Accurate Estimation of the volume flow rate in the cerebral artery using 3D cine phase-contrast MRI (4D-Flow)

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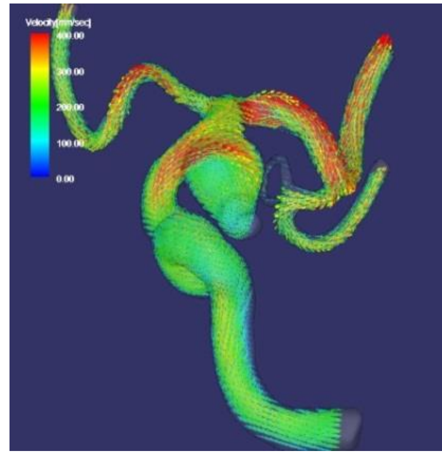
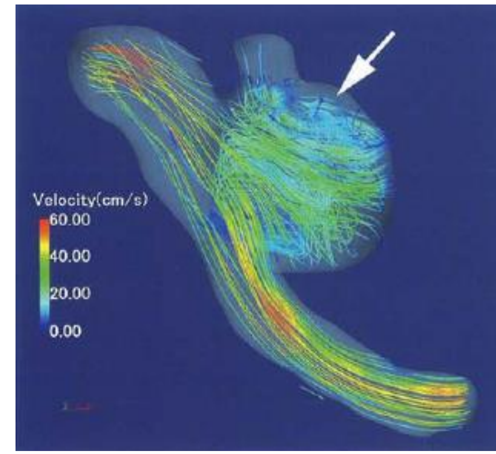
Introduction

Target of our research

Patient-specific vascular computational fluid dynamics (CFD) for intracranial aneurysms





Goal of our research

Accurate calculation of WSS, pressure, etc.
in aneurysms with CFD
and
making a tool for clinical quantitative
hemodynamic evaluation

Introduction (cont.)

Three requirements for patient-specific CFD

1. Accurate Vascular Shape,
2. Accurate Blood Viscosity Model,
3. Accurate Inlet and Outlet Boundary Conditions (BCs).

In this study, we focus on achieving
"Accurate Inlet and Outlet BCs"
using 4D Flow velocimetry.

Siemens scanner (Magnetom Verio 3.0T; Siemens AG, Healthcare Sector, Erlangen, Germany)

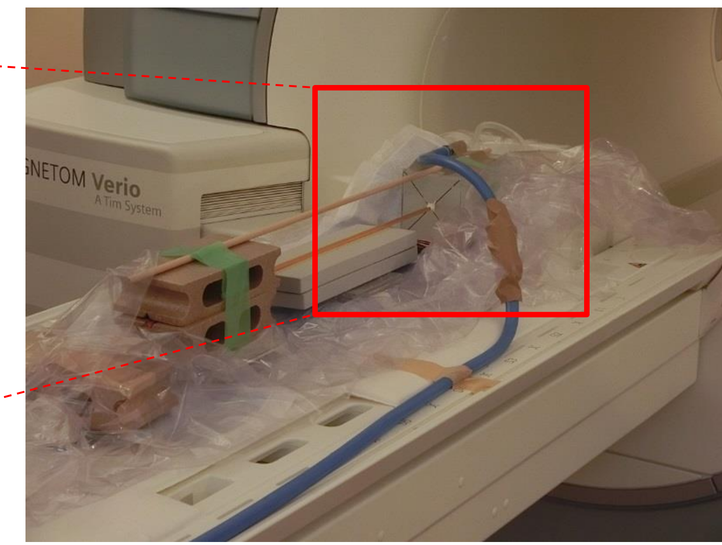
Problem in 4D Flow Velocimetry

The error of 4D Flow velocimetry is too large to ignore.

For example…

Settings of a typical phantom study

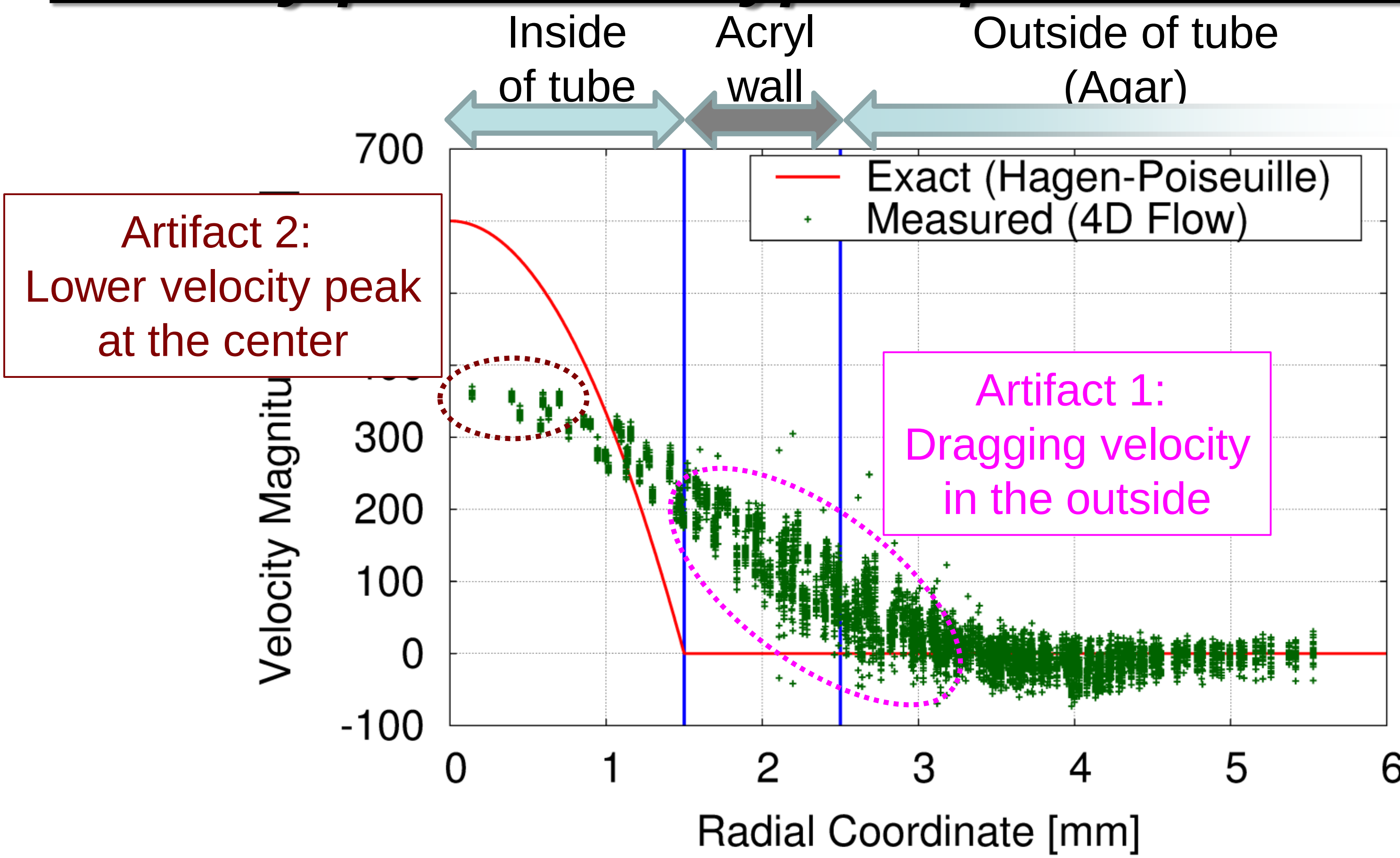
Target phantom
(acryl tube surrounded by agar)



Steady laminar flow of glycerol-water solution in the tube is measured.

Problem in 4D Flow Velocimetry (cont.)

Velocity profile of a typical phantom study



Acquisition Voxel Size: 1 mm^3

These artifacts are NOT due to the partial volume effect.

Cause of these artifacts: Phantom? 4D Flow itself? Or the both?
Anyway, it is difficult to obtain accurate velocity profile.

Strategy & Objective

Strategies for BC determination

- Estimation of the **volume flow rate (VFR)** is a lot easier than that of the velocity profile.
- Accurate VFR is a sufficient BC for CFD.

Objective

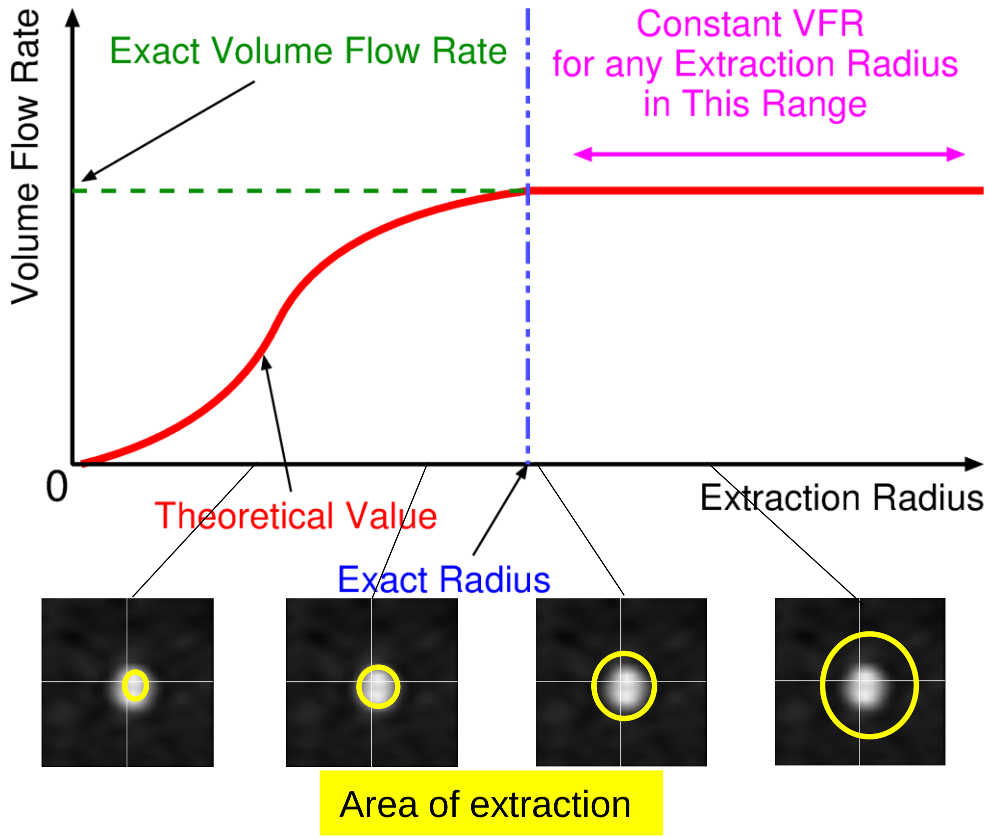
Propose a new method to estimate accurate **volume flow rate (VFR)** using 4D-Flow velocimetry

Method:
Procedure of our
VFR estimation method

Points

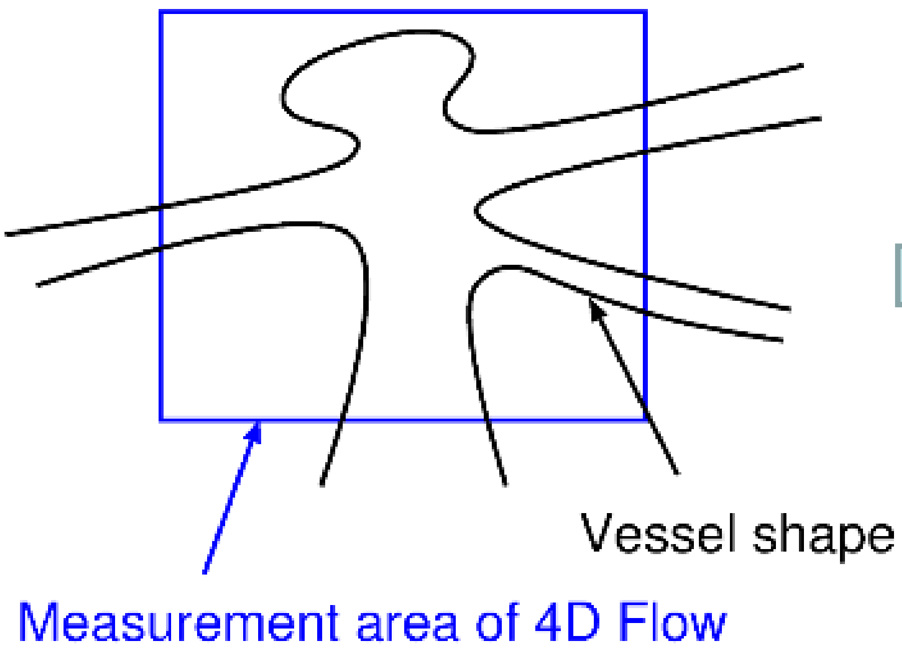
- The average velocity error of 4D Flow measurement is nearly zero [Y.Onishi et al., IJNMBE, 2013].
- The extravascular region is stationary.

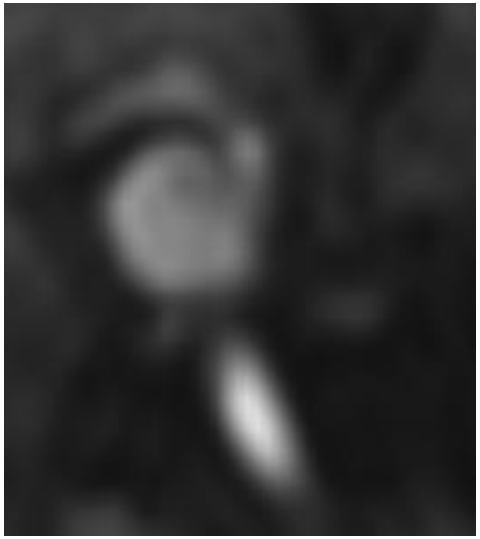
⇒ The mean velocity in the extravascular region is nearly zero.



Procedure (1 of 3)

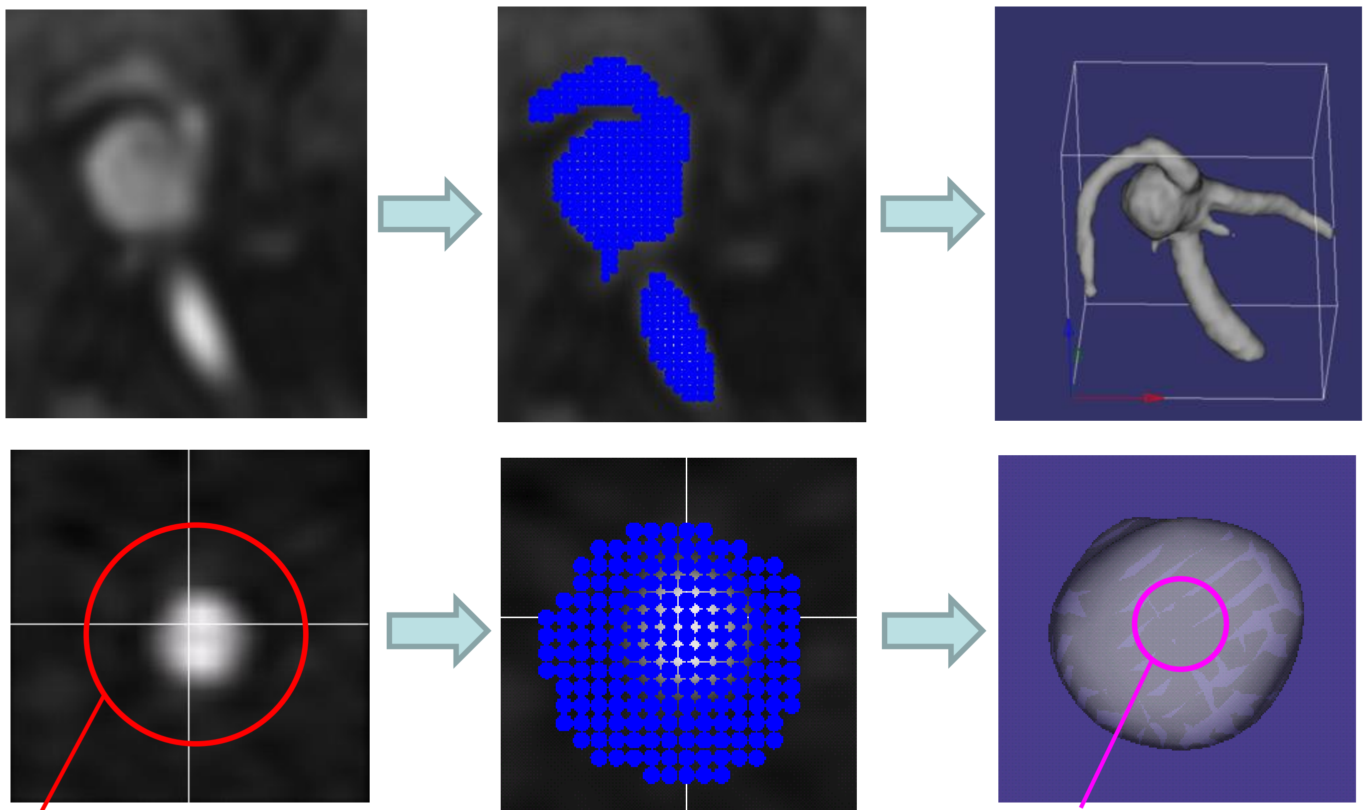
1. Measurement of the flow velocity vectors in all target vessel domains using 4D Flow.
2. Creation of 3D voxel data by combining the 4D Flow velocity magnitude images.





Procedure (2 of 3)

3. Extract a vessel region to be larger than the exact vessel shape using the region growing method.
4. Conversion to a polygon data.



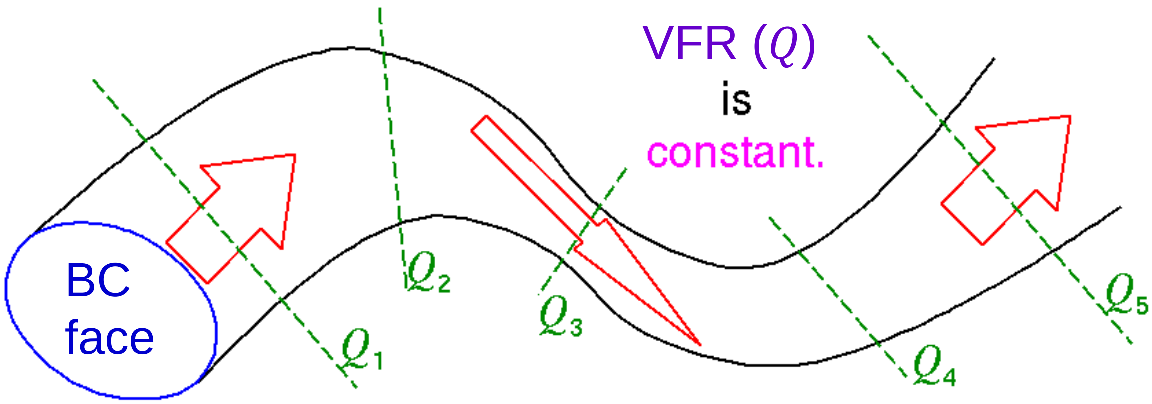
Cross-section view

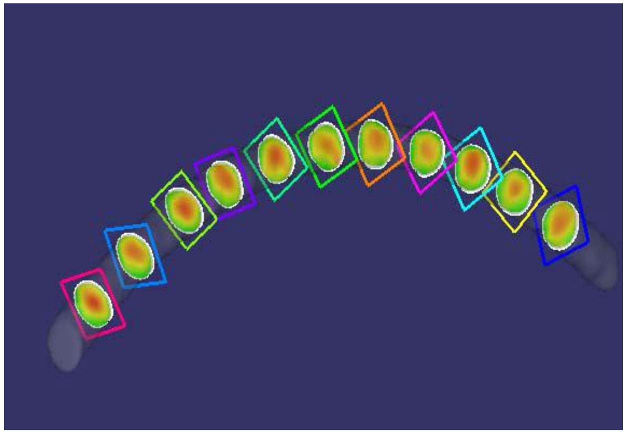
Extract this region

Exact vessel

Procedure (3 of 3)

5. Configure many virtual cross-sections near the BC face.
6. Calculate VFR on each virtual cross-section Q_k $(k = 1 \sim N)$.
7. Calculate the average of Q_ks, $\bar{Q}$ $(= \sum_{k=1}^{N} Q_k / N)$.

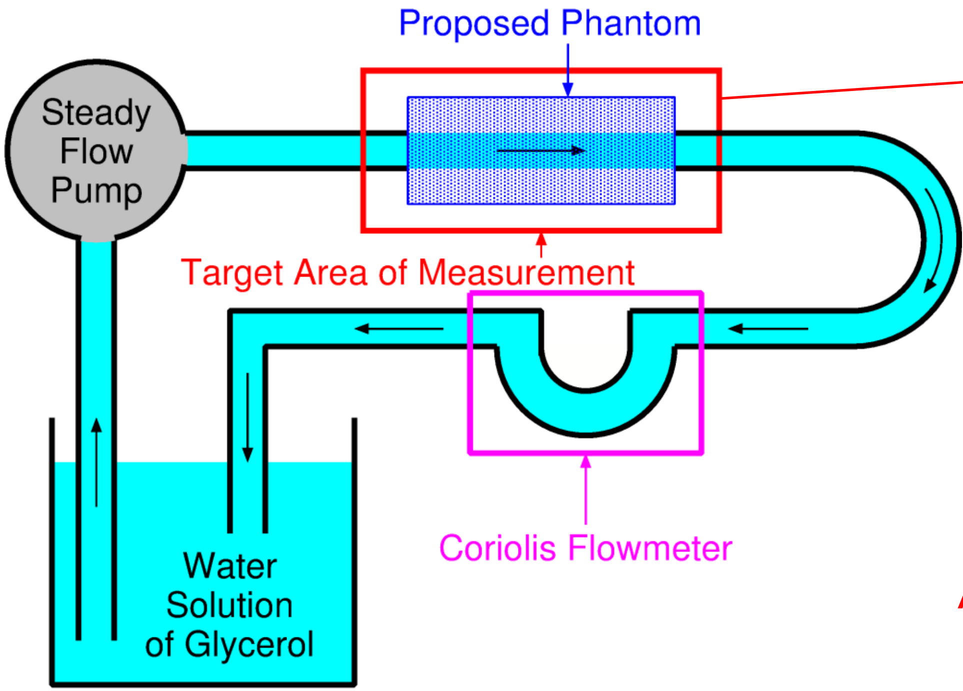


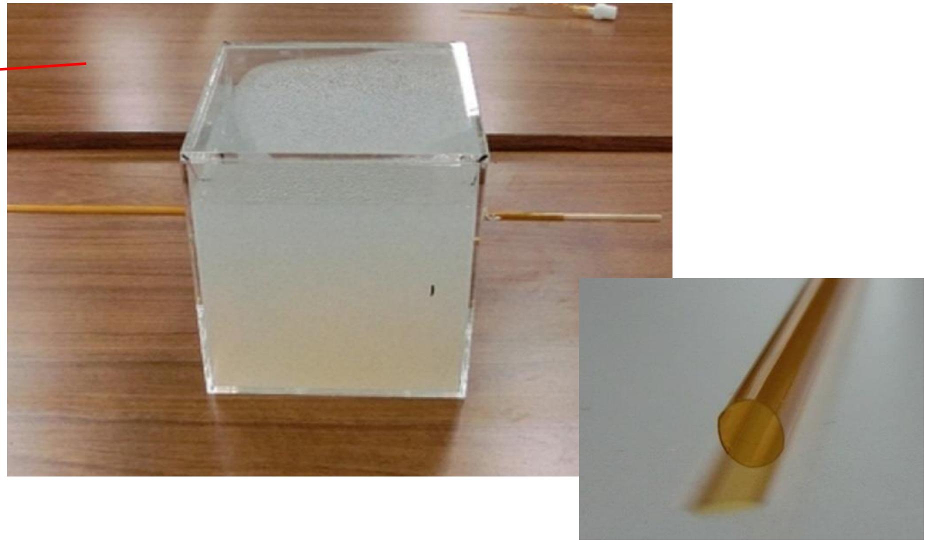


We use $\bar{Q}$ as the VFR BC

Result:
Validation experiments

Experiment Device

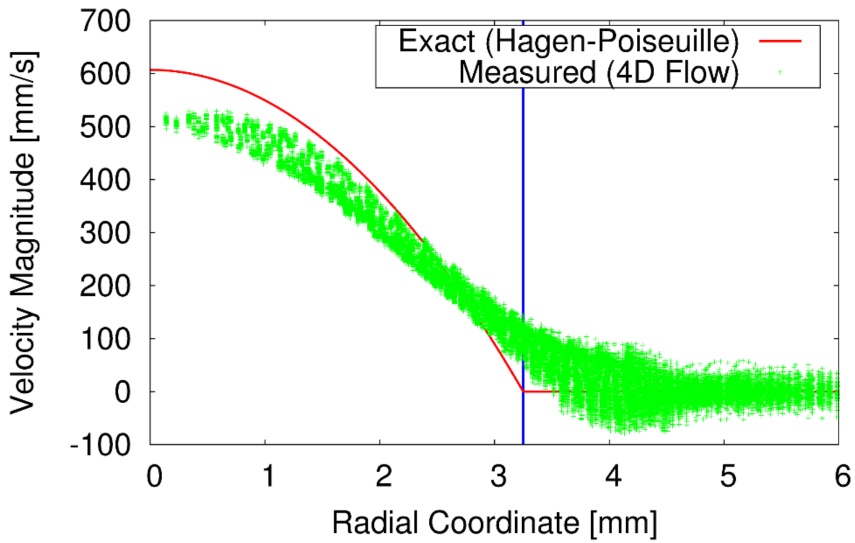




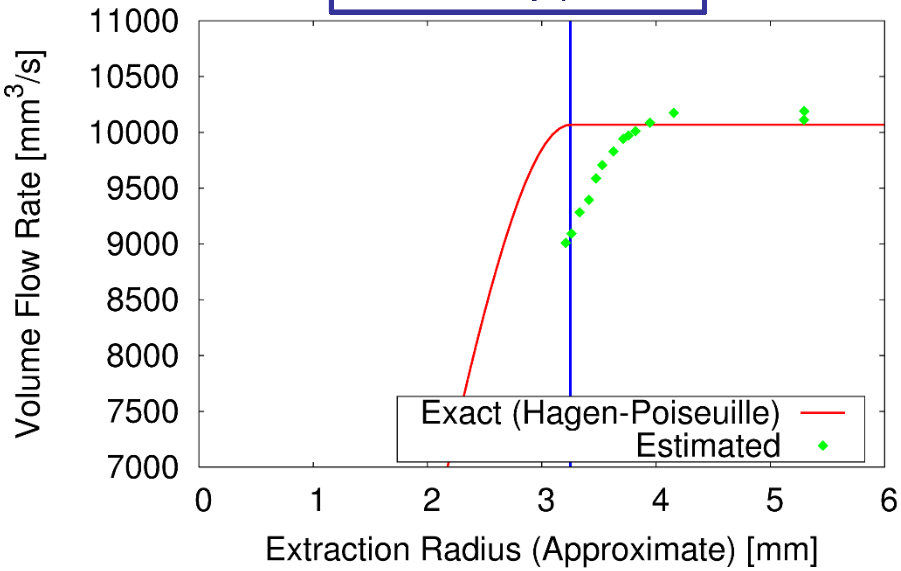
A thin-walled polyimide tube/agar phantom
(thickness: 0.05 mm)

- Measurement of Hagen-Poiseuille flow in the tube
- Straight tubes of ϕ=3.1, 6.5 mm
- Water solution of glycerol of 40wt% (no contrast agents)
- Steady laminar flow made by steady flow pump
- Coriolis flowmeter measures the actual VFR

Result 1: A Large Diameter Tube (ϕ=6.5 mm)



The velocity profile



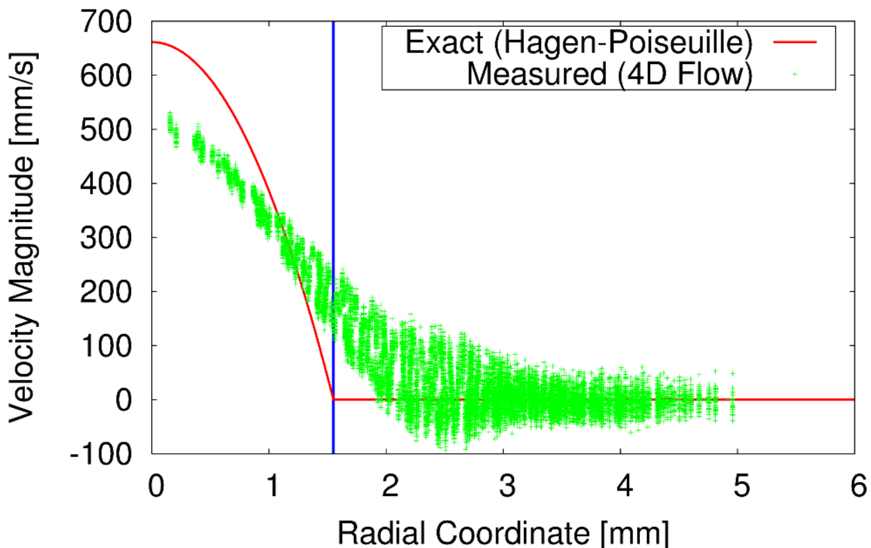
The VFR profile

- Our new phantom could reduce both the dragging velocity and lower velocity peak artifacts.
- The estimated VFR agreed with the theoretical curve.

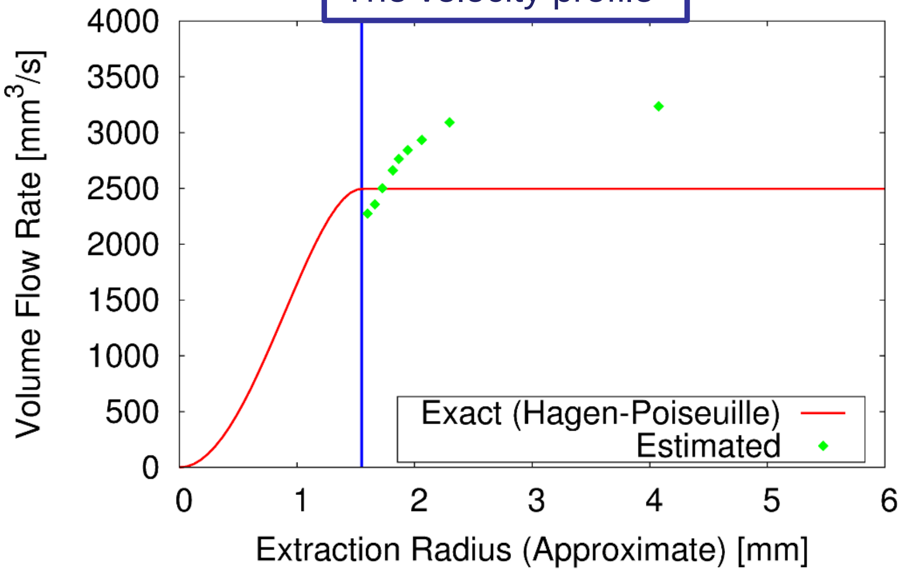
Actual VFR [mm^3/s]	10068
Estimated VFR [mm^3/s]	10190
Error	+1.9%

VFR is successfully estimated within 2% error.

Result 2: A Small Diameter Tube (ϕ=3.1 mm)



The velocity profile



The VFR profile

- The two artifacts were reduced but there still remains non-negligible measurement errors.
- The estimated VFR ultimately exceeded the exact VFR.
  - There remains a possibility of influence from the plastic wall.
  - Dispersion may occur in 4D Flow velocimetry itself.

Actual VFR [mm^3/s]	2496
Estimated VFR [mm^3/s]	3235
Error	+29.4%

VFR is estimated with 30% error, which is too large.

Summary

Summary

- A new method to estimate accurate VFR using 4D Flow velocimetry is proposed.
- In case of steady laminar flow, the VFR in a tube > 6 mm in diameter can be accurately estimated by our method. But, in a tube < 6 mm in diameter, the VFR cannot be estimated with a practically sufficient accuracy.
- It is NOT recommended to use thick-walled sold phantoms or bulk sold phantoms for 4D Flow validation tests.

Thank you for your attention.
And I appreciate your questions and comments
<u>in slow English without medical terms!!</u>

Appendix

Acquisition Parameters (acryl)

Scanner	Siemens Magnetom Verio 3.0T
Coil	12 ch Head coil
PAT	2
Phase partial Fourier	6/8
Slice partial Fourier	6/8
TR [ms]	33.6
TE [ms]	4.32
Acquisition Time	8:40
FOV [mm]	160×160
Matrix	160×160
Slice Thickness [mm]	1.00
FA [deg]	15
VENC [m/sec]	1.2

Acquisition Parameters (polyimide)

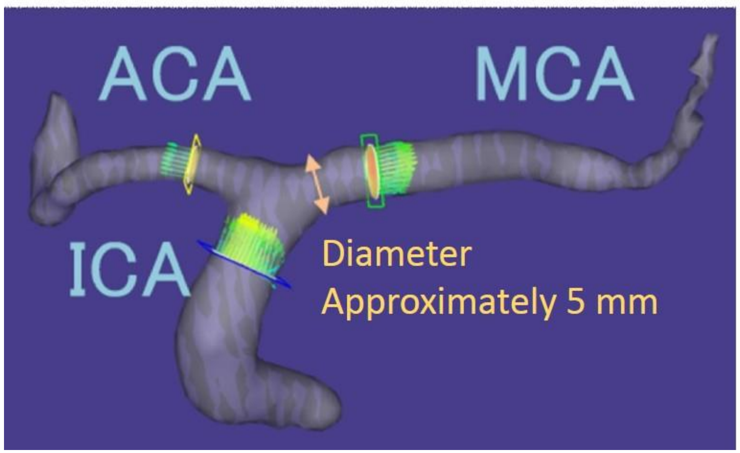
Scanner	Siemens Magnetom Verio 3.0T
Coil	12 ch Head coil
PAT	Off
Phase partial Fourier	Off
Slice partial Fourier	Off
TR [ms]	37.04
TE [ms]	5.06
Acquisition Time	26:41
FOV [mm]	160×160
Matrix	160×160
Slice Thickness [mm]	1.00
FA [deg]	15
VENC [m/sec]	1.2

Comparison of the maximum flow velocity

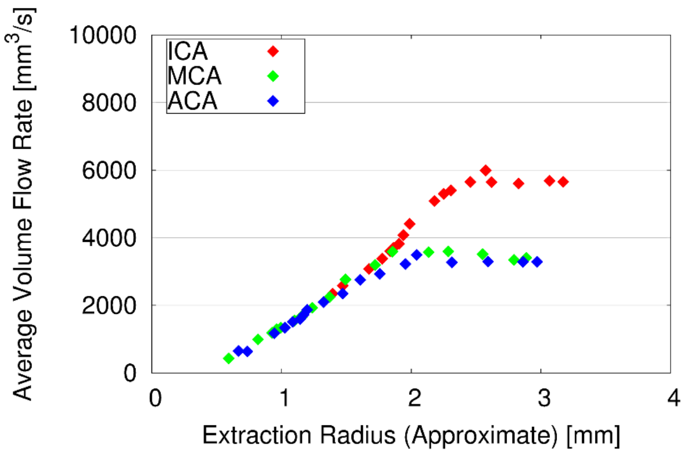
Case name	Exact maximum velocity [mm/s]	Measured maximum velocity [mm/s]	Error [%]
Acryl 3.0 mm	600.12	346.68	-42.2
Acryl 6.0 mm	599.95	458.77	-23.5
PL/Agar 3.1 mm	661.38	511.34	-22.7
PL/Agar 6.5 mm	606.85	516.95	-14.8

10-20% reduction in the lower velocity peak artifact.

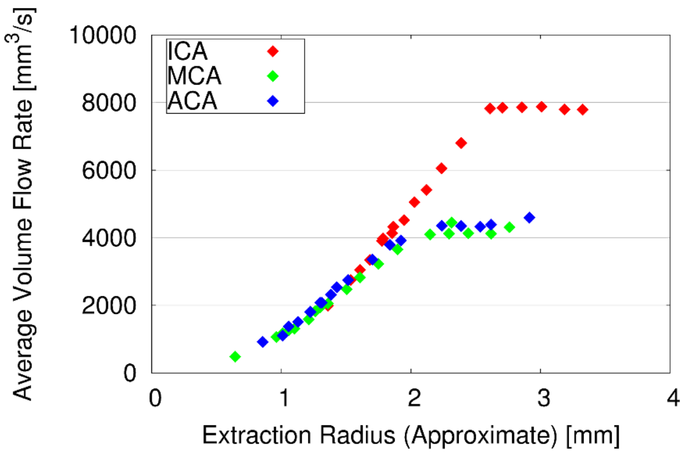
Validation Experiment on 1 Healthy Volunteer



We estimated average VFR in 1 heartbeat on 3 cross-sections (ICA, MCA and ACA).



Result with GE Scanner



Result with Siemens Scanner

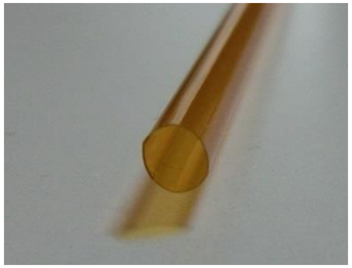
The VFR becomes constant at the point where it exceeds the exact radius (approximately 2.5 mm).

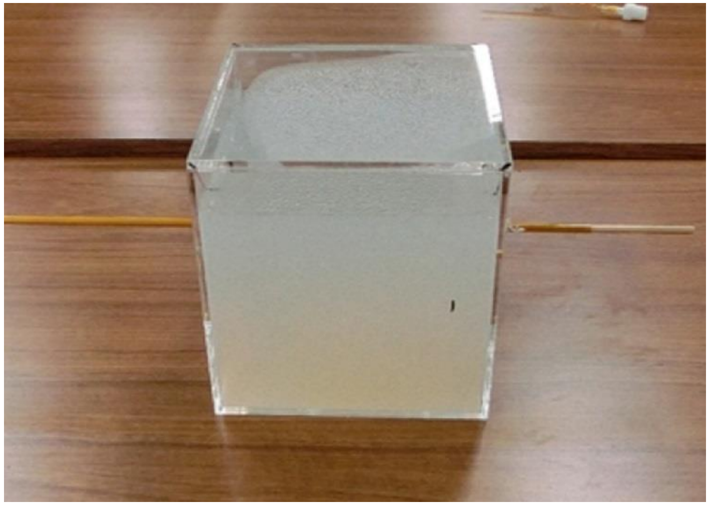
Points of Our New Phantom

Important factors for the phantom

- The continuity of the proton density between the inner and outer areas of the tube.
- The phantom moisture content is similar to the moisture content of the white matter of the brain.

Acquisition Voxel Size: 1 mm^3
Polyimide tube wall thickness: 0.05 mm



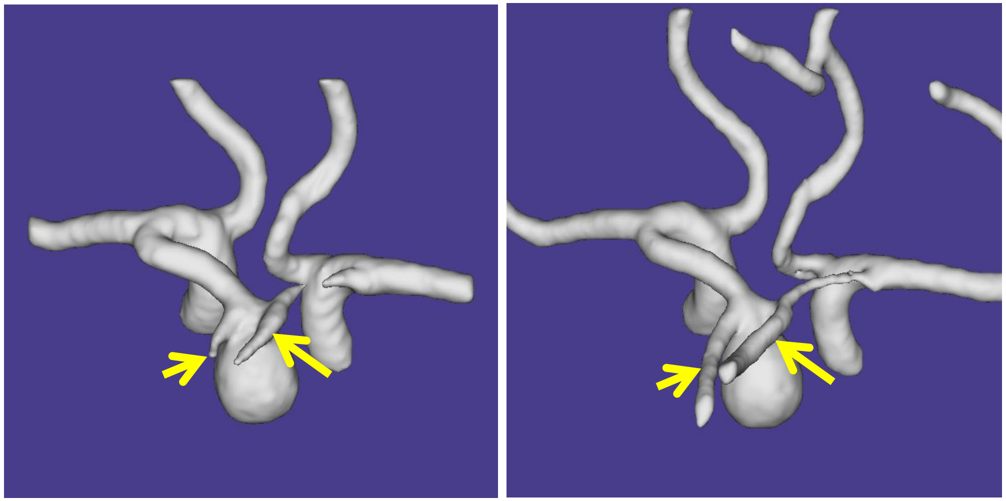


It is difficult for the scanner to detect the thickness if the ratio to the spatial resolution is < 0.1.

Extraction of Vessel Shape using 4D Flow

- Accurate extraction of vessel shapes using 4D Flow is difficult.

A comparison of extracted silicone cerebral aneurysm phantom vessel shapes.

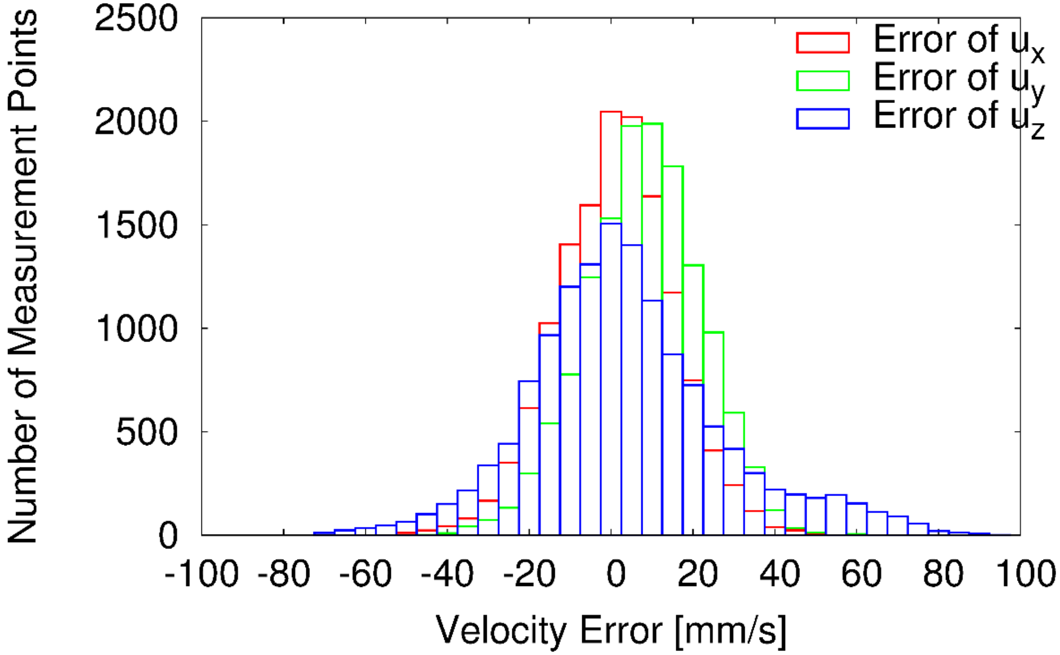


4D Flow rephased imaging　　3D TOF MRA

- A number of surface deterioration point were included.
- No vessel shapes were extracted (at arrow point).

Review: Error Eval. of 4D-Flow

Histogram of error distribution of 4D Flow velocimetry



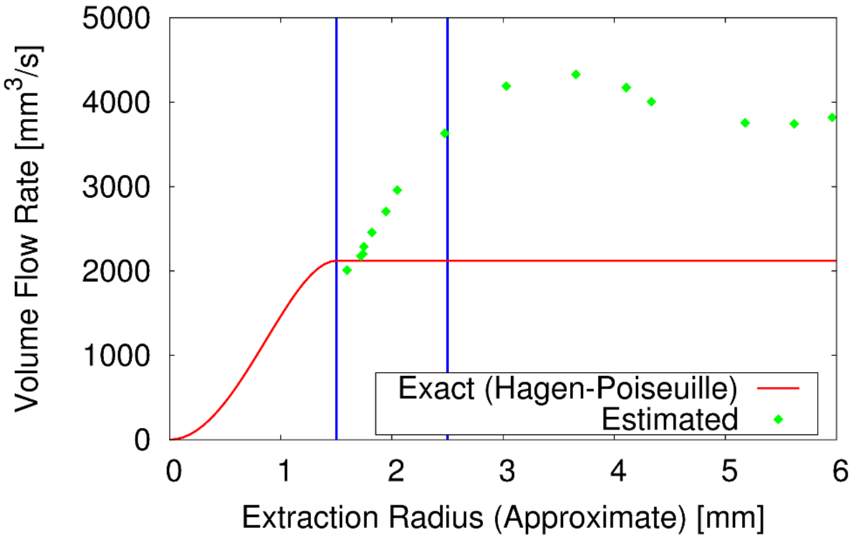
Using a velocity profile in outside of the tube.

- Each error of flow velocity components has similar distribution ($\mu = 1.73$ mm/s).

The average velocity error of measurement is almost zero.

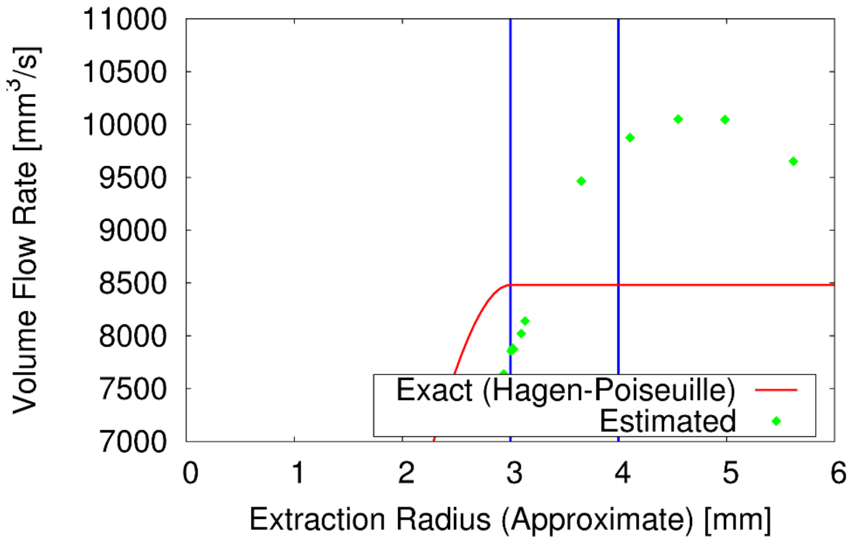
Result: Acryl Tube

3.0 mm in inner diameter



The VFR profile

6.0 mm in inner diameter



The VFR profile

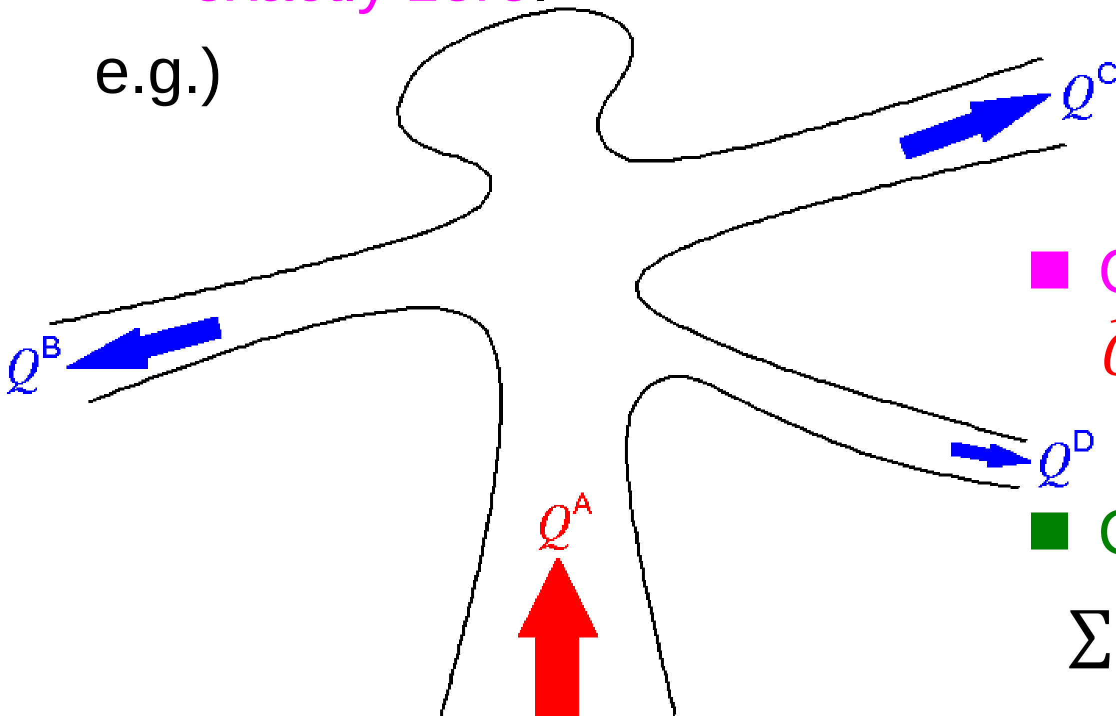
	3.0 mm in inner diameter	6.0 mm in inner diameter
Actual VFR [mm^3/s]	2121.0	8482.0
Estimated VFR [mm^3/s]	4318.0	10167
Error	+103.6%	+19.8%

Procedure: Estimation of VFR

Estimation procedure

- Correct $\bar{Q}$s of all inlets/outlets so that the sum of VFRs is exactly zero.

e.g.)



- Constraint

$$\widehat{Q^A} - \widehat{Q^B} - \widehat{Q^C} - \widehat{Q^D} = 0$$

- Cost Function

$$\sum_{i=A,B,C,D}\left(\widehat{Q^i} - \overline{Q^i}\right)^2 \rightarrow \min$$

- Set the corrected VFR ($\hat{Q}$) as the estimated VFR.