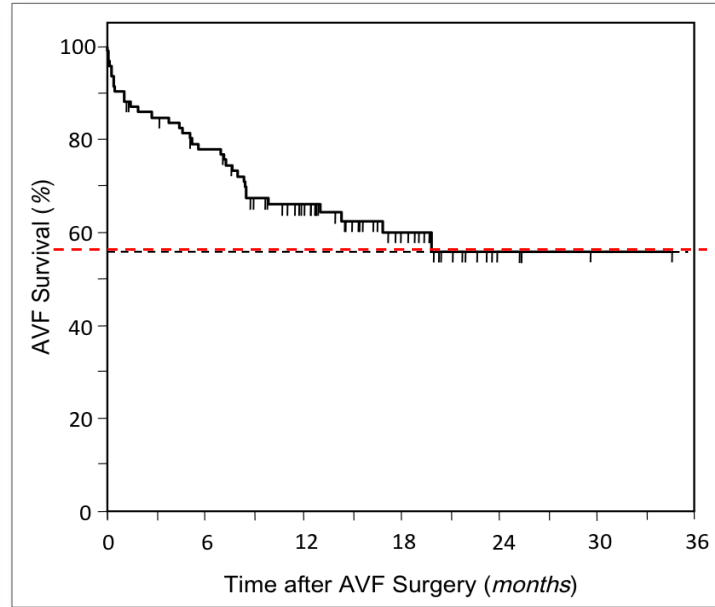
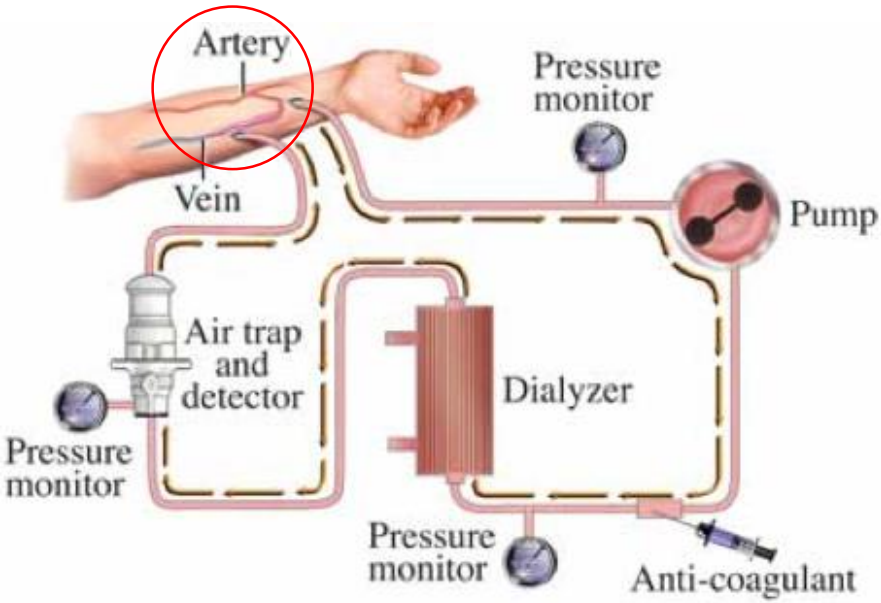


New insights into imaging techniques to improve  
Arterio-Venous Fistula (AVF) outcome

*Michela Bozzetto*

University of Bergamo  
Istituto di Ricerche Farmacologiche Mario Negri IRCCS

## The clinical problem of AVF failure



### Multicentric clinical trial FP7-EU ARCH

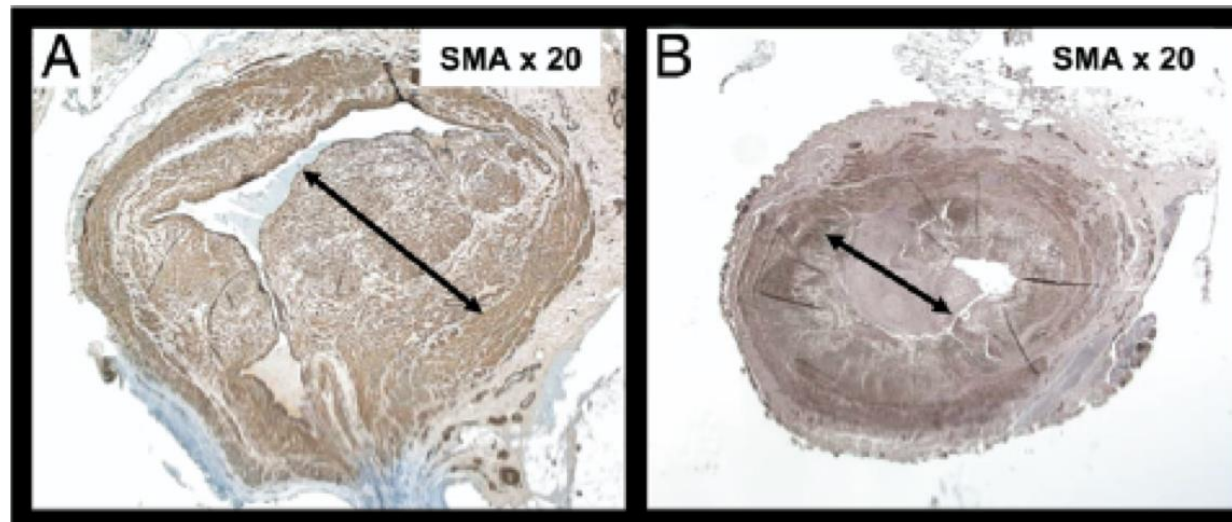
- AVF patency 67% at 1 year, 58% at 2 years (Caroli et al., 2013)

### Recent reviews

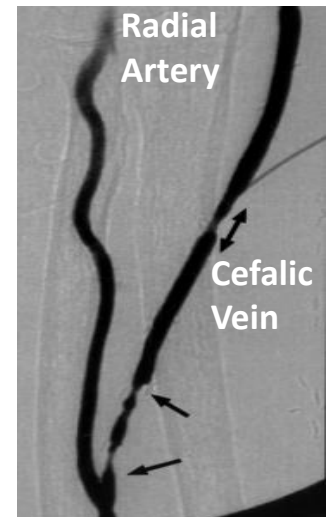
- Maturation failure rates of 20-60% (Dember et al., 2014)
- Primary failure rate of 23% (Al-Jaishi et al., 2014)

Main cause of AVF failure:

- 1) INSUFFICIENT DILATATION**  
(resulting in non maturation)
- 2) VASCULAR STENOSIS**



Roy-Chaudhury et al., AJKD, 2007



Asif et al., KI, 2005

## Imaging in the AVF

### 1) Imaging for AVF surgical planning

- Pre-operative mapping of arteries and veins using **US**

### 2) Imaging for elucidating mechanisms of AVF failure

- Acquisition of AVF geometry using **MRI** and flow boundary conditions using **US**

### 3) Imaging for AVF clinical routine surveillance

Blood flow volumes assessment and stenosis detection using **US**

## Imaging in the AVF

### 1) Imaging for AVF surgical planning

- Pre-operative mapping of arteries and veins using **US**

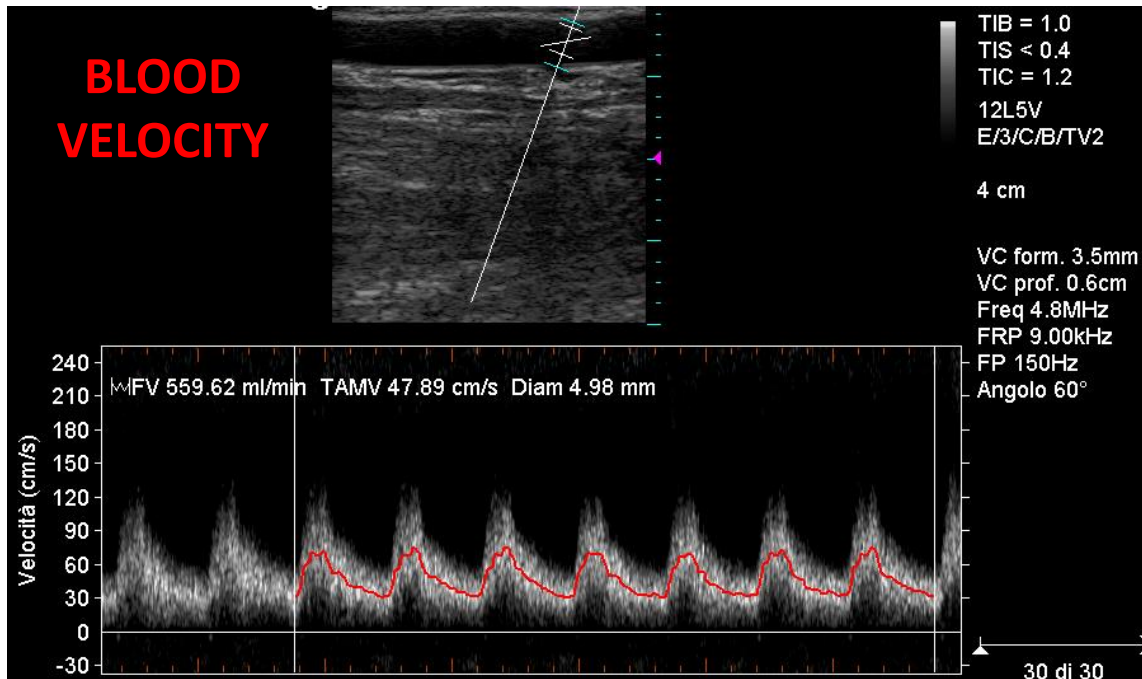
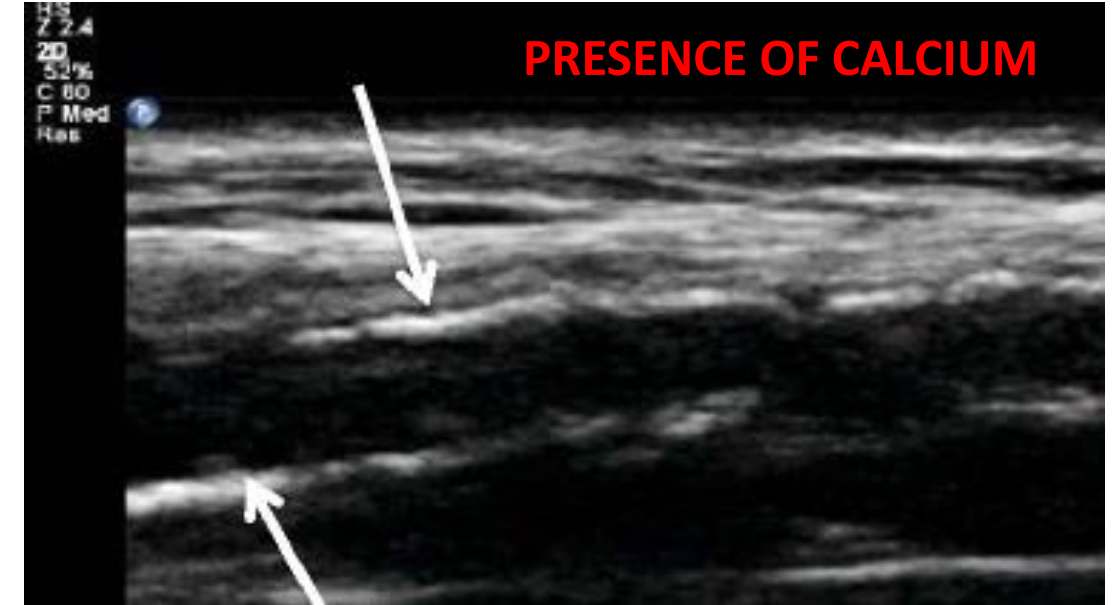
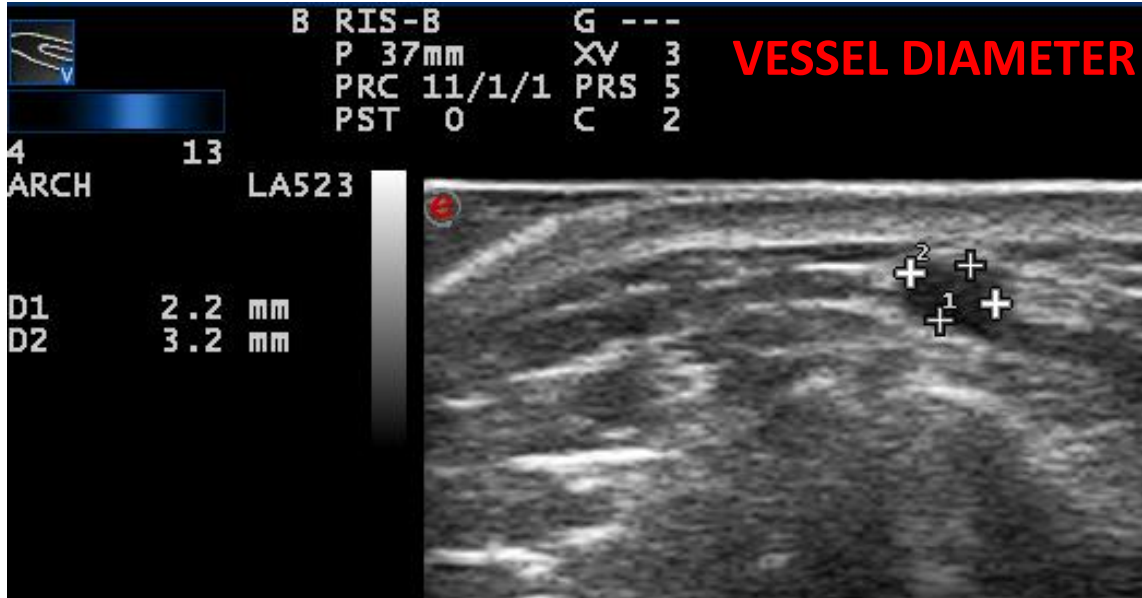
### 2) Imaging for elucidating mechanisms of AVF failure

- Acquisition of AVF geometry using **MRI** and flow boundary conditions using **US**

### 3) Imaging for AVF clinical routine surveillance

Blood flow volumes assessment and stenosis detection using **US**

# 1) Imaging for AVF surgical planning

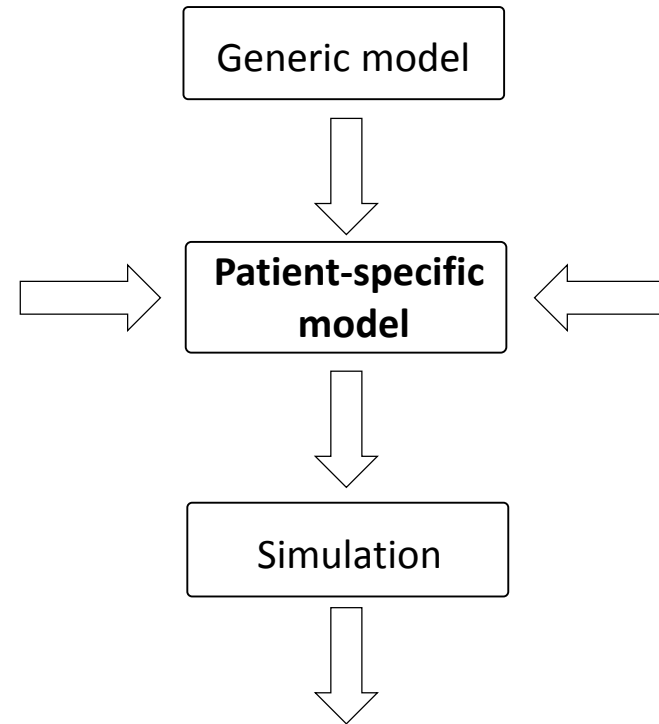
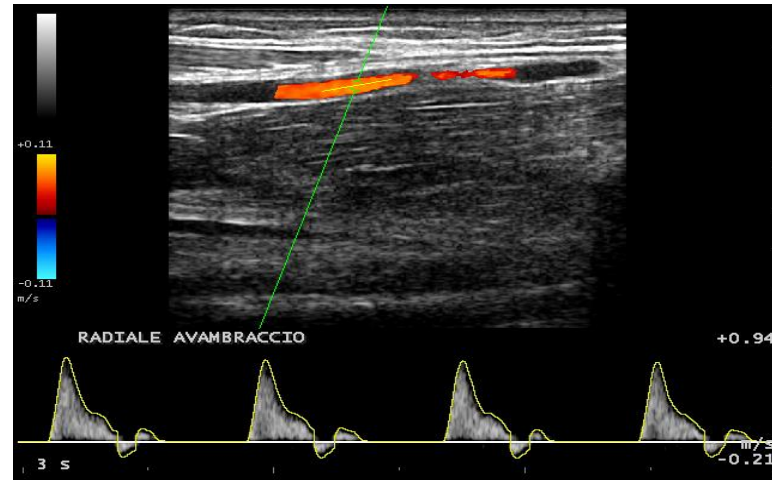


US is recommended to ensure the selection of the **most suitable site** for AVF creation

*Clinical practice guidelines for vascular access*  
(Am J Kidney Dis, 2006)

# Computational model for AVF surgical planning

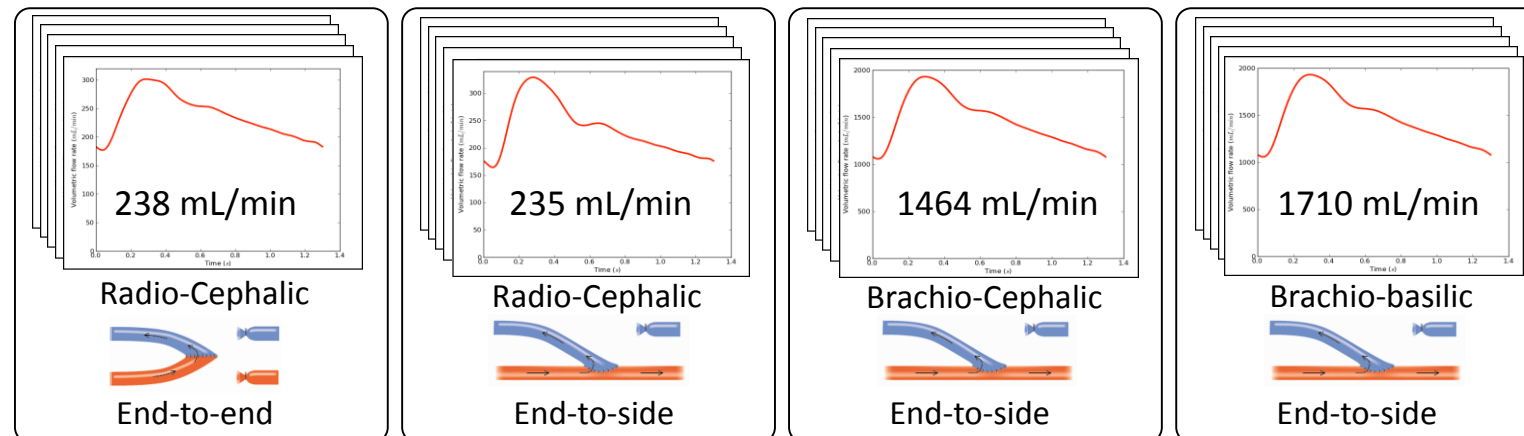
## Ultrasound imaging data



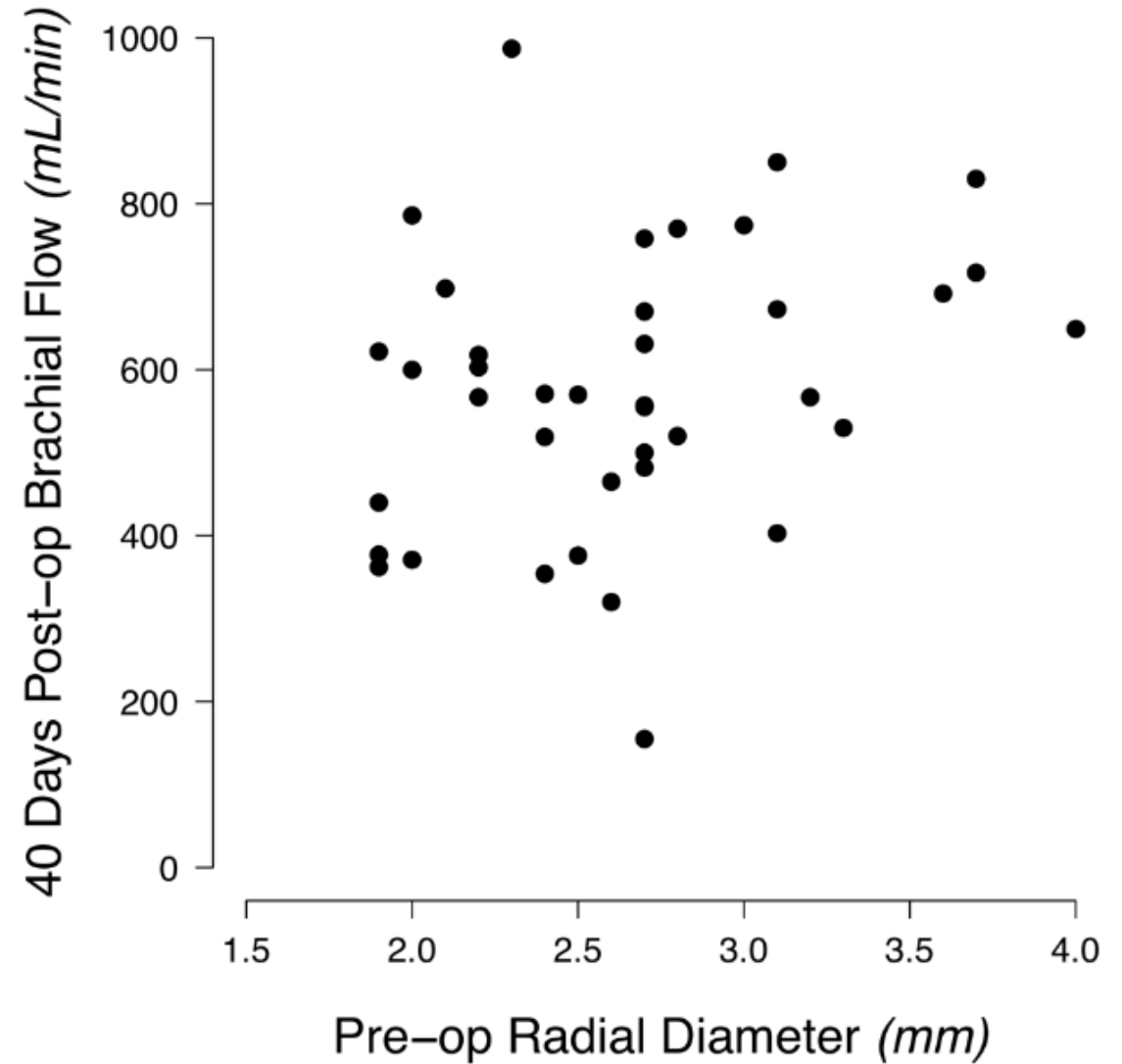
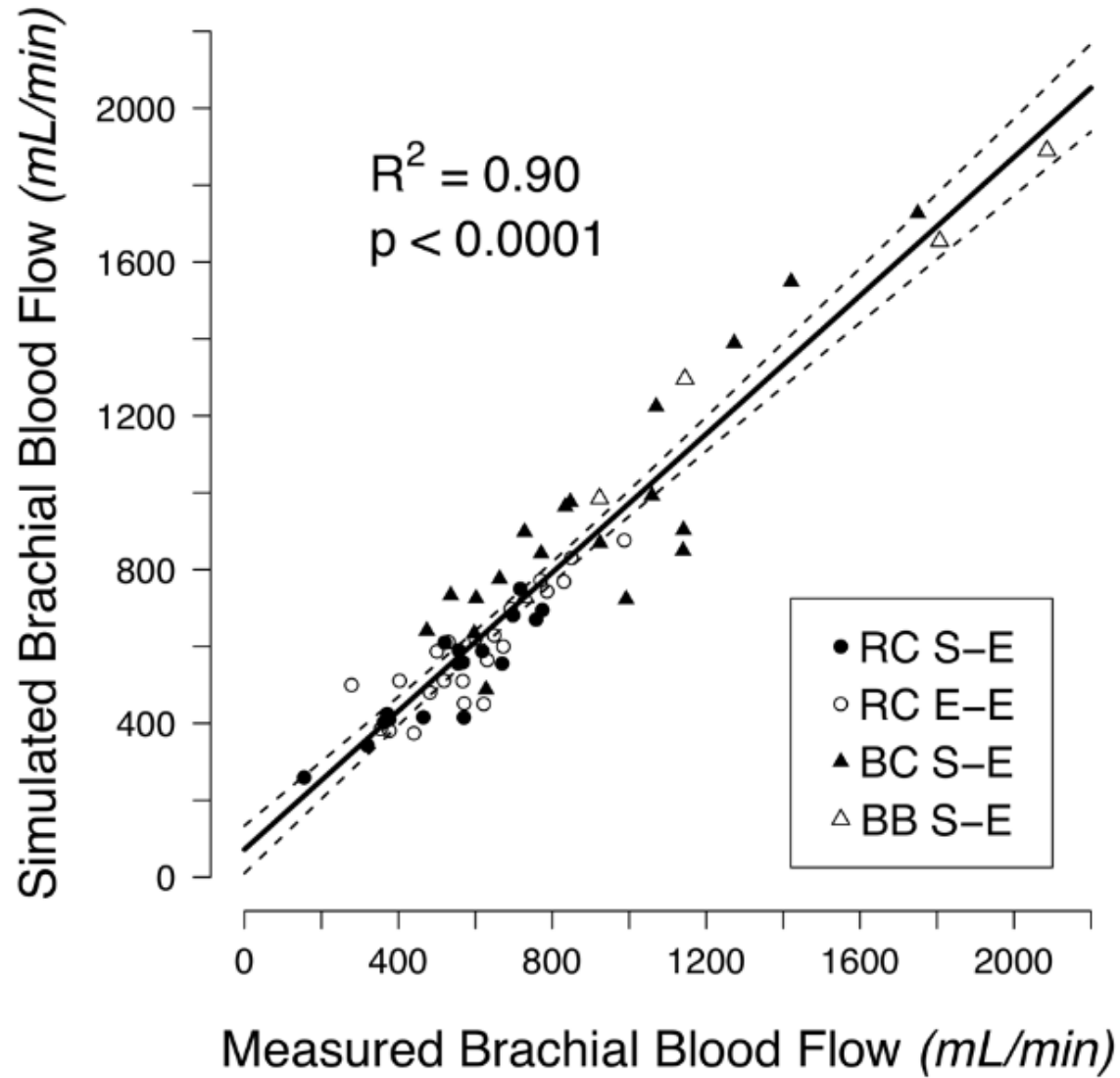
|                           |                  |
|---------------------------|------------------|
| Height (cm)               |                  |
| Weight (Kg)               |                  |
| Hematocrit (%)            |                  |
| Blood proteins (g/dL)     |                  |
| Cardiac output (mL/min)   |                  |
| Cardiac frequency (bpm)   |                  |
| Systolic pressure (mmHg)  |                  |
| Diastolic pressure (mmHg) |                  |
| Brachial Flow (mL/min)    |                  |
| Radial Flow (mL/min)      |                  |
| Ulnar Flow (mL/min)       |                  |
| Hypertension              | Not Hypertension |
| Diabetic                  | Not Diabetic     |
| Left arm                  | Right arm        |

Clinical and demographic patient data

## Simulation results for different AVF configurations



## Validation of the computational model during ARCH clinical study



# From the clinical study to the clinical practice: AVF.SIM SYSTEM

## Pre-operative US



### Demography

Date of examination (dd/mm/yyyy)

Investigator name

#### Demographic data

Patient ID

Initials

Date of birth (dd/mm/yyyy)

Gender (M/F)

Height (cm)

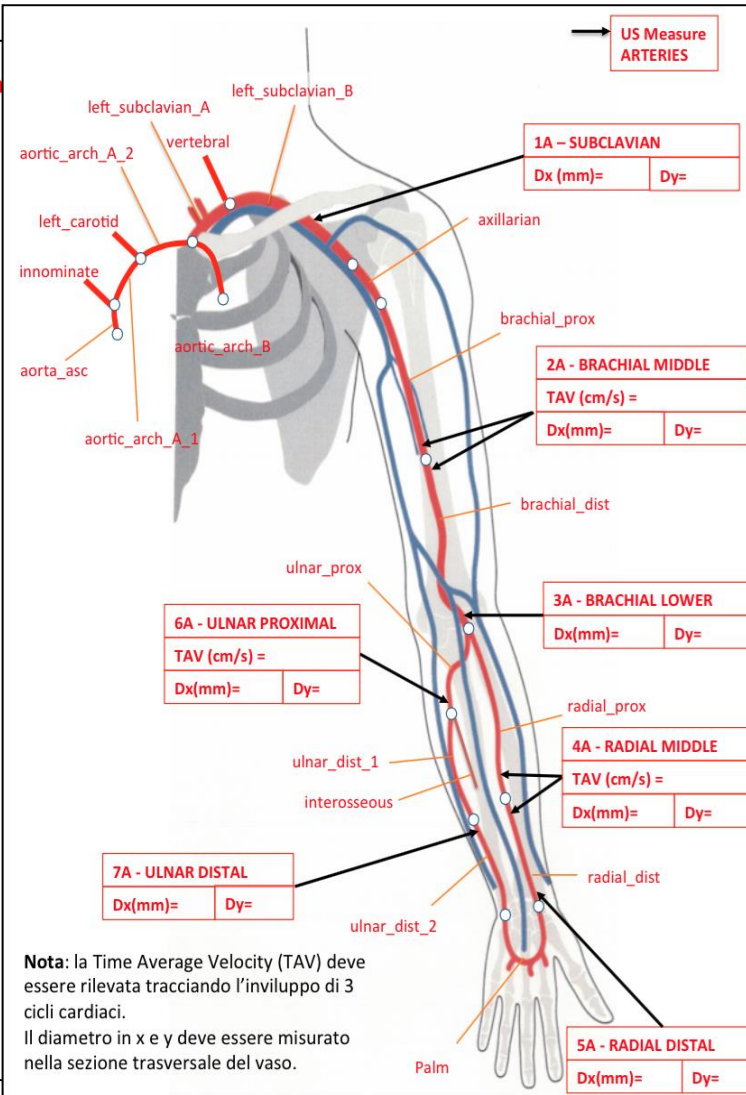
Weight (Kg)

Notes

**Nota:** compilazione del Patient ID a cura di chi esegue la simulazione

### Arteries

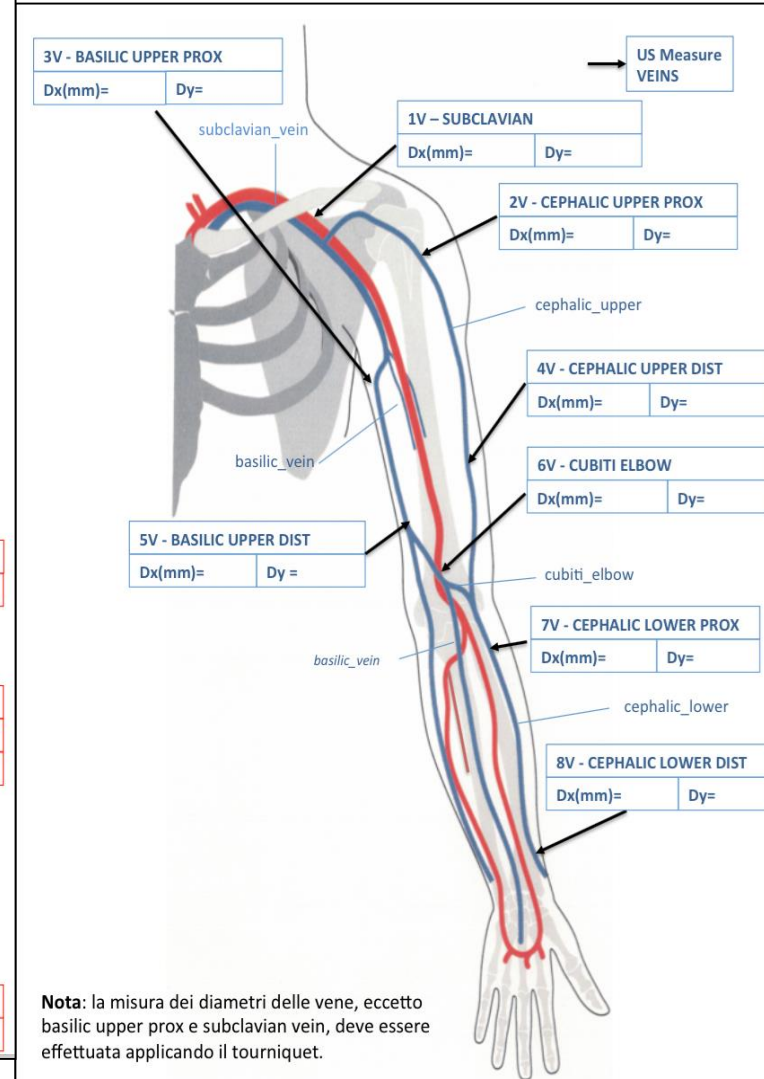
Entry-form



**Nota:** la Time Average Velocity (TAV) deve essere rilevata tracciando l'involuppo di 3 cicli cardiaci.

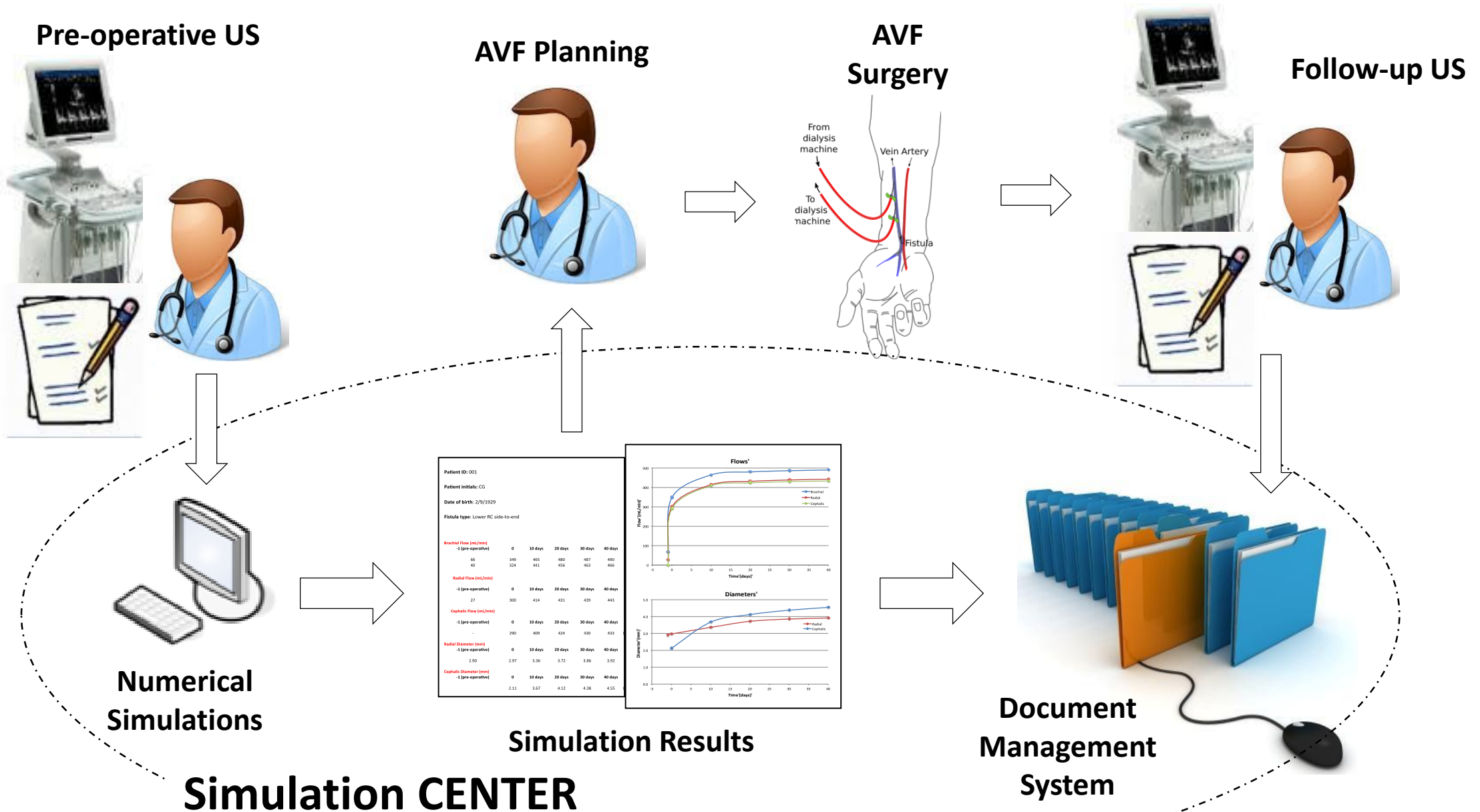
Il diametro in x e y deve essere misurato nella sezione trasversale del vaso.

### Veins



**Nota:** la misura dei diametri delle vene, eccetto basilic upper prox e subclavian vein, deve essere effettuata applicando il tourniquet.

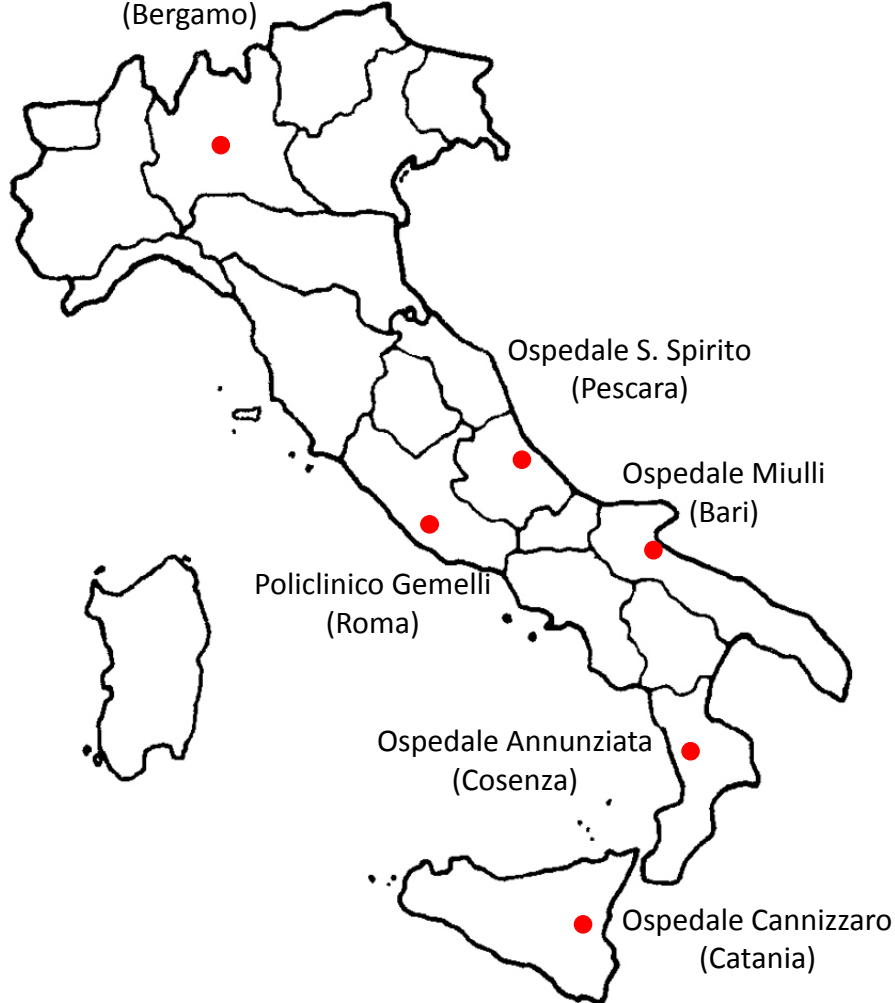
# From the clinical study to the clinical practice: AVF.SIM SYSTEM



## AVF.SIM system usability test

AVF.SIM was tested in the routine clinical practice of 6 Italian hospitals for a 6-month period

Ospedale Papa Giovanni XIII  
(Bergamo)



8 clinicians filled a questionnaire

Strongly  
disagree



Strongly  
agree



Appropriateness of data collection and transmission



Complete and clear reports with AVF.SIM results  
provided with haste by the Simulation Center



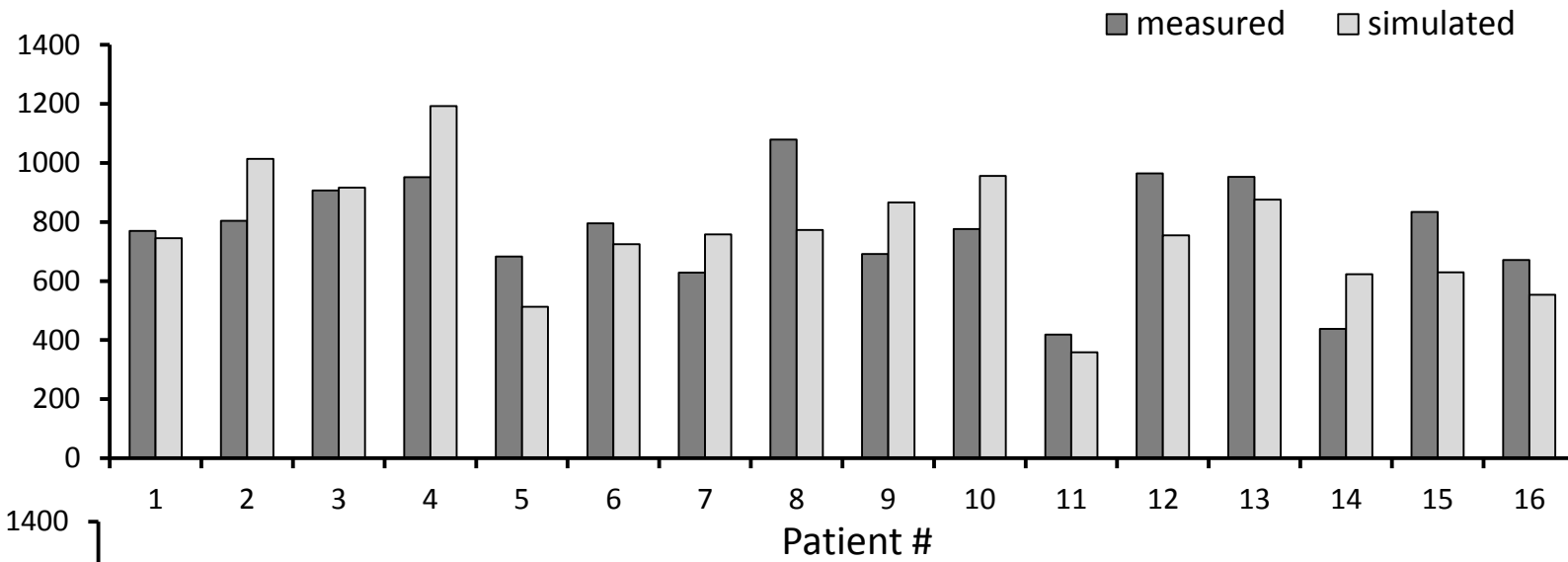
Appropriateness of data storage (DMS)



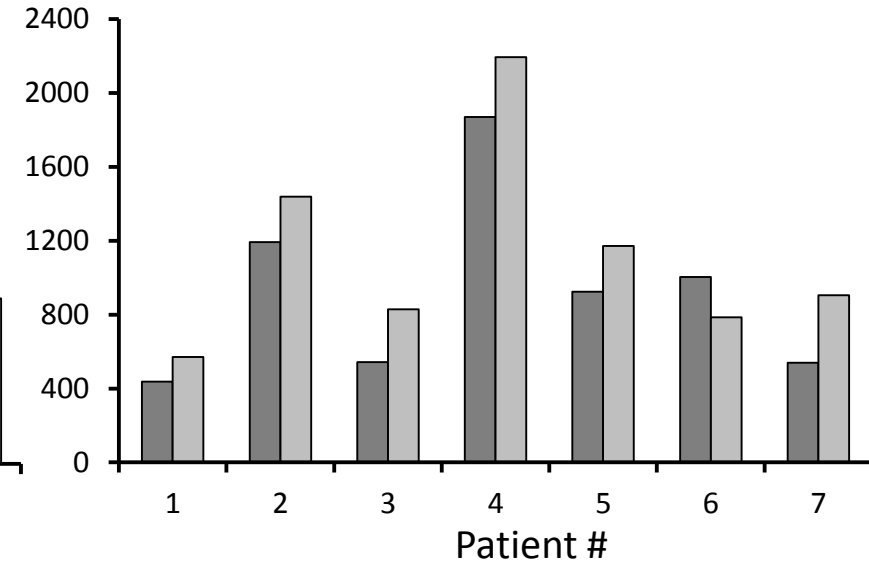
All want to use AVF.SIM system for AVF planning

# AVF.SIM usability test: simulation results

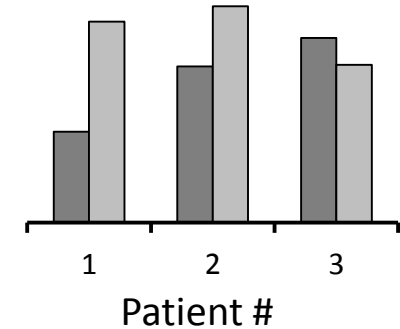
## Radiocephalic Side-to-End



## Brachiocephalic Side-to-End

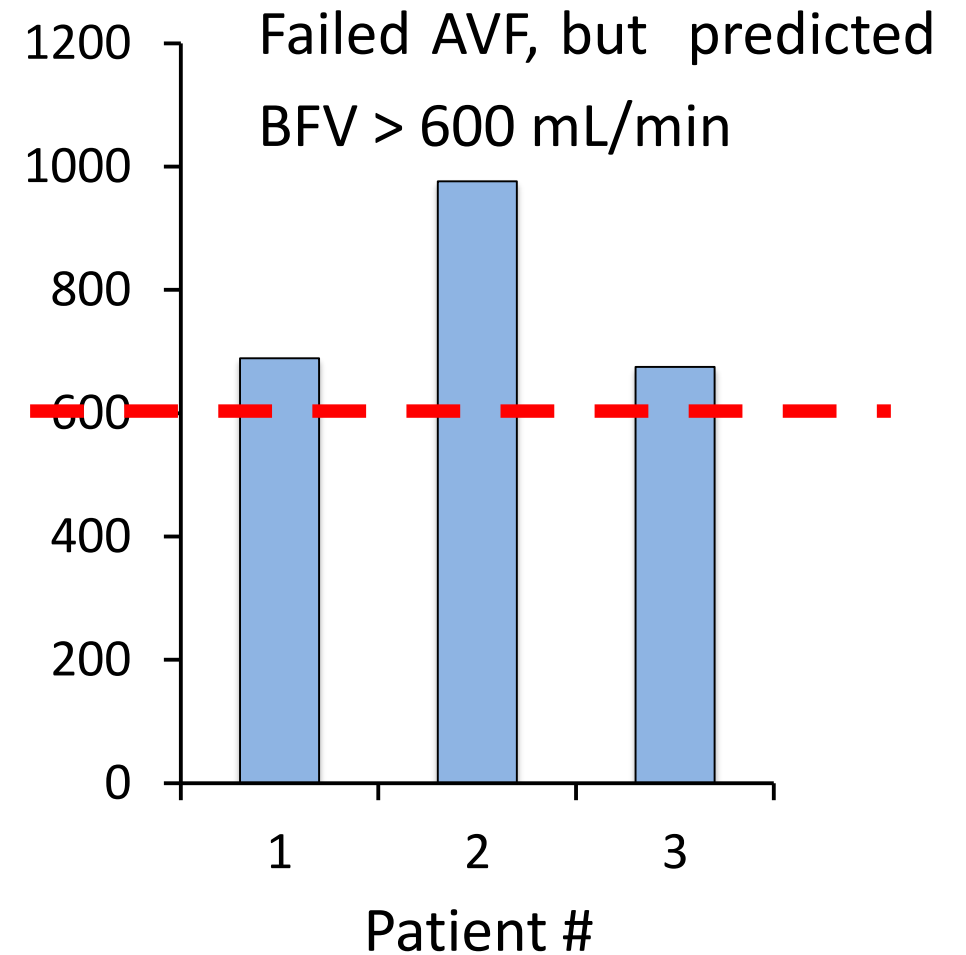
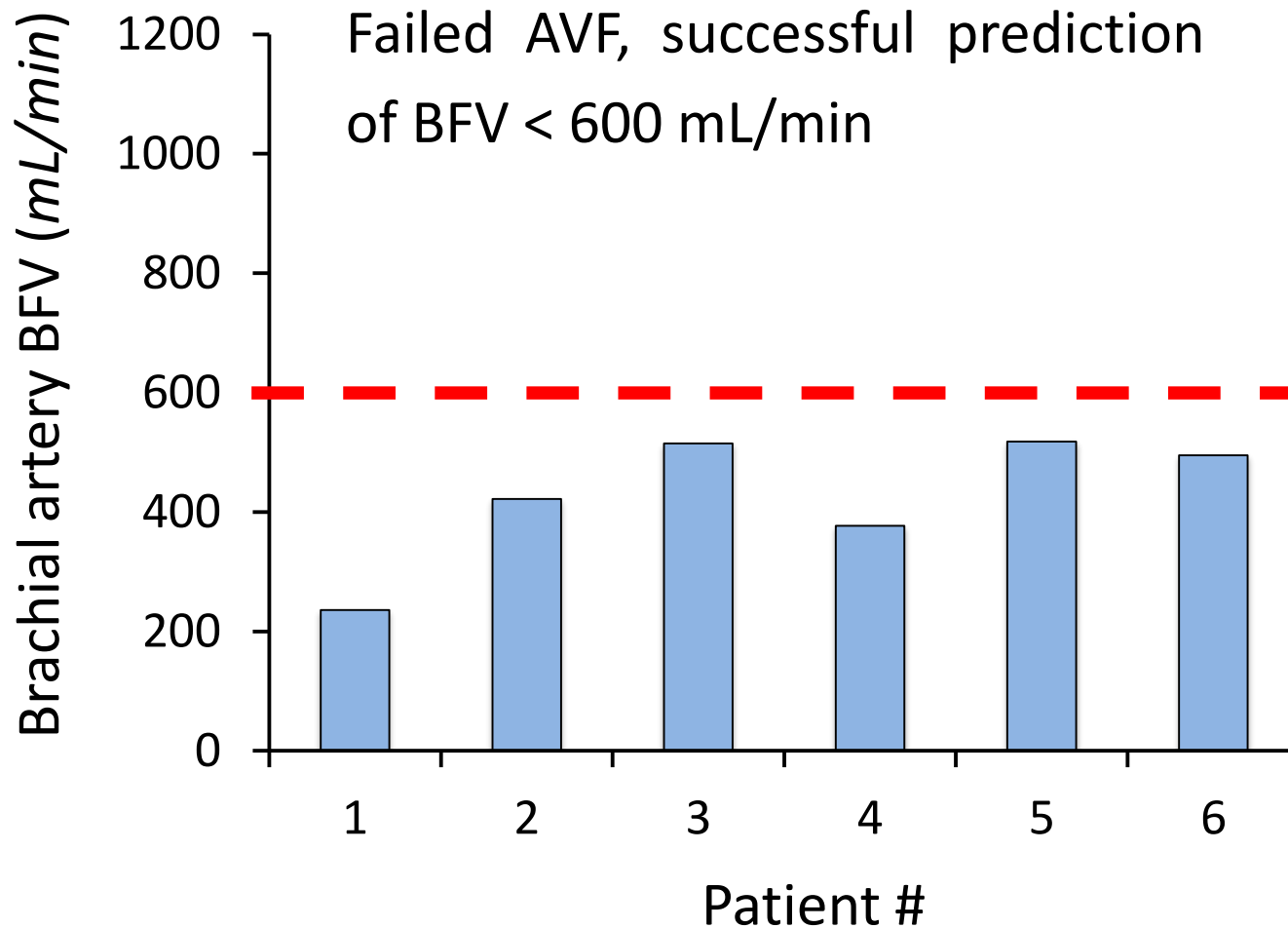


## Brachiocephalic Side-to-Side



## AVF.SIM simulation results

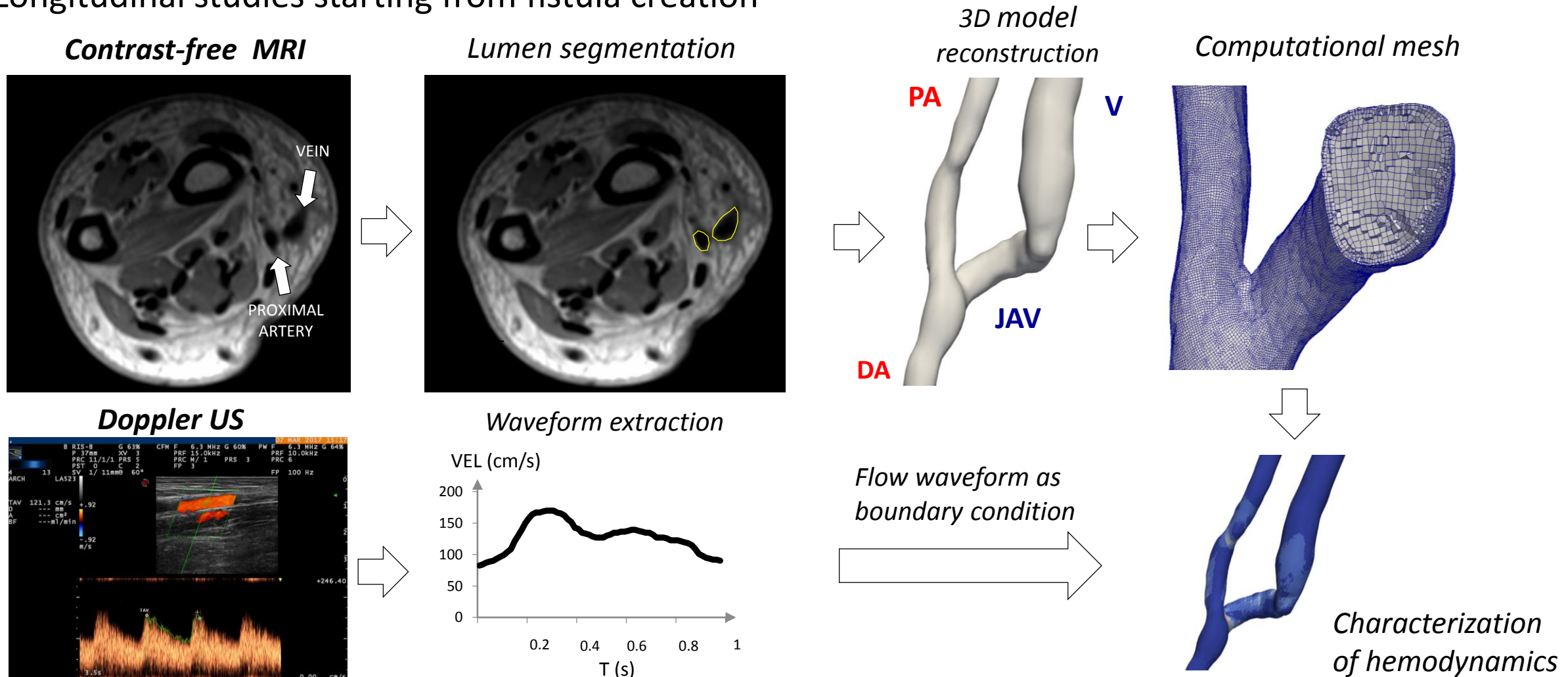
AVF.SIM successfully predicted the ***non-maturation of*** 6 out of 9 AVF cases.



## 2) Imaging for elucidating mechanisms of AVF failure

Investigate the relationship between disturbed flow and vessel remodeling after AVF creation

- ***Advances in imaging techniques acquisition (novel contrast-free MRI protocols)***
- Advances in high-resolution computational fluid dynamic (CFD) simulations
- Longitudinal studies starting from fistula creation



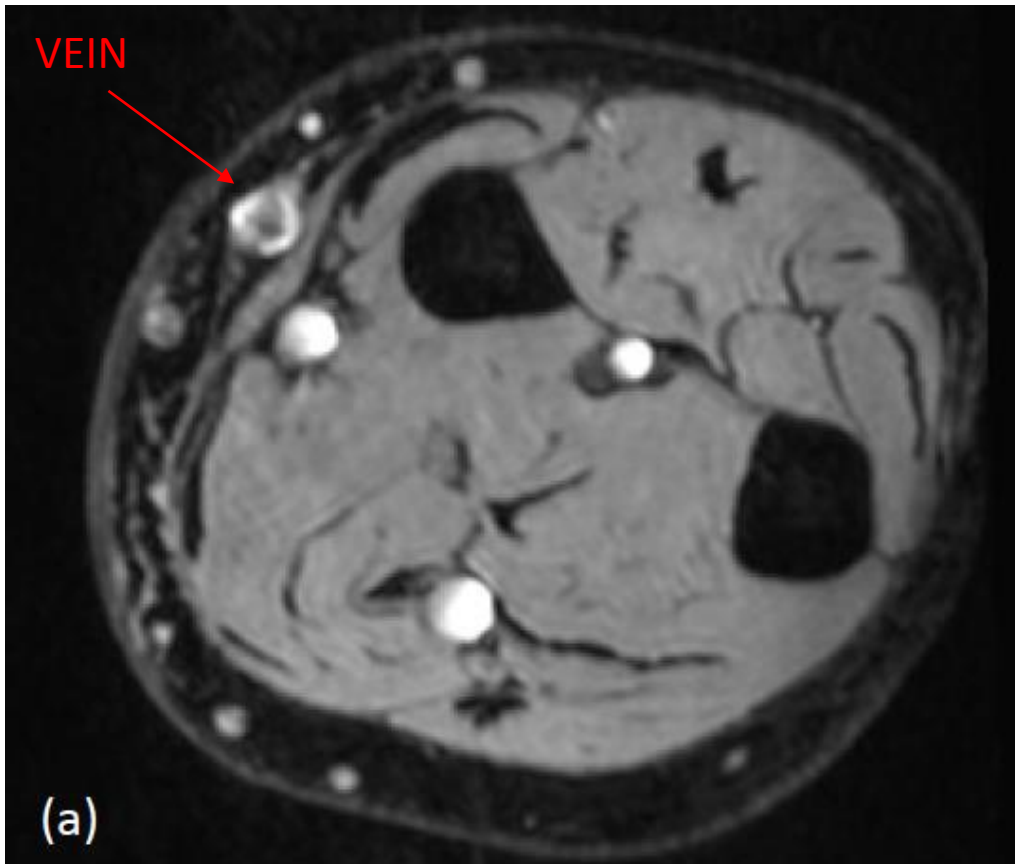
# State of the art in the application of NCE-MRI in AVF

E Murphy, Cardiovas Eng and Techn, 2017

**MR sequence:** Multi Echo data image combination (MEDIC)

**Study design:** 4 volunteers at 1 timepoint

**Limitations of imaging:** dephasing artefacts



M Sigovan, Ann Biomed Eng, 2013

**MR sequence:** Time of flight (TOF) MRA

**Study design:** 3 patients at 3 timepoints

**Limitations of imaging:** image quality affected by blood flow velocity and asymmetry of the geometry.

**Limitations of the study:** short follow-up, normal resolution CFD

Y He, J Biomechanics, 2012

**MR sequence:** Black-blood MRI

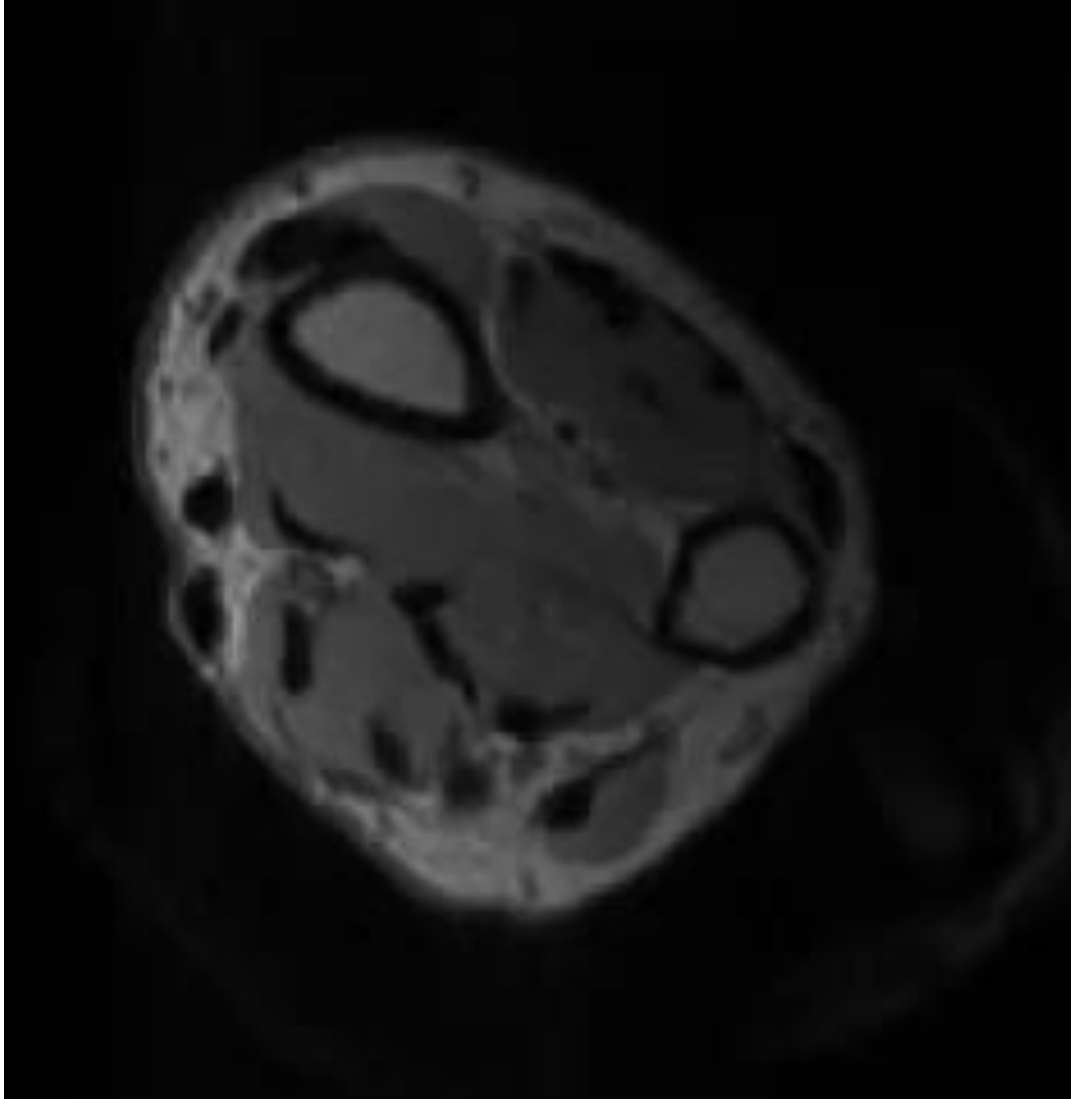
**Study design:** 1 patient at 3 timepoints

**Limitations of imaging:** time duration of MRI (>30mins)

**Limitations of the study:** only one patient, normal resolution CFD, not relevant time-points for AVF history

## A novel NCE-MRI protocol for AVF acquisition

### 3D fast-spin echo (GE, CUBE)

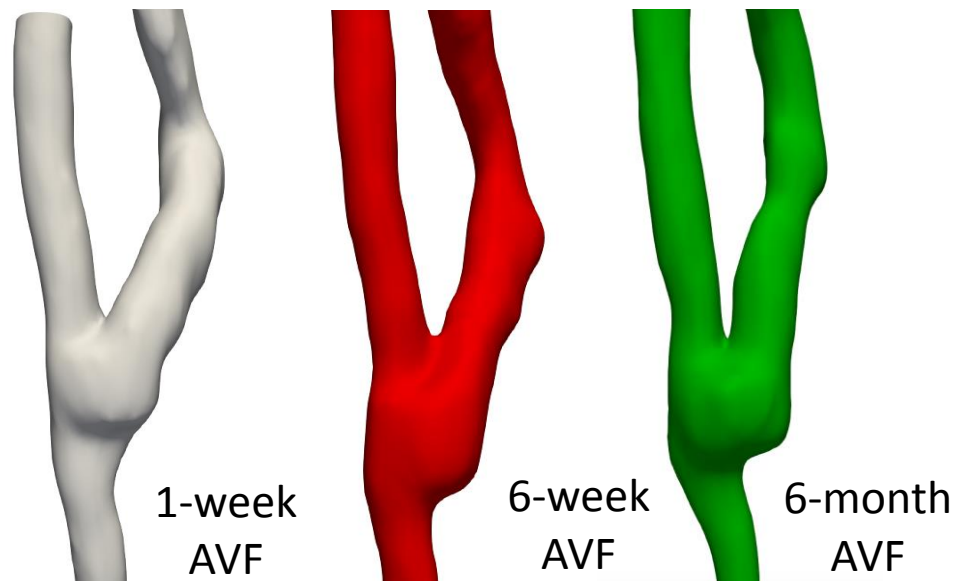


- Isotropic 3D sequence, reformatted with equal resolution in any direction
- Cardiac gating (PG)

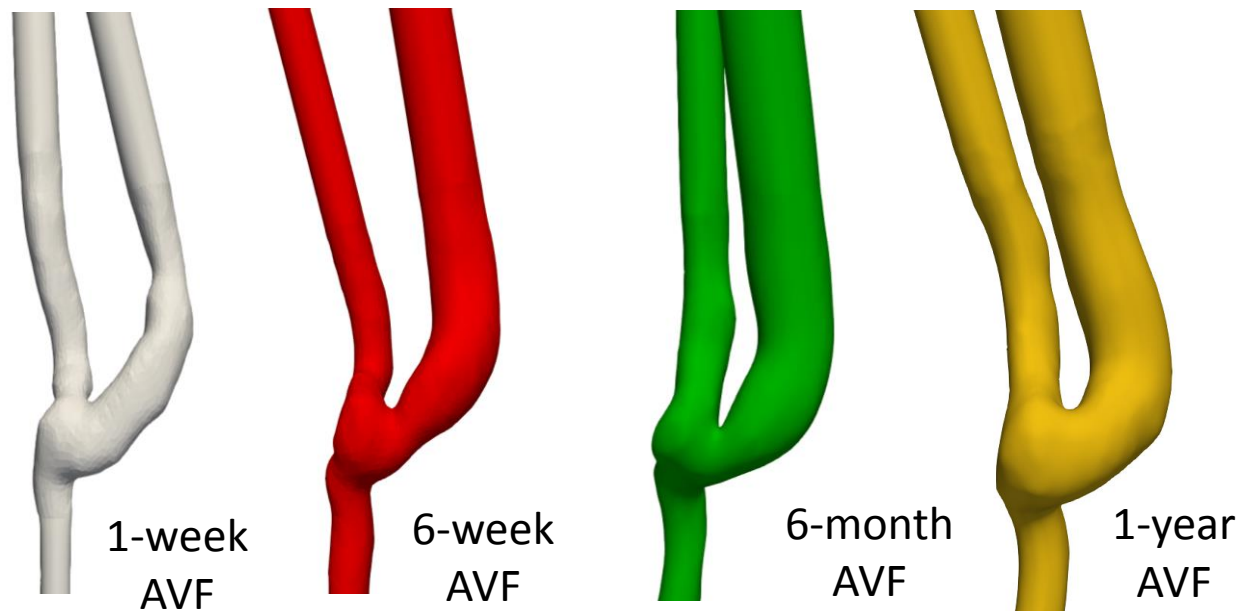
| MR IMAGING PARAMETERS       |           |
|-----------------------------|-----------|
| <i>Acquisition duration</i> | 5-10 mins |
| <i>Acquisition plane</i>    | Axial     |
| <i>Slice thickness</i>      | 2 mm      |
| <i>Slice spacing</i>        | 0 mm      |
| <i>Echo time</i>            | 14-19 ms  |
| <i>Echo train length</i>    | 24 ms     |
| <i>Repetition time</i>      | 2340-2470 |
| <i>Matrix</i>               | 256 x 256 |

## Follow-up of 3 patients over time

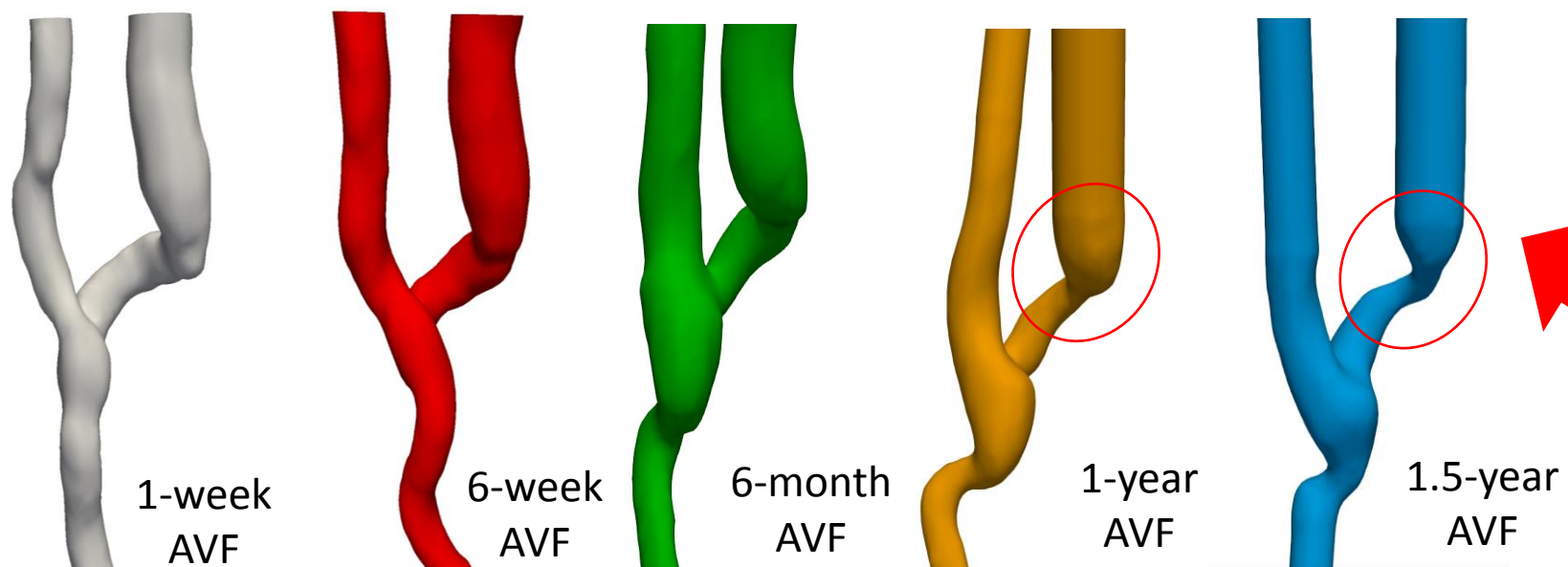
**PATIENT 1**



**PATIENT 2**



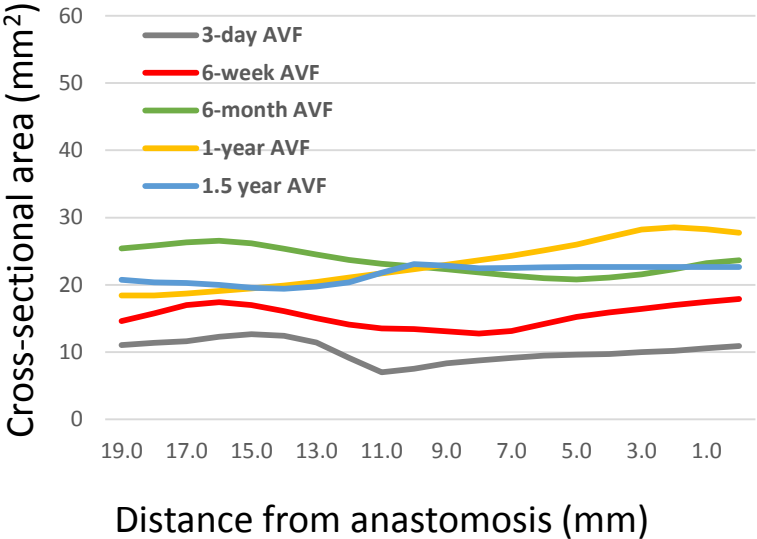
**PATIENT 3**



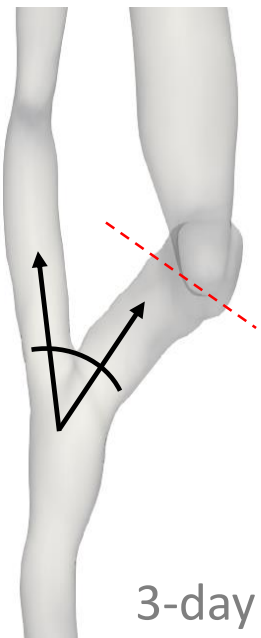
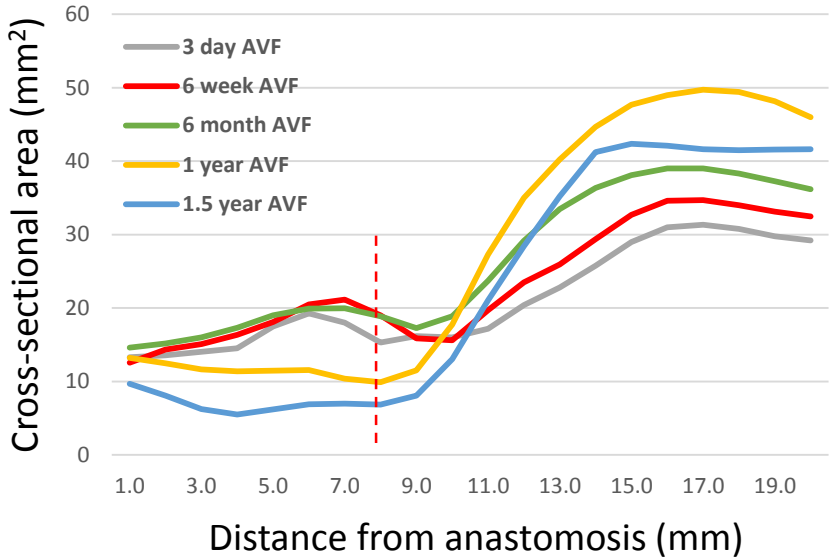
**Patient 3  
developed a  
stenosis**

# AVF morphological changes over time

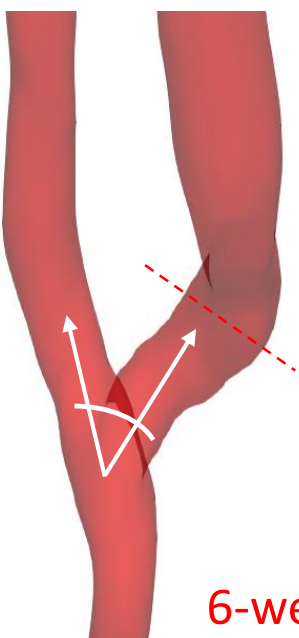
Proximal  
artery



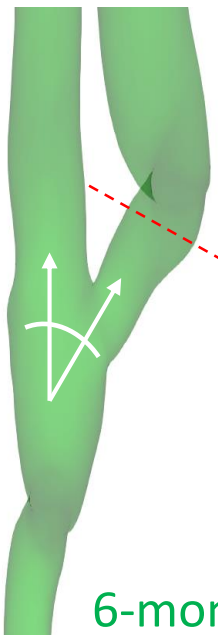
Vein



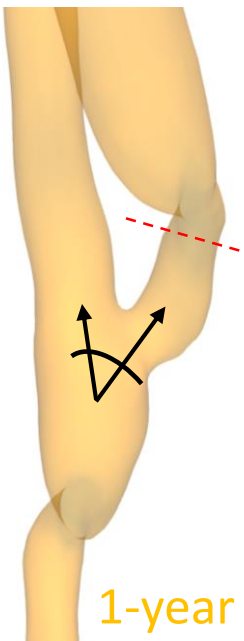
3-day AVF



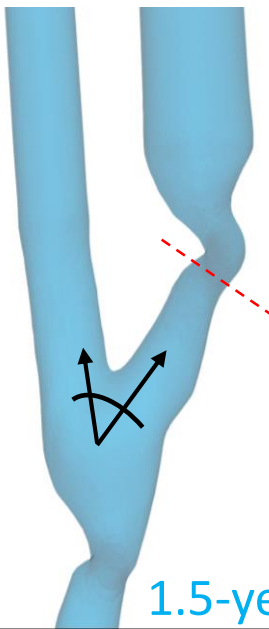
6-week AVF



6-month AVF



1-year AVF



1.5-year AVF

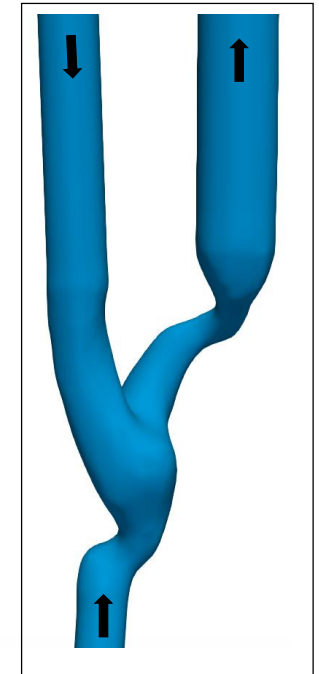
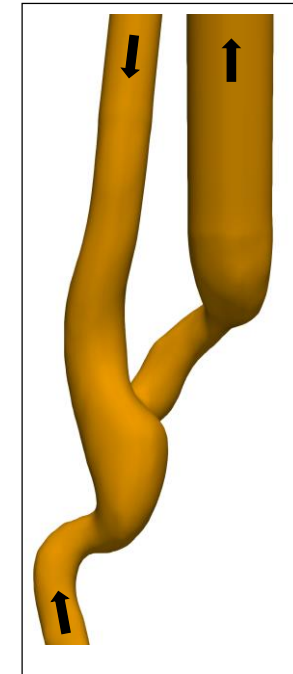
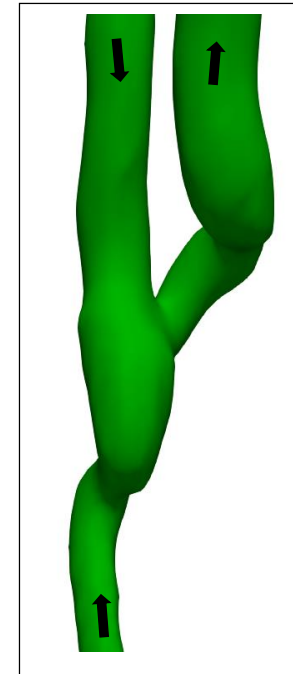
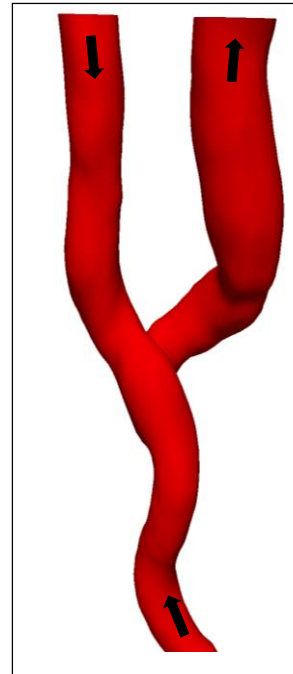
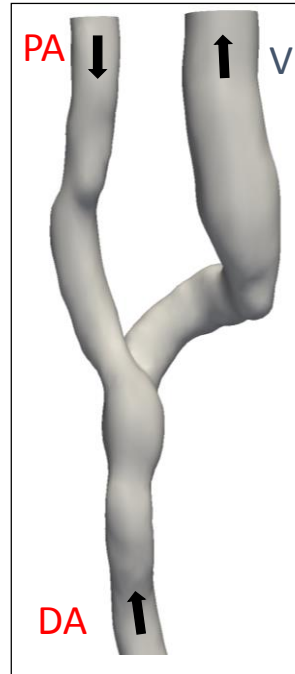
## High-resolution CFD: 3D models and parameters

### Mesh

FoamyHexMesh  
(OpenFoam 5)

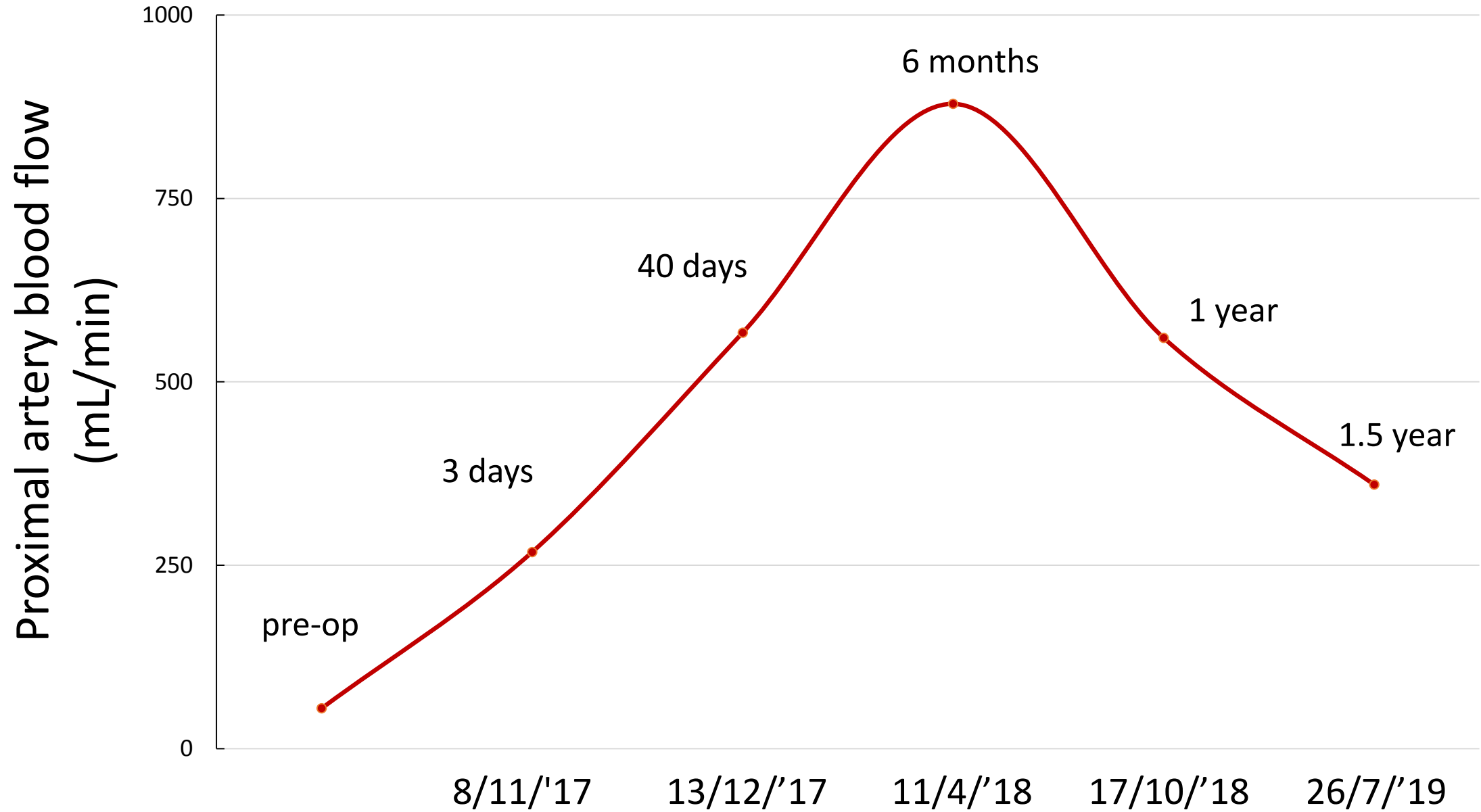
### CFD solver

pimpleFoam  
(OpenFoam 5)



| <i>CFD parameter</i>                                           | <i>3-day AVF</i> | <i>6-week AVF</i> | <i>6-month AVF</i> | <i>1-year AVF</i> | <i>1.5-year AVF</i> |
|----------------------------------------------------------------|------------------|-------------------|--------------------|-------------------|---------------------|
| <i>Mesh cells (<math>\times 10^3</math>)</i>                   | 1200             | 1098              | 1098               | 1275              | 1058                |
| <i><math>\Delta T</math> (<math>\times 10^{-5}</math> sec)</i> | 19               | 22                | 16                 | 18                | 19                  |
| <i><math>Q_{PA}</math> (mL/min)</i>                            | 268              | 576               | 879                | 560               | 360                 |
| <i><math>Q_{DA}</math> (mL/min)</i>                            | - 65             | - 101             | - 80               | - 91              | - 59                |

## Temporal evolution of radial artery blood flow



*Estimated by Doppler US*

## Velocity streamlines over time



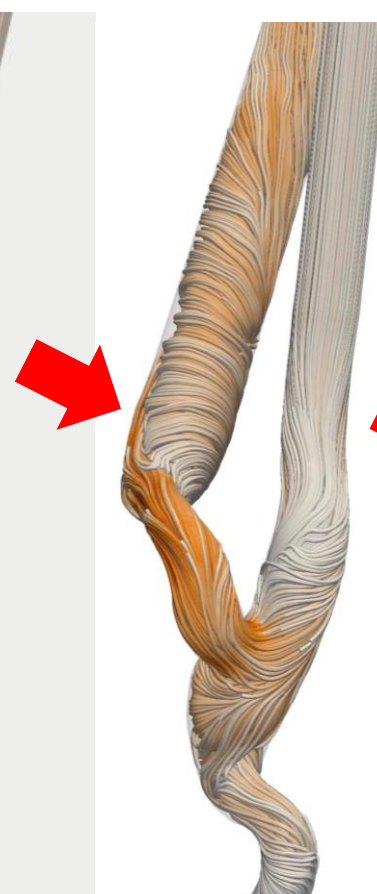
3-day AVF



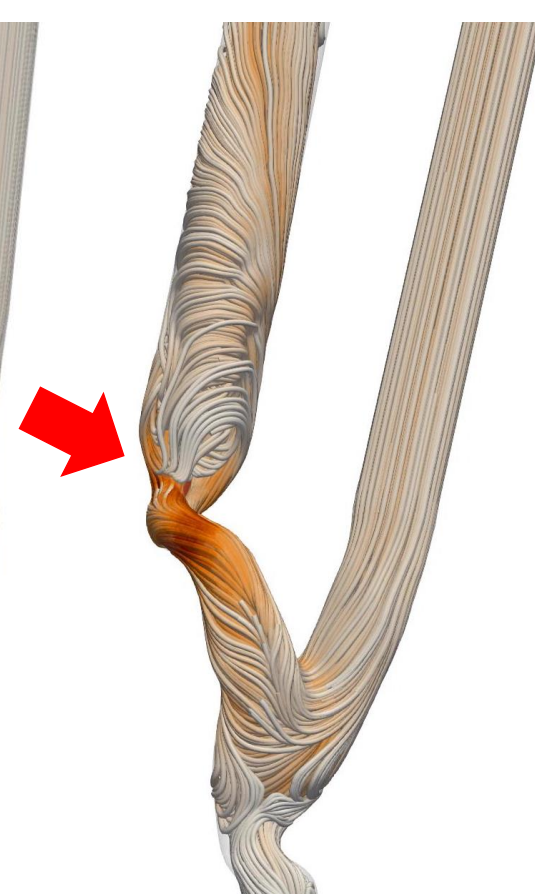
40-day AVF



6-month AVF

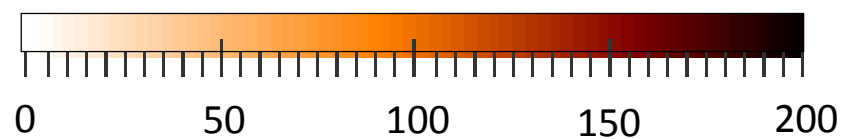


1-year AVF



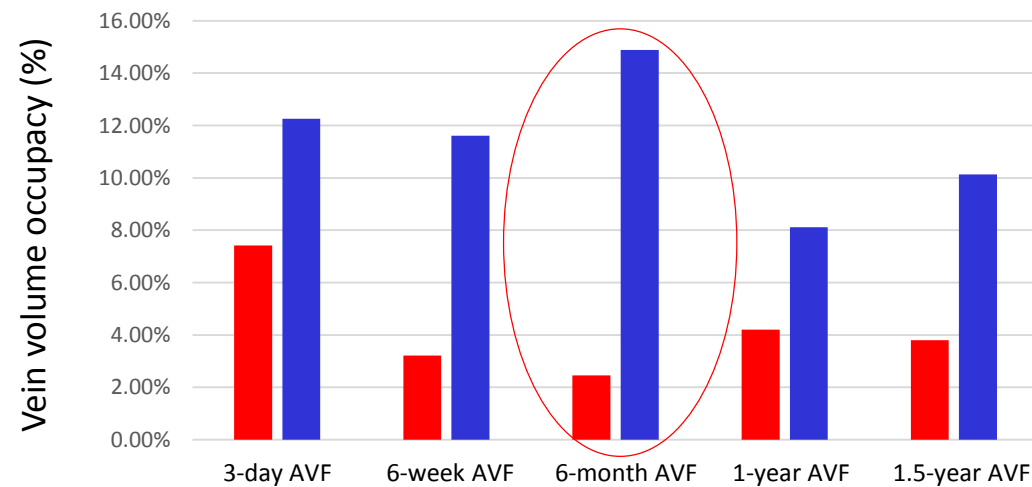
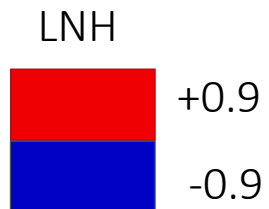
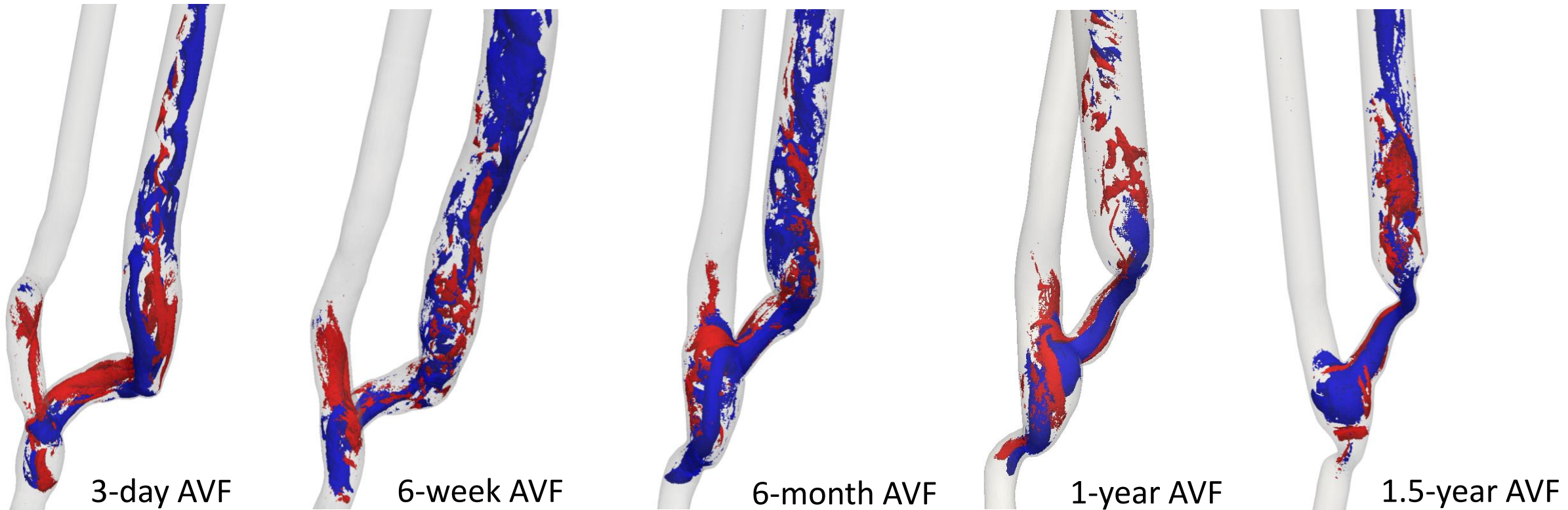
1.5-year AVF

Velocity (cm/s)



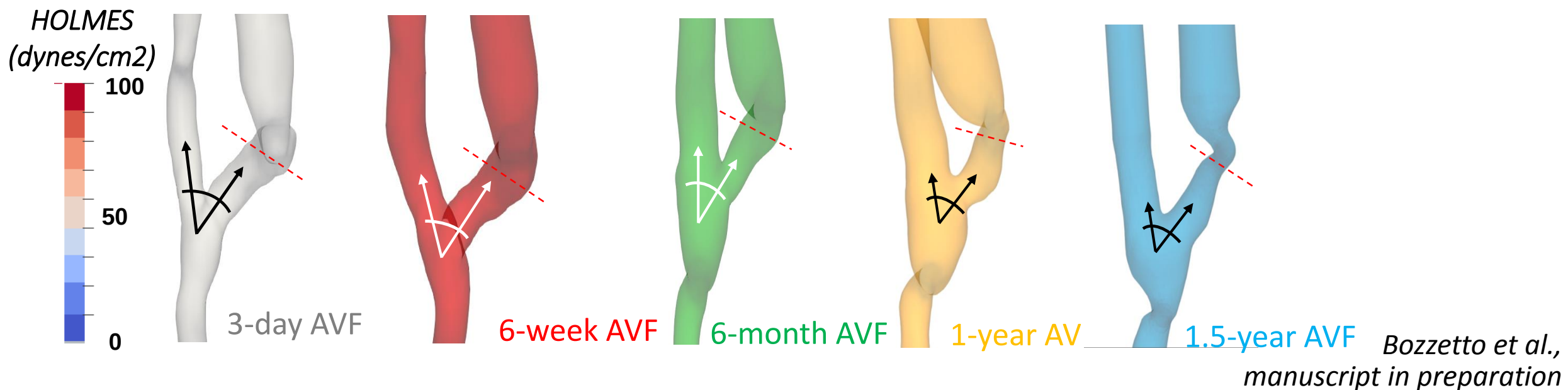
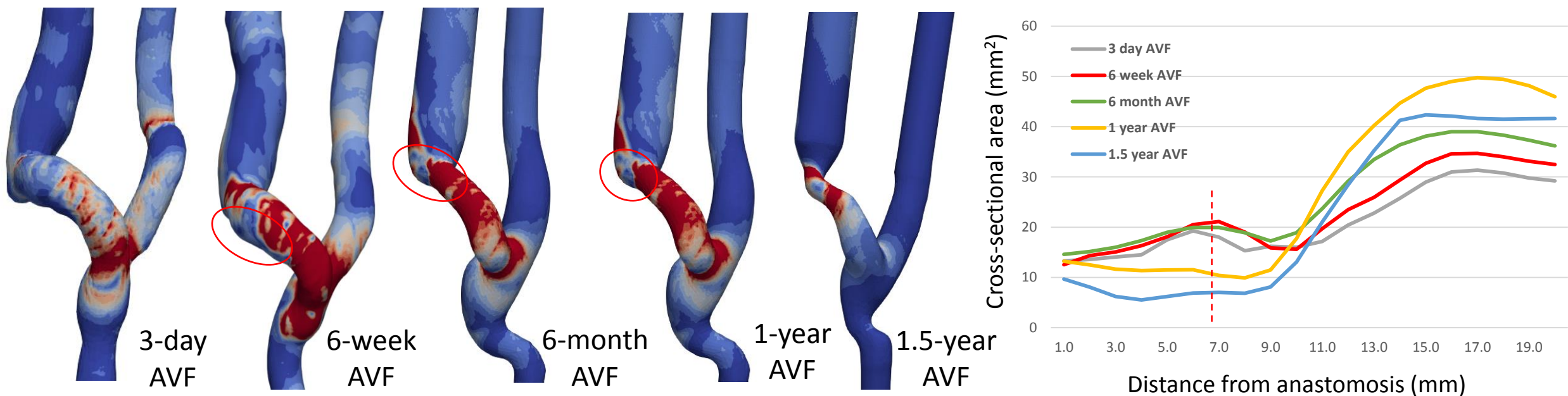
*Bozzetto et al.,  
manuscript in preparation*

## Localized normalized helicity (LNH)



*Bozzetto et al.,  
manuscript in preparation*

# HOLMES descriptor and morphological changes



# Conclusions

## 1) Imaging for surgical planning

- Imaging techniques (US) may support optimal **surgical planning** and ameliorate **clinical outcome** of AVF
- AVF.SIM system was **successfully introduced in the routine clinical setting**
- Mario Negri Institute provides a **free service**, if interested in testing write an email to [avf.sim@marionegri.it](mailto:avf.sim@marionegri.it)

## 2) Imaging for elucidating mechanisms of AVF failure

- Imaging techniques (MRI and US) may be useful to identify **hemodynamic predictors** of AVF stenosis.
- Our novel MRI protocol provided **high-resolution images** and, combined with **CFD**, allows to characterize AVF's **morphological and hemodynamic evolution**
- On going sequential investigations will help to elucidate the **role of local hemodynamics** in stenosis formation

## Acknowledgments

### ***Istituto di Ricerche Farmacologiche Mario Negri IRCCS***

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Dr. Stefano Rota

Dr. Valentina Portalupi



