Accurate Determination of Inlet/Outlet Boundary Conditions in Vascular CFD Analysis using 4D-Flow Velocimetry

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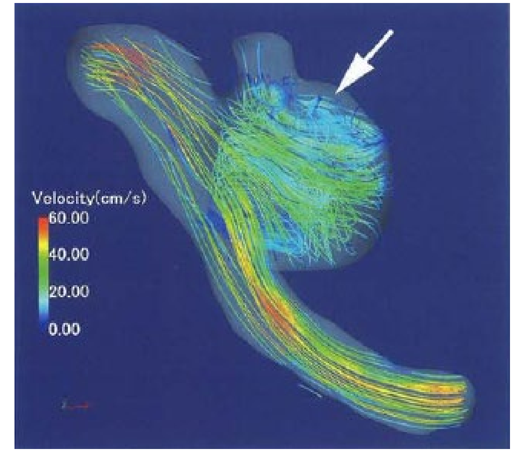
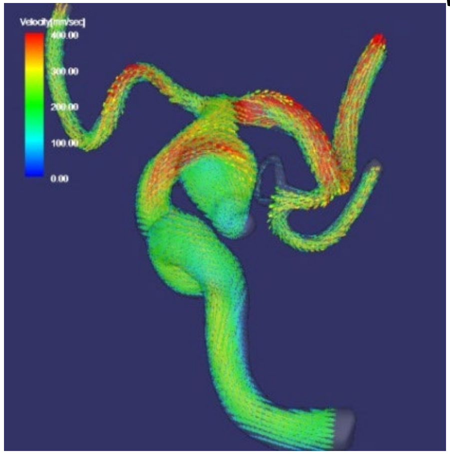
Introduction

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

Tool for clinical quantitative hemodynamic evaluation

Introduction (cont.)

Three requirements for vascular CFD

1. Accurate Extraction of Vascular Shape
2. Accurate Setting of Blood Viscosity Model
3. Accurate Determination of Inlet/Outlet BC

All of them are essential for the practical vascular CFD.

+

Density and Viscosity?

Newtonian or Non-Newtonian?

+

Flow Rate, Velocity or Pressure?

⟹

Accurate Vasclular CFD

In this study, we focus on "3. Accurate Determination of Inlet/Outlet BC".

Conventional Methods

Conventional methods of BC determination

- Giving the standard (well-used) volume flow rate (VFR)
- Giving a VFR so that representative WSS is the standard
- Giving a Womersly velocity profile of the standard VFR

→ Physical basis is too weak.

- Giving a velocity profile measured by 2D/3D cine PC-MR.

→ Measurement error (artifact) is too large.

The method to determine the inlet/outlet BC accurately have not been established yet.

Objective

Objective

Propose a new method

to determine <u>accurate</u> inlet/outlet BC

for vascular CFD

using 4D-Flow

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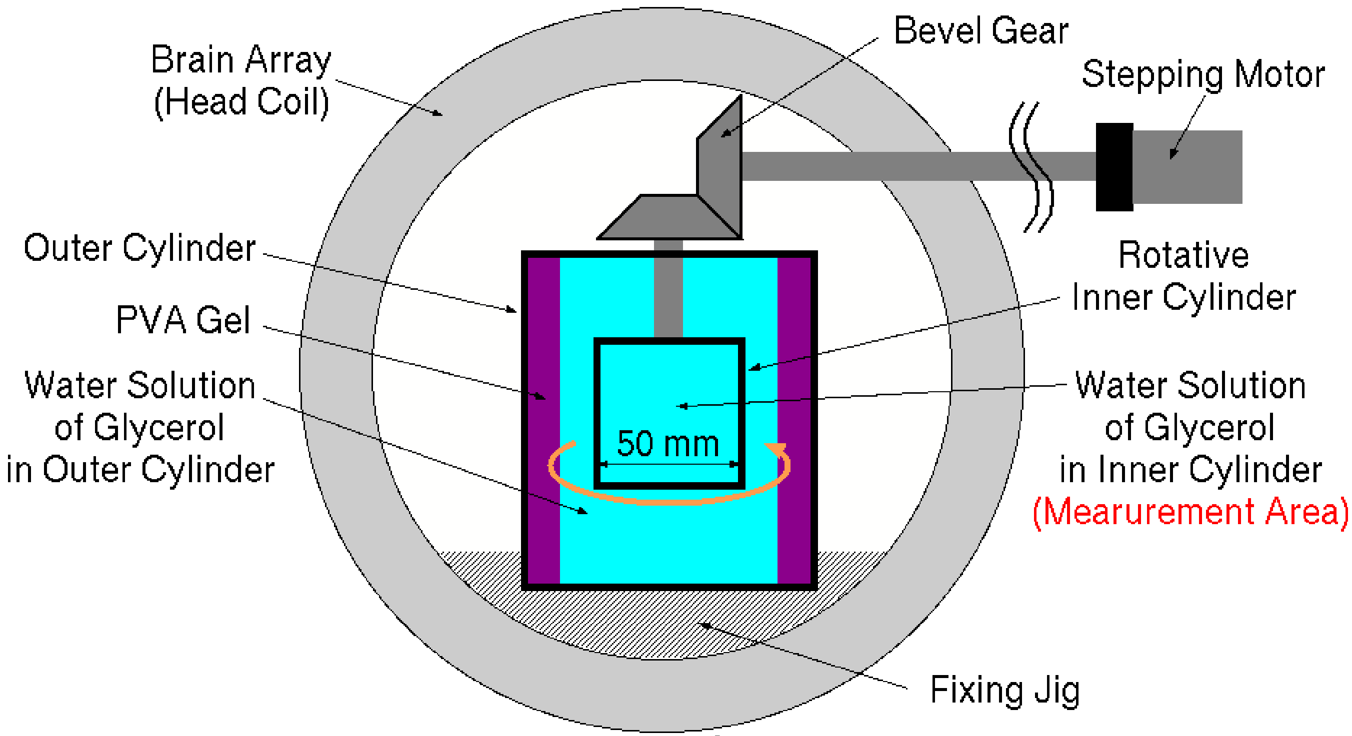
Part 1:

Experiments for error evaluation of 4D-Flow

Error Eval. of 4D-Flow (Device)

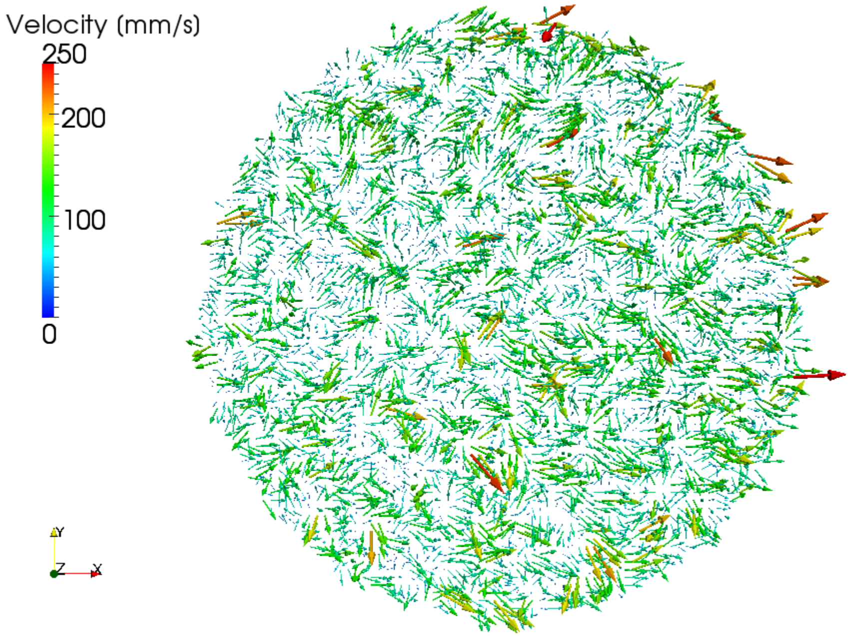


- Rotative phantom (nested two cylinders)
- Water solution of glycerol of 40wt% (no contrast agents)
- GEHC Signa HDxt 3.0T with 8ch brain array
- Rotate the inner cylinder at a constant speed

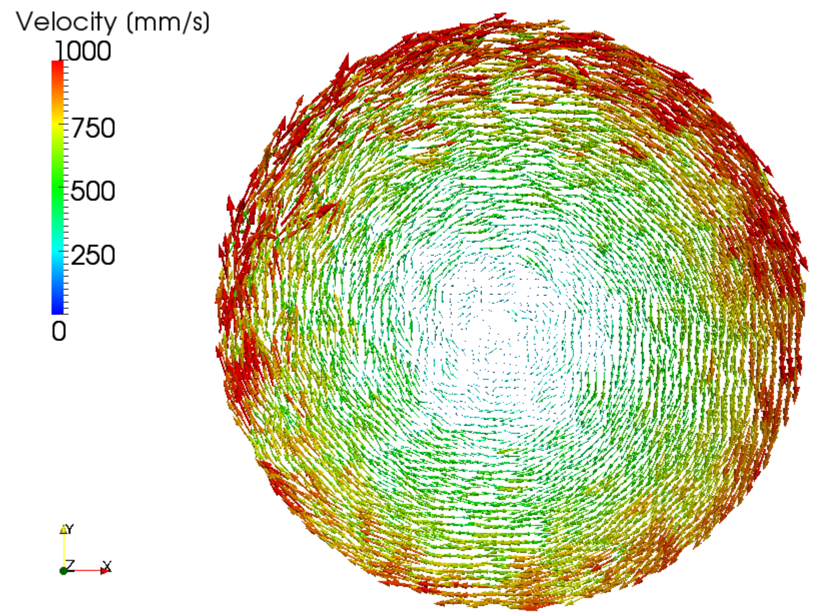
⇒ inner fluid rotates rigidly

Error Eval. of 4D-Flow (Results)

Velocity distribution on a horizontal plane



Rotating speed: 0 rpm

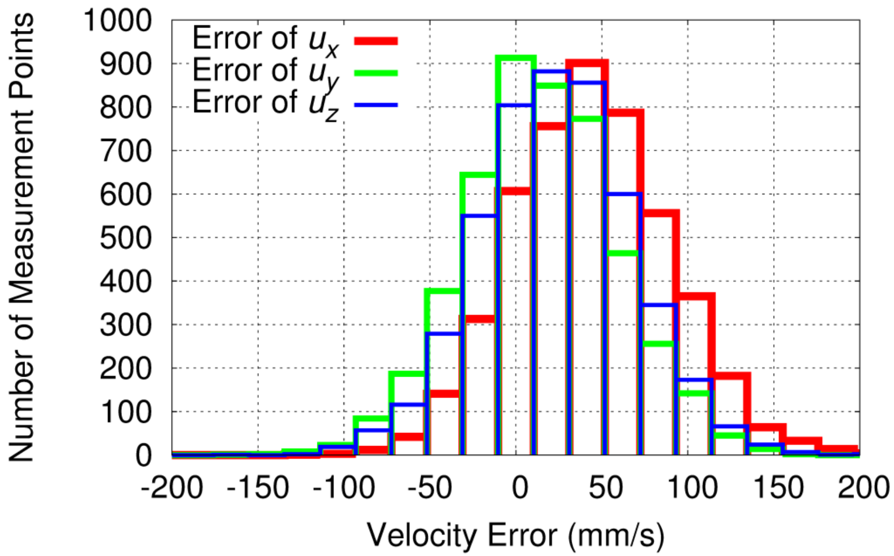


Rotating speed: 360 rpm

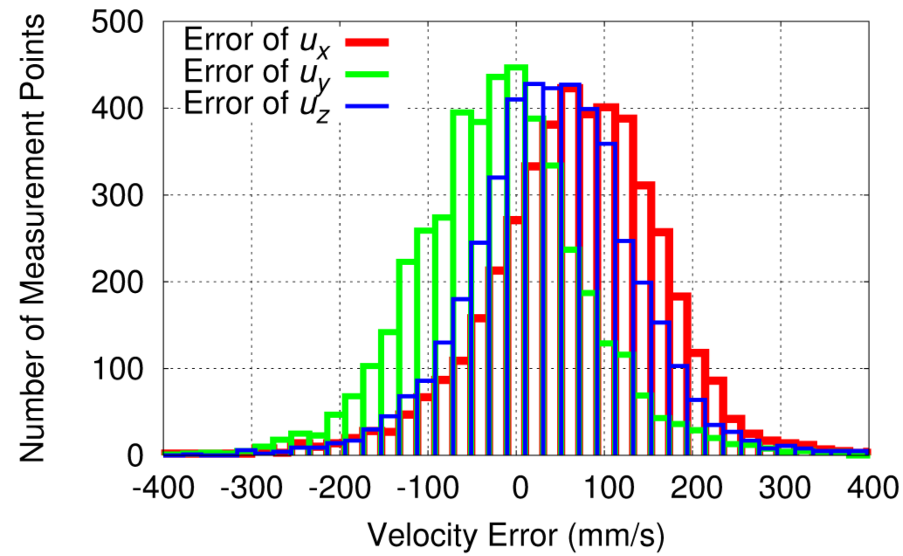
- Roughly agreed with actual velocity
- Many pixel have apparently incorrect velocity
- Seems to contain the random error

Error Eval. of 4D-Flow (Results)

Histogram of velocity component error



Rotating speed: 0 rpm



Rotating speed: 360 rpm

- Calculate $u_i^{\text{error}} = u_i^{\text{measured}} - u_i^{\text{exact}} \quad (i = x, y, z)$
- Distributed normally with average $\mu \simeq 0$
- Standard deviation is relatively large
  (0 rpm: σ =34.5 mm/s, 360 rpm: σ =98.3 mm/s)

Error Eval. of 4D-Flow (Findings)

Findings through the experiment

1. The raw 4D-Flow velocity data at each pixel is inaccurate, and thus unsuitable to be directly assigned as the BCs in vascular CFD analyses;

2. The averaged or lumped data calculated from the raw 4D-Flow velocity data (e.g. volume flow rate) can be accurate according to the law of large numbers.

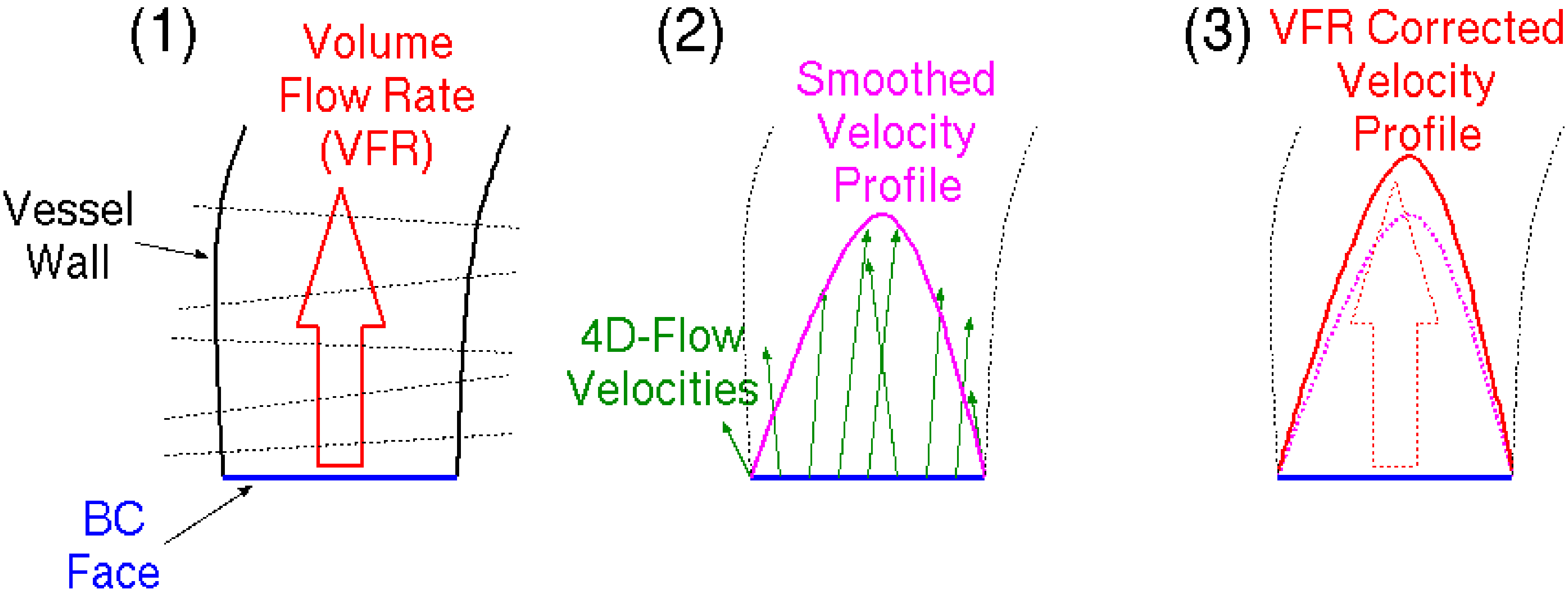
Part 2:

Procedure of our

BC determination method

BC Determination Method

Procedure of our method



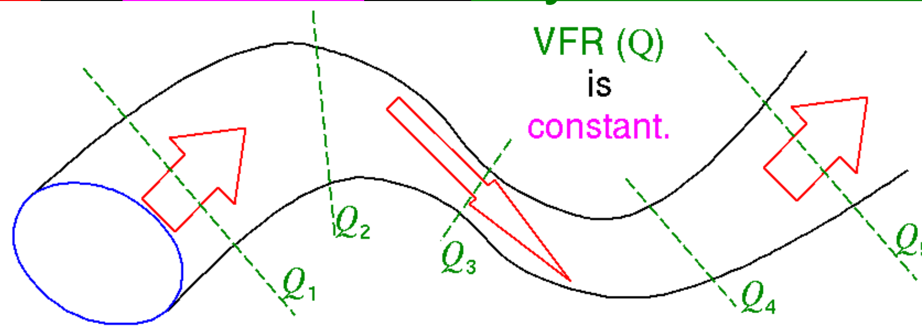
Estimation of Volume Flow Rate (VFR)	Smoothing of Velocity Profile	Correction of Velocity Profile with VFR

Procedure (1): Estimation of VFR

Points

- Blood can be regarded as incompressible fluid.
- The rate of the expansion and contraction of the blood vessel volume is small compared to the VFR.

⇒If no bifurcation is there, VFR is constant on any cross-section



Estimation procedure

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

According to the law of large numbers,

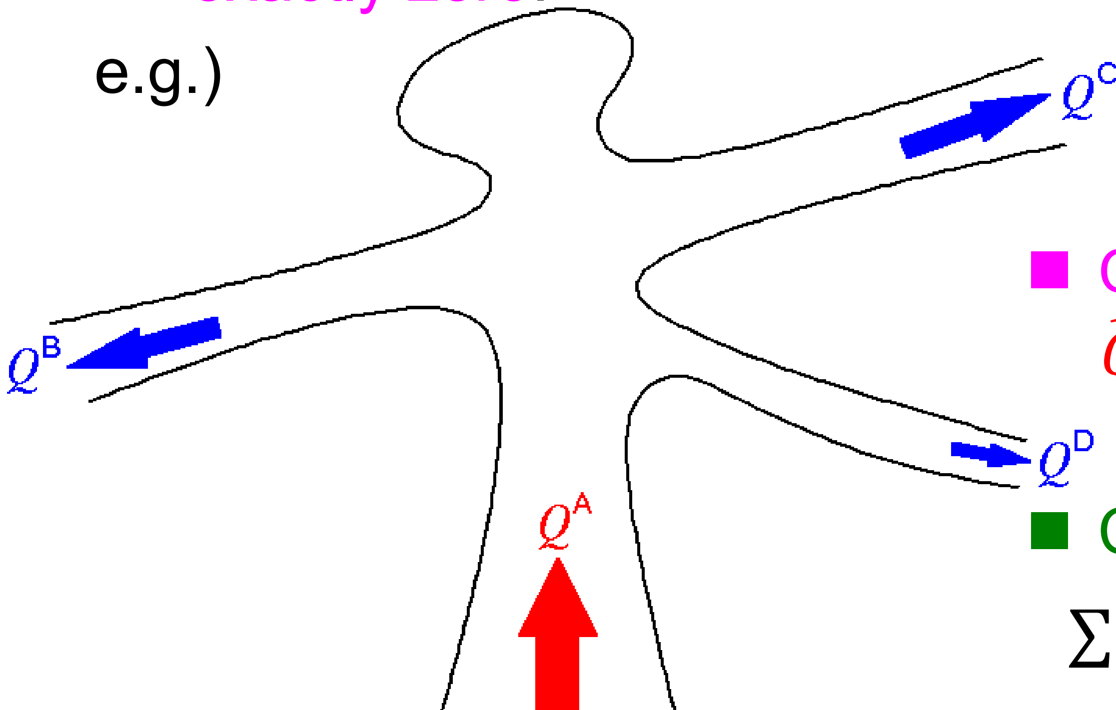
$\bar{Q}$ converges to the true value as increasing N.

Procedure (1): Estimation of VFR

Estimation procedure (cont.)

- 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

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

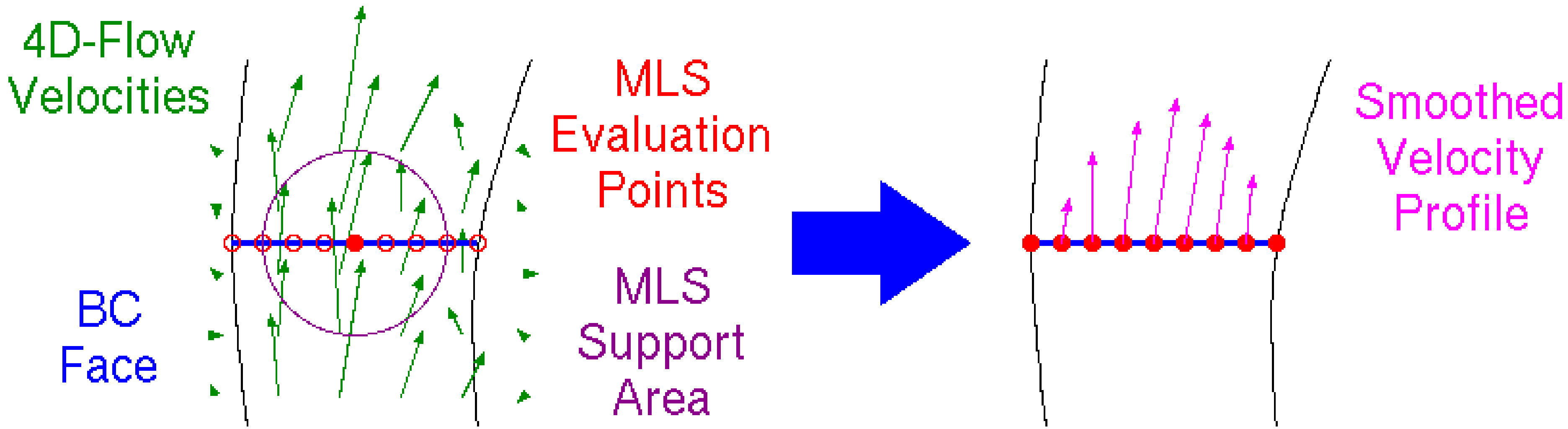
- Set the corrected VFR ($\hat{Q}$) as the estimated VFR.

If the extracted inlet/outlet vessel is sufficiently long, use $\hat{Q}$ as the VFR BC

Procedure (2): Smoothing of Profile

Point

Velocity profiles on BC faces obtained from the raw 4D-Flow data are jagged. ⇒ Need smoothing with a low-pass filter.



Smoothing procedure

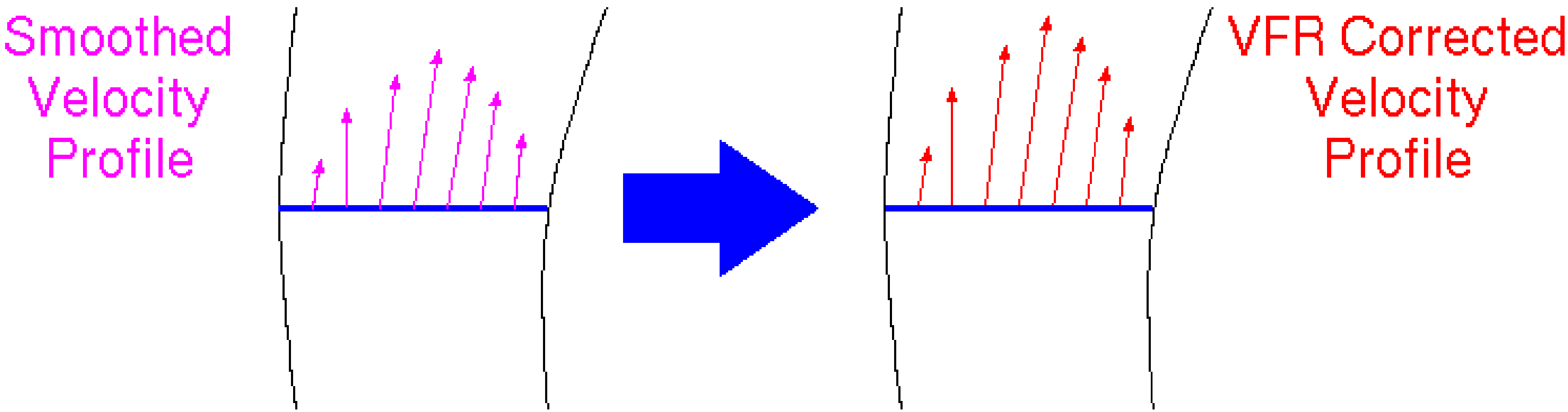
- Generate meshes over the BC face
- Interpolate the velocity at the center of each mesh using moving least square (MLS) method.

Procedure (3): Correction of Profile

Point

- Procedure (1) gives the accurate VFR ($\hat{Q}$).
- Procedure (2) gives a smooth velocity profile.

⇒ modify the profile so that its VFR agrees with $\hat{Q}$



Correction procedure

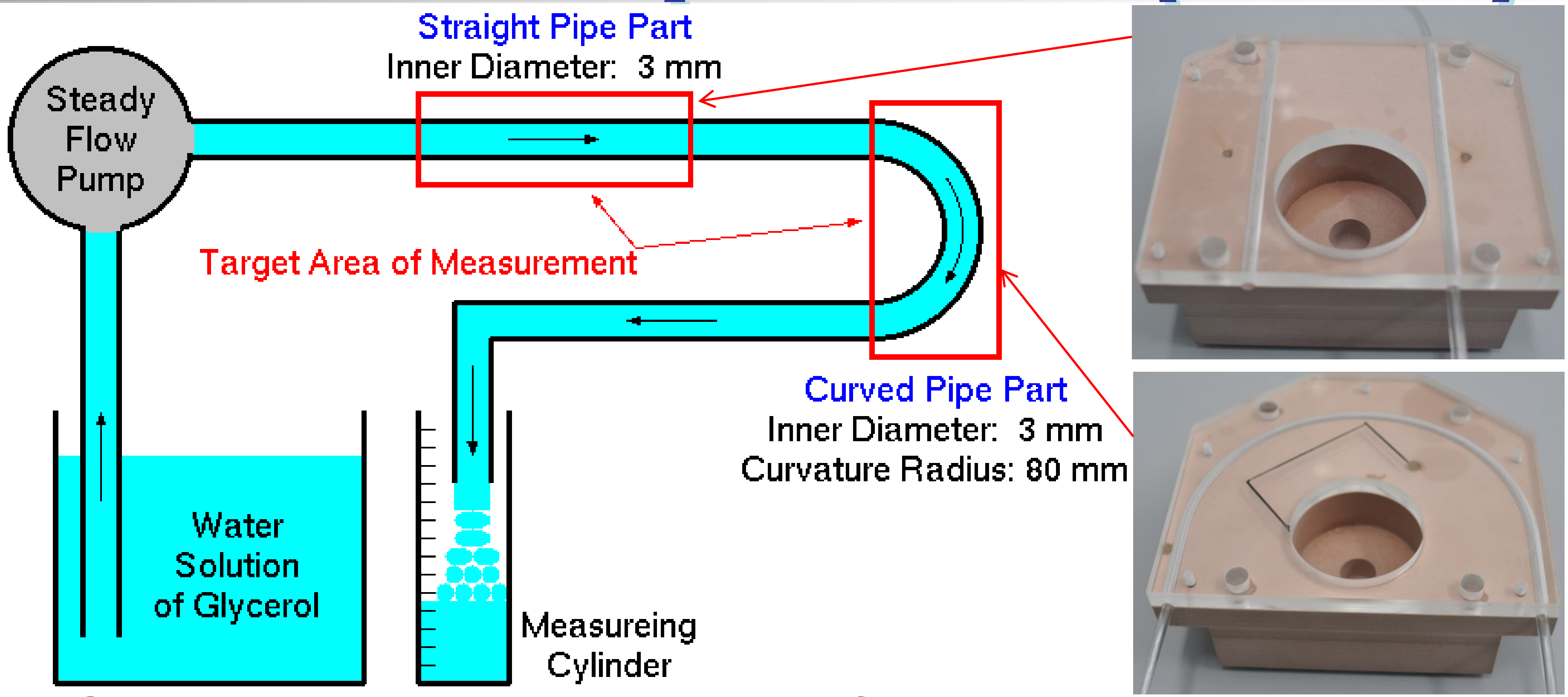
- Magnify the velocities by a constant factor

If the extracted inlet/outlet vessel is short, use the VFR corrected velocity profile as the velocity BC.

Part 3:

Validation experiments

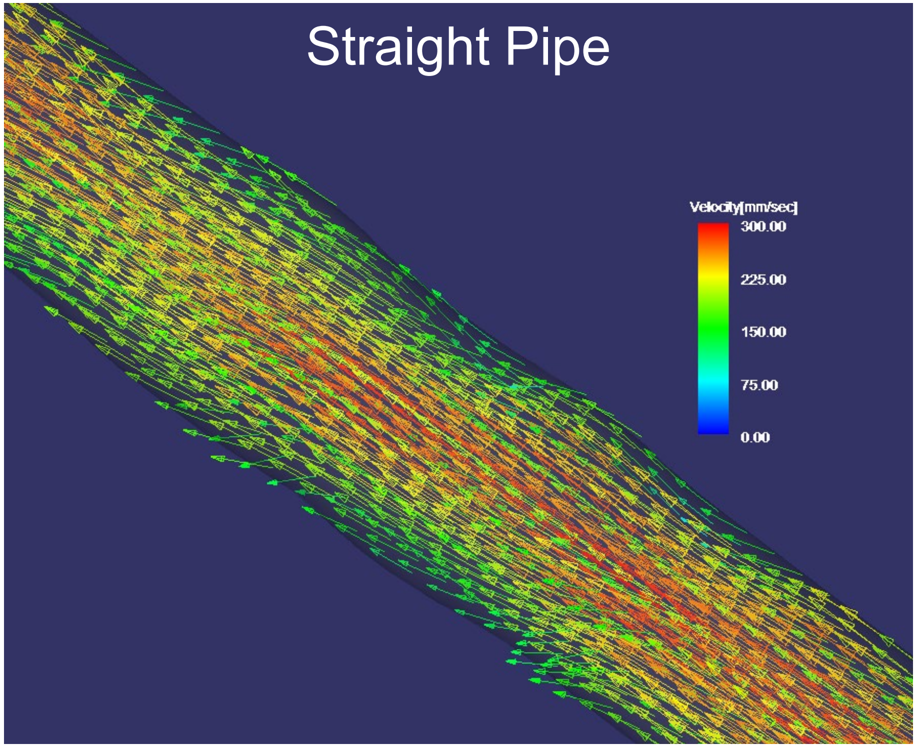
Validation Experiments (Device)

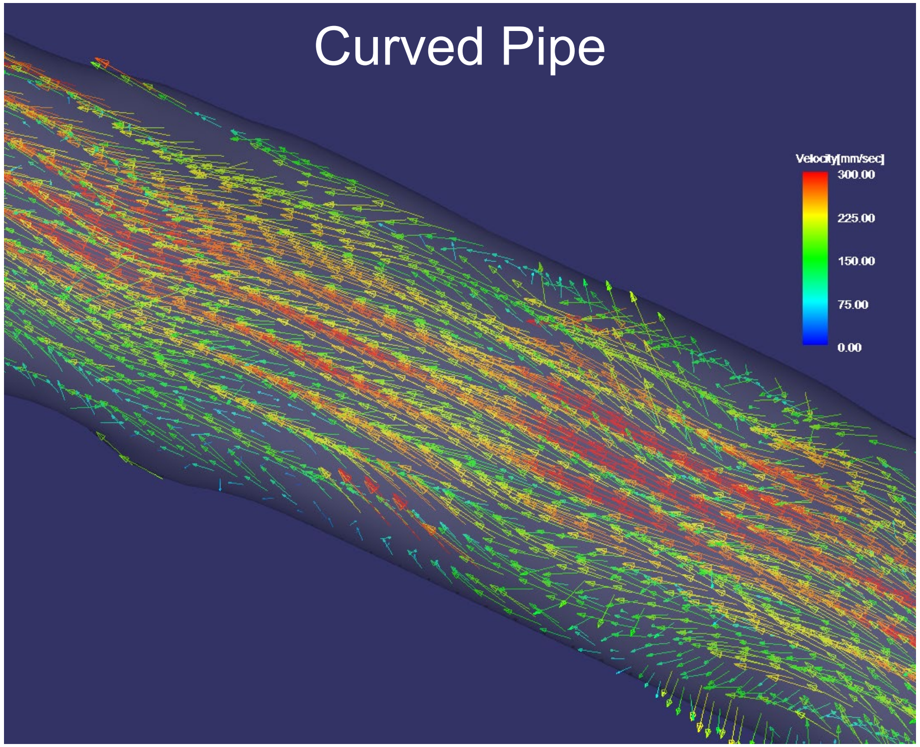


- Straight and curved pipes of ϕ=3 mm
- Water solution of glycerol of 40wt% (no contrast agents)
- Steady laminar flow made by steady flow pump
- Measuring cylinder measures the actual VFR

Validation Experiments (Results)

Raw 4D-Flow velocity data





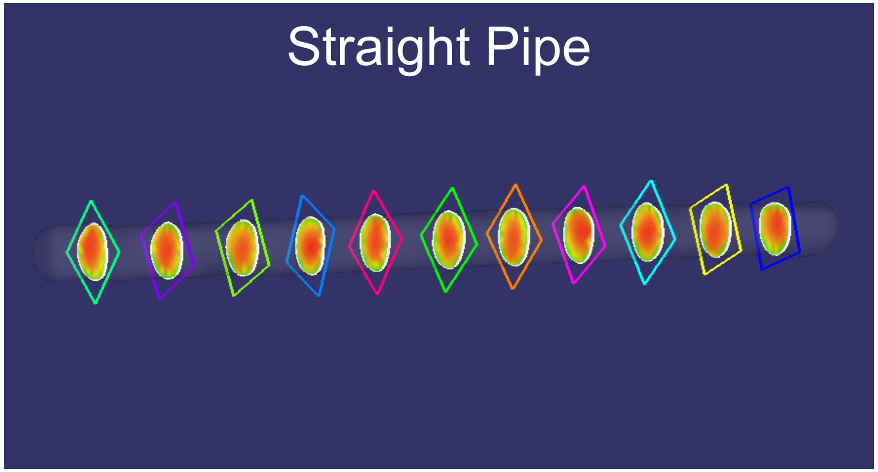
The actual flow is a laminar flow

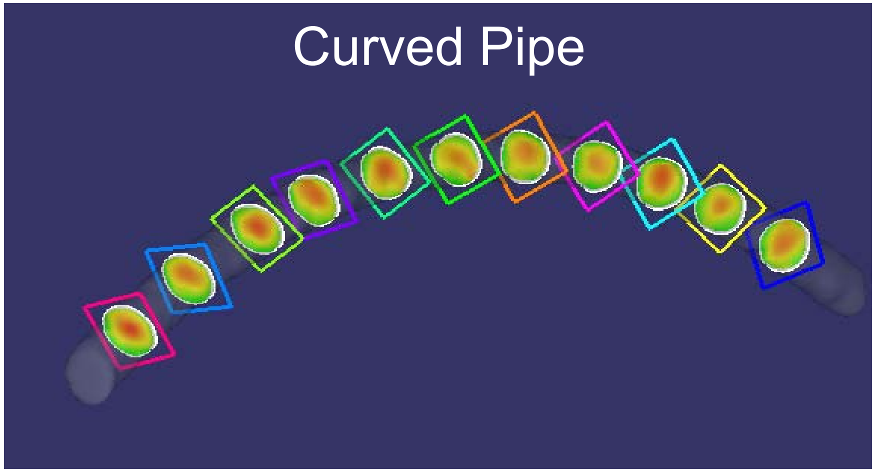
but it appears as if a turbulent flow

because of the large error of 4D-Flow.

Comparison of VFR

VFR estimated by our method with 11 virtual cross-sections





	Actual VFR [mm^3/s]	Estimated VFR [mm^3/s]	Error
Straight	1150.1	1130.3	1.7%
Curved	1860.2	1882.9	1.2%

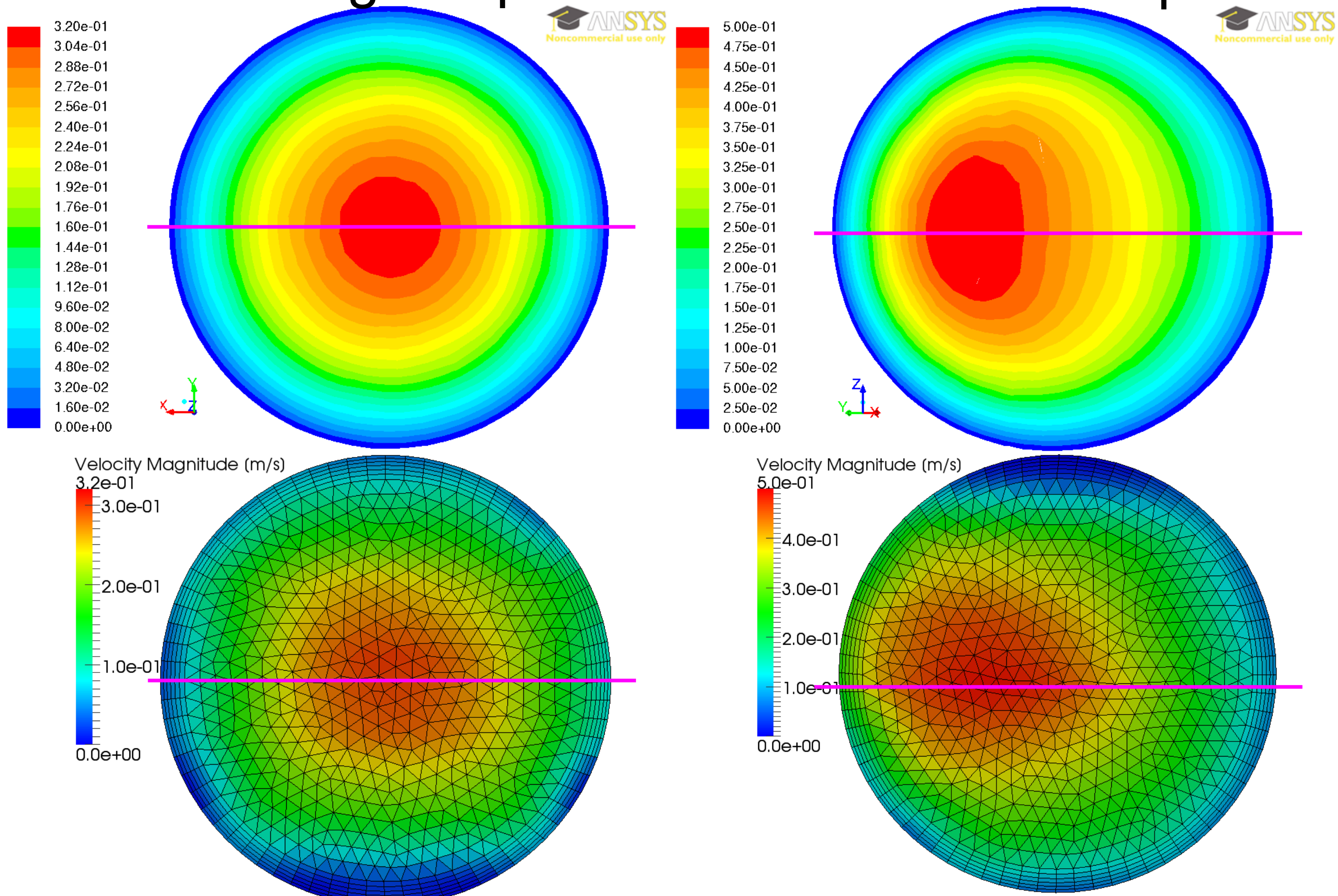
VFR is successfully estimated within 2% error.

Comparison of Velocity Profile

Straight Pipe | Curved Pipe

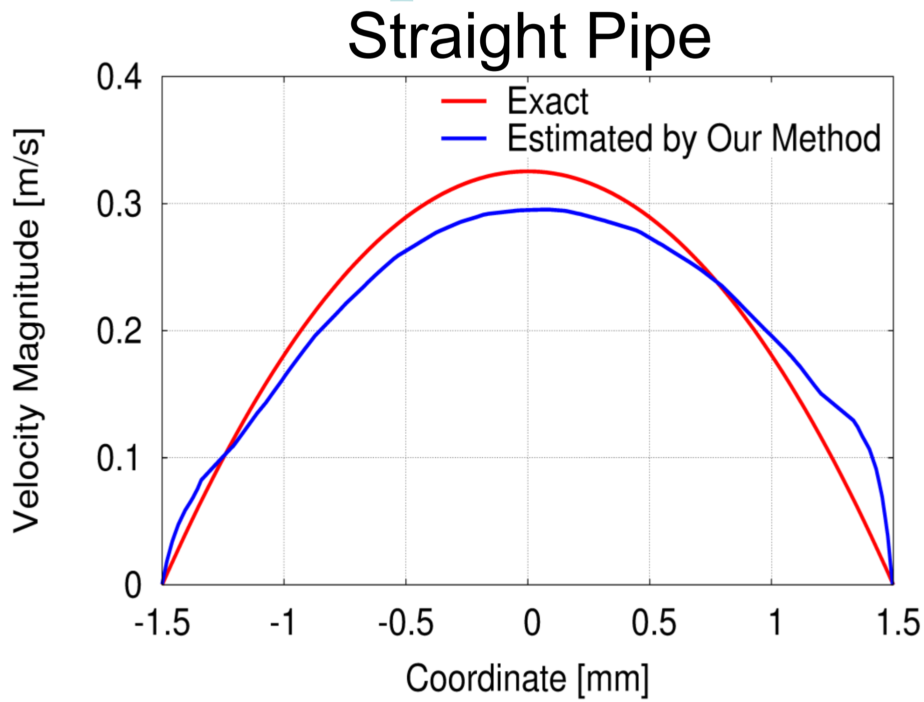
Actual Profile

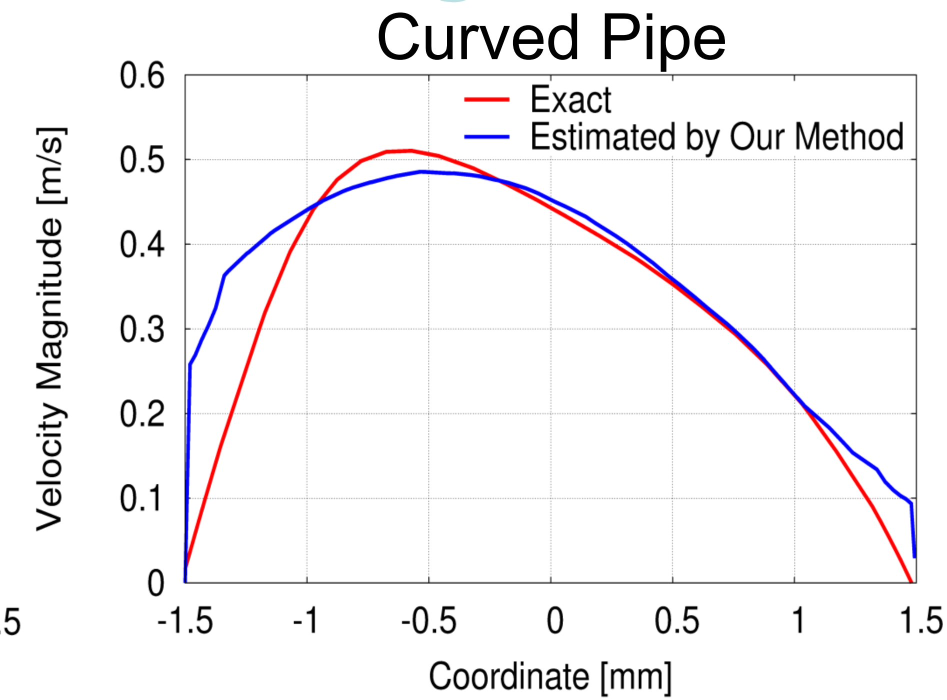
Estimated Profile



Estimated velocity profiles are in good agreement with actual velocity profile

Comparison of Velocity Profile





VFR is accurate + Velocity profile is similar

↓

A short inlet/outlet length makes the profile accurate.

↓

Our method can determine the velocity BC with practically sufficient accuracy.

Part 4:
Summary

Summary

- A new method to determine the **accurate** inlet/outlet BC for vascular CFD analysis using 4D-Flow is proposed.
- Its practically sufficient accuracy is validated through the experiments with straight and curved pipe phantoms.
- Our method can satisfy one of the three requirements for vascular CFD analysis.

Thank you for your attention.
And give me questions
in slow English without medical terms!!

Appendix

Measurement Parameters

TR [ms]	39.28
TE [ms]	05.26
Acquisition Time	16:49
FOV [mm]	160 × 160
Matrix	320 × 320
Slice Thickness [mm]	0.8
FA [deg]	15
Band Width [Hz/pixel]	488
VENC [m/sec]	1.2

This is just an example.

An Example of Breakdown of VFR

Cross-section #	VFR [mm^3/s]
CS-01	1090
CS-02	1141
CS-03	1155
CS-04	1107
CS-05	1117
CS-06	1163
CS-07	1226
CS-08	1150
CS-09	1221
CS-10	1310
CS-11	1324

Ave.: 1182.2 mm^3/s, Stand. Dev.: 75.1 mm^3/s
Exact: 1150.3 mm^3/s, Error: 2.8 %

Advantage/Disadvantage of 4D-Flow

Advantage

The vessel shape and velocity distribution
can be obtained at the same time
by only one-time measurement.

⟹Reducing the cost and strain of patients.

Disadvantage

Low spatial resolution

…

…

Why is CFD necessary?