

# Who Needs Hemodynamic Cath When We Have MR 4D Flow ?

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**McCormick**

Northwestern Engineering

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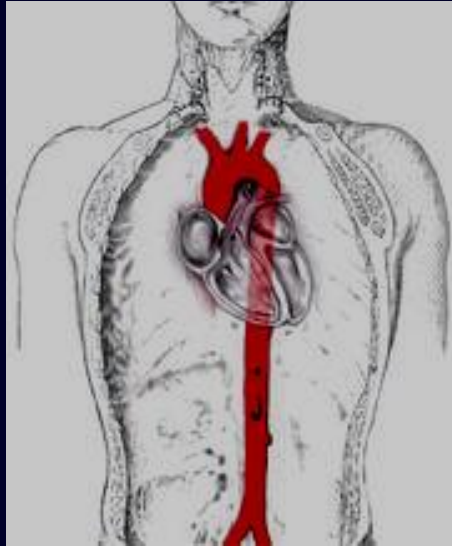
# *Disclosures*

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- Research Support for Northwestern Cardiovascular Imaging Program: *Siemens*
- Consultant: *Circle Cardiovascular Imaging Inc.*

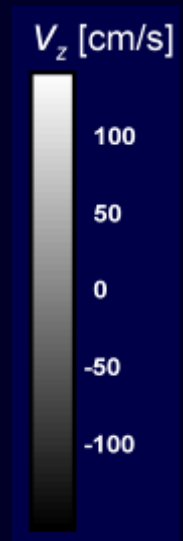
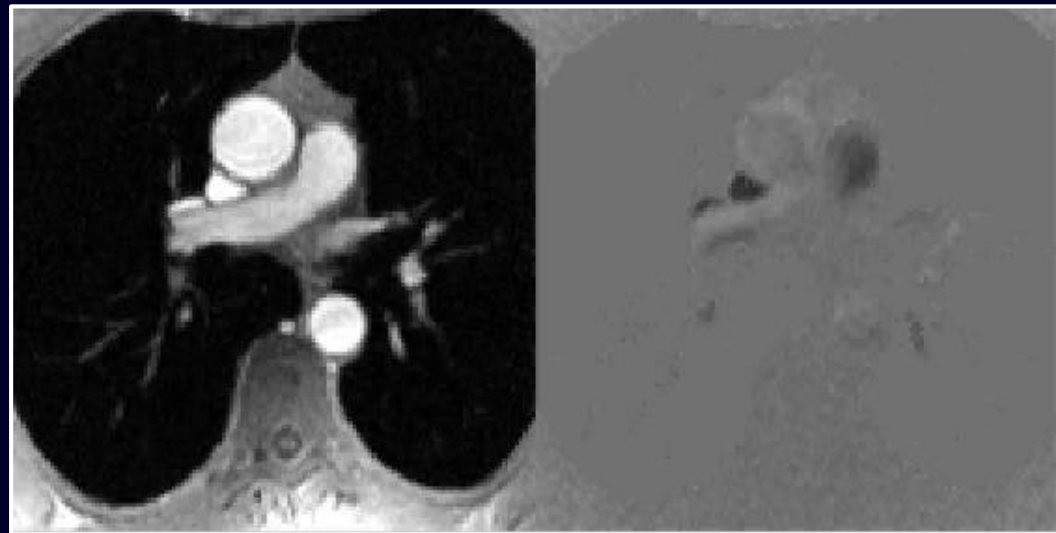
# Cardiovascular MRI

## Imaging of Blood Flow



### 2D Phase-Contrast (PC) MRI

- ECG synchronized
- Anatomy and pulsatile blood flow

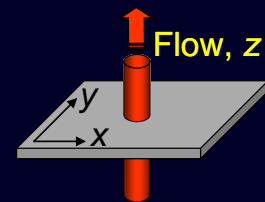


Anatomy

Flow

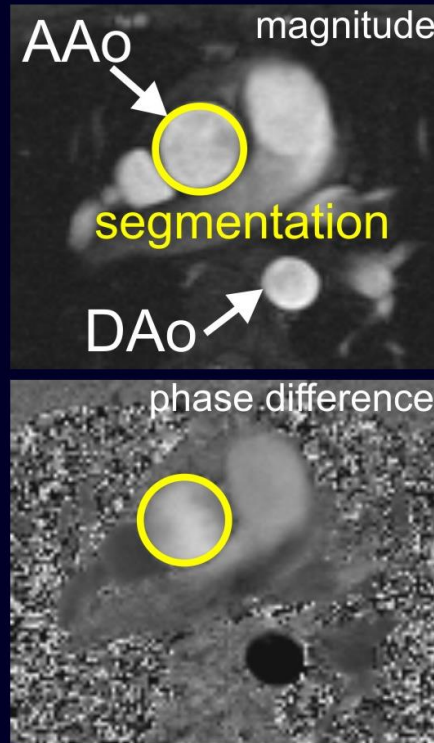
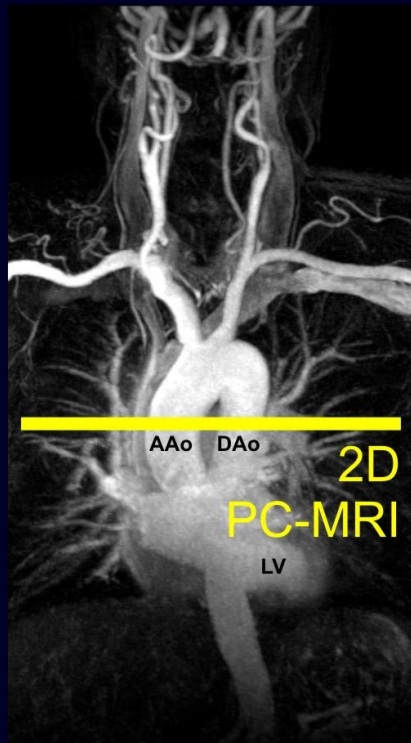


Aorta, 3D CE-MRA

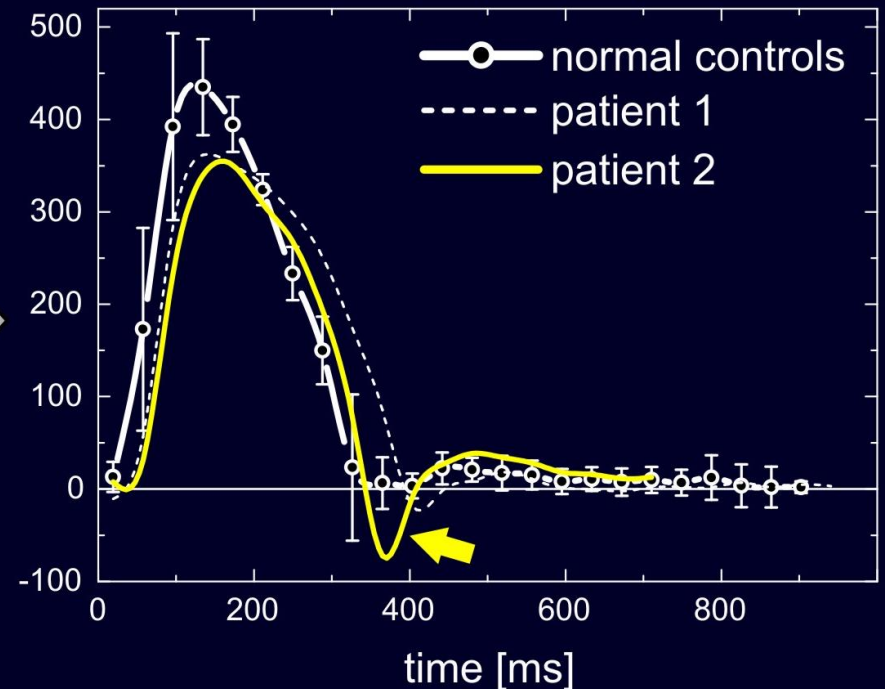


## Flow Quantification

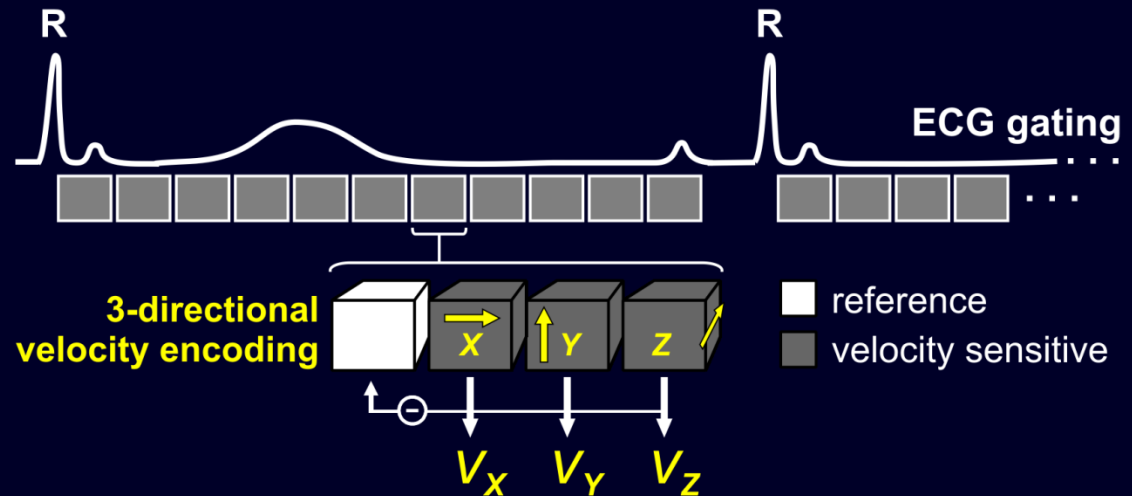
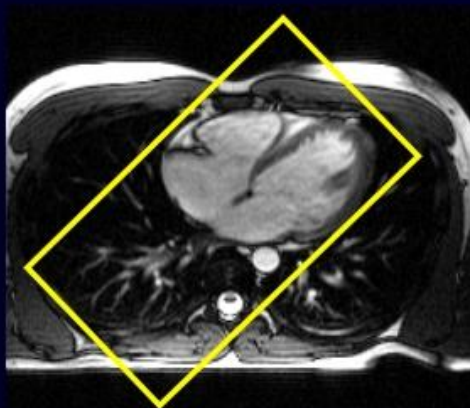
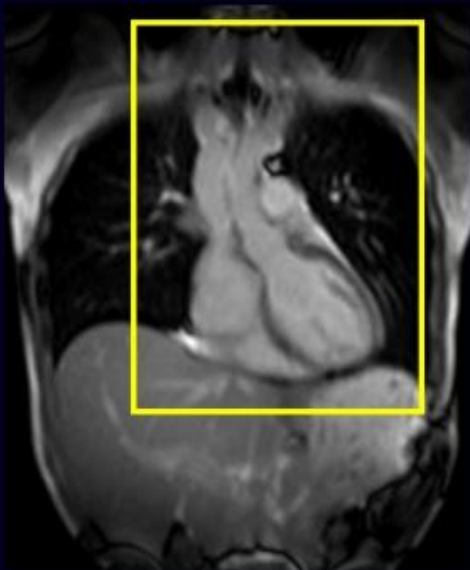
- Net flow, cardiac output
- Regurgitation, valve function, peak velocity, etc.



## Blood flow ascending aorta [ml/s]

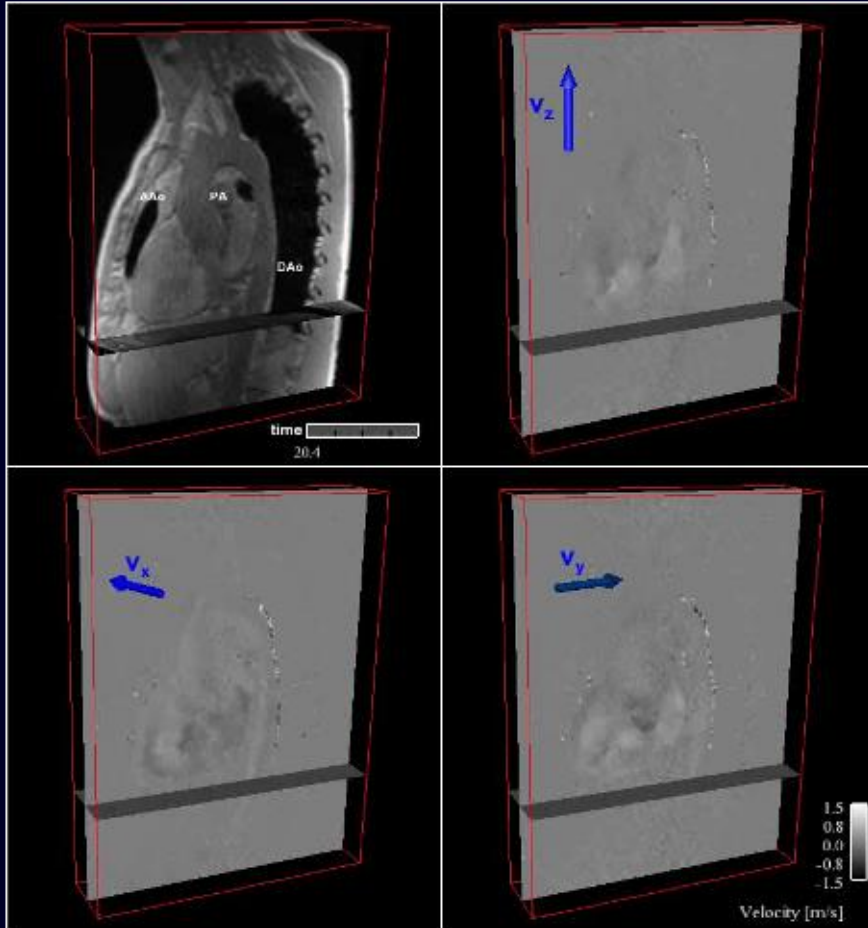


### Full Volumetric Coverage: 3D & 3-directional blood flow



- resolution  $\sim (2\text{mm})^3$  &  $\sim 40\text{ms}$
- FOV  $320 \times 320 \times 64\text{mm}$
- velocity encoding:  $4\text{TR} \sim 20\text{ms}$ 
  - 2560 RR intervals, respiration control
  - **$\sim 40\text{-}80$  min total scan time**

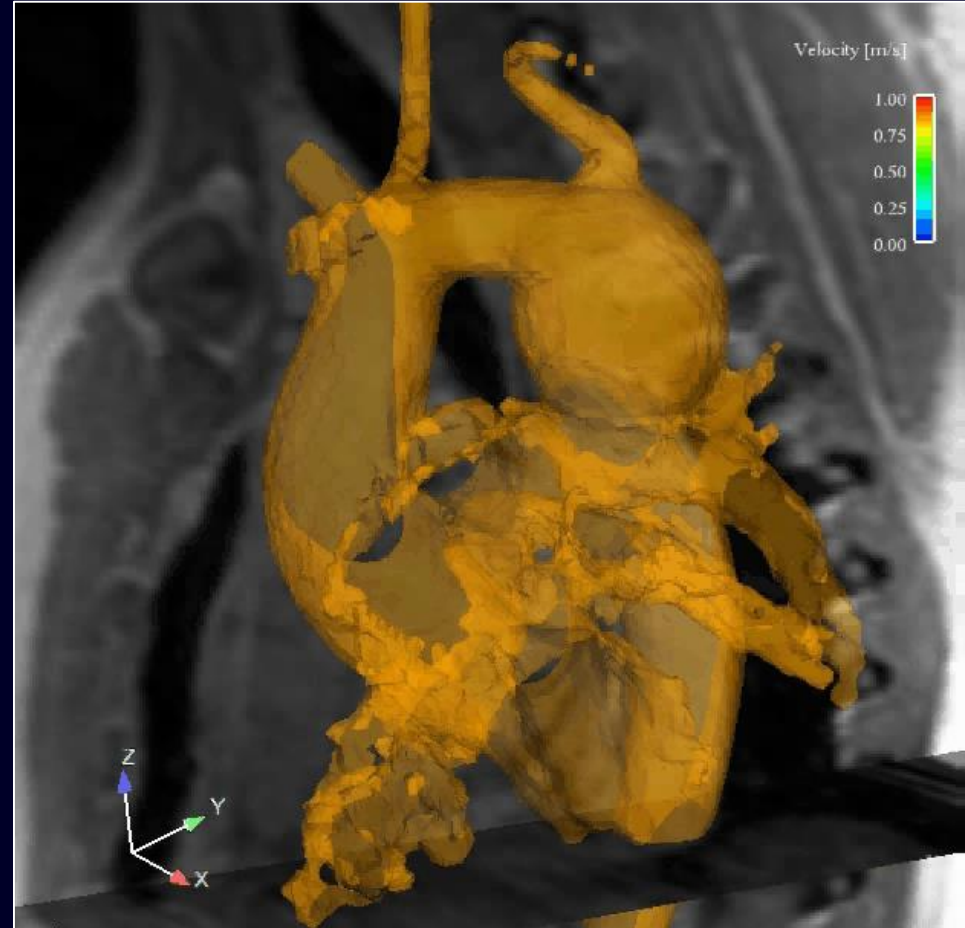
## 4D Flow MRI



• Res.  $\sim 2\text{mm}^3$ ,  $T_{Res} \sim 40\text{ms}$ ,  $T_{Acq} \sim 5\text{-}15\text{min}$

> 2k-10k images

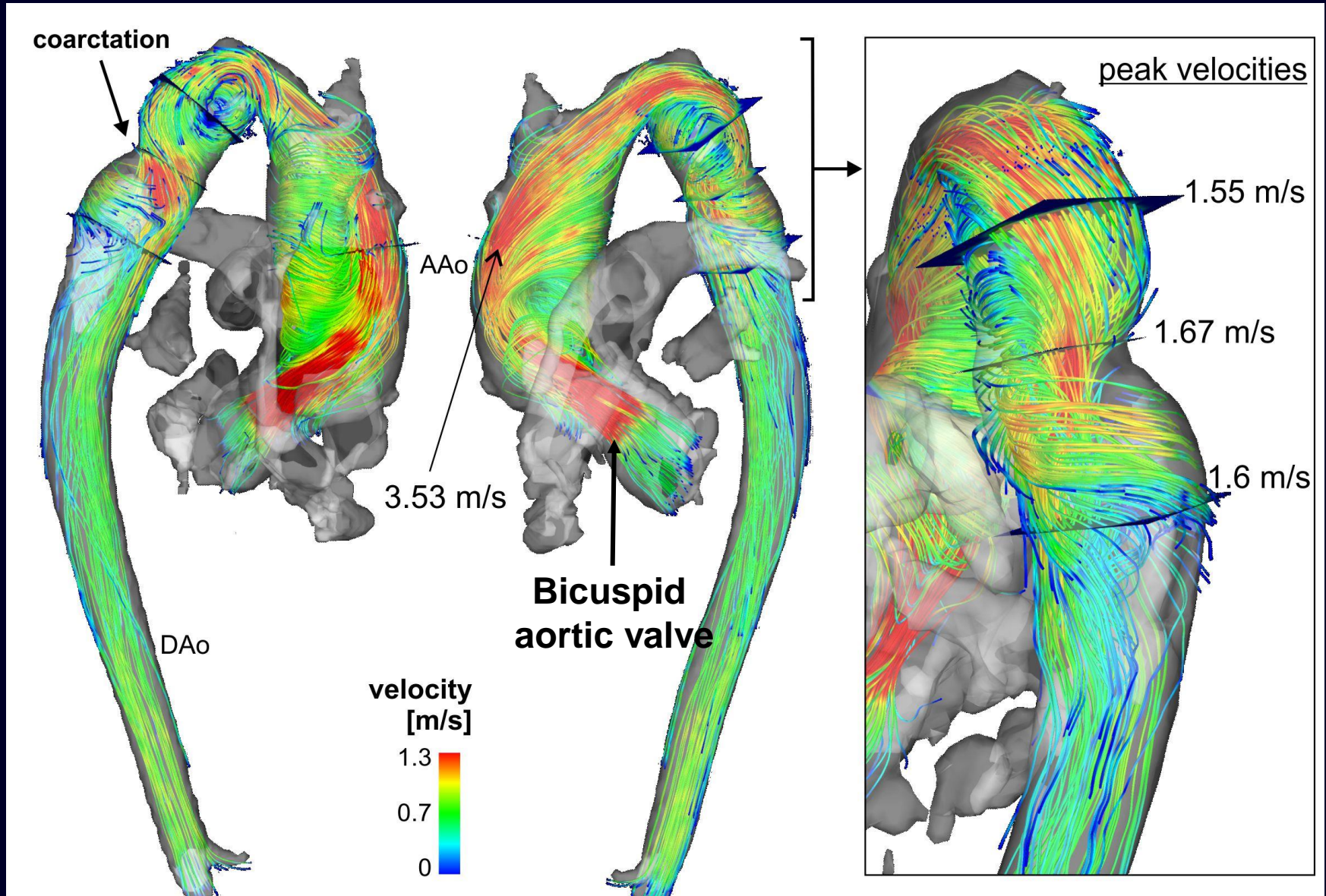
## In-vivo 3D Blood Flow



➔ **4D** (3D volume + time)  
**flow** (3-dir. velocity encoding) **MRI**

# 4D Flow MRI

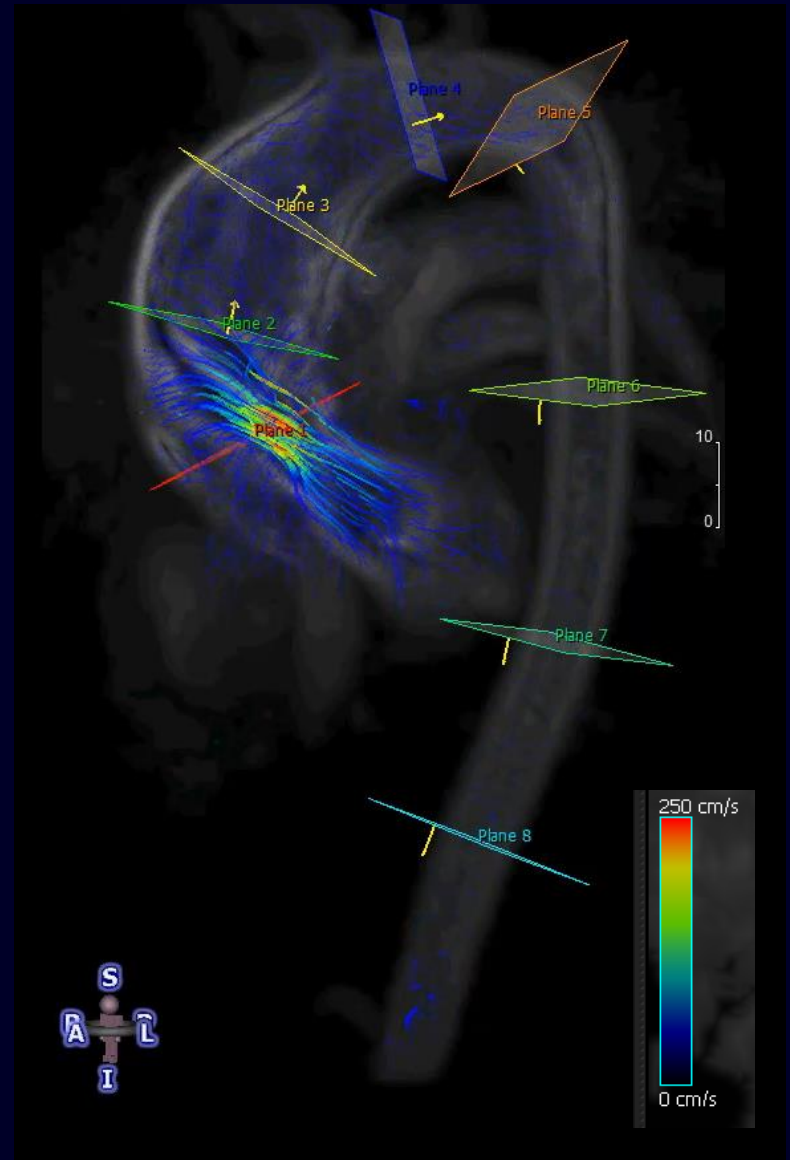
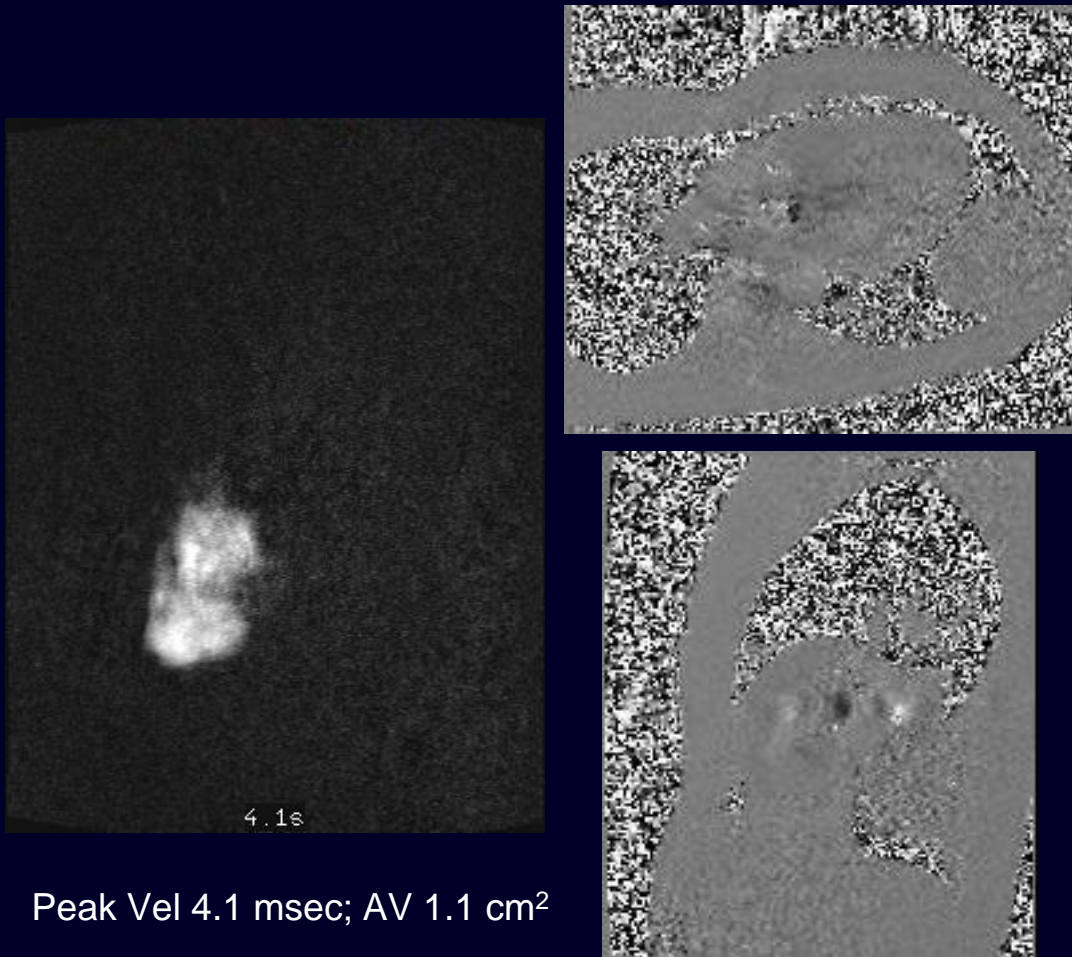
# Aortic Hemodynamics



# 4D Flow MRI

# Aortic Hemodynamics

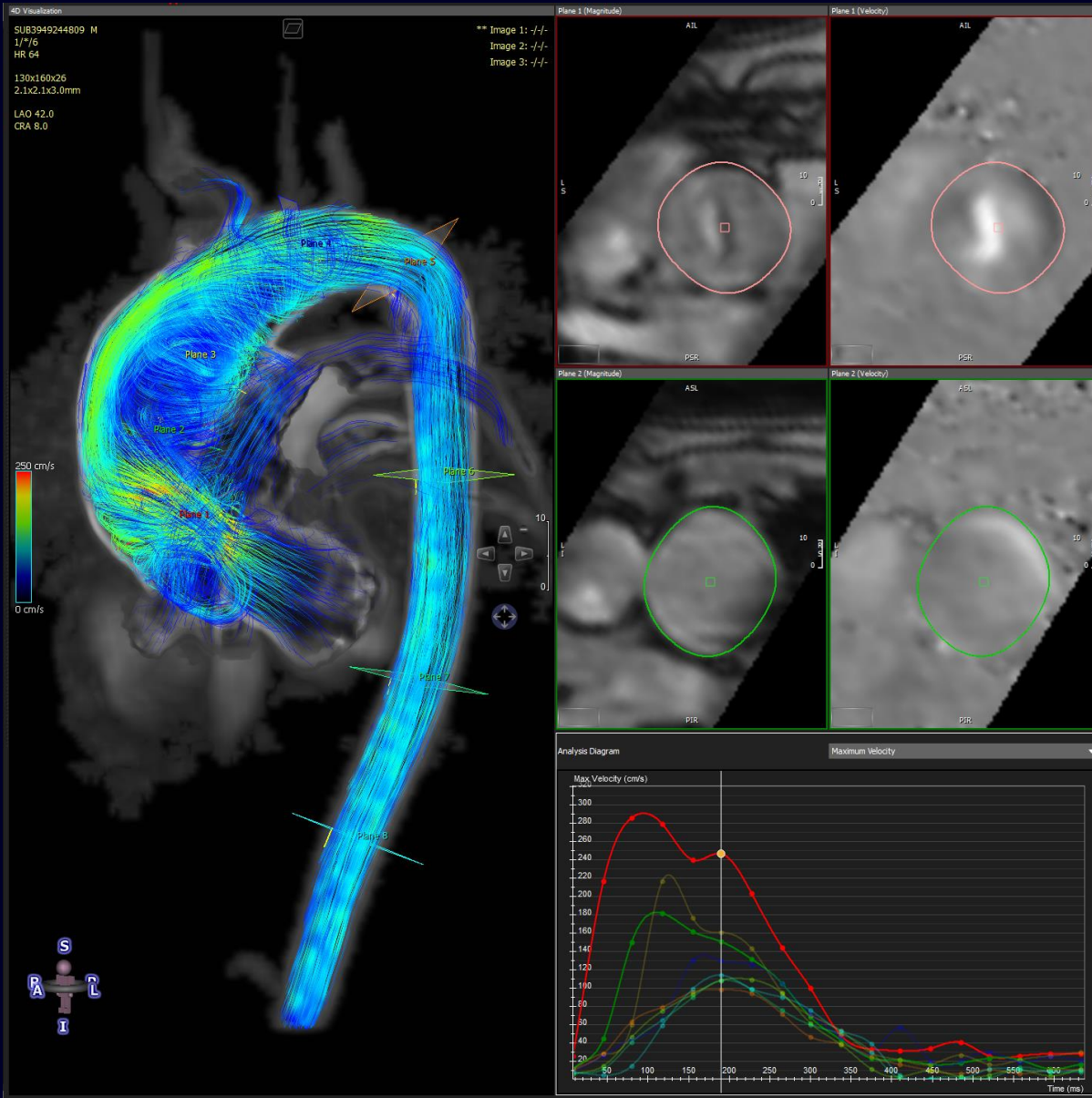
**Patient:** 54-yo, bicuspid aortic valve with severe aortic valve stenosis





# 4D Flow MRI

# Aortic Hemodynamics



## Flow Analysis Report

Multiplane PWV(m/s): 3.51  
 Planar Analysis:

### Plane 1:

Net Flow (ml/cycle): 110.68  
 Peak Velocity (cm/s): 286.00  
 Regurgitation (%): 0.60

### Plane 2:

Net Flow (ml/cycle): 106.37  
 Peak Velocity (cm/s): 182.00  
 Regurgitation (%): 2.55

### Plane 3:

Net Flow (ml/cycle): 99.81  
 Peak Velocity (cm/s): 217.00  
 Regurgitation (%): 3.93

### Plane 4:

Net Flow (ml/cycle): 62.78  
 Peak Velocity (cm/s): 130.00  
 Regurgitation (%): 12.65

### Plane 5:

Net Flow (ml/cycle): 50.17  
 Peak Velocity (cm/s): 98.00  
 Regurgitation (%): 13.66

### Plane 6:

Net Flow (ml/cycle): 51.36  
 Peak Velocity (cm/s): 109.00  
 Regurgitation (%): 11.23

### Plane 7:

Net Flow (ml/cycle): 44.04  
 Peak Velocity (cm/s): 108.00  
 Regurgitation (%): 13.34

### Plane 8:

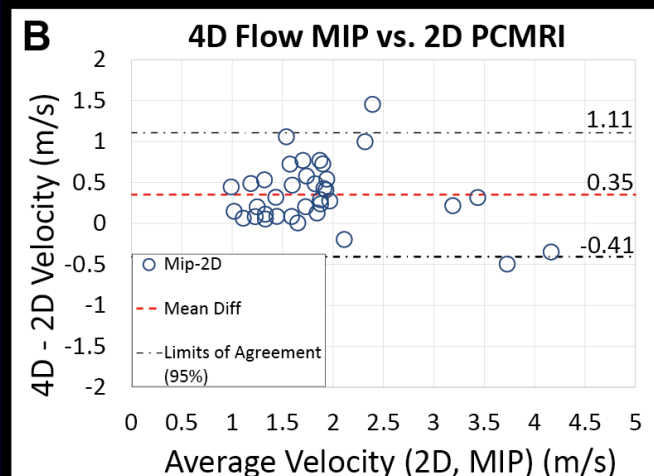
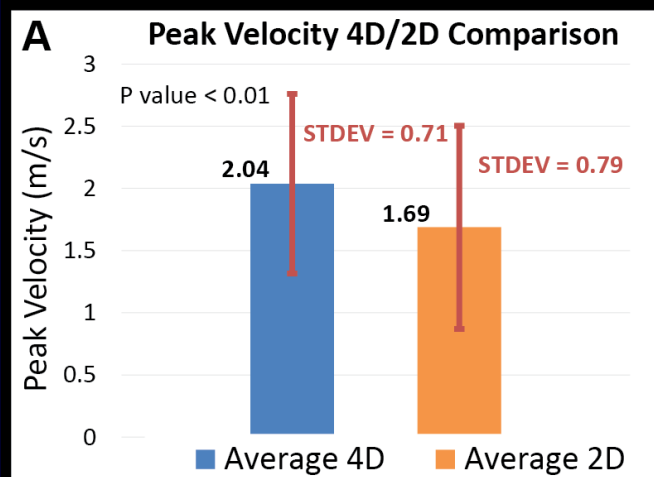
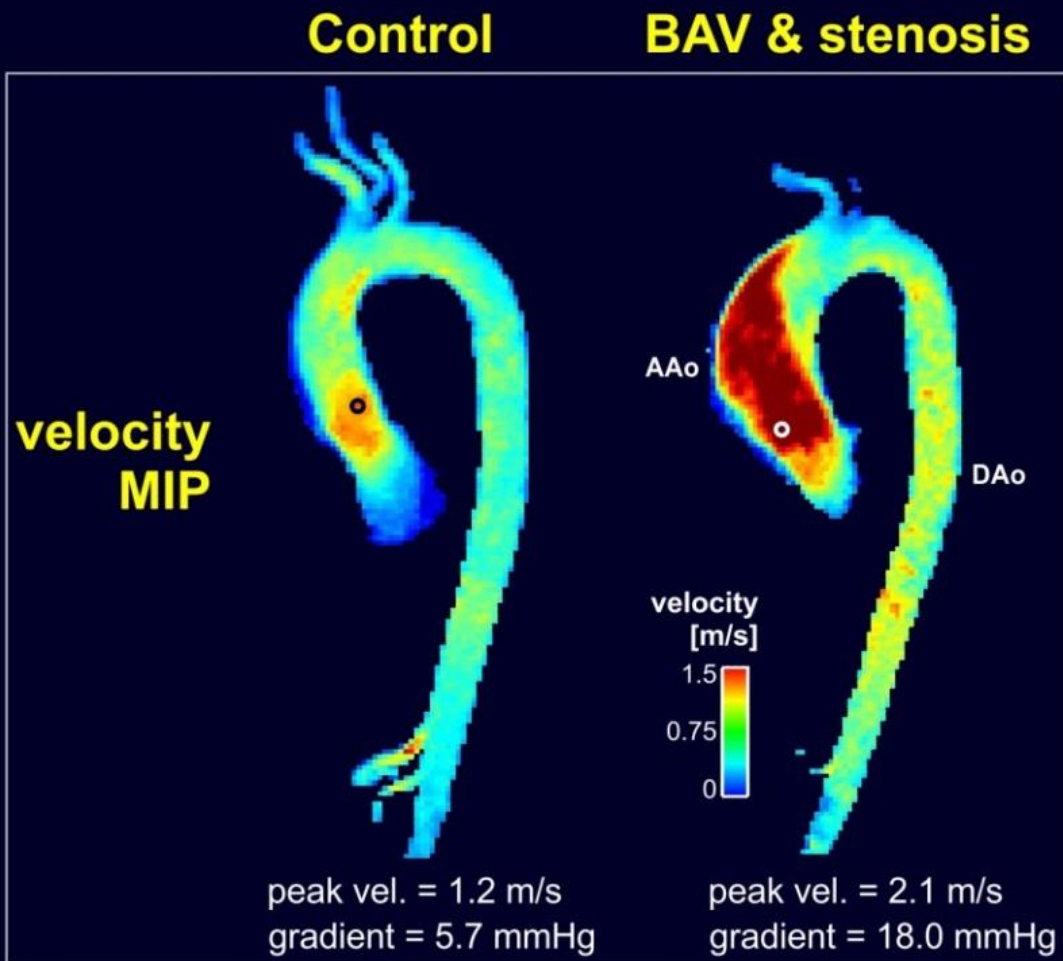
Net Flow (ml/cycle): 41.73  
 Peak Velocity (cm/s): 114.00  
 Regurgitation (%): 12.94

# 4D Flow MRI

# Analysis Workflow

## Peak Velocity MIPs

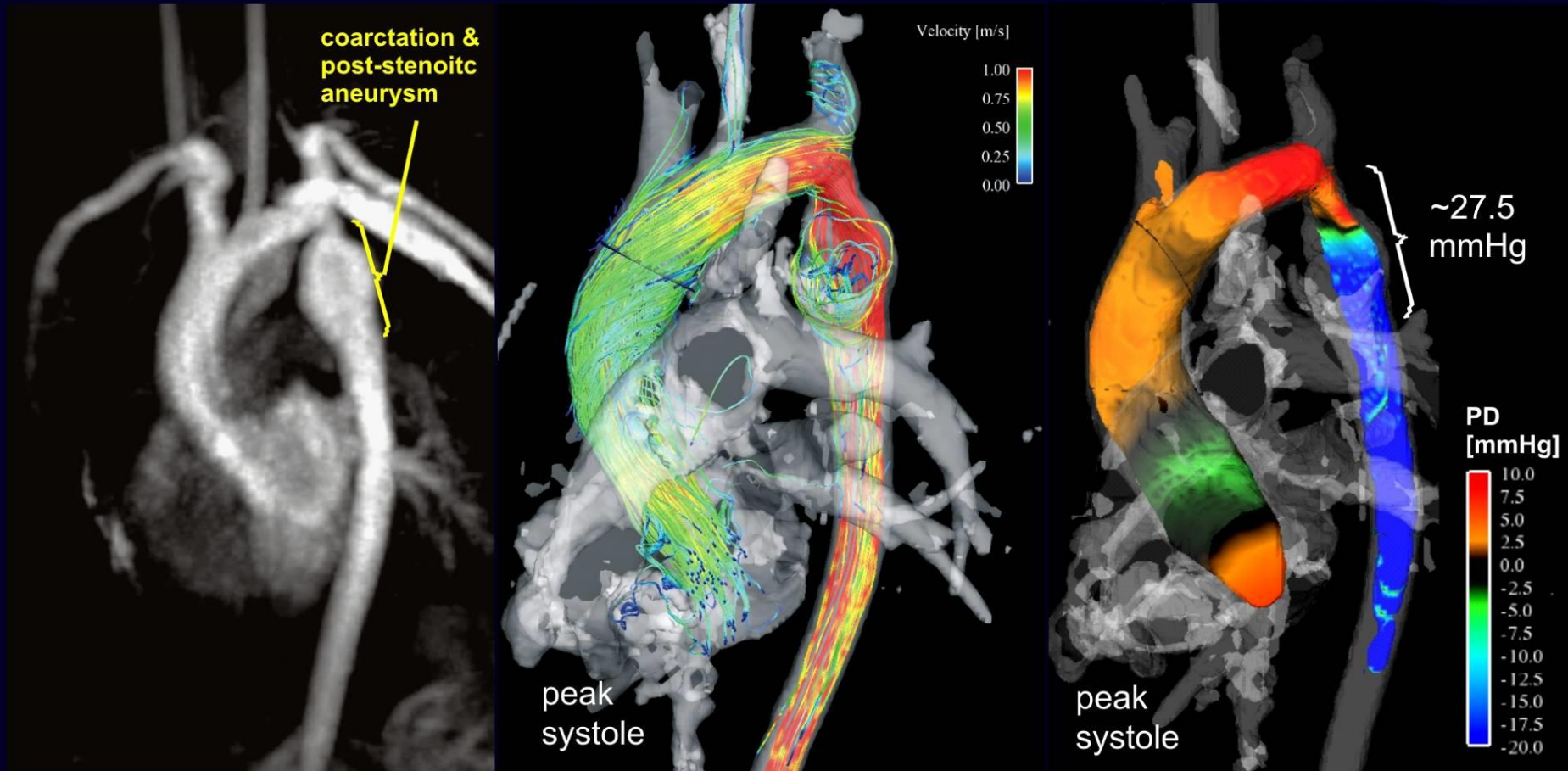
- Study in n=51 pediatric BAV patients: 4D flow vs. 2D PC



# 4D Flow MRI

# Pressure Mapping

**Patient:** Coarctation & post-stenotic dilatation



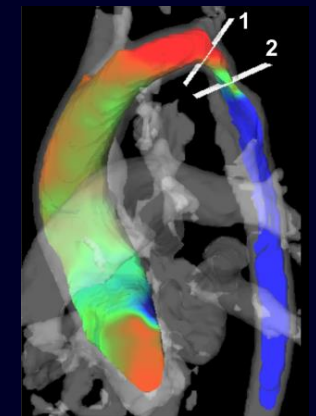
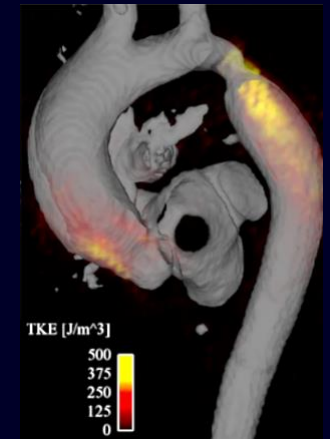
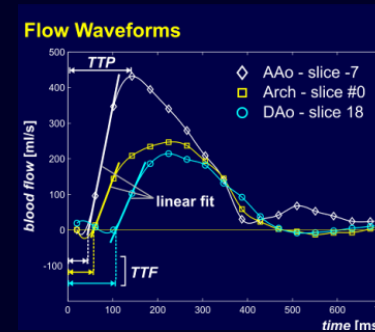
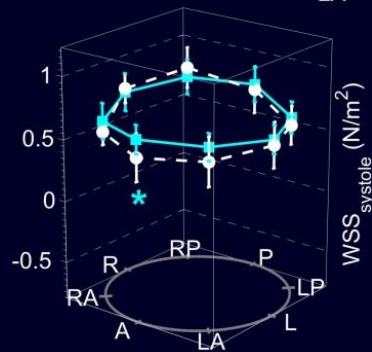
MR Angiography

3D flow visualization

3D pressure difference

## Quantification & Biomechanical Modeling

- Wall shear stress <sup>1-5</sup>
- Pressure difference mapping <sup>6-8</sup>
- Turbulence & turbulent kinetic energy <sup>9,10</sup>
- Pulse wave velocity & vessel elasticity <sup>11-15</sup>
- .....



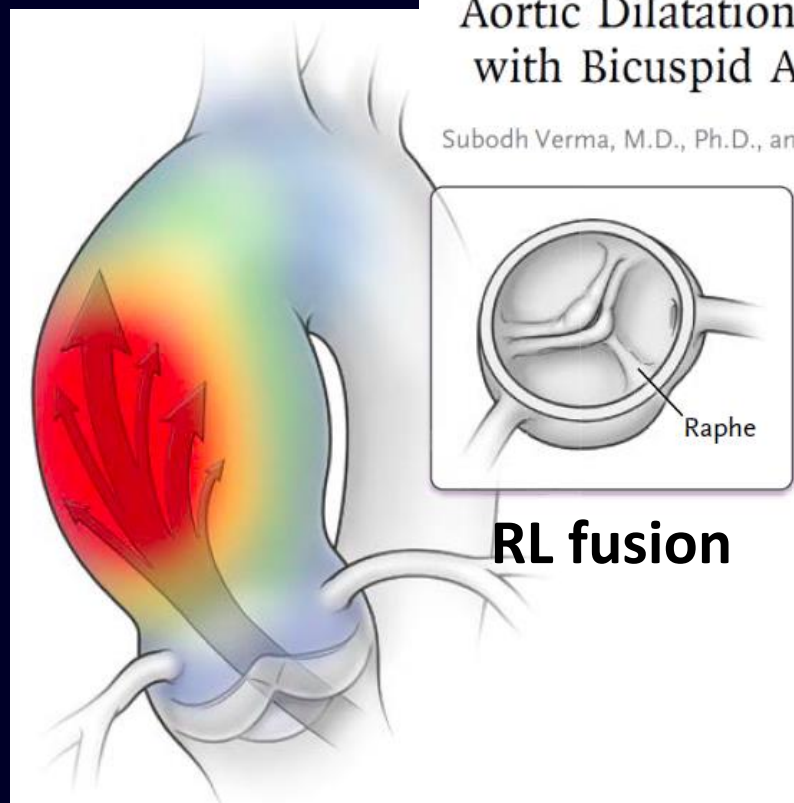
1. Stalder AF, et al. *Magn Reson Med* 2008;60(5):1218-1231.
2. Oshinski JN, et al. *J Magn Reson Imaging* 1995;5(6):640-647.
3. Oyre S, et al. *Eur J Vasc Endovasc Surg* 1998;16(6):517-524.
4. Harloff A, et al. *Magn Reson Med*. 2010;63(6):1529-1536
5. Frydrychowicz A et al. *J Magn Reson Imaging*. 2009;30(1):77-84
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11. Laffon E, et al. *J Magn Reson Imaging* 2005;21(1):53-58.
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13. Peng HH, et al. *J Magn Reson Imaging* 2006;24(6):1303-1310.
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15. Hardy CJ, et al. *Magn Reson Med* 1994;31(5):513-520

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## Aortic Dilatation in Patients with Bicuspid Aortic Valve

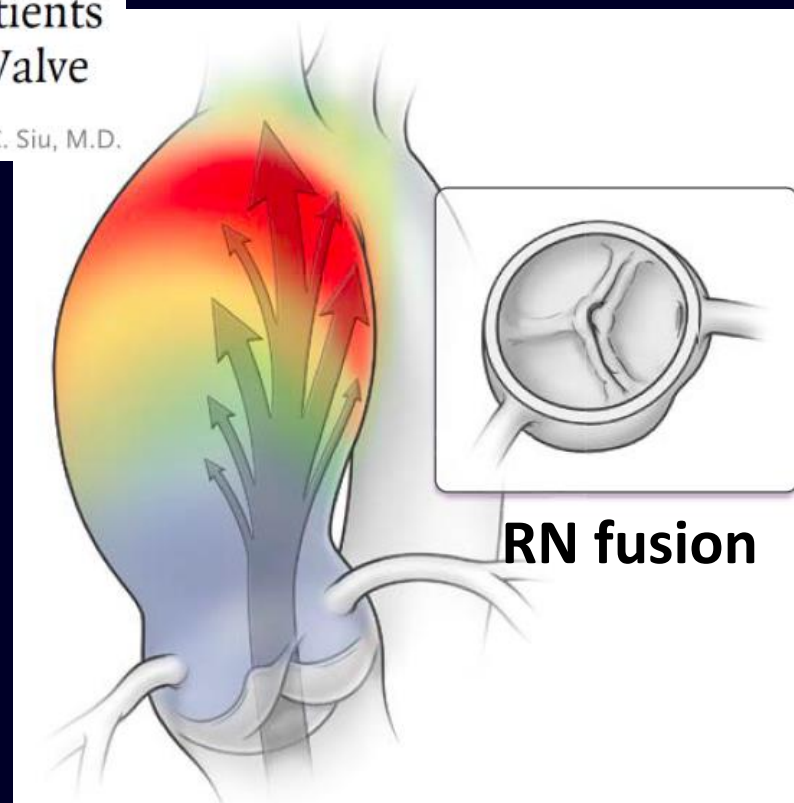
Subodh Verma, M.D., Ph.D., and Samuel C. Siu, M.D.



Flow jet → right anterior wall



'type 2' tubular aortopathy

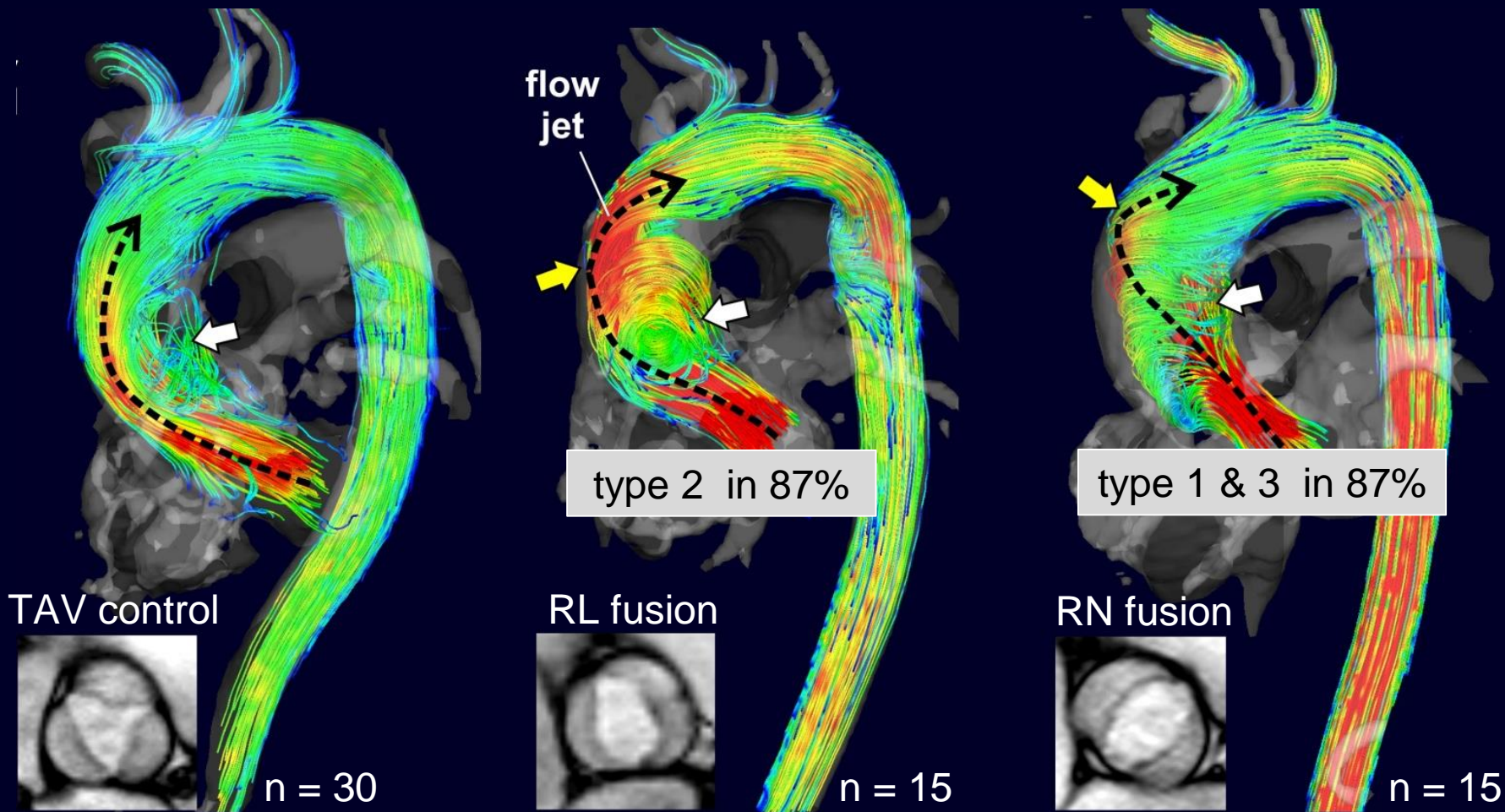


Flow jet → right posterior wall



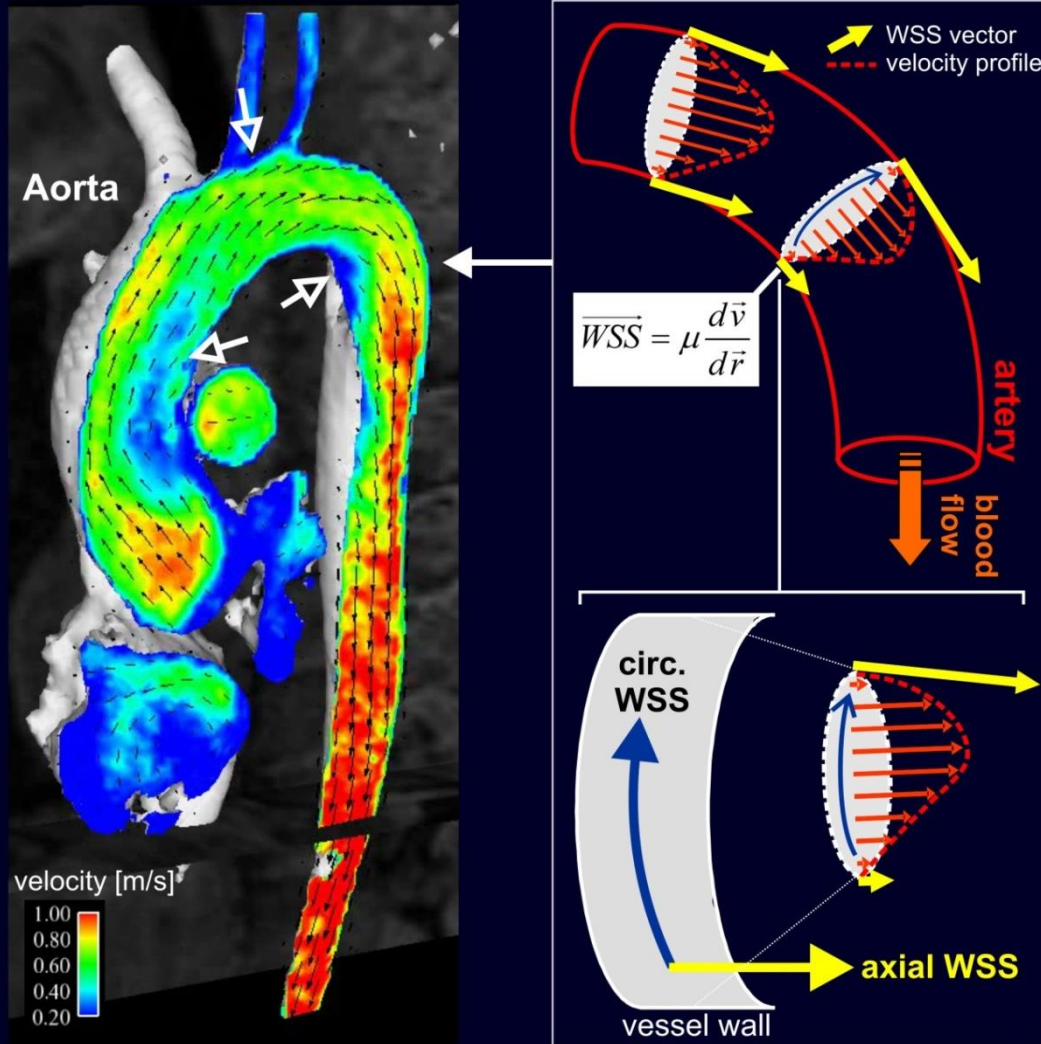
'type 3' tubular/arch aortopathy

## BAV Fusion: Impact on flow patterns & aortopathy phenotype



# 4D Flow MRI

# Wall Shear Stress



- Drag force of blood on aortic wall
- Regulates endothelial cell function

Stalder AF, et al. *MRM* 2008;60(5):1218-1231

Malek et al. *JAMA* 1999;282:2035-2042

**Mechanistic Link:** Altered flow → aortic remodeling & dilatation

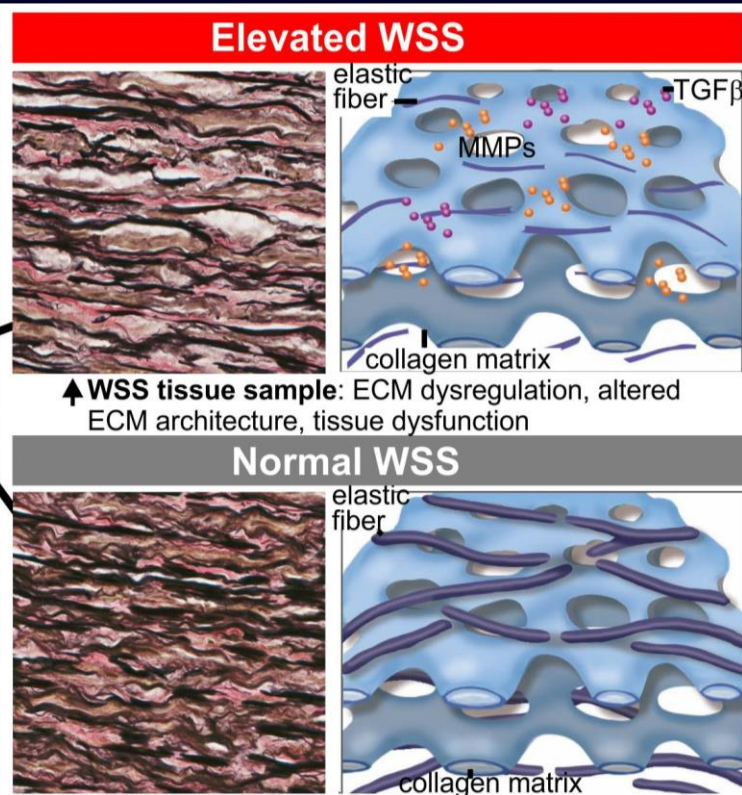
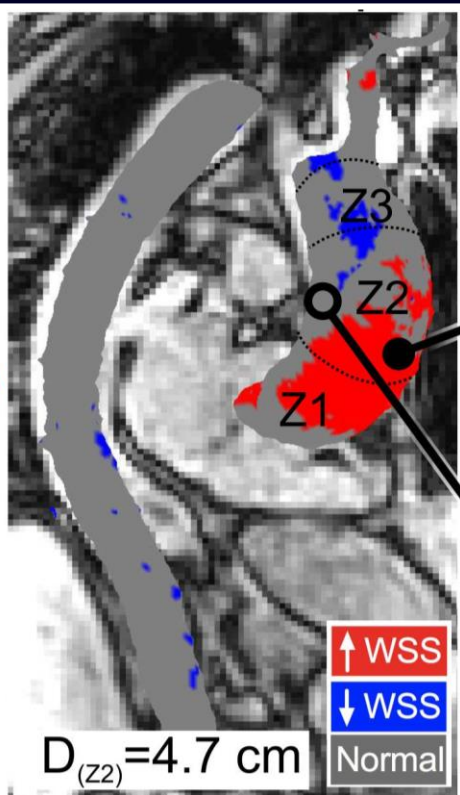
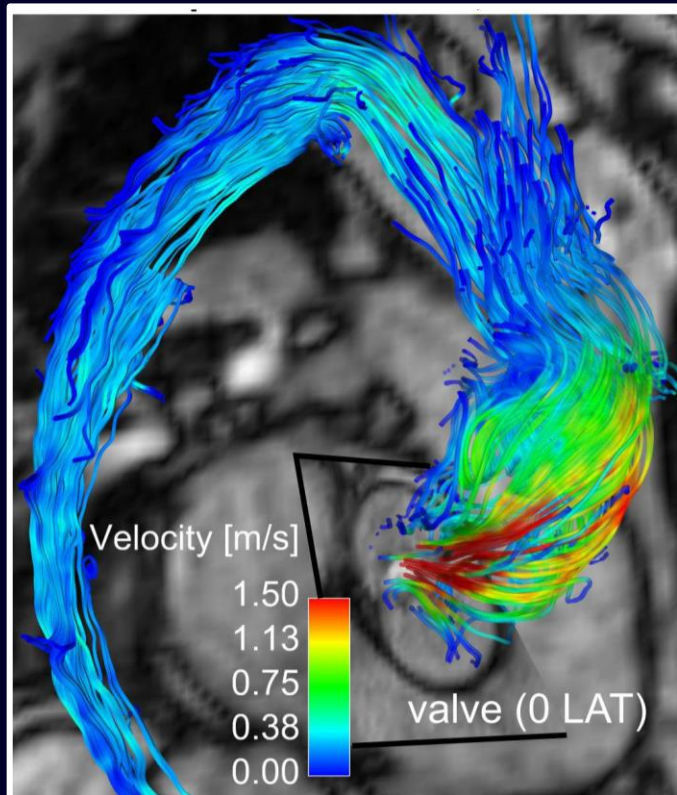
# 4D Flow MRI

# BAV & Wall Tissue Degeneration

4D flow MRI  
in BAV patient

Atlas based  
WSS heatmap

Aorta wall  
histopathology



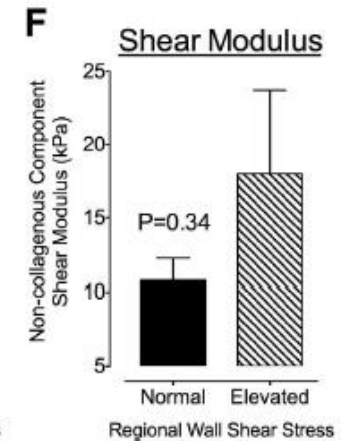
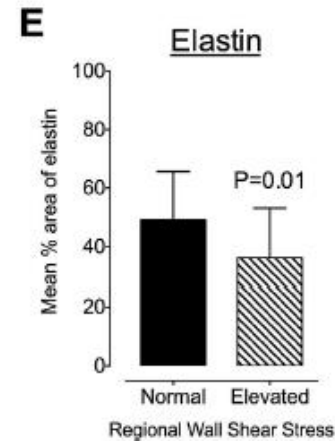
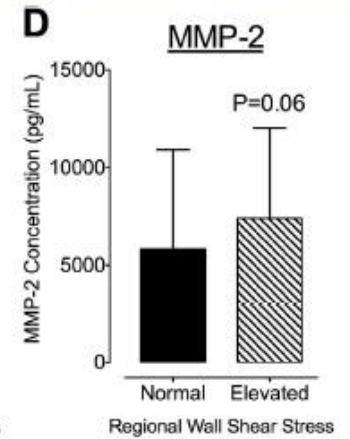
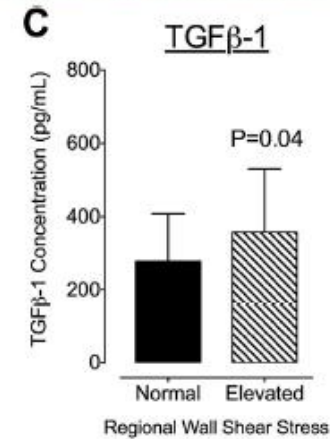
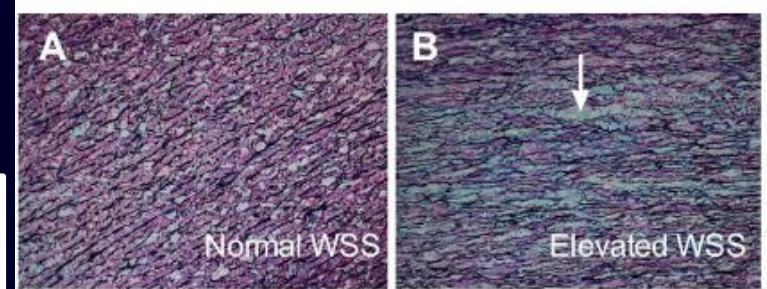
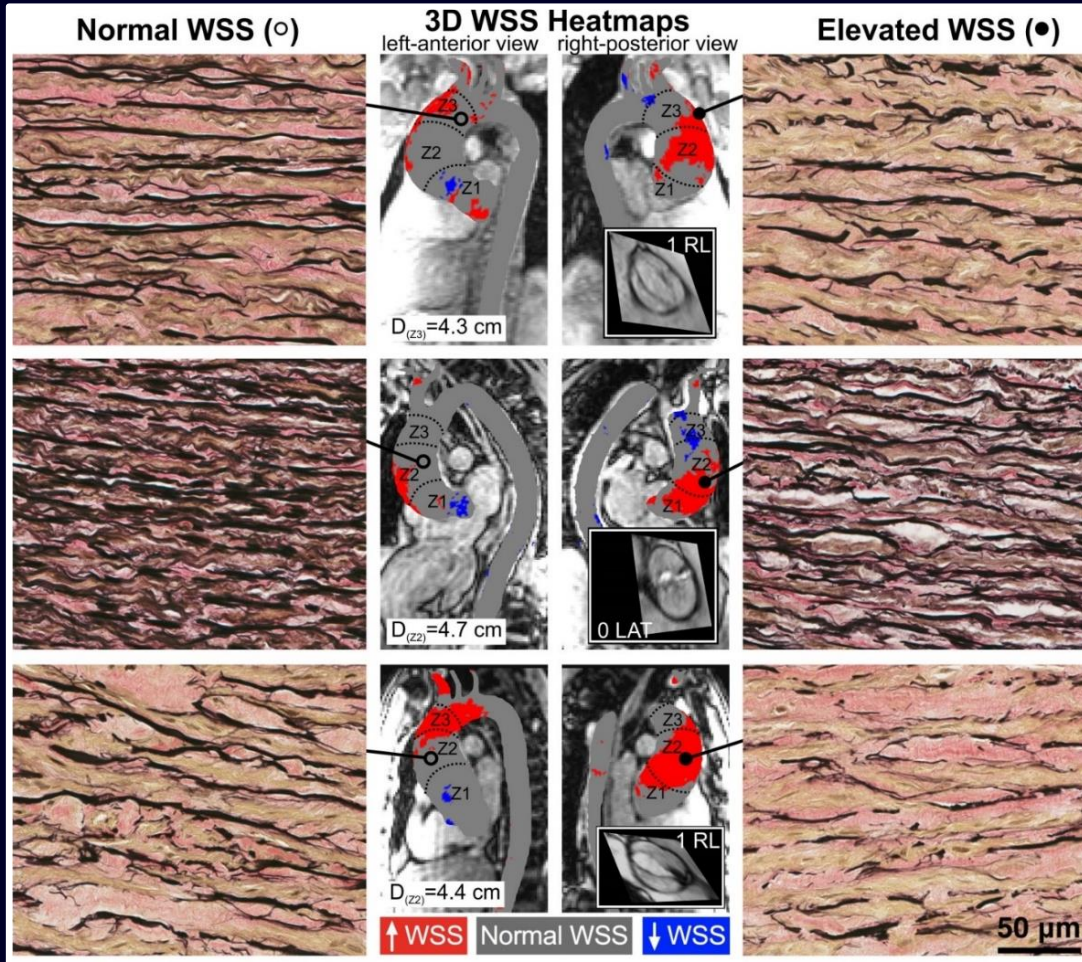
**Hypothesis:** Changes in aortic WSS are directly associated with aortic wall degeneration in BAV aortopathy

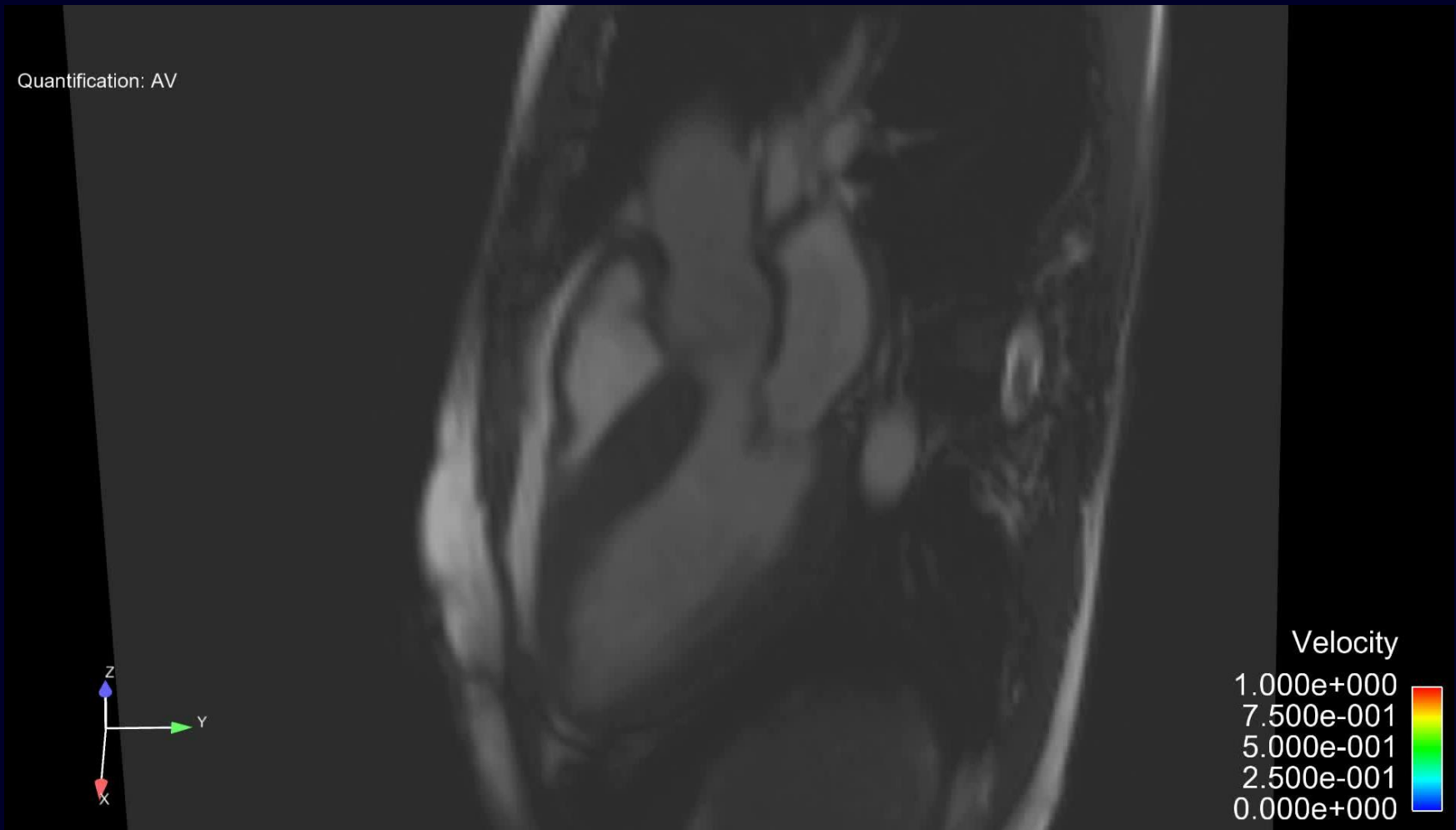


# 4D Flow MRI

# BAV & Wall Tissue Degeneration

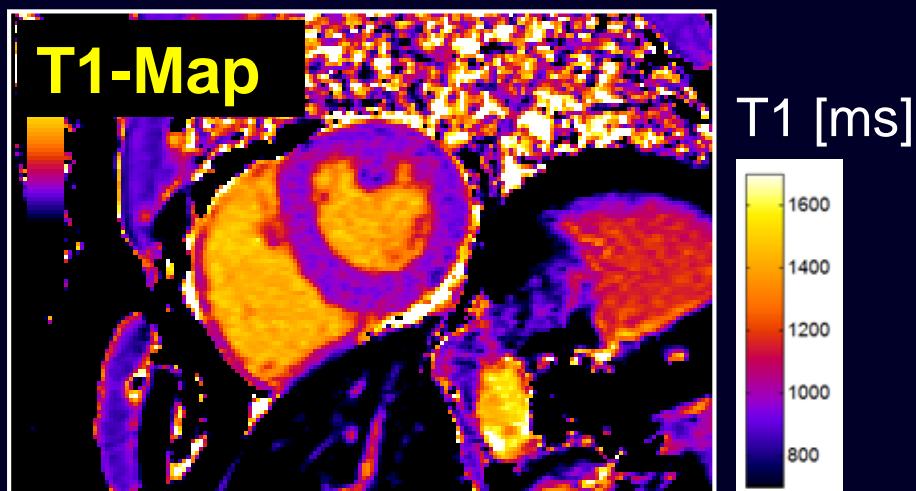
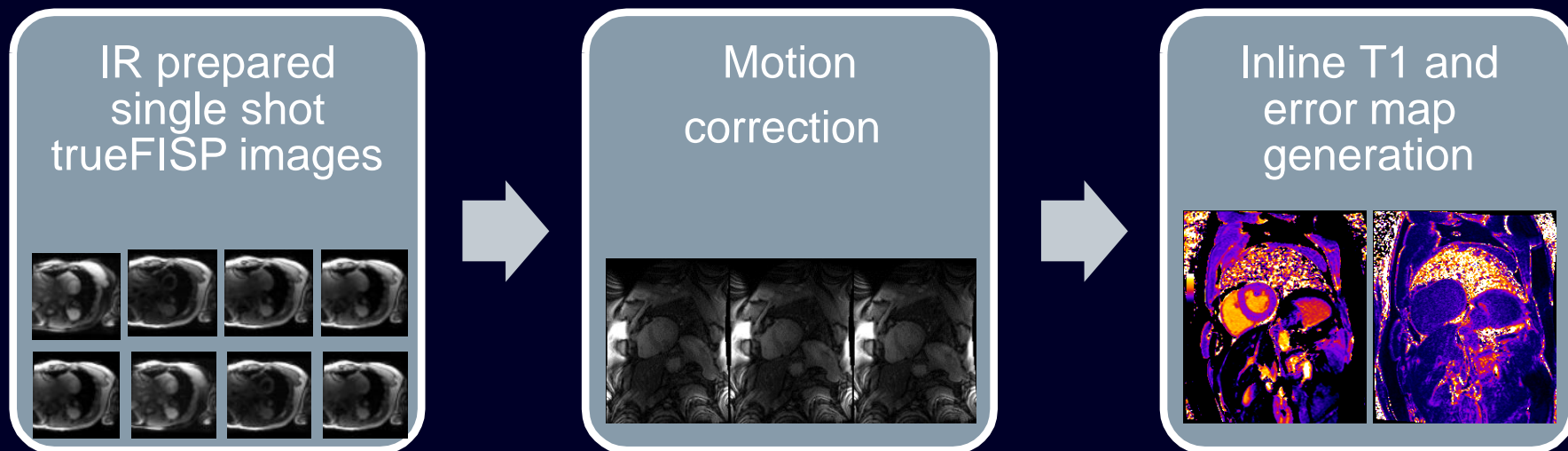
Pre-operative 4D flow MRI & wall tissue samples (n=20)





HCM: Cause of aortic flow disturbance & elevated LVOT pressure

## T1-Mapping: Data reconstruction pipeline



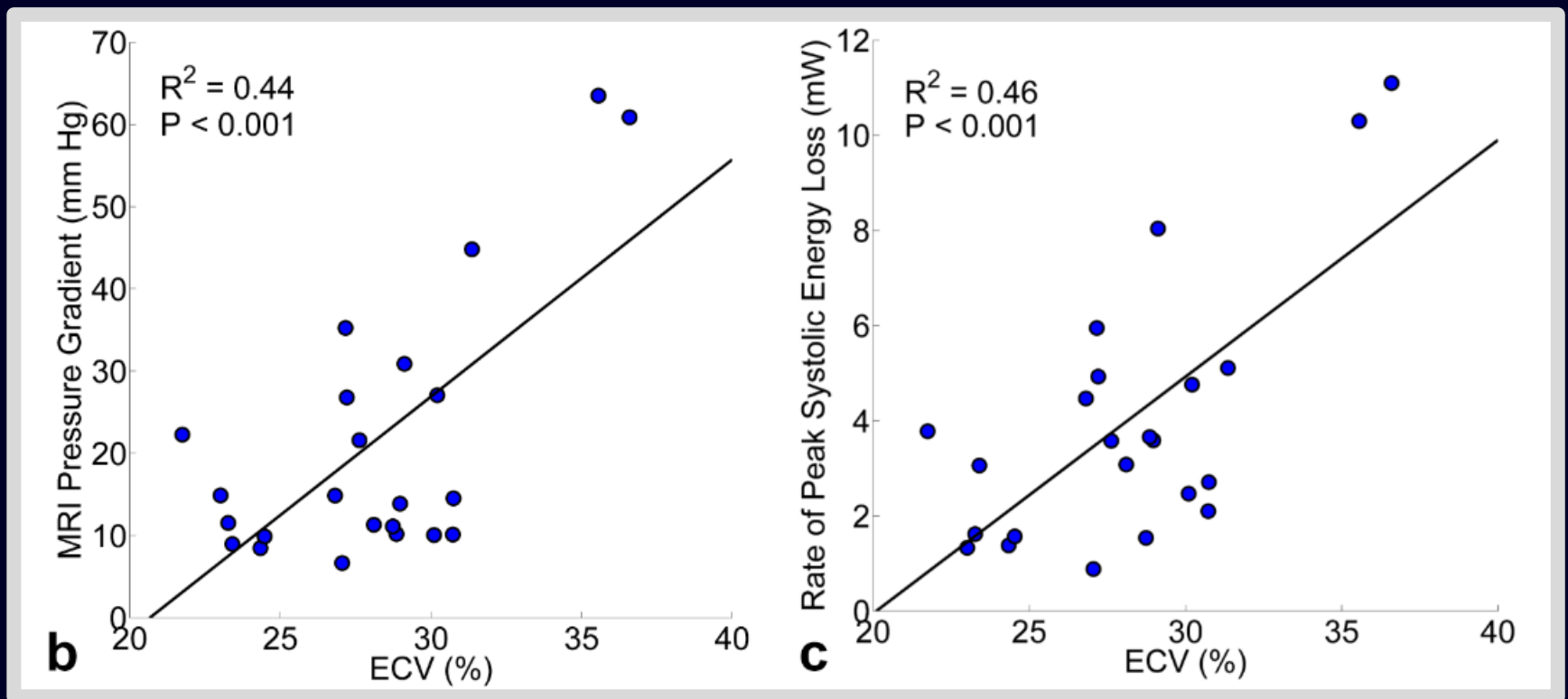
**Pre & post Gd-contrast T1**

- Extracellular volume fraction (ECV)
- regional LV fibrosis

1 Messroghli et al. *Magn Reson Med* 2004  
2 Kellman et al. *Magn Reson Med* 2013  
3 Xue et al. *Magn Reson Med* 2013  
4 Kellman et al. *JCMR* 2013

## HCM Patient Study, n=23

- T1-mapping: Extracellular volume fraction (fibrosis)
- 4D low MRI: LVOT pressure gradient & energy loss



- Association pressure gradient / energy loss with LV fibrosis

# 4D Flow MRI

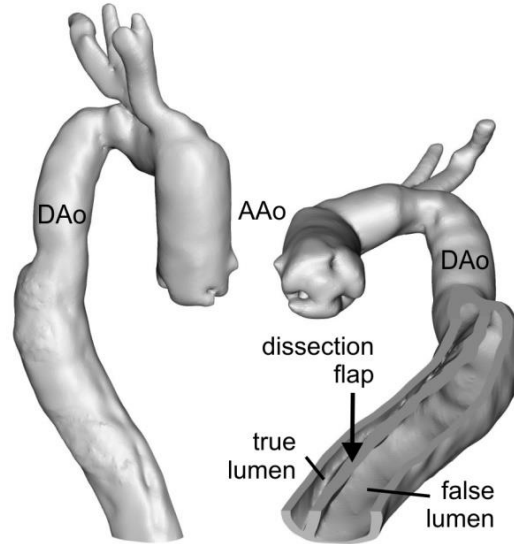
# Analysis Workflow

## Integration of Other Modalities

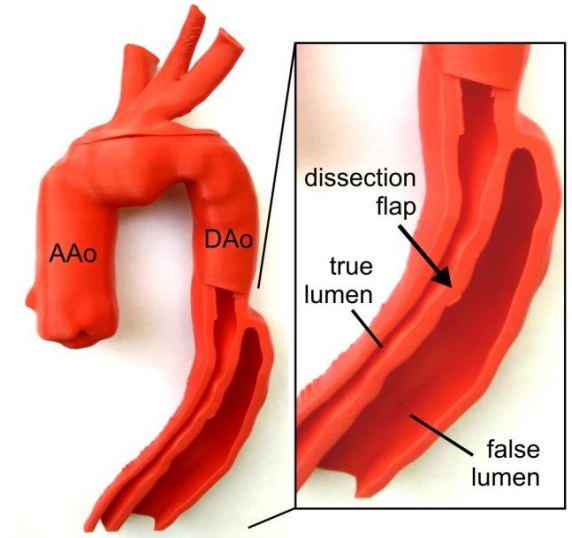
### 3D Printing

- 55 year old patient
- type-B dissection

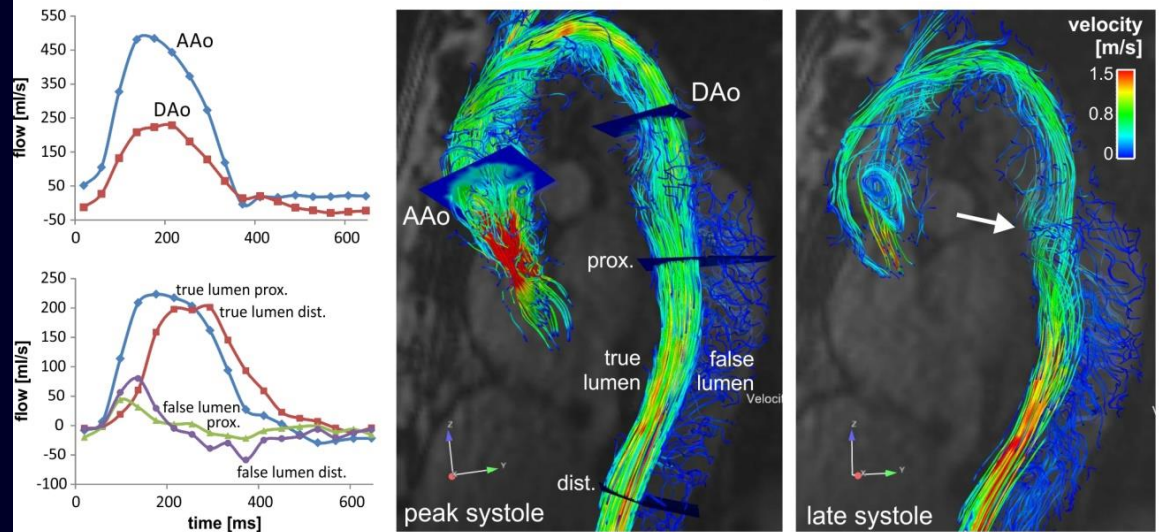
A: CEMRA & 3D segmentation



B: 3D printing: Aortic dissection model

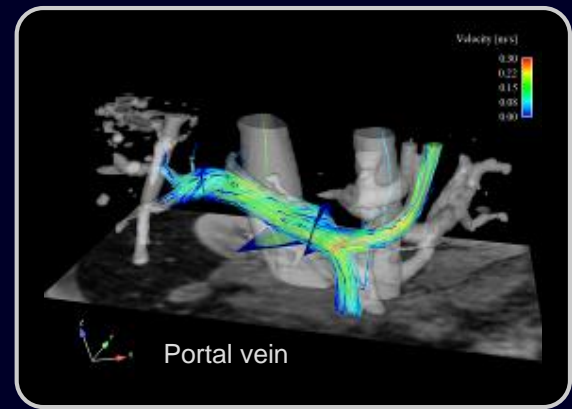
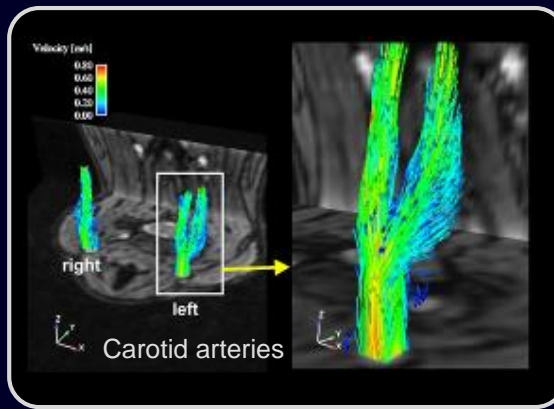
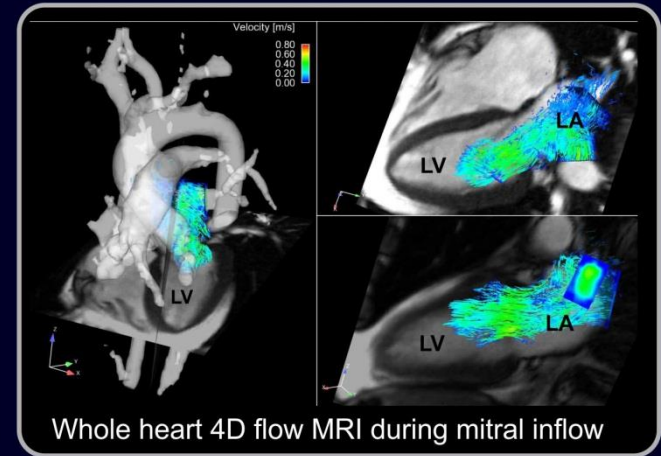
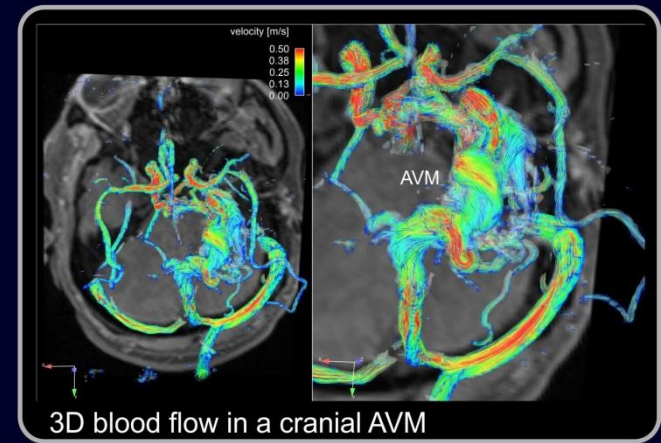
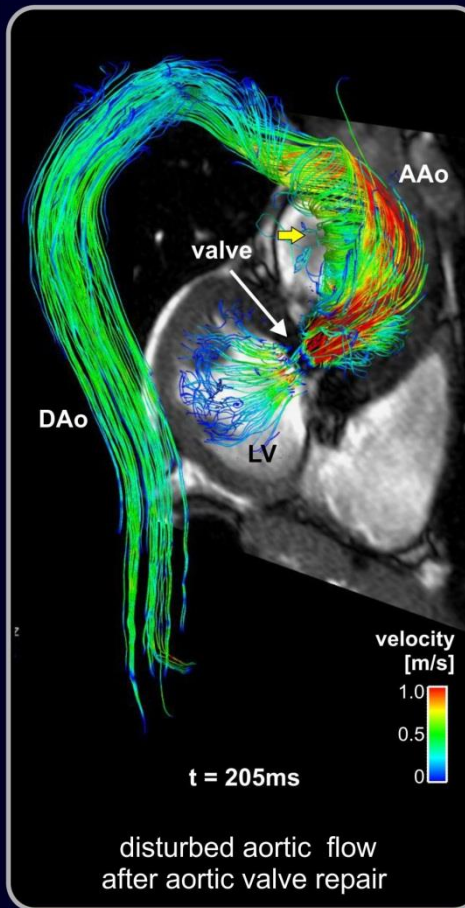


C: In-vivo 4D flow MRI: 3D blood flow visualization & quantification



Alex Barker, Rouzbeh Ahmadian  
Northwestern University

# 4D Flow MRI Applications



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Northwestern University, Chicago, USA

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- Clyde Yancy                    Alan Anderson
- Keith Benzuli                 Ben Freed
- Jyothy Puthumana            Jane Wilcox

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- Joshua Robinson

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- Jianing Pang                    Shivraman Giri

## Who Needs Hemodynamic Cath When We Have MR 4D Flow ?

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AHA - pre/postdoc fellowships

McCormick Catalyst Award

