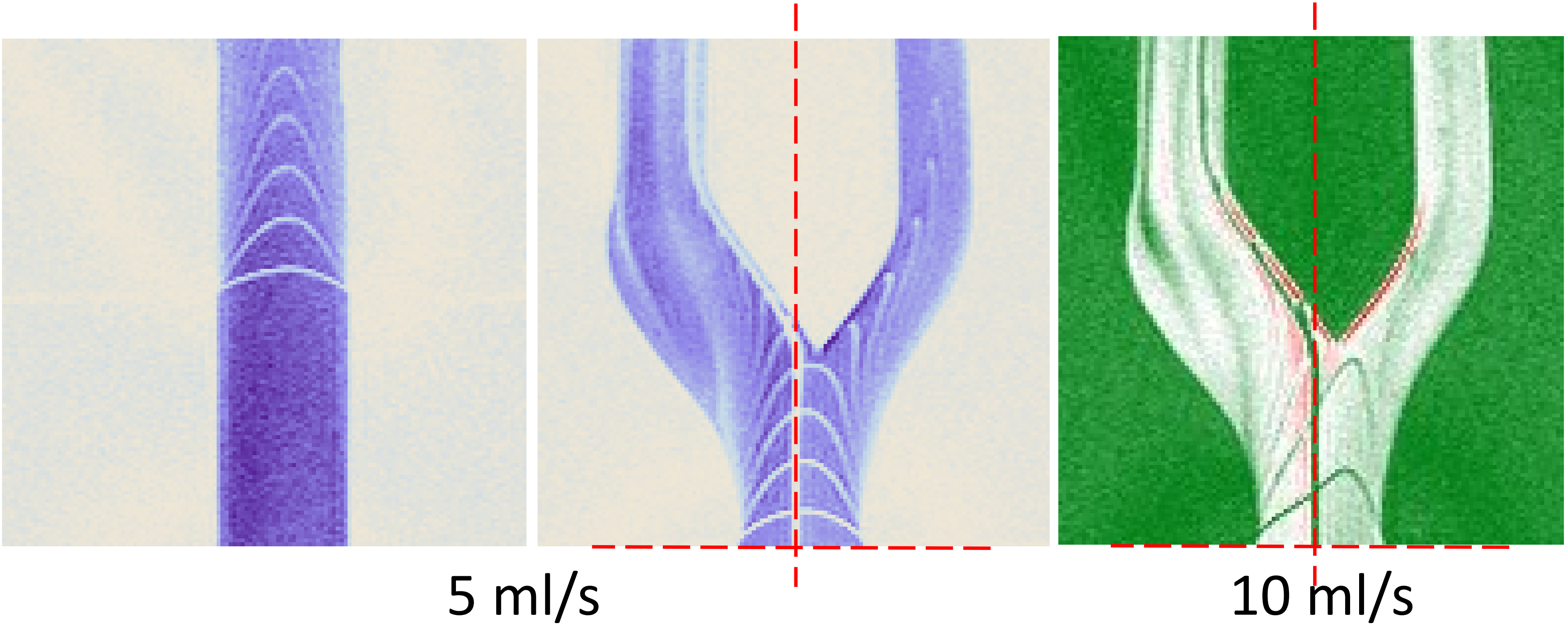


Averaged velocity profile



Comparison with numerical simulation

Fluid surfaces in stationary flow (Bruker 11.7 T)

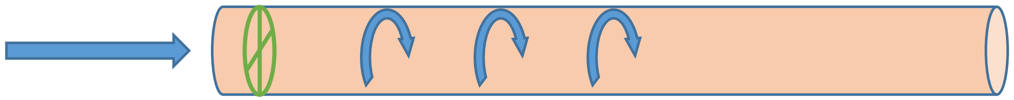


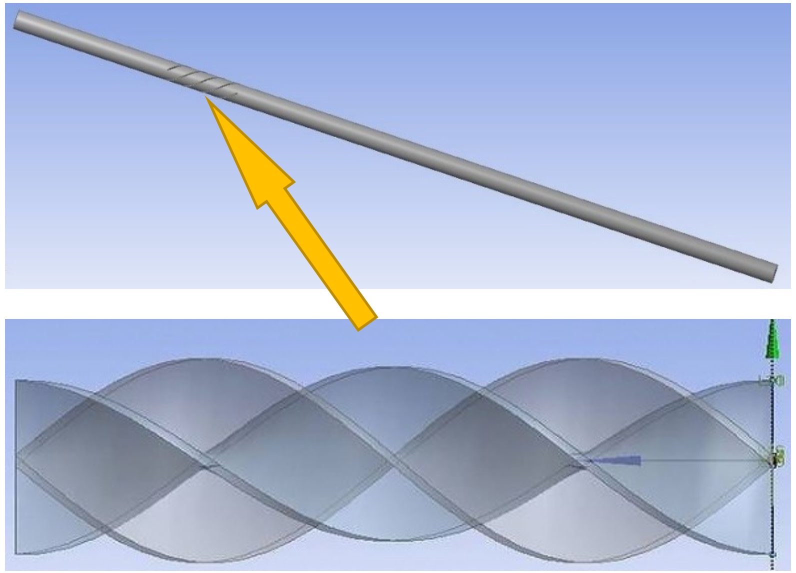
Experiments 4D Qflow

Session 1				
	1	Swirl generator v.1	96 × 96 × 7 (280)	18 ± 3 ml/s, 0.5 Hz
Session 2				
	a	Swirl generator v.1	160 × 160 × 11 (440)	18 ± 3 ml/s, 0.5 Hz
	b	Swirl generator v.1	160 × 160 × 11 (440)	18 ± 3 ml/s, 0.5 Hz
	c	Swirl generator v.1	240 × 240 × 20 (800)	18 ± 3 ml/s, 0.5 Hz
Session 3				
	1	Swirl generator v.1	96 × 96 × 7 (280)	18 ± 3 ml/s, 0.5 Hz
	2	Swirl generator v.1	160 × 160 × 11 (440)	18 ± 3 ml/s, 0.5 Hz
Session 4				
	2a	Swirl generator v.1	96 × 96 × 7 (280)	18 ± 3 ml/s, 0.5 Hz
	2b	Swirl generator v.1	160 × 160 × 11 (440)	18 ± 3 ml/s, 0.5 Hz
	2c	Swirl generator v.1	240 × 240 × 20 (800)	18 ± 3 ml/s, 0.5 Hz
	3a	Swirl generator v.2	96 × 96 × 7 (280)	18 ± 3 ml/s, 0.5 Hz
	3b	Swirl generator v.2	160 × 160 × 11 (440)	18 ± 3 ml/s, 0.5 Hz
Session 5				
	1	Aneurysm model	176 × 176 × 25 (1000)	12 ± 3 ml/s, 0.5 Hz
	2	Aneurysm model	176 × 176 × 25 (1000)	15 ± 3 ml/s, 0.5 Hz
Session 6				
	1	Aneurysm model	176 × 176 × 25 (1200)	15 ± 3 ml/s, 0.5 Hz
	2	CCA bifurcation	96 × 96 × 7 (280)	15 ± 3 ml/s, 0.5 Hz
	3	CCA bifurcation	160 × 160 × 11 (440)	15 ± 3 ml/s, 0.5 Hz

Flow in elastic tube

- Silicone tube with a swirl generator
- Flow rate: 18 + 3 sin(π*t*) ml/s, *f* = 0.5 Hz.

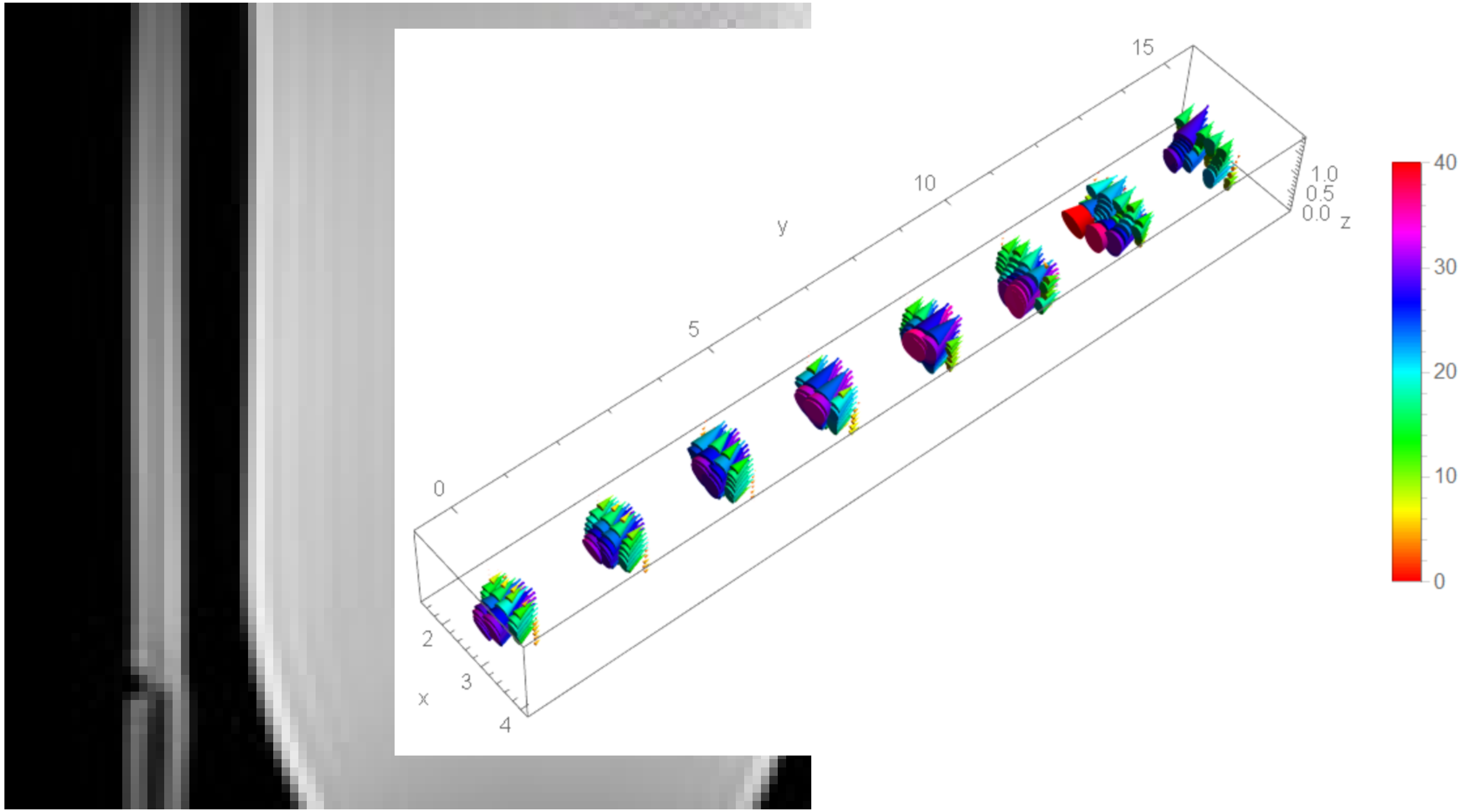




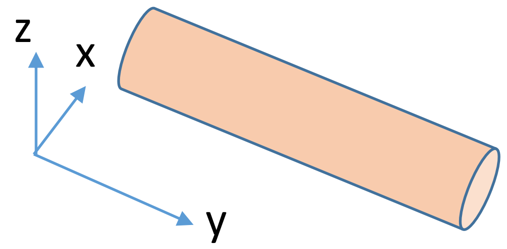
Silicone tube with swirl generator

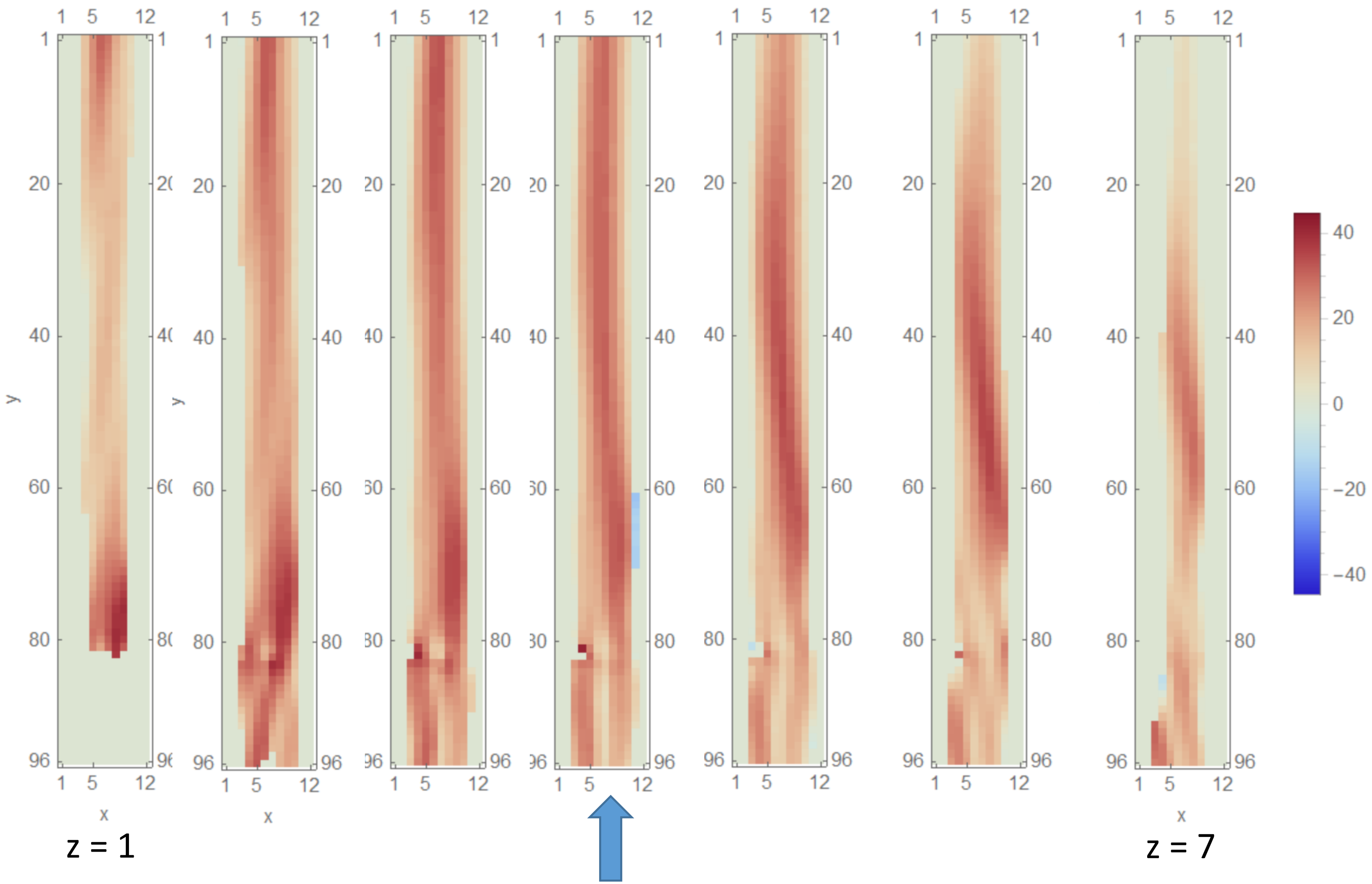
3D matrix	Time steps	Voxel, mm^3	Domain, mm^3	Files
96×96×7	20	1.56×1.56×1.5	150×150×10.5	4 × 280
160×160×11	20	0.94×0.94×1.25	150×150×13.75	4 × 440
240×240×20	20	1.25×1.25×1.25	300×300×25	4 × 800

Matrix 96×96×7

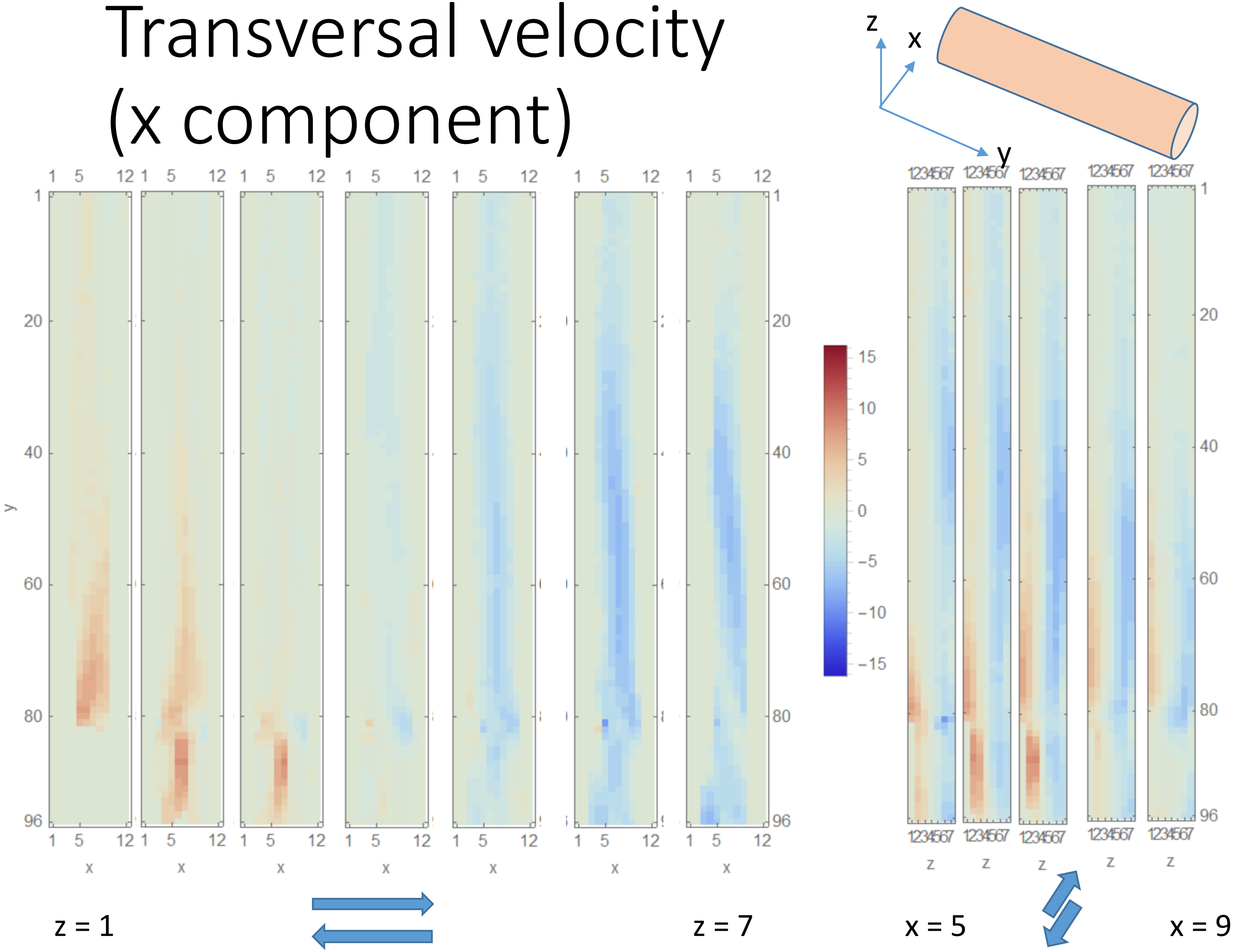


Axial velocity

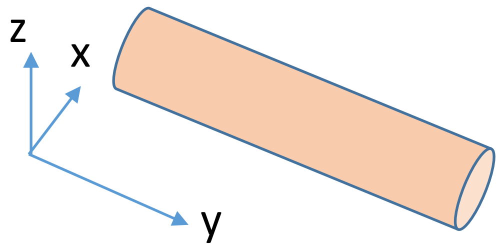


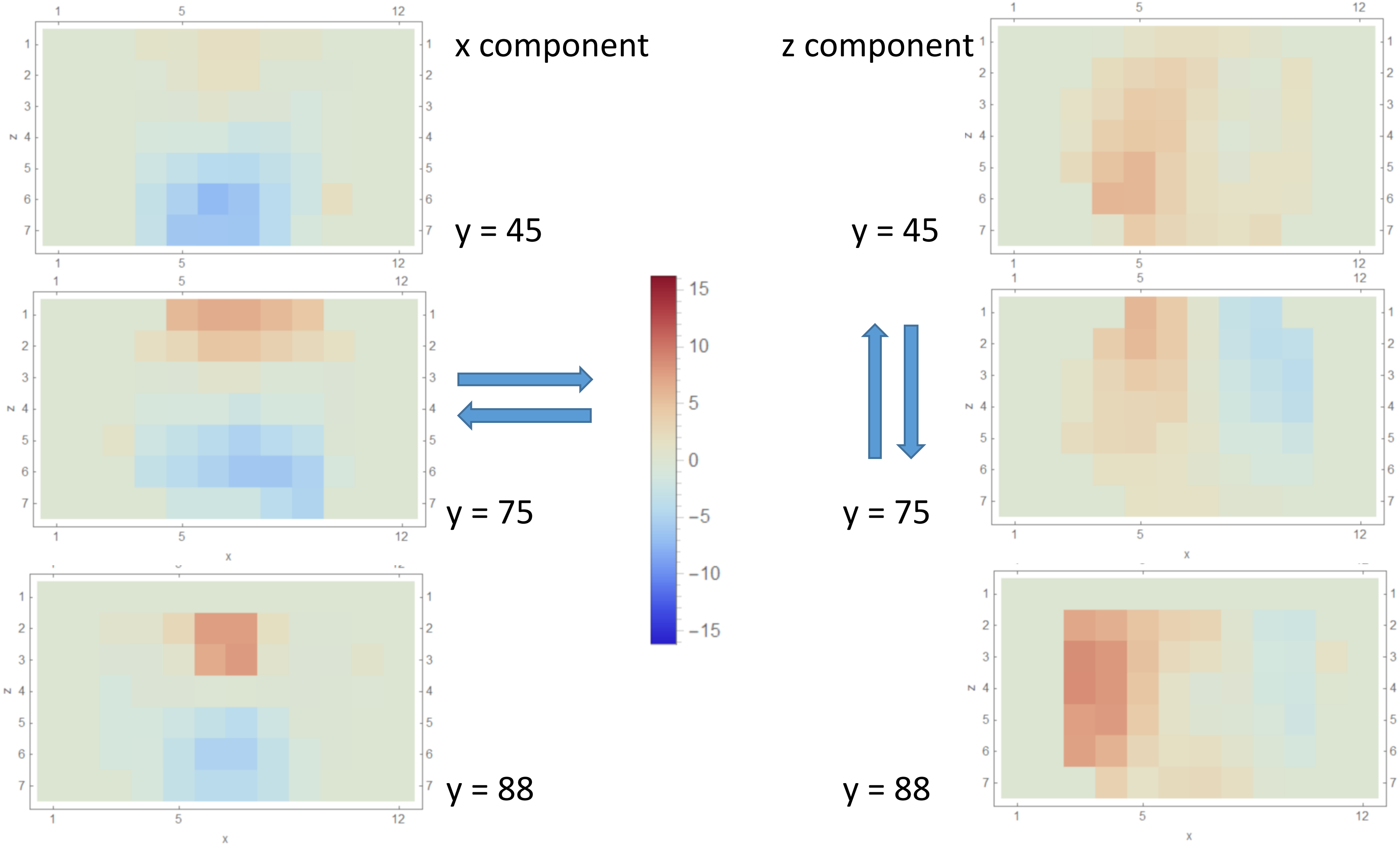


Transversal velocity (x component)

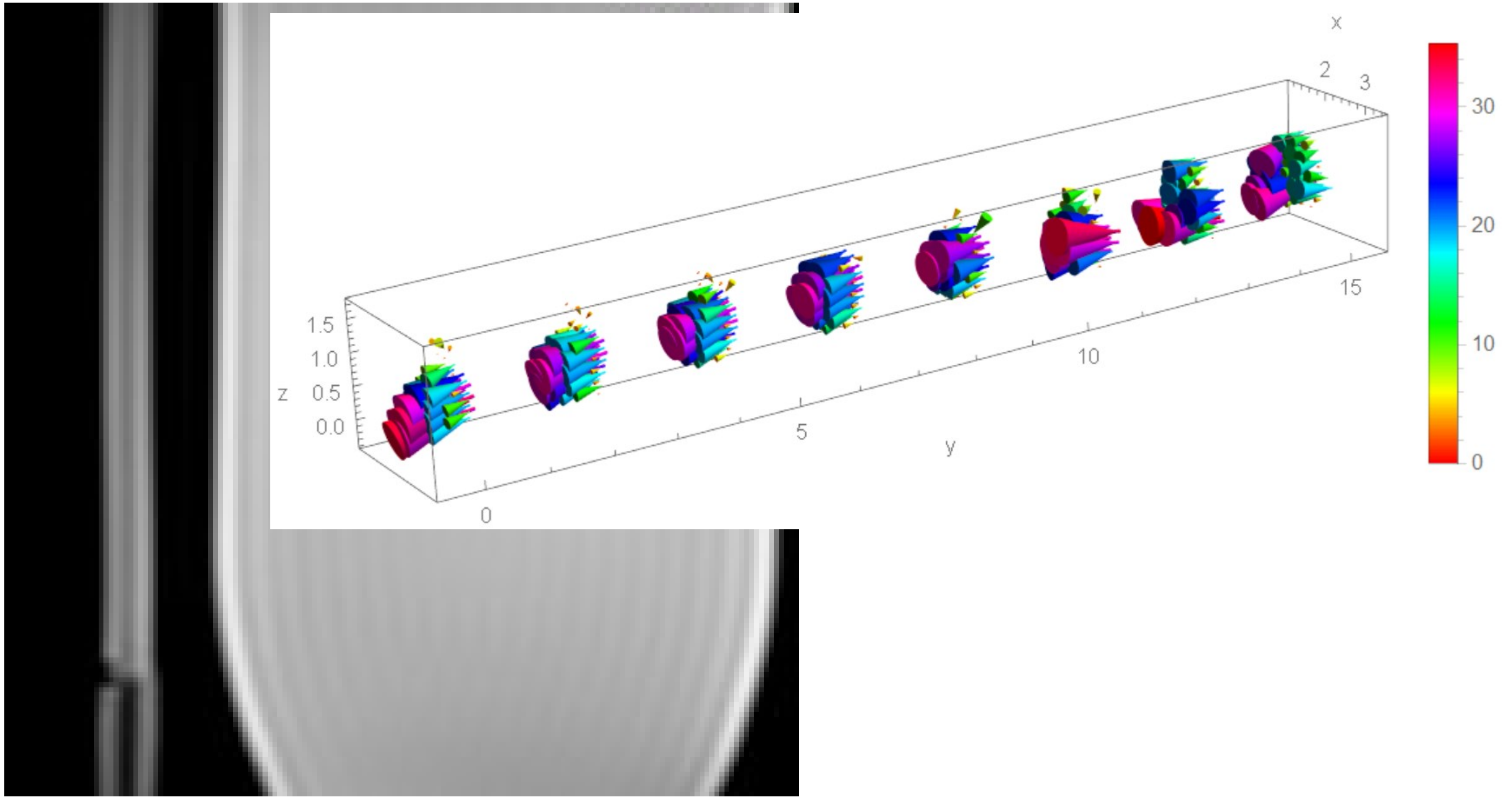


Transversal velocity

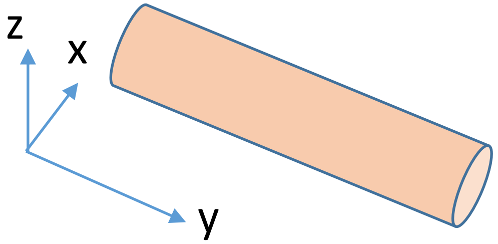




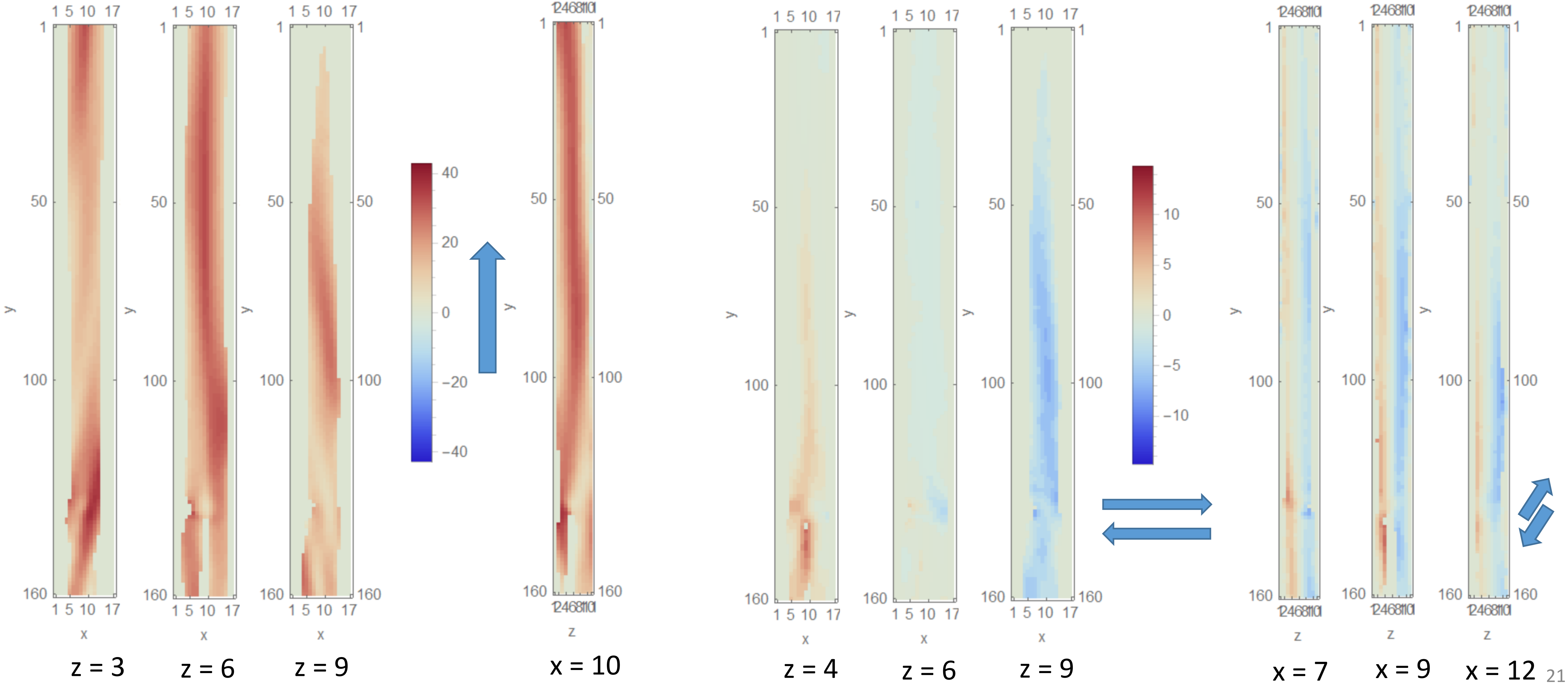
Matrix 160×160×11



Axial velocity

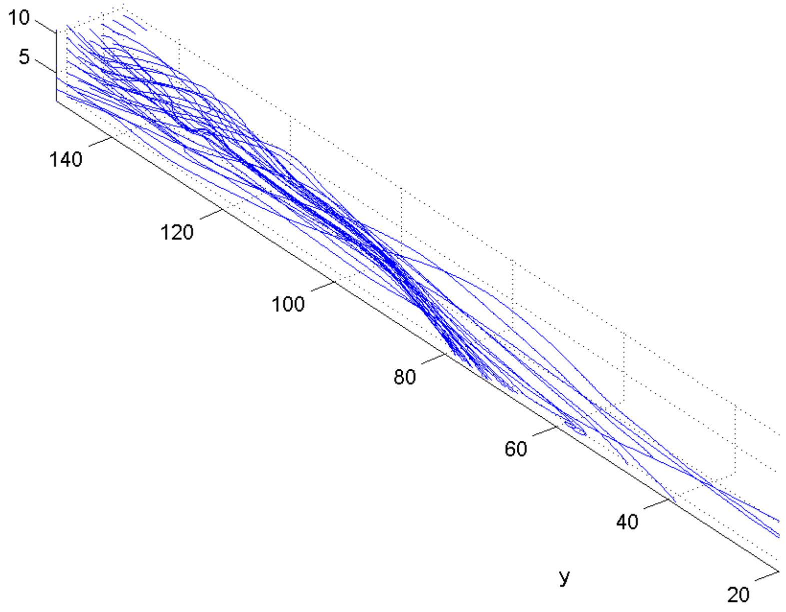


Transversal velocity (x component)

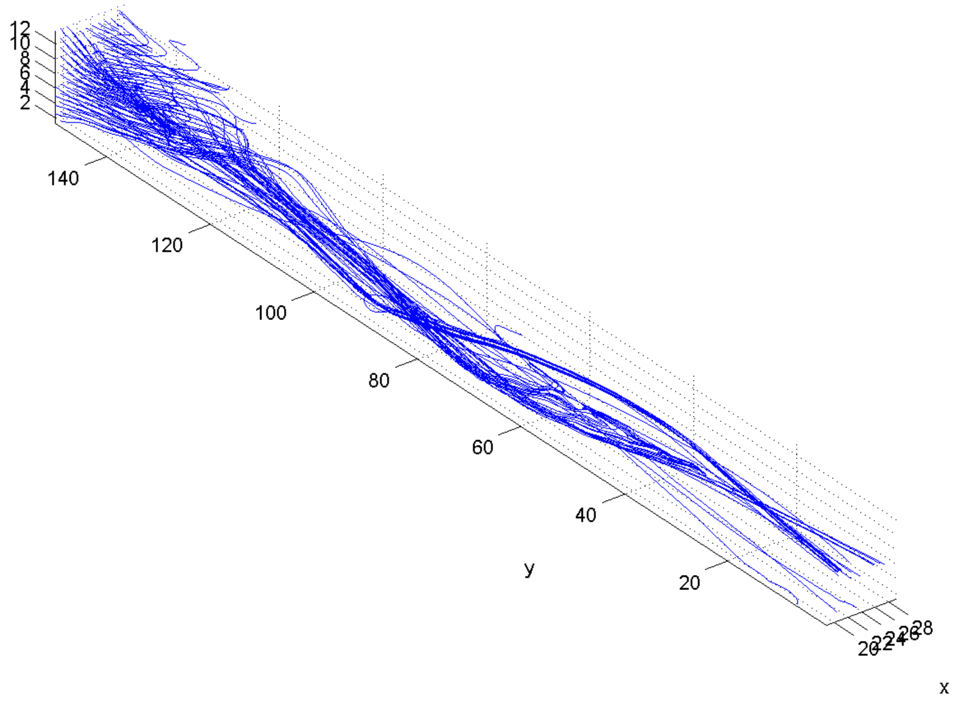


Streamlines

96×96×7



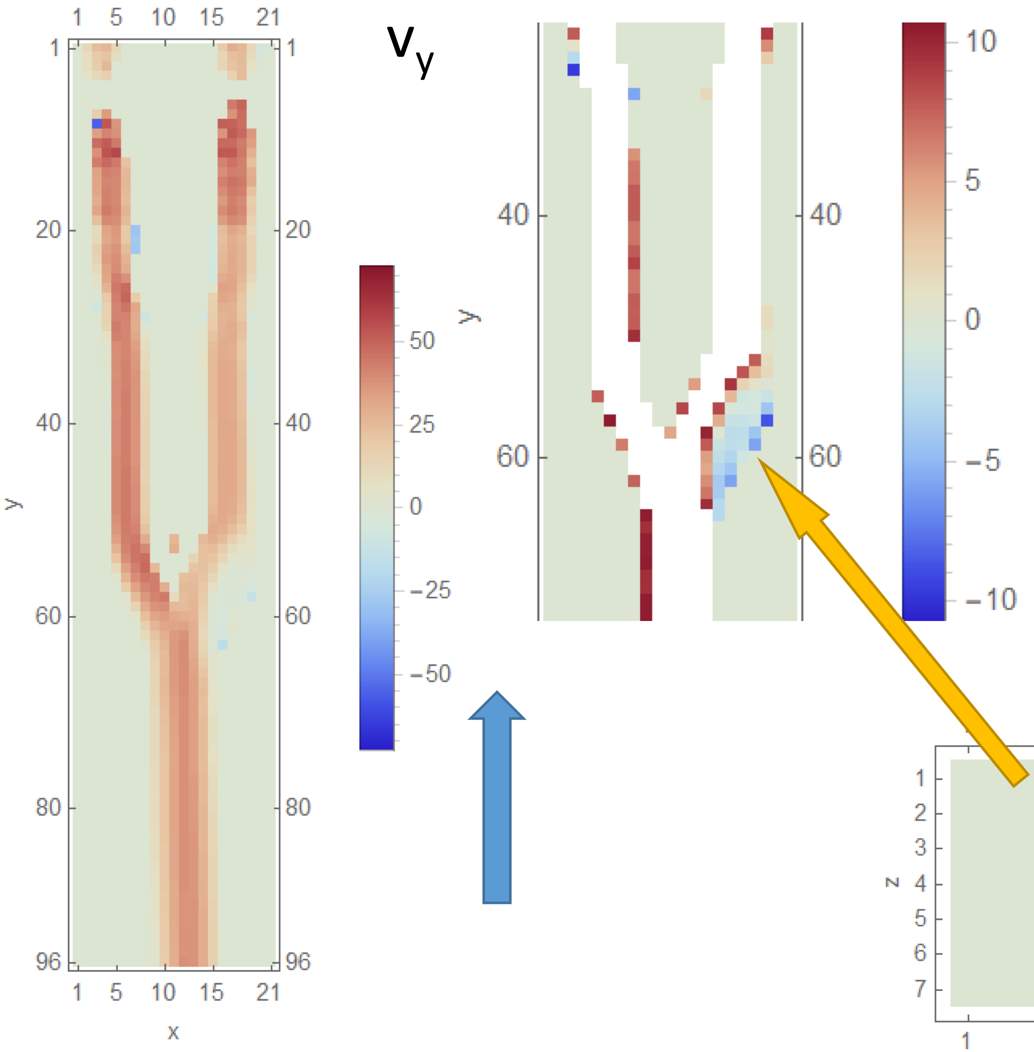
160×160×11

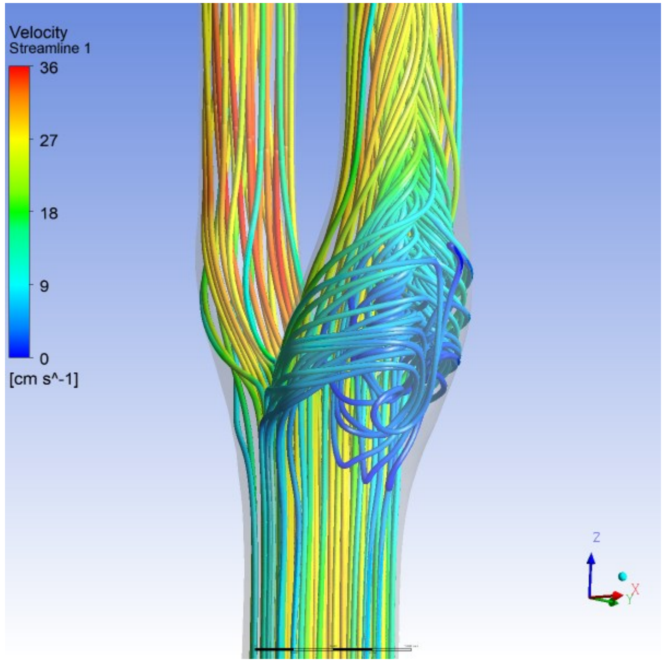


CCA bifurcation

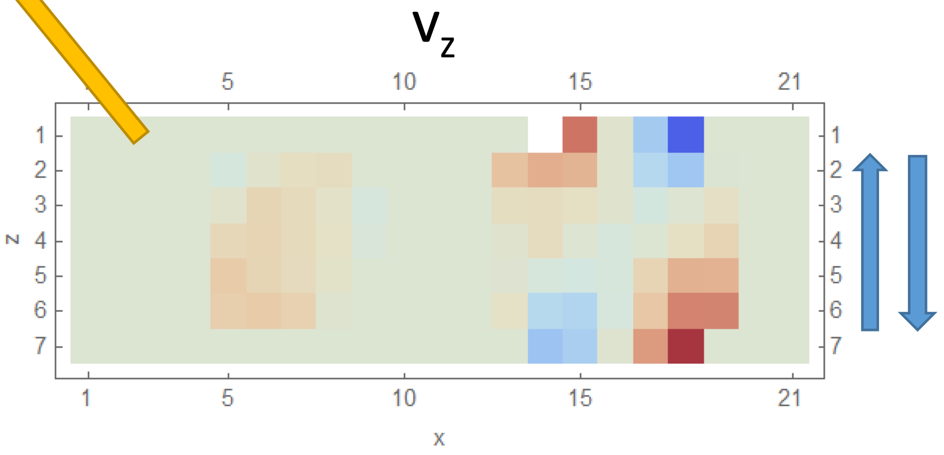
3D matrix	Time steps	Voxel, mm^3	Domain, mm^3	Files
96×96×7	20	1.56×1.56×1.5	150×150×10.5	4 × 280

Velocity field

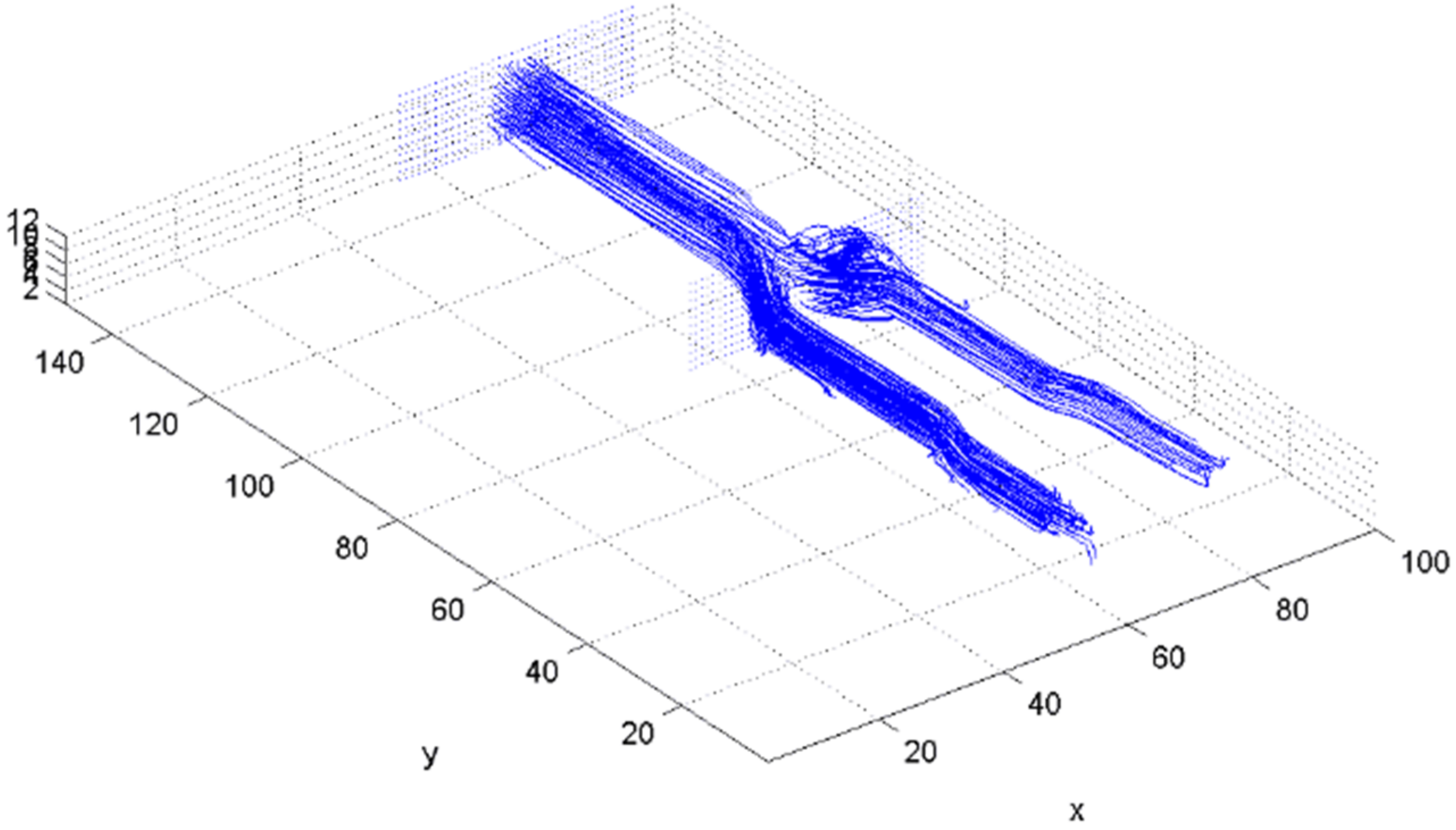




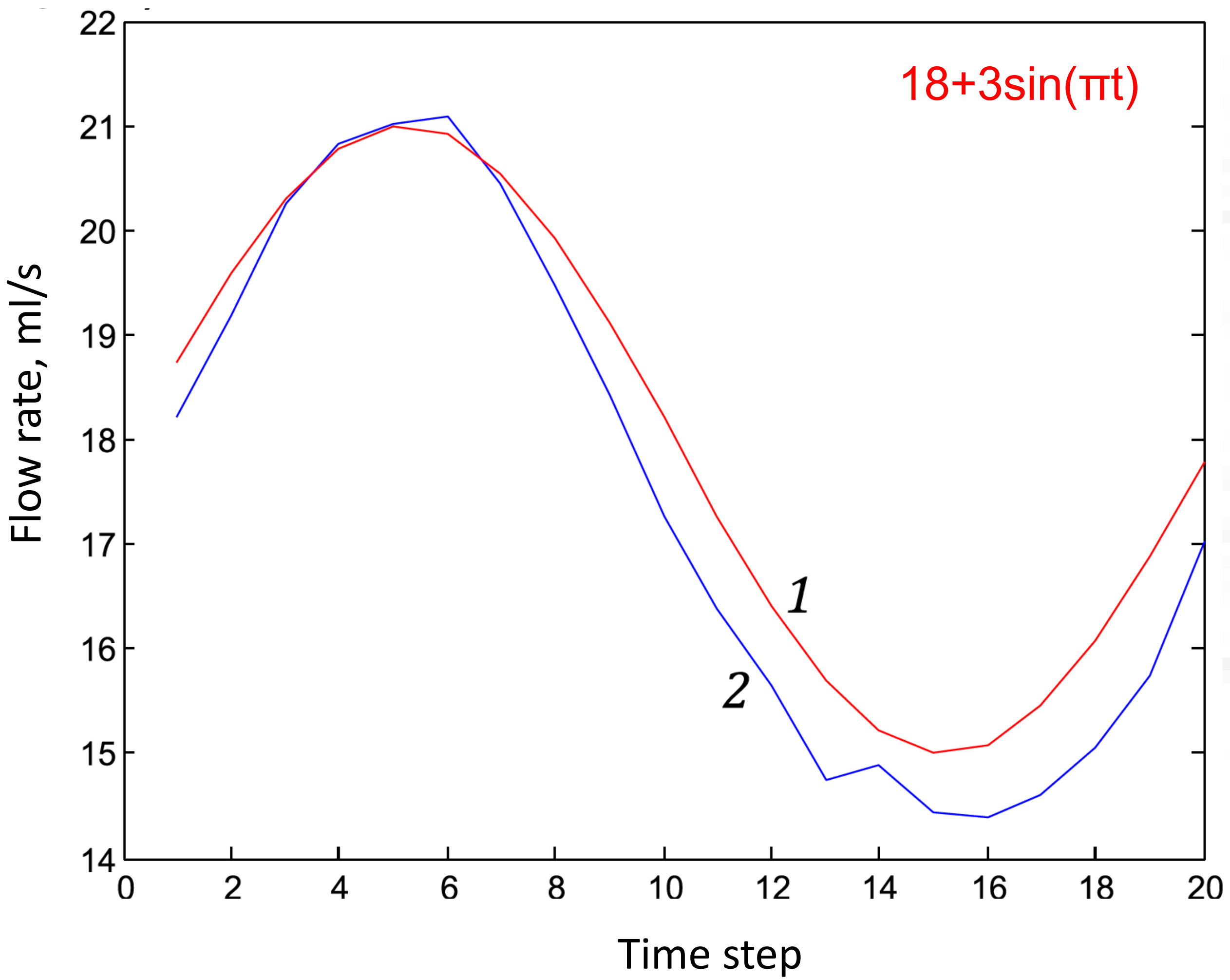
CFX simulation

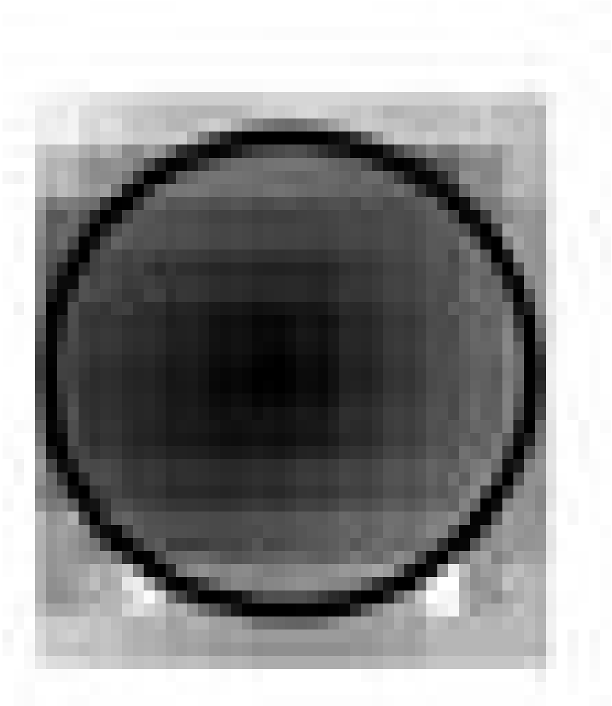


Streamlines



Flow rate in tube





Tube cross-section

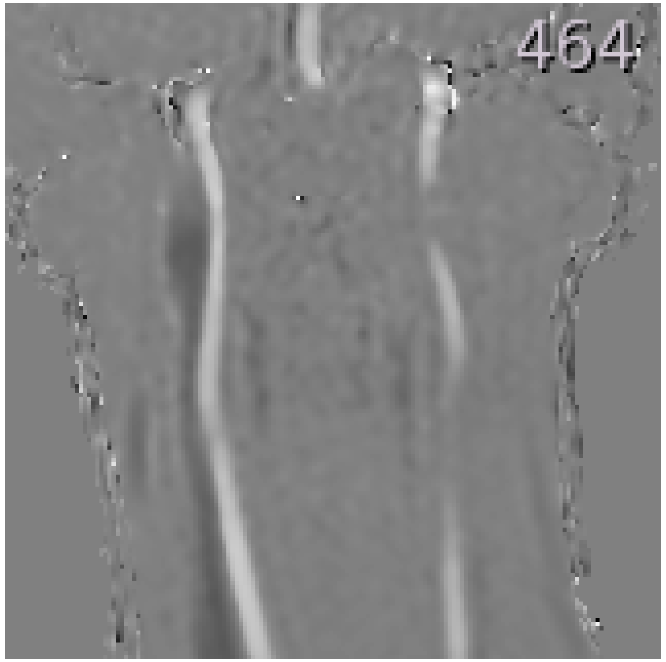
Patients and volunteers

	Patient	ROI	Cross-Section
1	GTS [F, 24 y/o]	BA	Transverse, coronal
2	KMY [M, 39 y/o]	BA, CCA	Transverse, sagittal
3	CTE [F, 33 y/o]	BA	Transverse
4	YGS [F, 24 y/o]	CCA+VA	Coronal
5	LAI [F, 22 y/o]	CCA+VA	Coronal
6	KYO [F, 23 y/o]	CCA+VA	Coronal

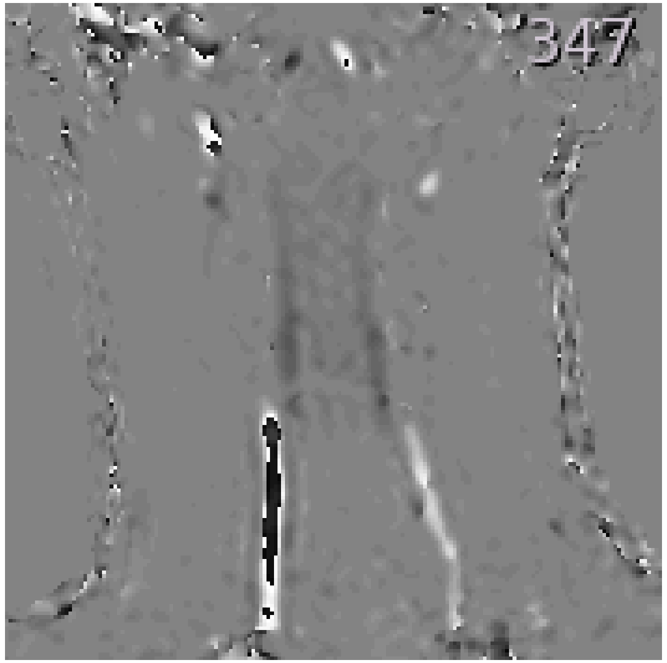
LAI [F, 22 y/o]

Density

High velocity

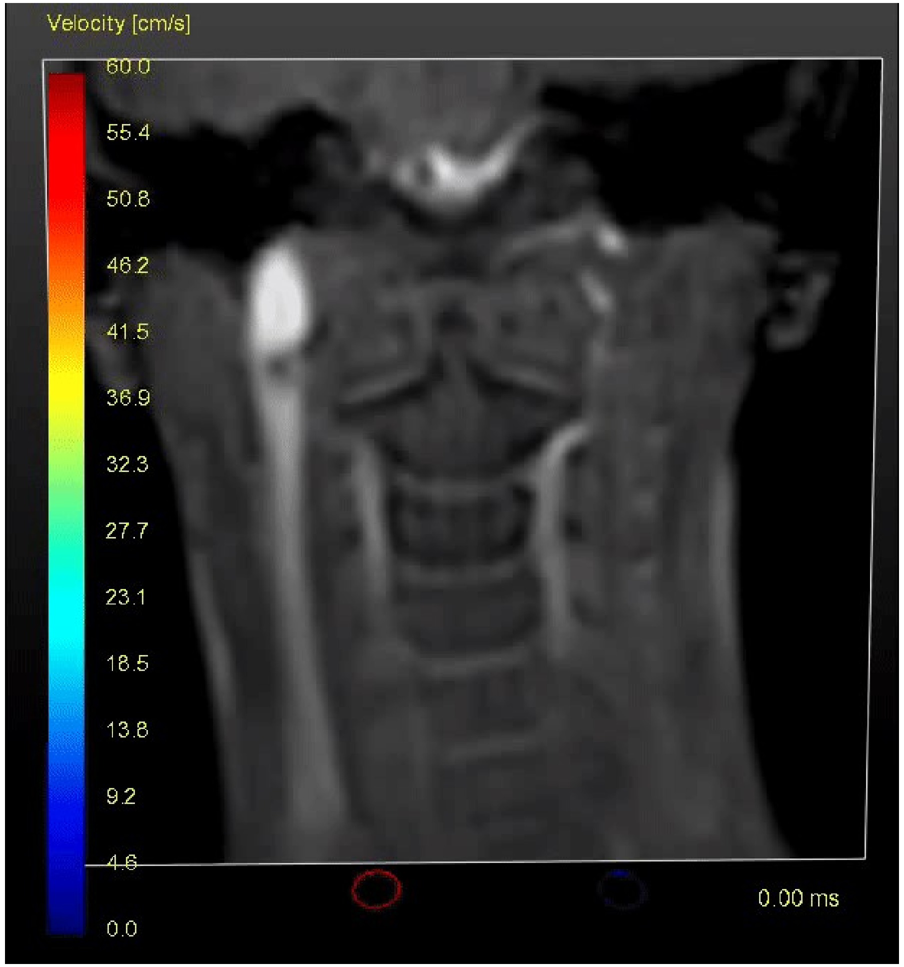


Low velocity



Resolution	Time steps	Voxel size, mm³	ROI size, mm³	Max velocity
160 × 160 × 14	20	0.94 × 0.94 × 1.25	150 × 150 × 17.5	100
176 × 176 × 14	20	0.86 × 0.86 × 1.35	152 × 152 × 18.9	18

LAI [F, 22 y/o]


Velocity [cm/s]
60.0
55.4
50.8
46.2
41.5
36.9
32.3
27.7
23.1
18.5
13.8
9.2
4.6
0.0
0.00 ms


0.0
4.2
8.3
12.5
16.7
20.8
25.0
Velocity [cm/s]
0.00 ms

Conclusion

- Possibility to study non-stationary three-dimensional structure of the blood flow with magnetic resonance imaging is shown.
- This allows one to estimate not only volumetric flow rate and linear velocity but also secondary (rotational) flows.
- The scanning protocol is planned to be used in medical examinations for studying the blood and cerebrospinal fluid flow structure and its influence on the functioning of the circulation system and on the development and growth of the pathologies.