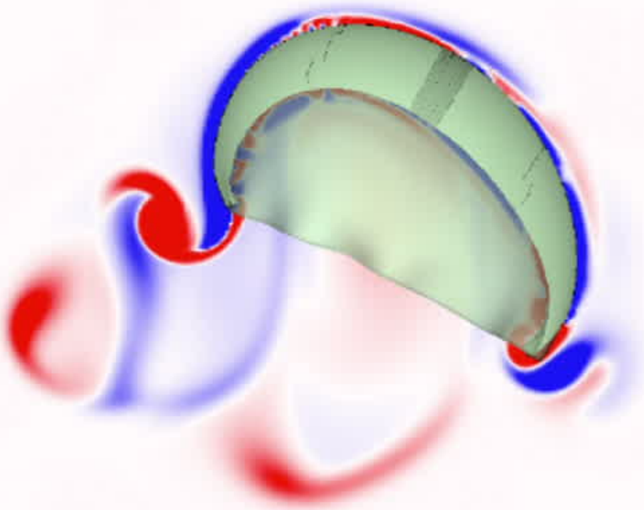
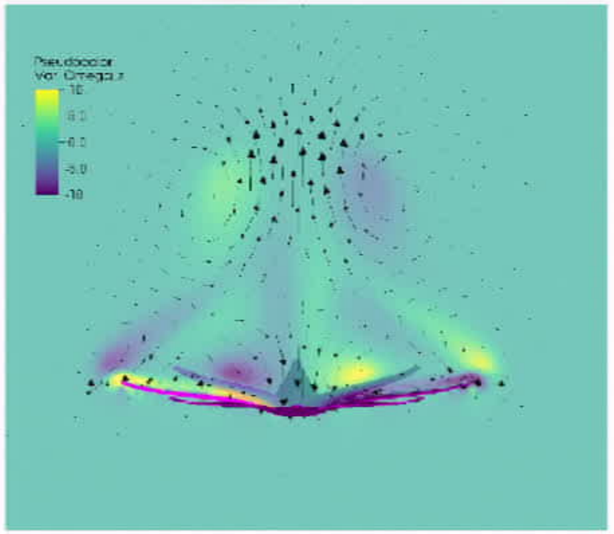


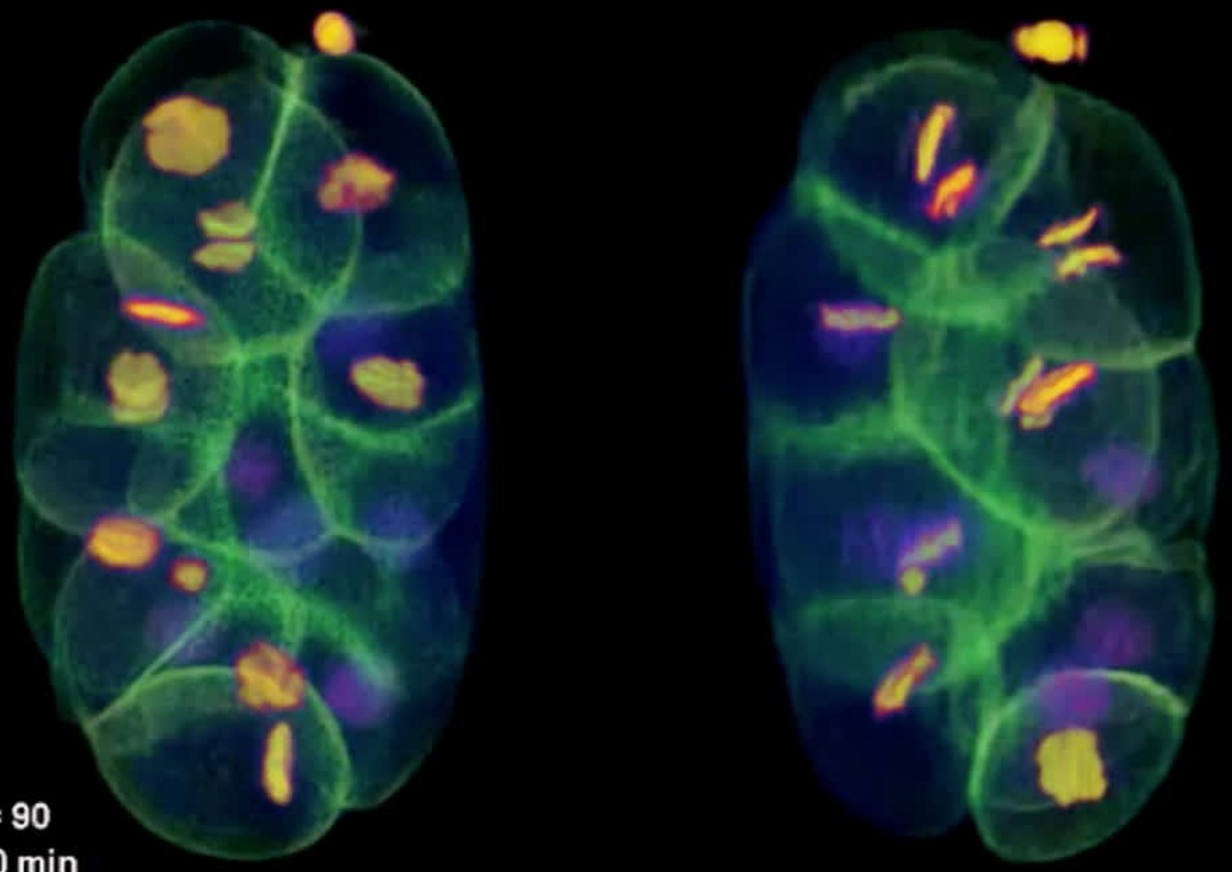


Fluid-Structure Interaction in Medicine and Biology: Methods, Models, and Applications

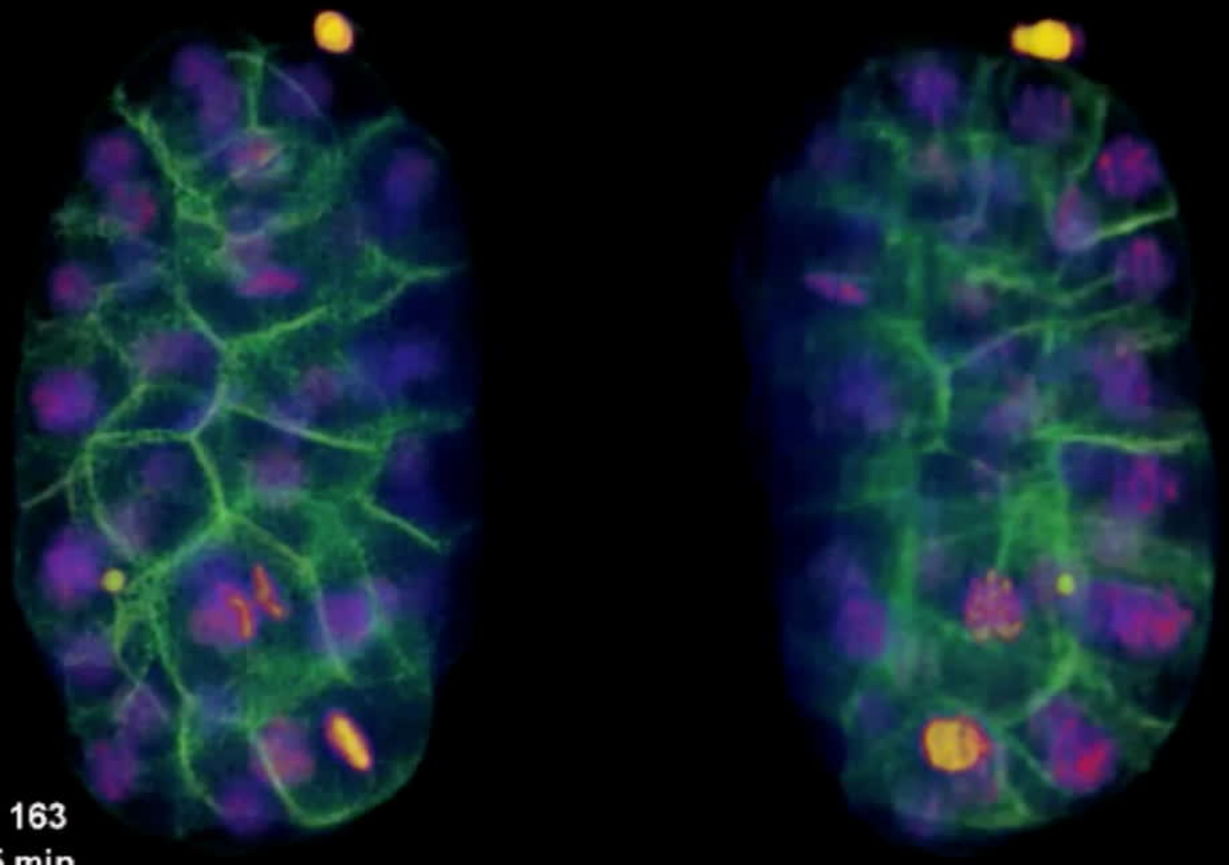
Boyce Griffith
The University of North Carolina at Chapel Hill

American Heart Association
Learn and Live
NIH National Heart, Lung, and Blood Institute
NSF

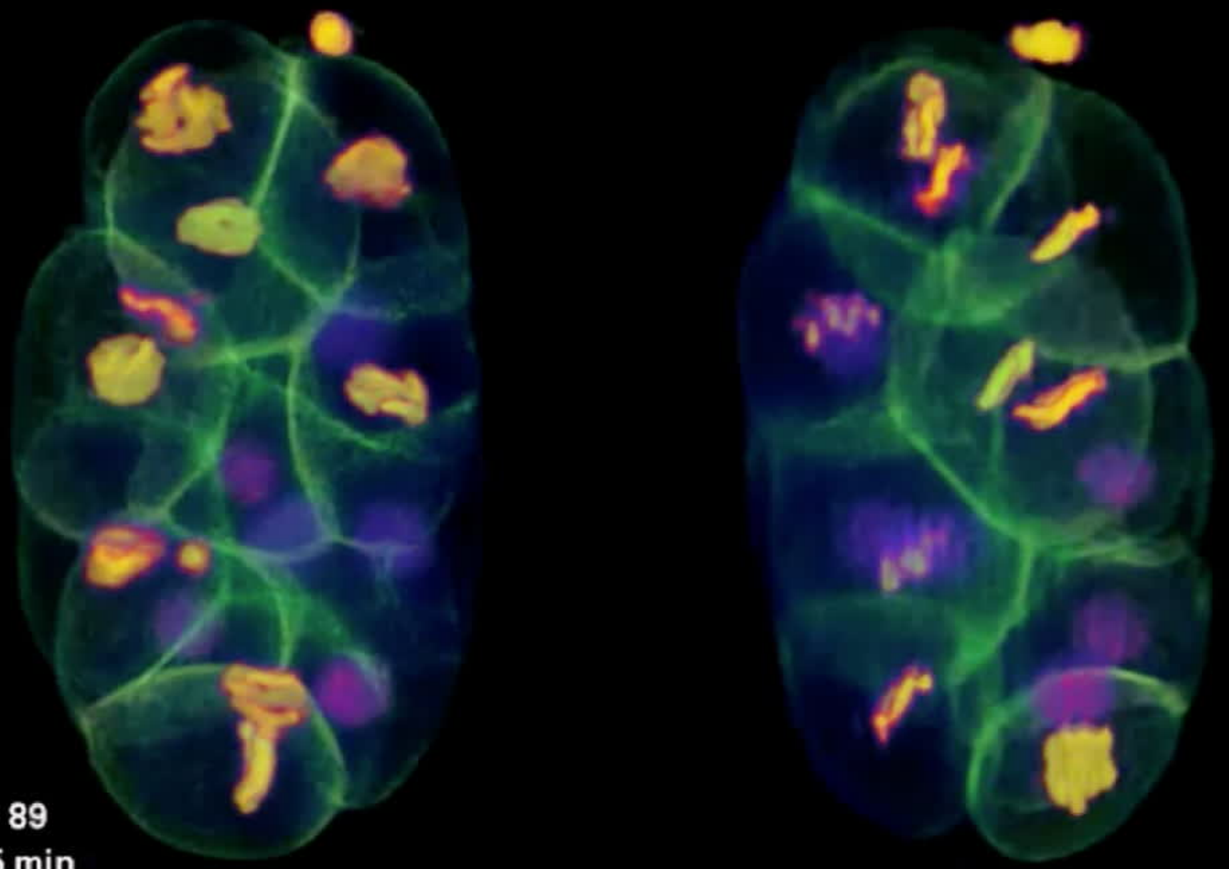
fluid-structure interaction
occurs at all biological scales



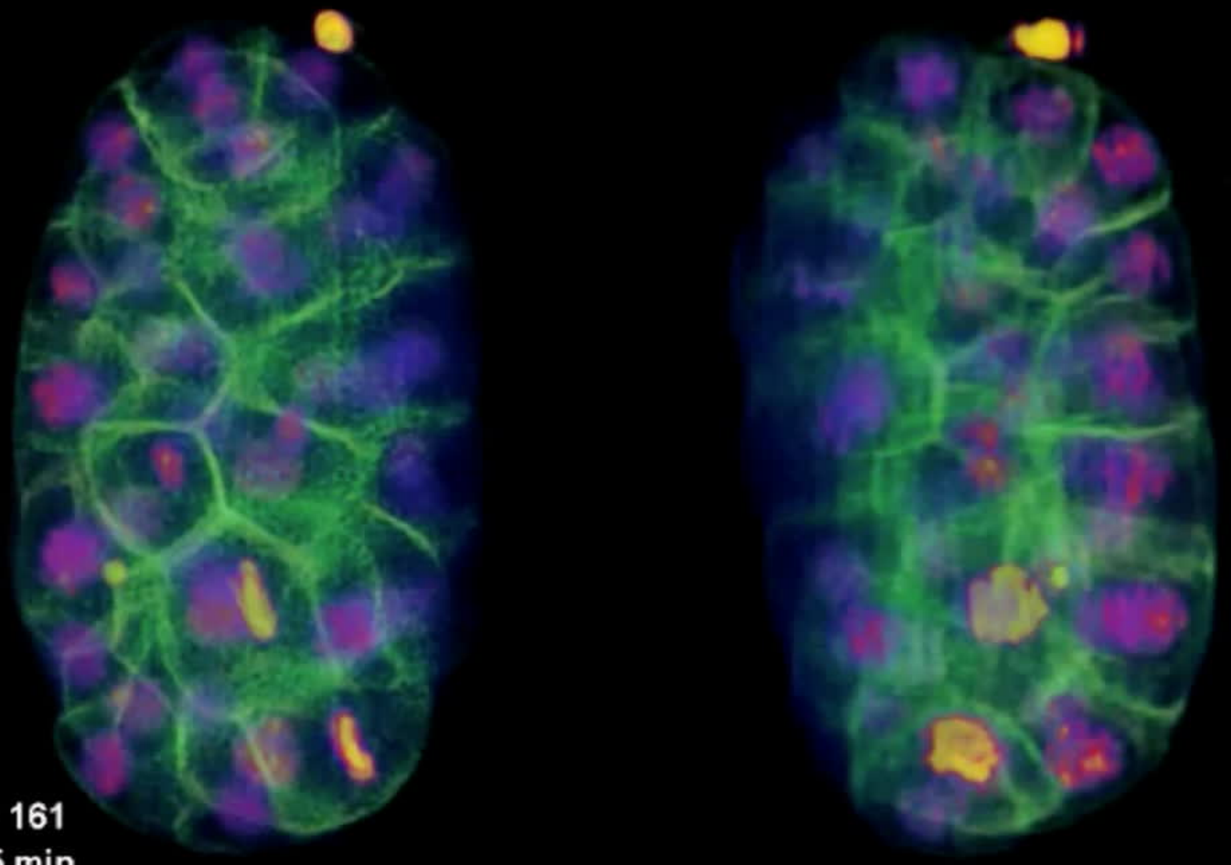
Fu, Martin, Matus, and Gao, *Nat Commun*, 2016



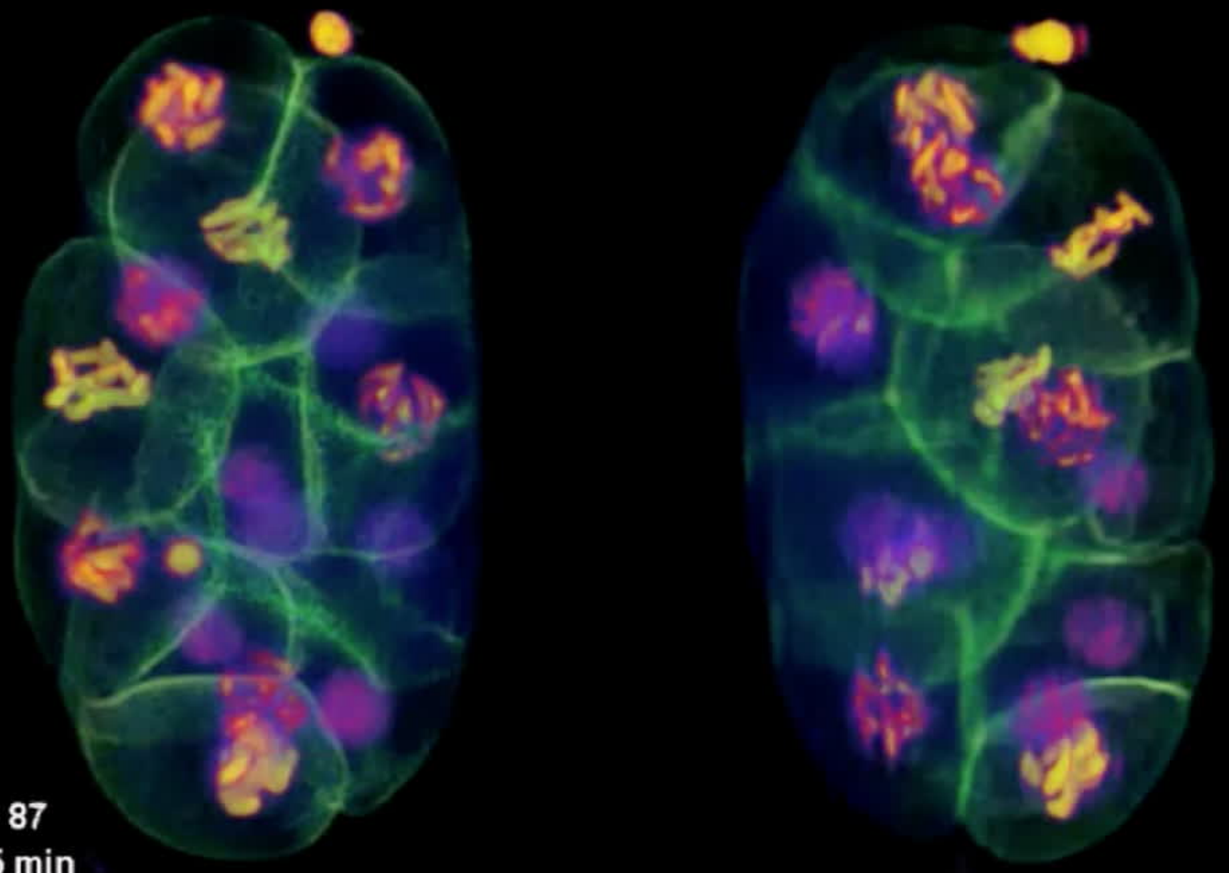
Fu, Martin, Matus, and Gao, *Nat Commun*, 2016



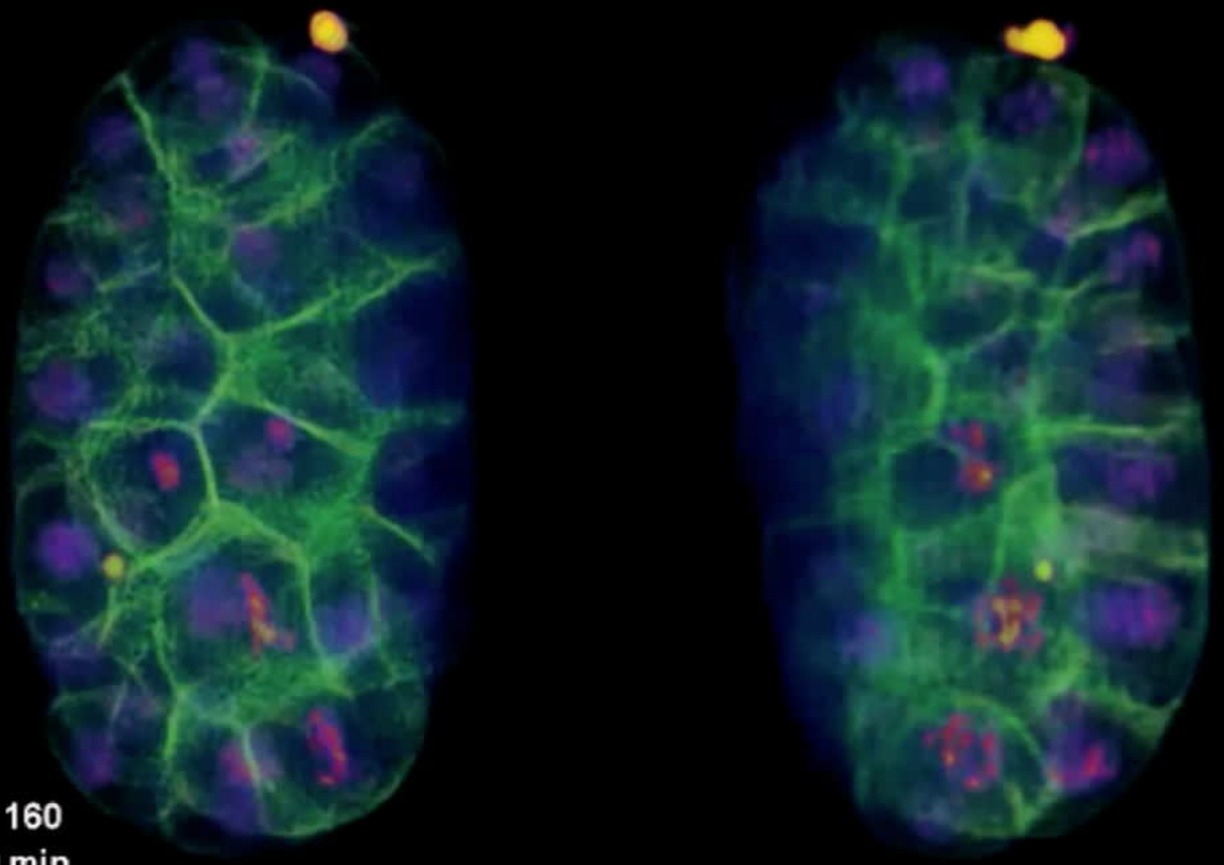
Fu, Martin, Matus, and Gao, *Nat Commun*, 2016



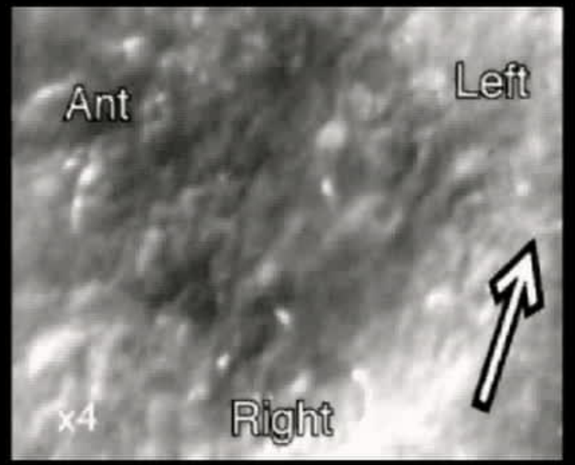
Fu, Martin, Matus, and Gao, *Nat Commun*, 2016



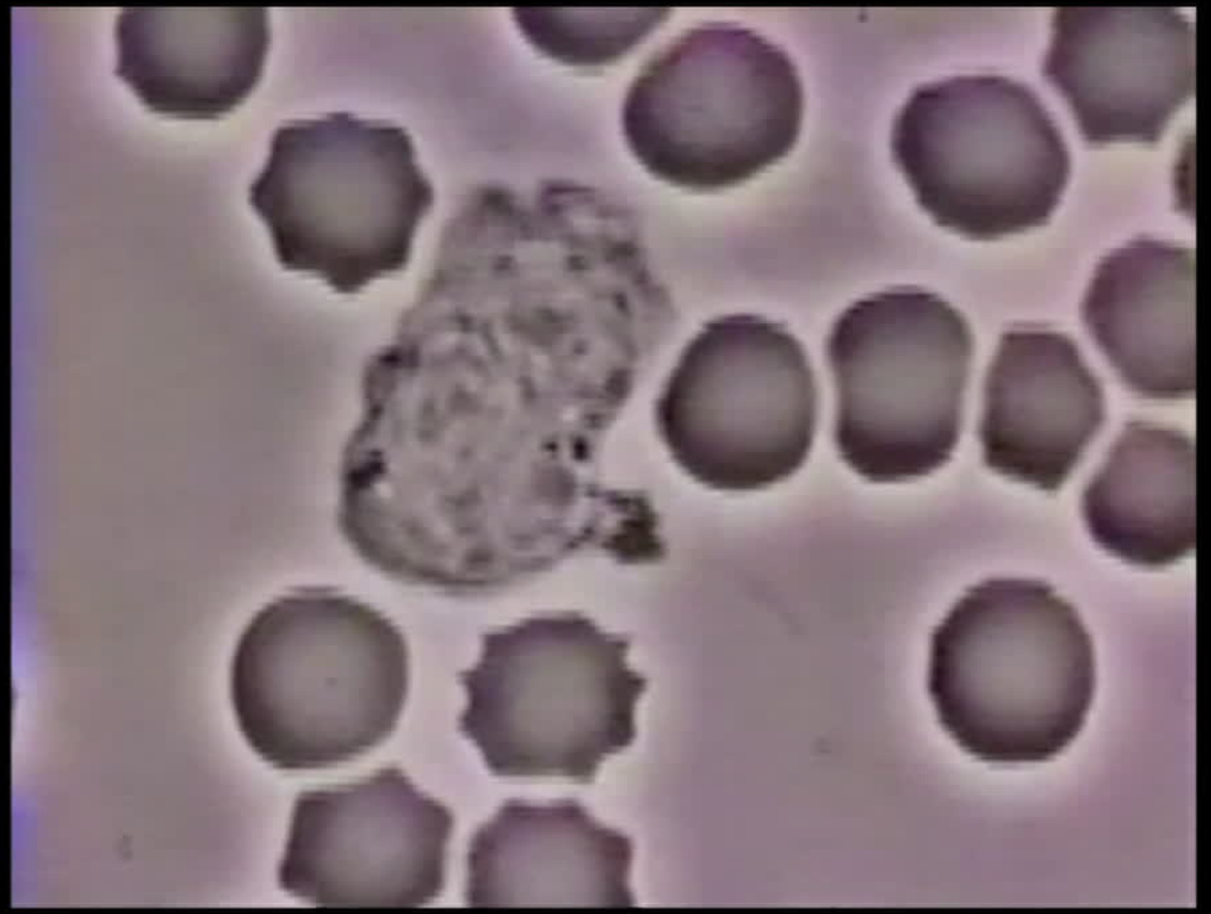
Fu, Martin, Matus, and Gao, *Nat Commun*, 2016



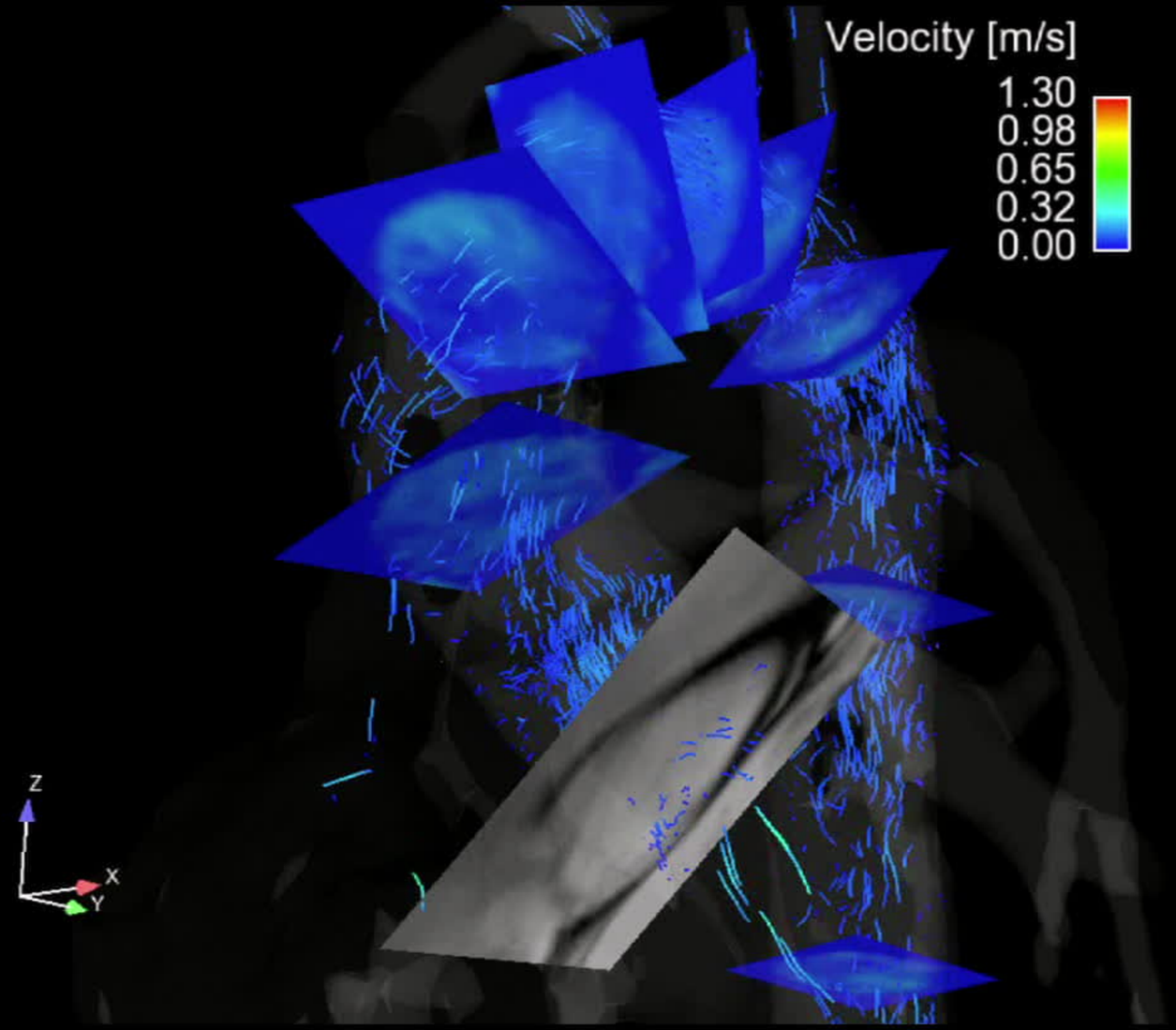
Fu, Martin, Matus, and Gao, *Nat Commun*, 2016



Hirokawa, Tanaka, and Okada, *Cold Spring Harb Perspect Biol*, 2009

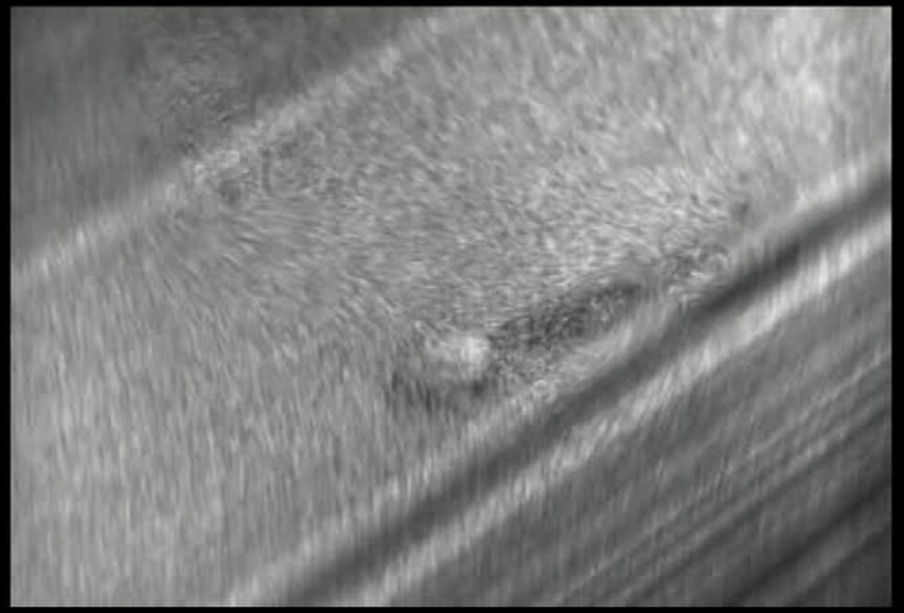


David Rogers, Vanderbilt University, circa 1950



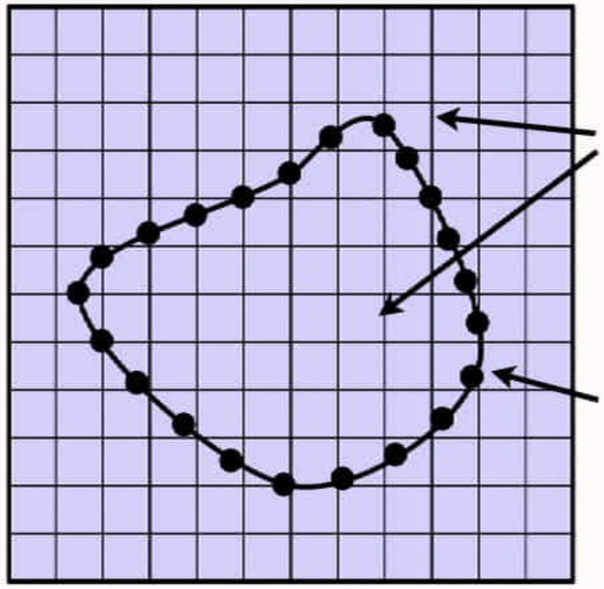
Barker, Markl, Bürk, et al., *Circ Cardiovasc Imaging*, 2012

Grace McLaughlin and Laura Miller, UNC-Chapel Hill



Lentik and Dickinson, *Science*, 2009

The immersed boundary method



(i, j, k) labels Cartesian grid cells
$\mathbf{x}_{i,j,k}$ is the physical position of grid cell (i, j, k)
$\mathbf{u}_{i,j,k}$ is the Eulerian velocity at grid cell (i, j, k)
$\mathbf{f}_{i,j,k}$ is the Eulerian force at grid cell (i, j, k)

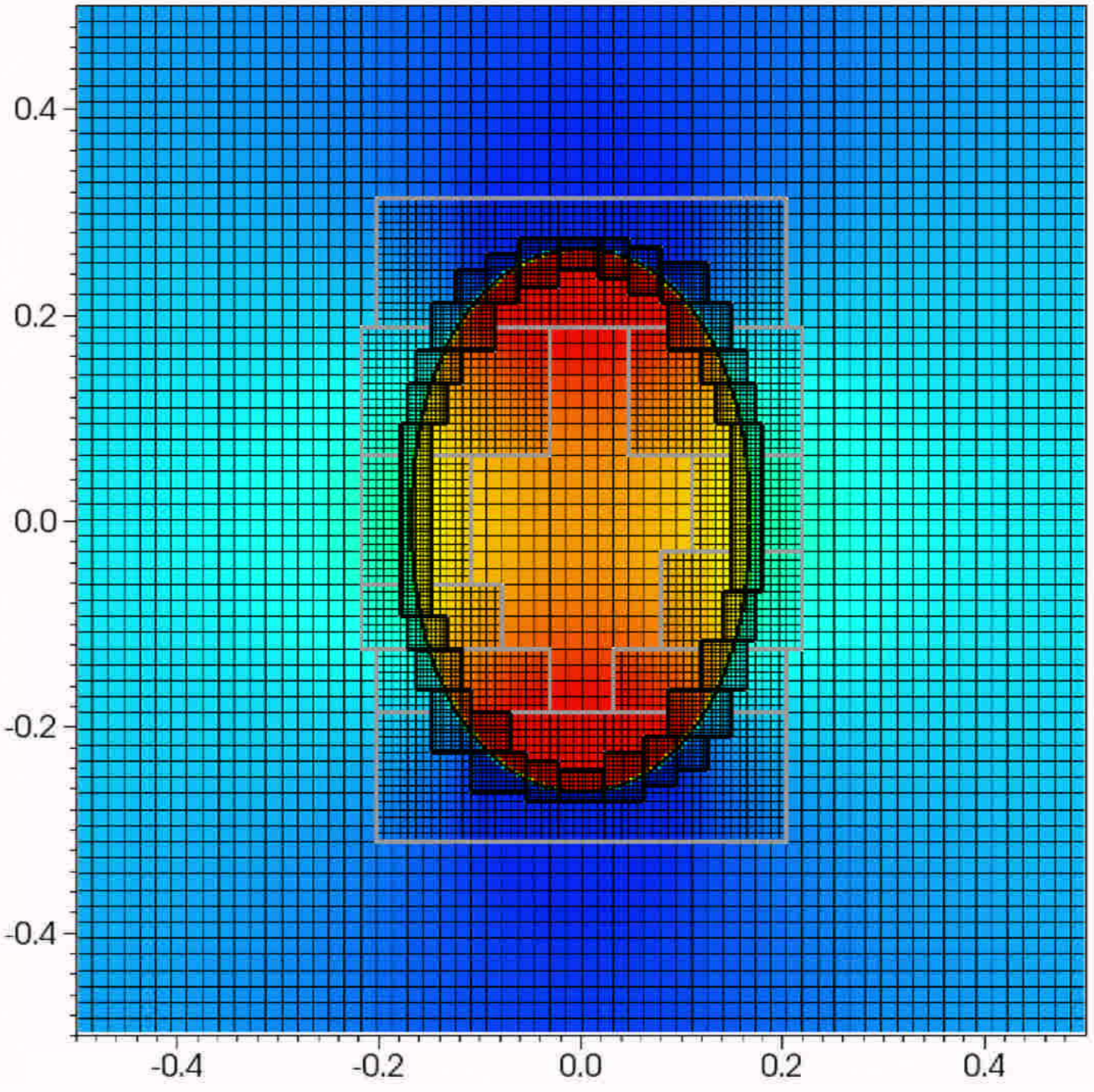
l labels Lagrangian mesh nodes
$\boldsymbol{\chi}_l$ is the physical position of node l
$\mathbf{U}_l$ is the Lagrangian velocity at node l
$\mathbf{F}_l$ is the Lagrangian force at node l

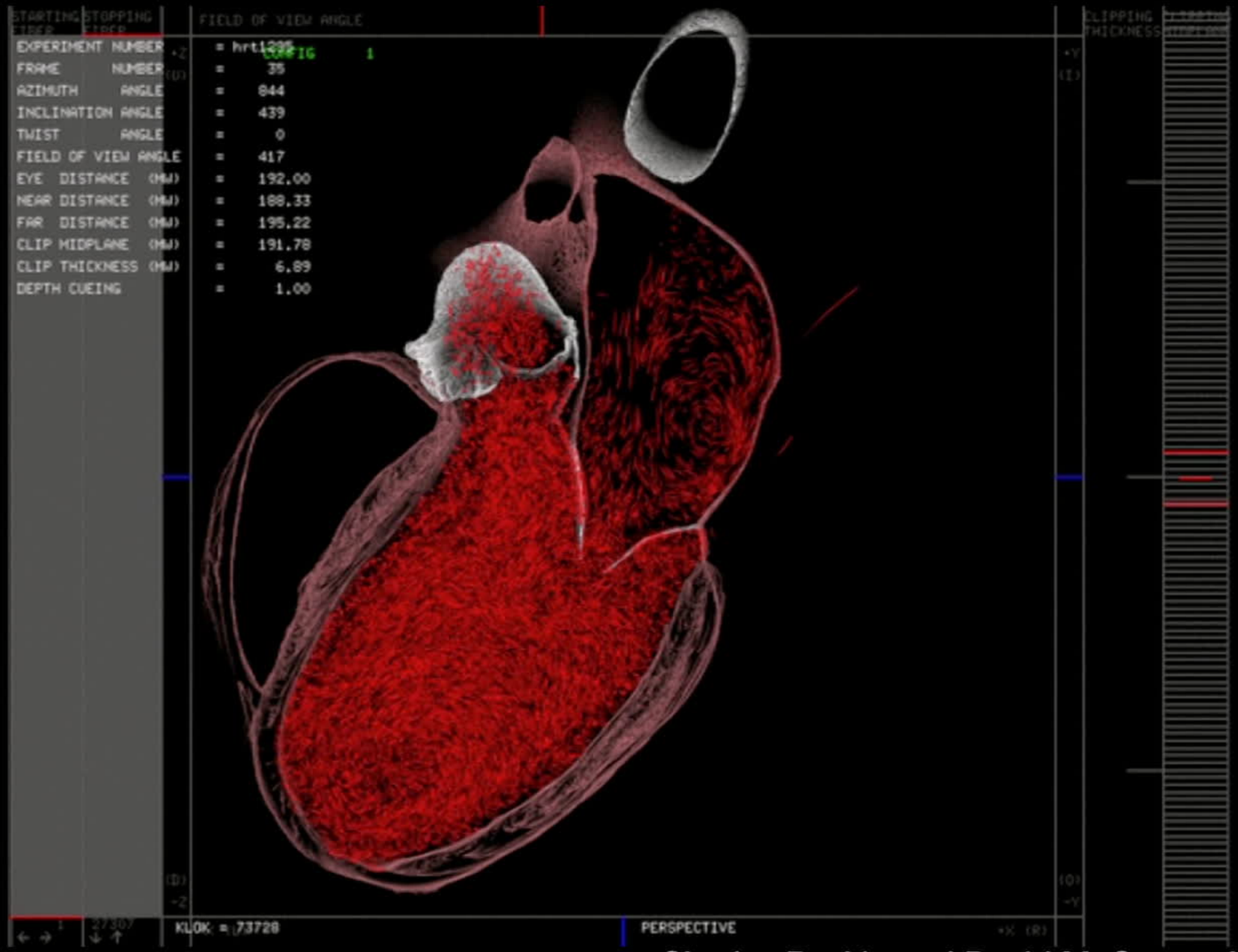
Forces are *spread* from the boundary to nearby Cartesian grid points:

$$\mathbf{f}_{i,j,k} = \sum_l \mathbf{F}_l \, \delta_h(\mathbf{x}_{i,j,k} - \boldsymbol{\chi}_l) \, \Delta\mathbf{q}$$

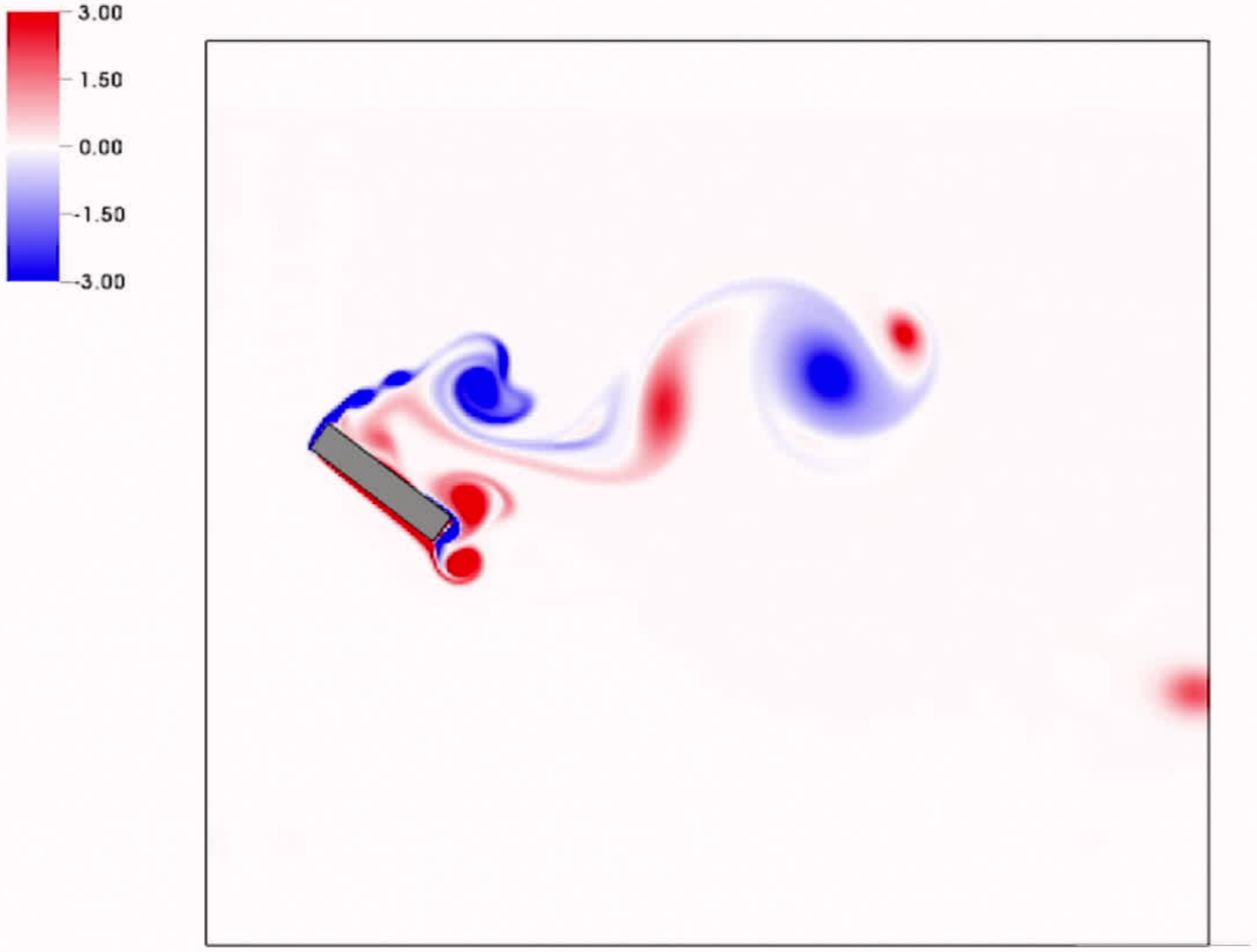
Velocities are *interpolated* to the boundary from nearby Cartesian grid points:

$$\mathbf{U}_l = \sum_{i,j,k} \mathbf{u}_{i,j,k} \, \delta_h(\mathbf{x}_{i,j,k} - \boldsymbol{\chi}_l) \, \Delta\mathbf{x}$$

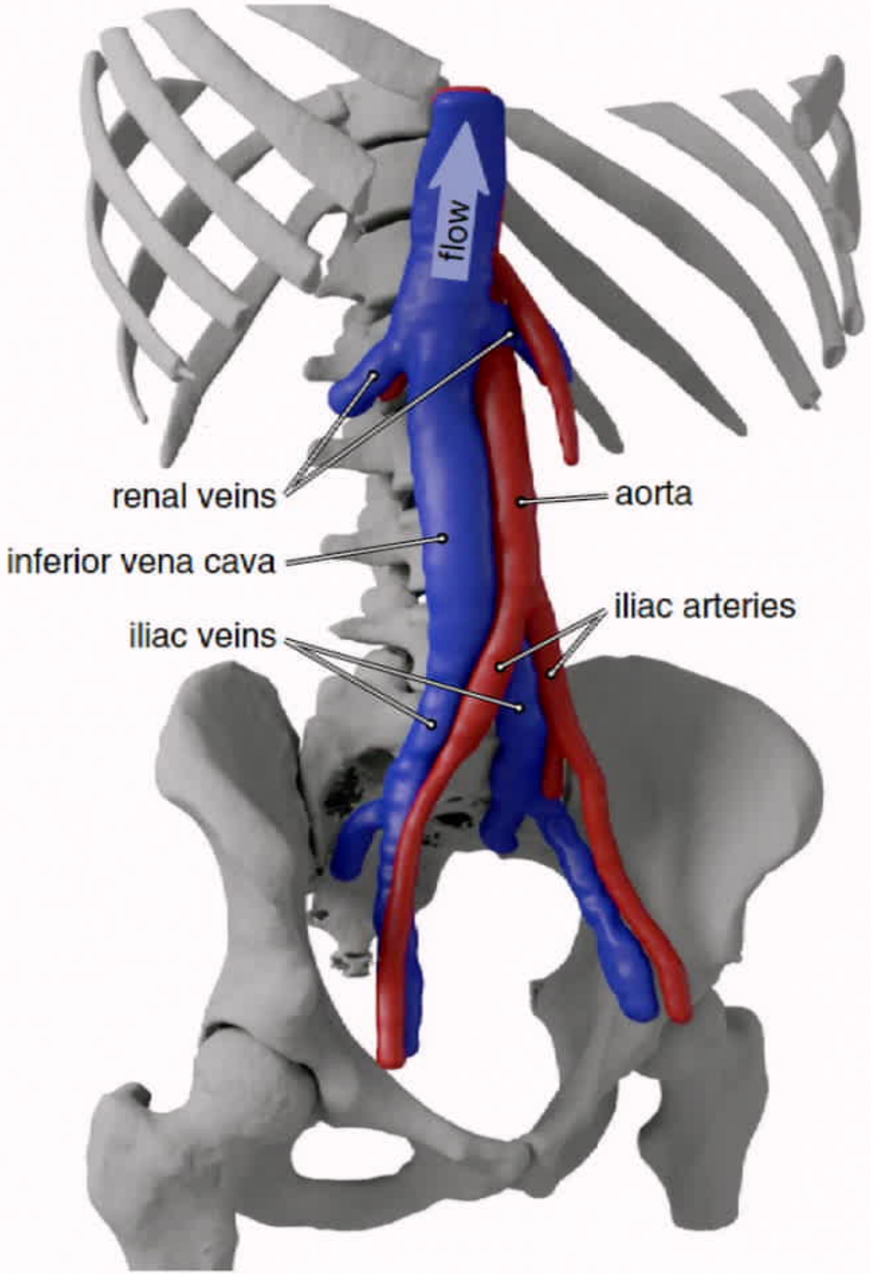

0.4
0.2
0.0
-0.2
-0.4
-0.4
-0.2
0.0
0.2
0.4



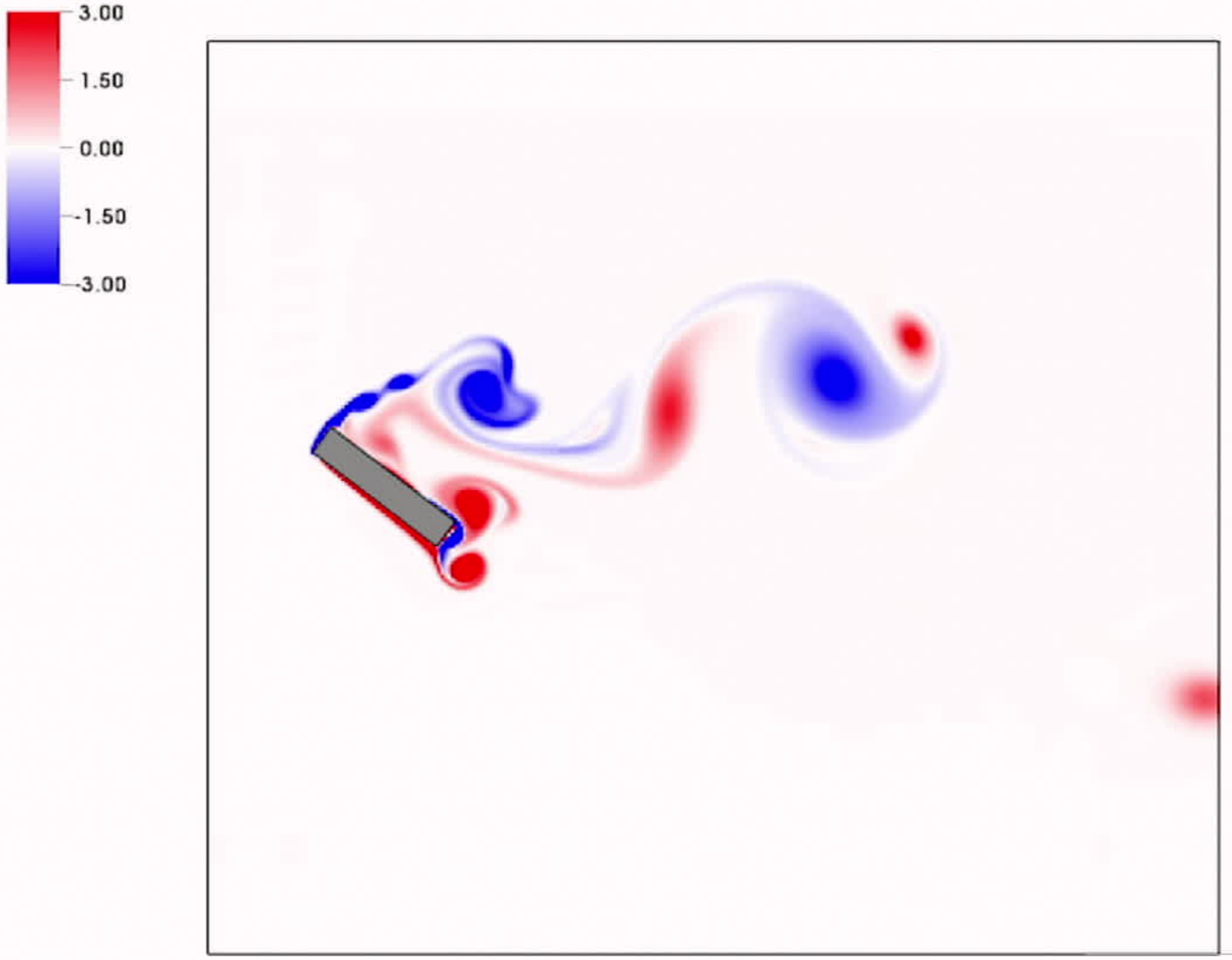
Charles Peskin and David McQueen, NYU



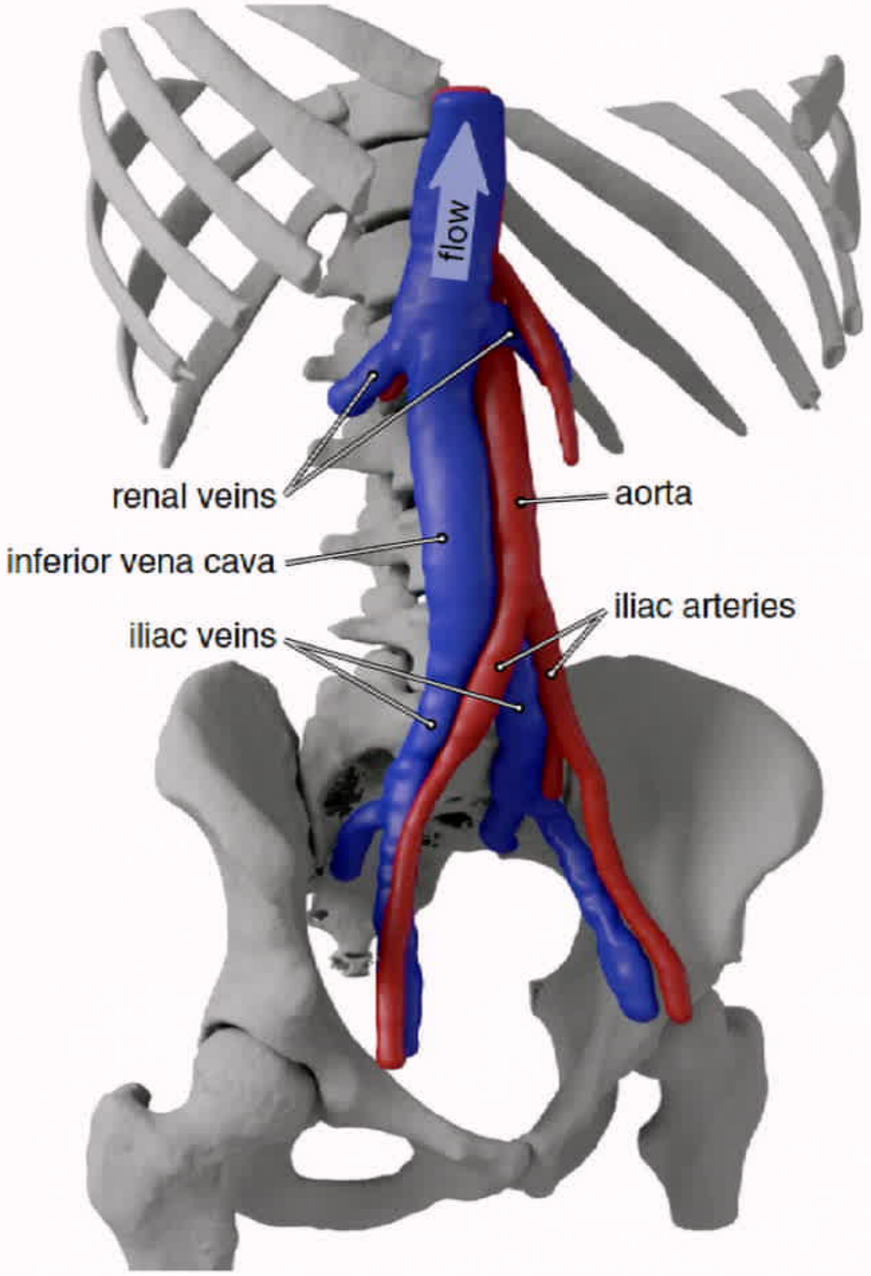
Amin Kolahdouz (UNC-Chapel Hill & FDA) and Brent Craven (FDA)

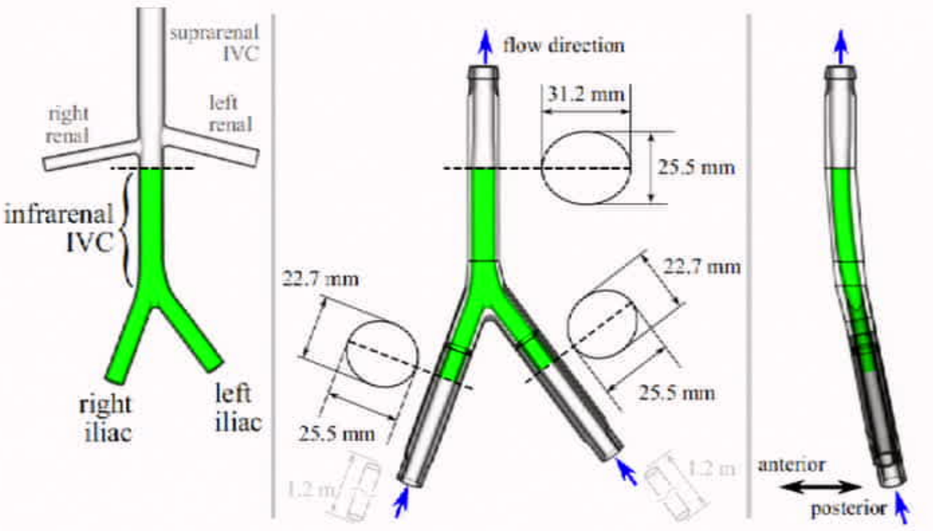


Amin Kolahdouz (UNC-Chapel Hill & FDA) and Brent Craven (FDA)

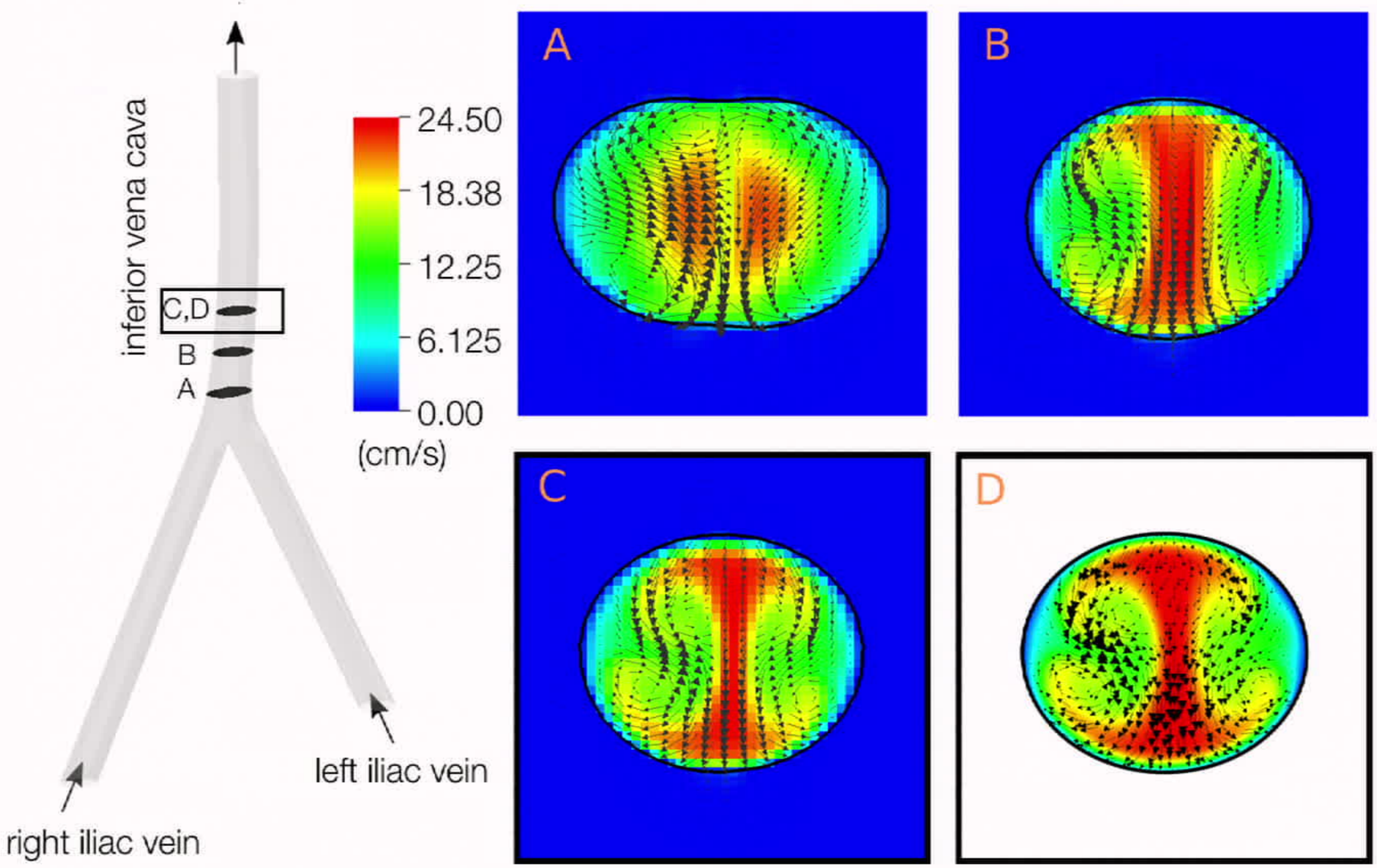


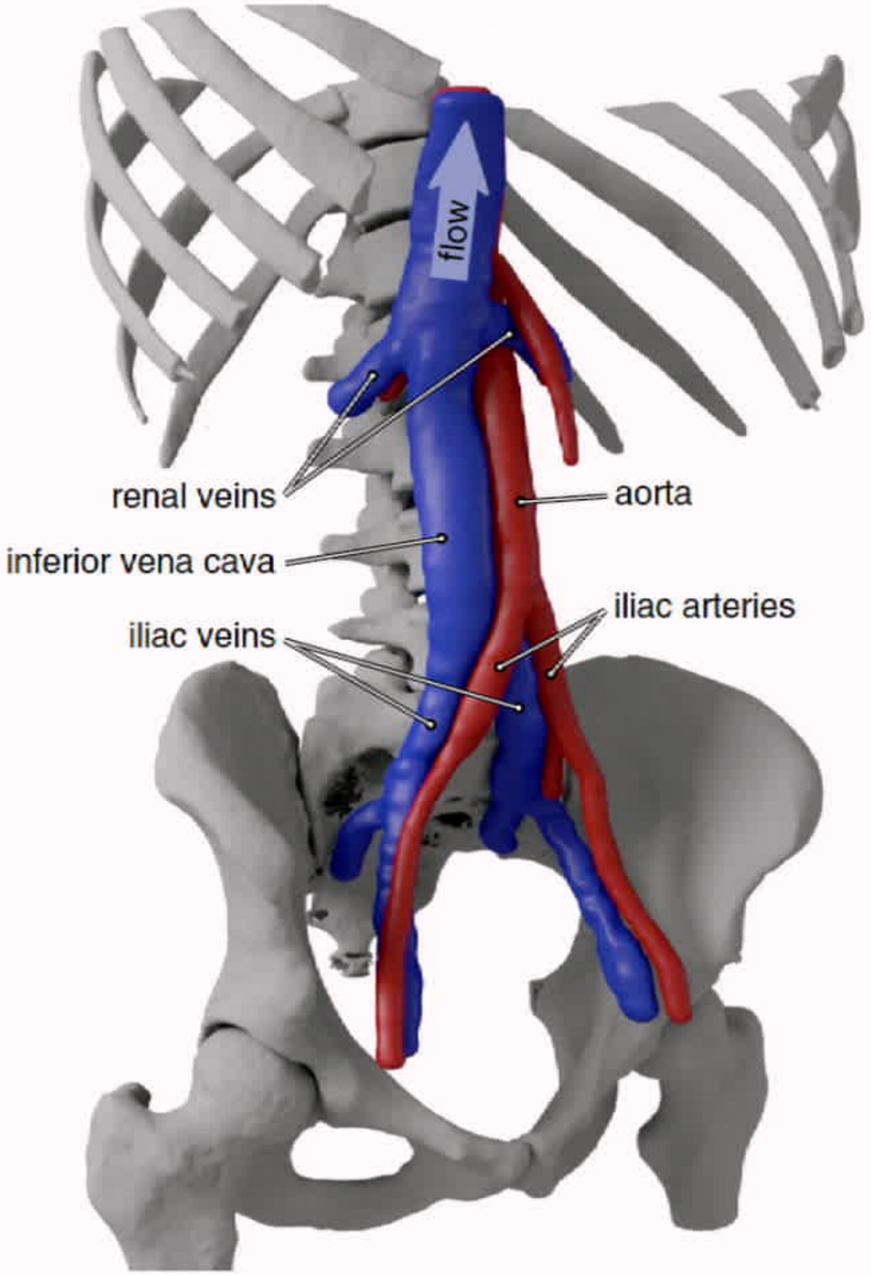
Amin Kolahdouz (UNC-Chapel Hill & FDA) and Brent Craven (FDA)

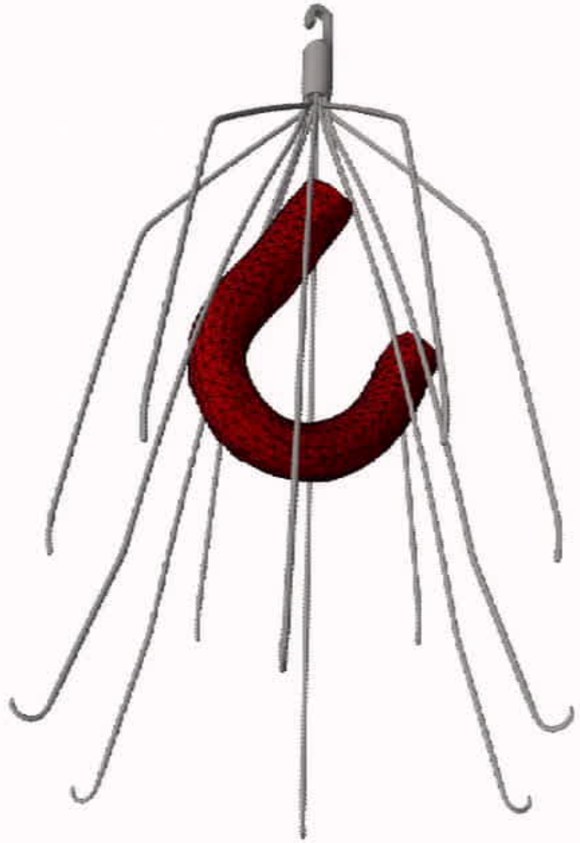




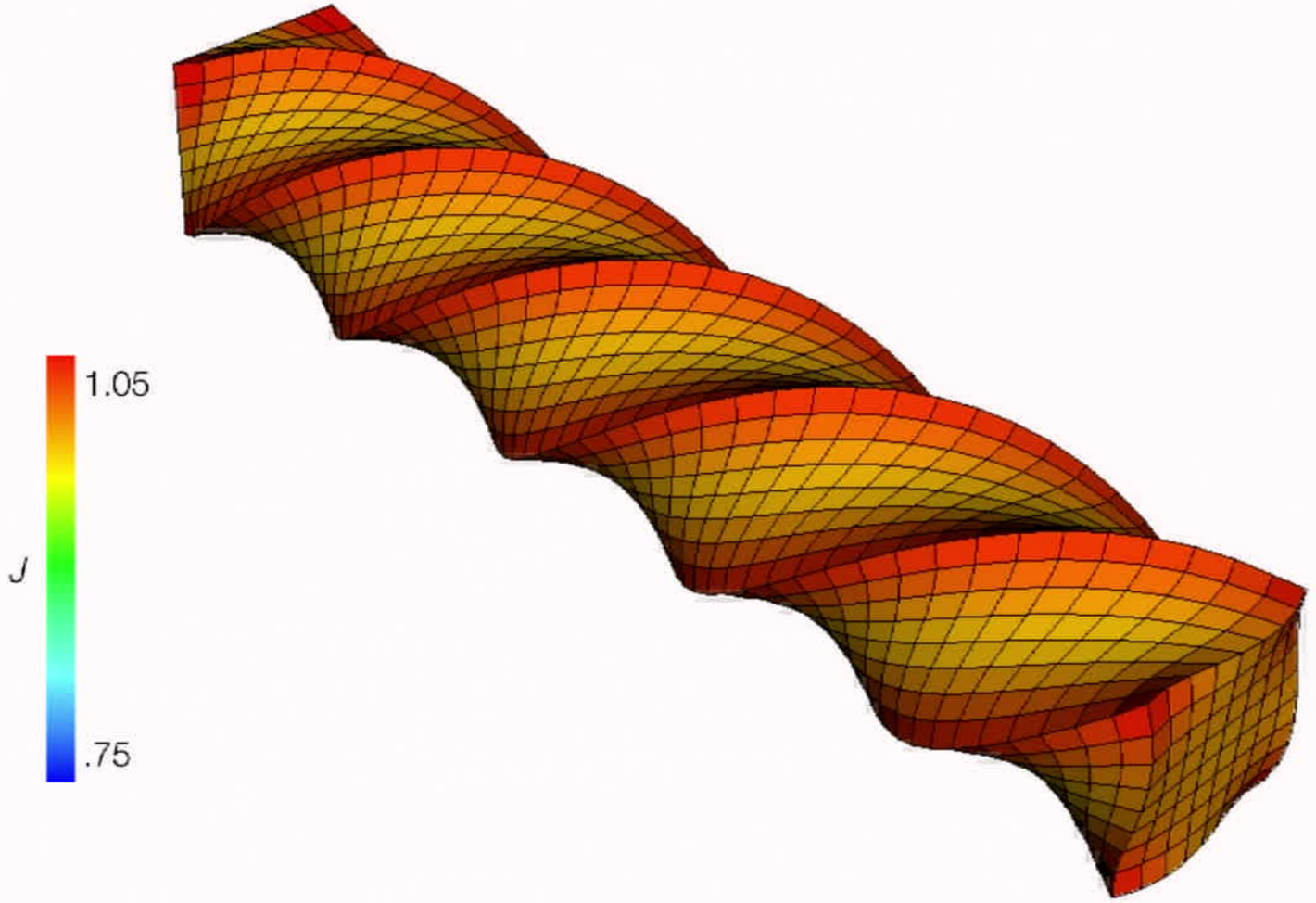
Amin Kolahdouz (UNC-Chapel Hill & FDA) and Brent Craven (FDA)


inferior vena cava
C,D
B
A
24.50
18.38
12.25
6.125
0.00
(cm/s)
A
B
C
D
left iliac vein
right iliac vein





With Amin Kolahdouz (UNC-Chapel Hill & FDA) and Alex Rygg and Brent Craven (FDA)



Hyperelasticity: $\mathbb{P}^{\text{ps}} = \frac{\partial W}{\partial \mathbb{F}}, \mathbb{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}}, J = \det(\mathbb{F})$

Mooney-Rivlin: $W = a(I_1 - 3) + b(I_2 - 3), I_1 = \text{tr}(\mathbb{C}), I_2 = \frac{1}{2}(I_1^2 - \text{tr}(\mathbb{C}^2)), \mathbb{C} = \mathbb{F}^T\mathbb{F}$

Add a volumetric energy to *stabilize*: $W_{\text{stab}} = W(\mathbb{F}) + \beta_{\text{s}} U(J)$ (incompressible: $J \equiv 1$)

Use *modified* deformation gradient: $\overline{W}_{\text{stab}} = W(\overline{\mathbb{F}}) + \beta_{\text{s}} U(J), \overline{\mathbb{F}} = J^{-\frac{1}{3}}\mathbb{F}$

These computations use the open-source **IBAMR** software.

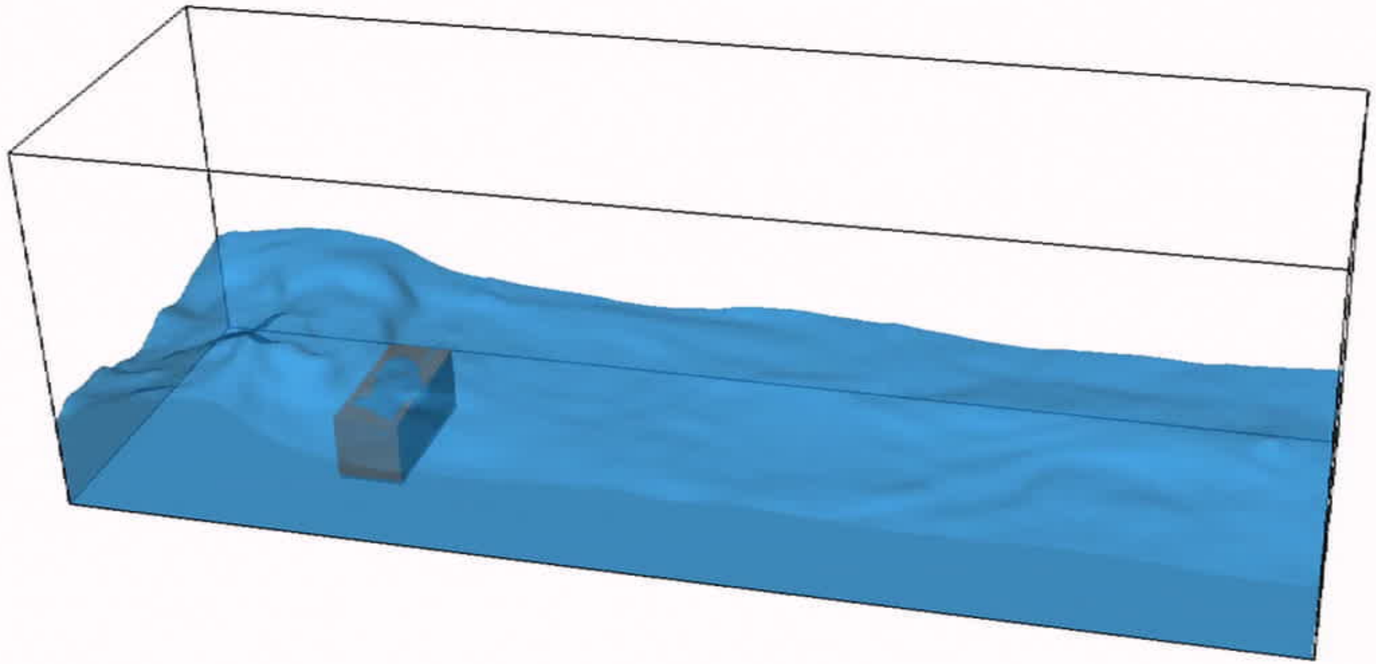
Software infrastructure: IBAMR relies on other open-source software, including PETSc, SAMRAI, and *hypre*. Finite element computations rely on `libMesh`.

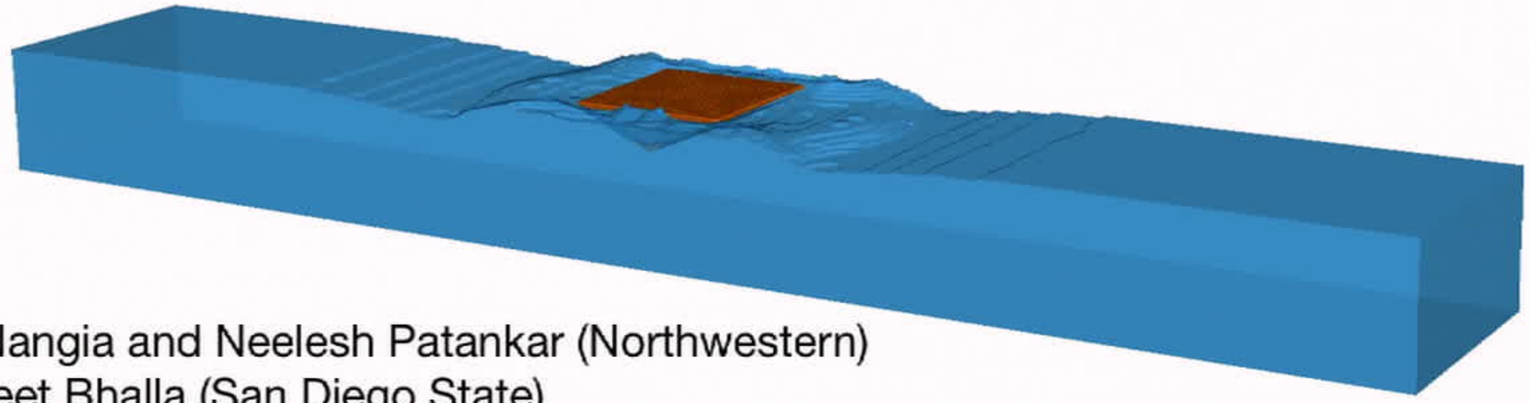
Impact: 80+ peer-reviewed publications, 15+ PhD theses, many undergraduate theses and conference abstracts

Other modeling approaches provided by IBAMR include:

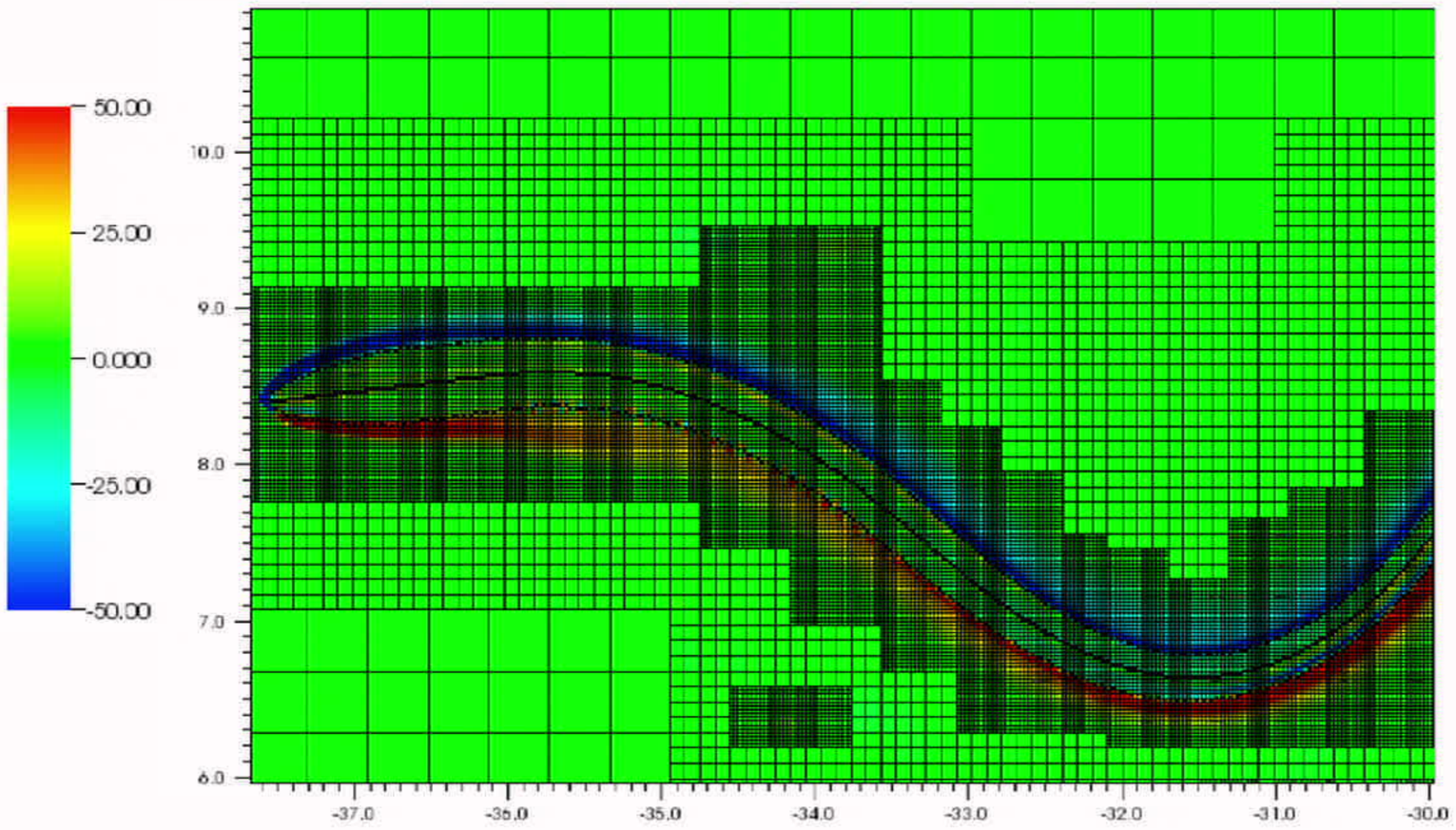
- *thin rods*, with Sook Lim (Cincinnati)
- *deformational constraints*, with Amneet Bhalla (San Diego State), Aleks Donev (NYU-Courant), and Neelesh Patankar (Northwestern)
- *thermal fluctuations*, with Donev, Patankar, and co-workers
- *complex fluids*, in work by Aaron Barrett (UNC) with Greg Forest (UNC) and Bob Guy and Becca Thomases (UC-Davis)
- *multiphase flows*, in work by Nishant Nangia (Northwestern) with Bhalla and Patankar

`ibamr.github.io`

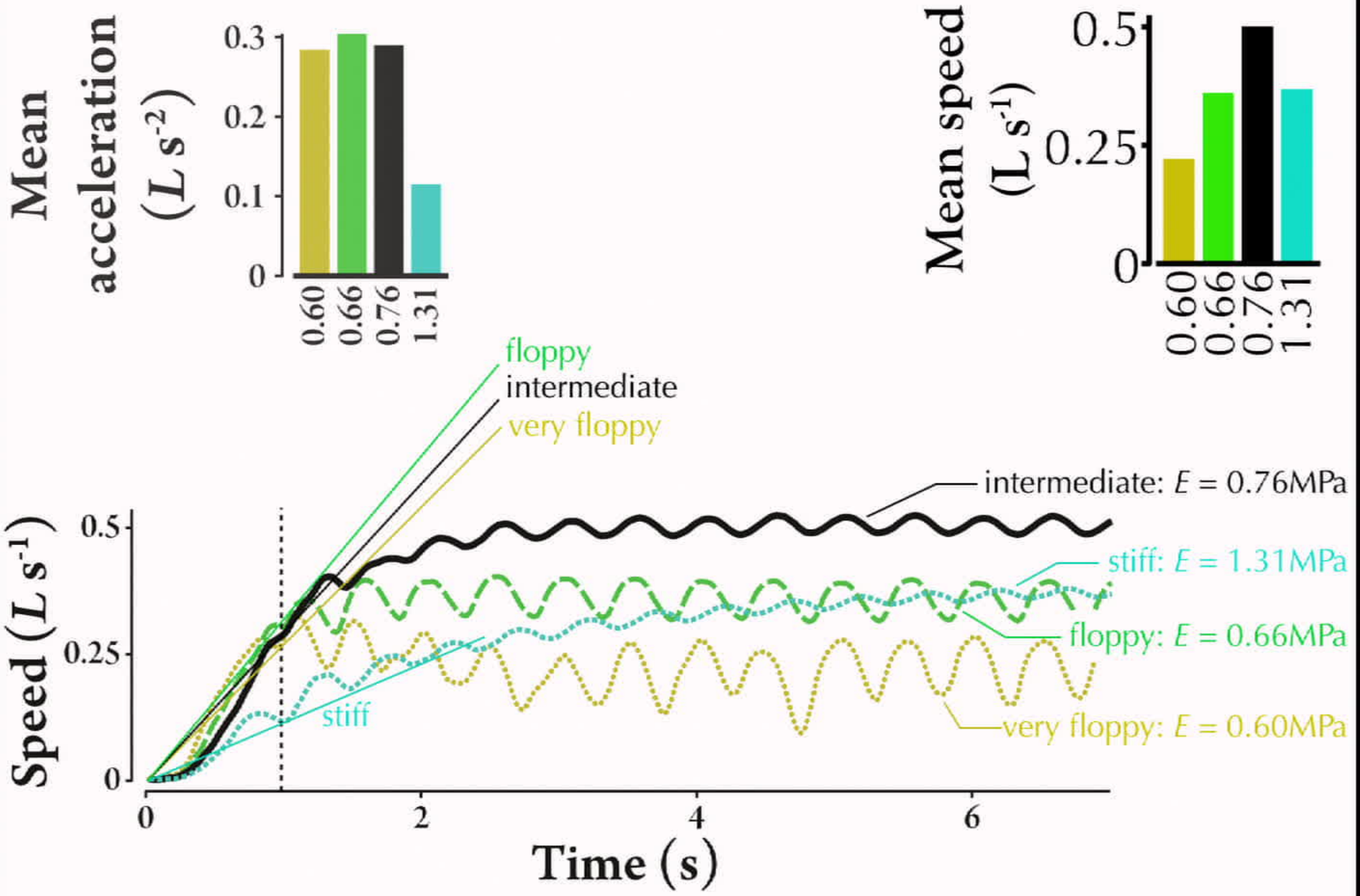




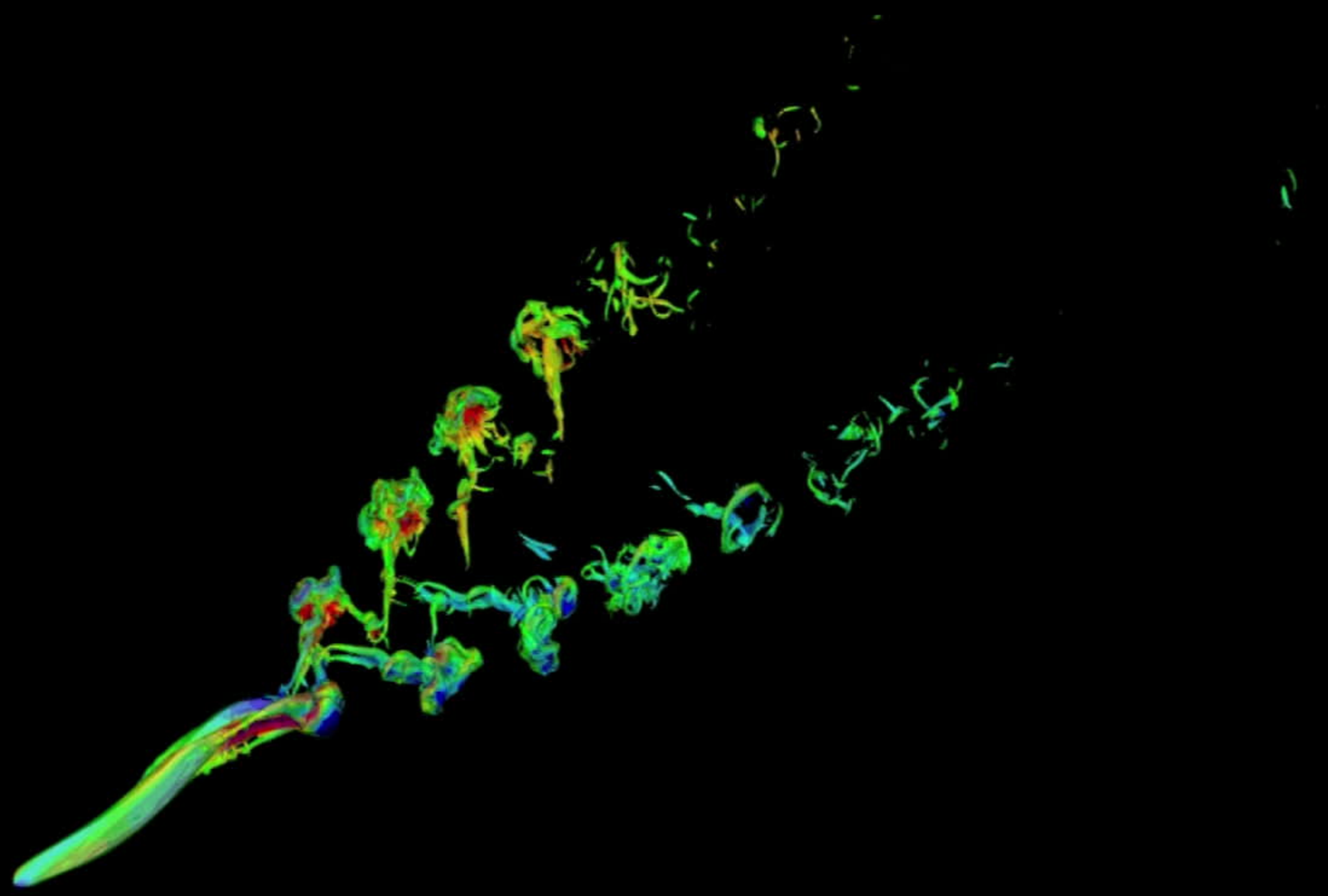
Nishant Nangia and Neelesh Patankar (Northwestern)
and Amneet Bhalla (San Diego State)



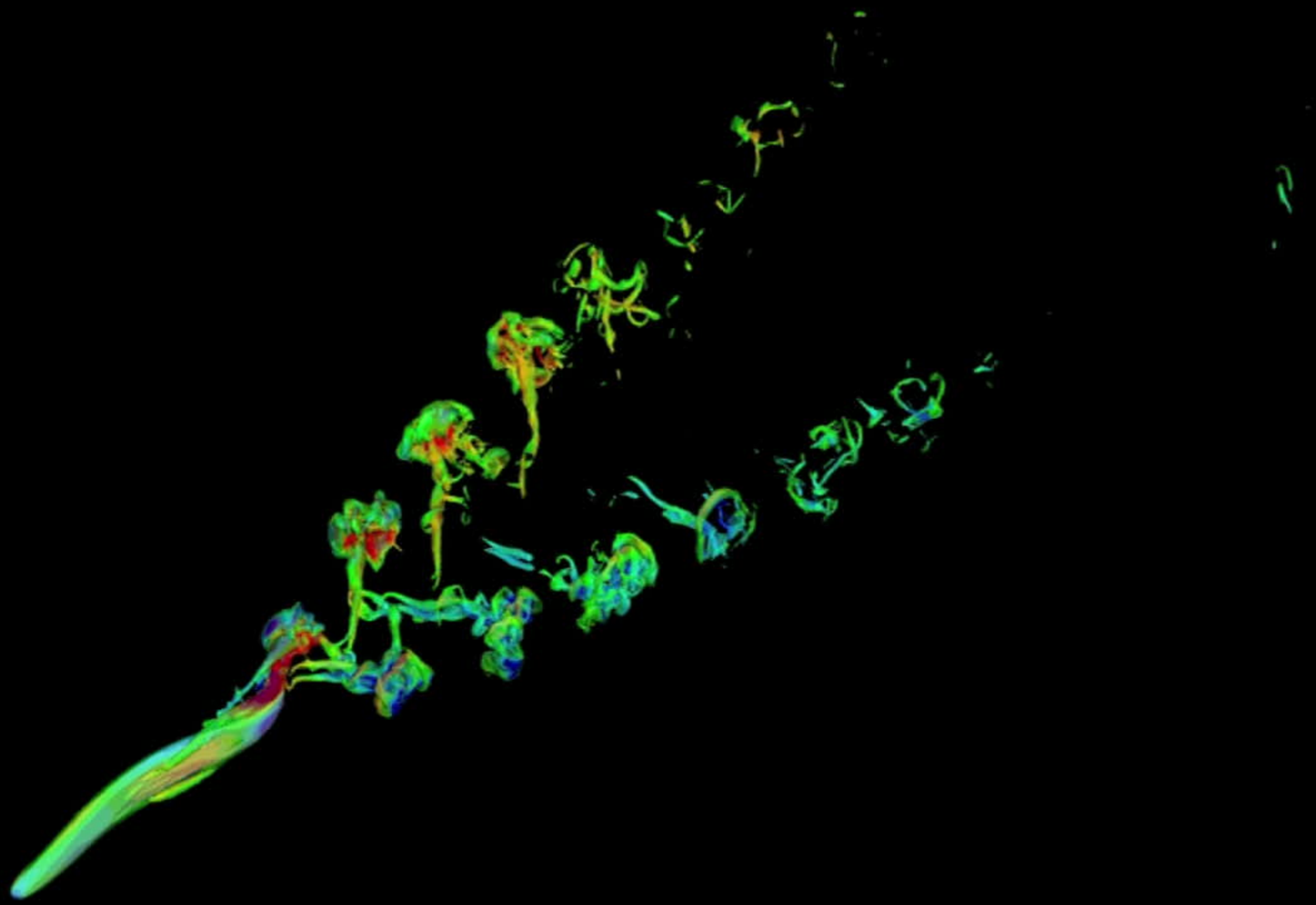
Tytell, Hsu, Williams, Cohen, Fauci, *PNAS* 2010



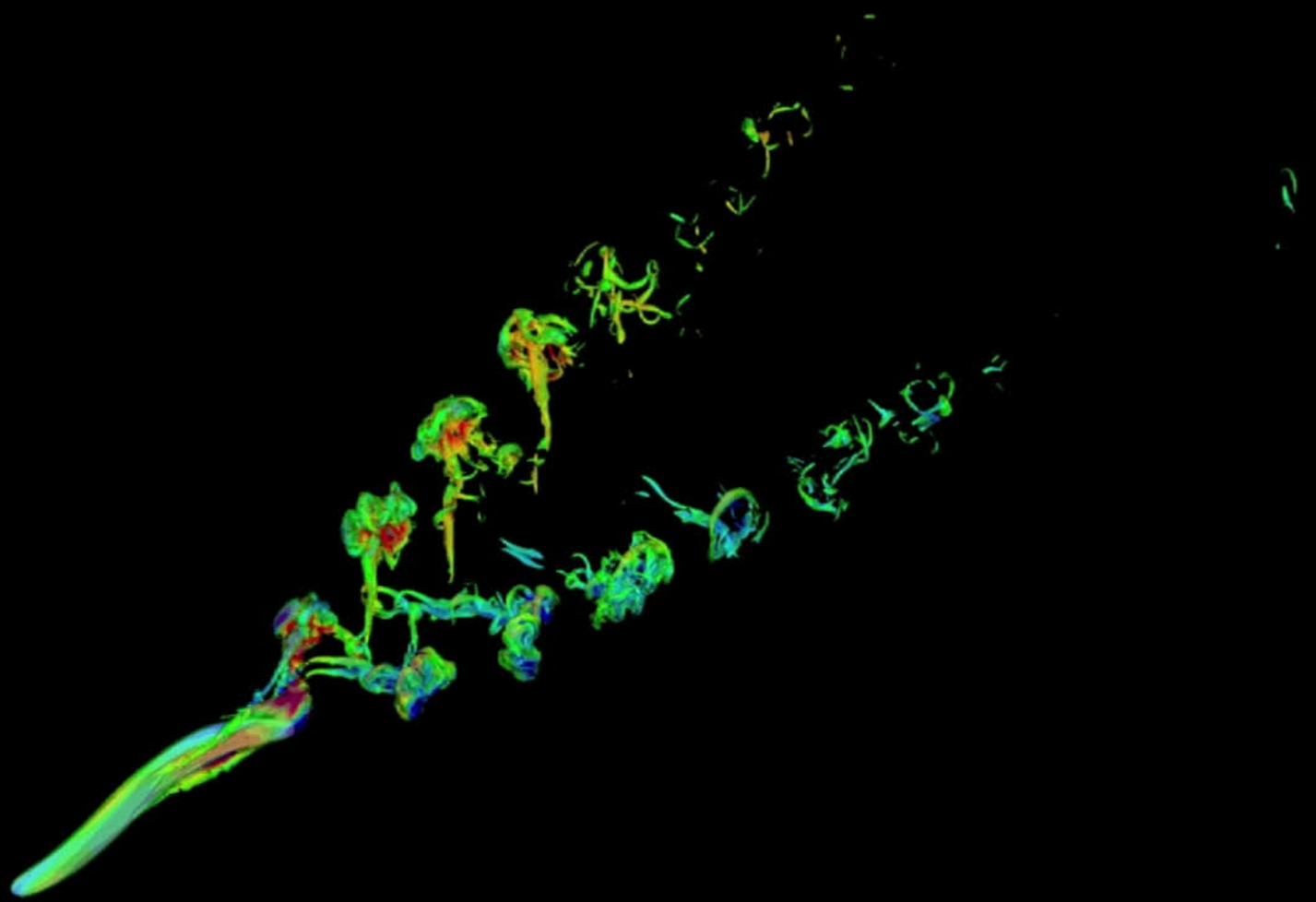
Tytell, Hsu, Williams, Cohen, Fauci, *PNAS* 2010



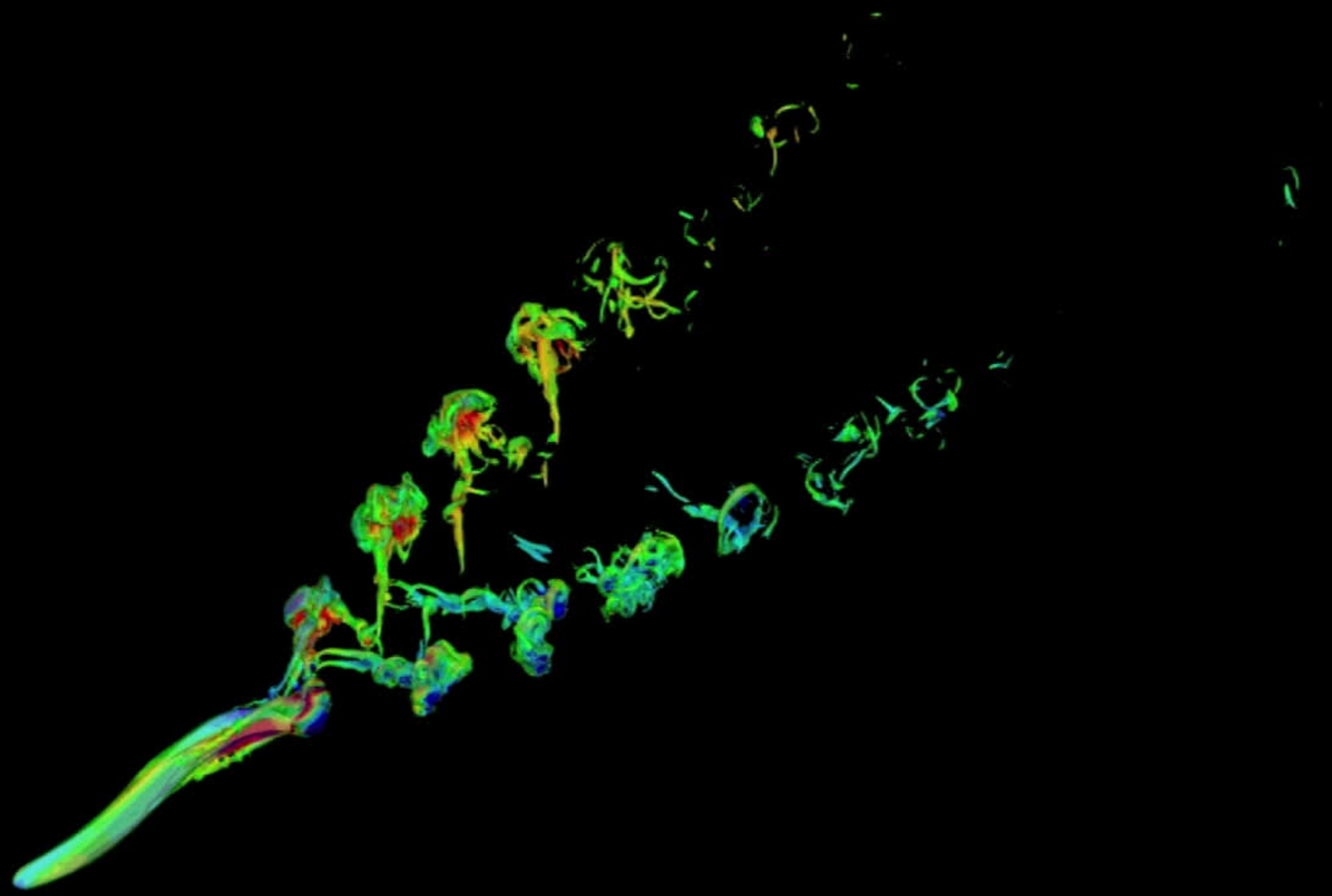
Amneet Bhalla (San Diego State) and Neelesh Patankar (Northwestern)



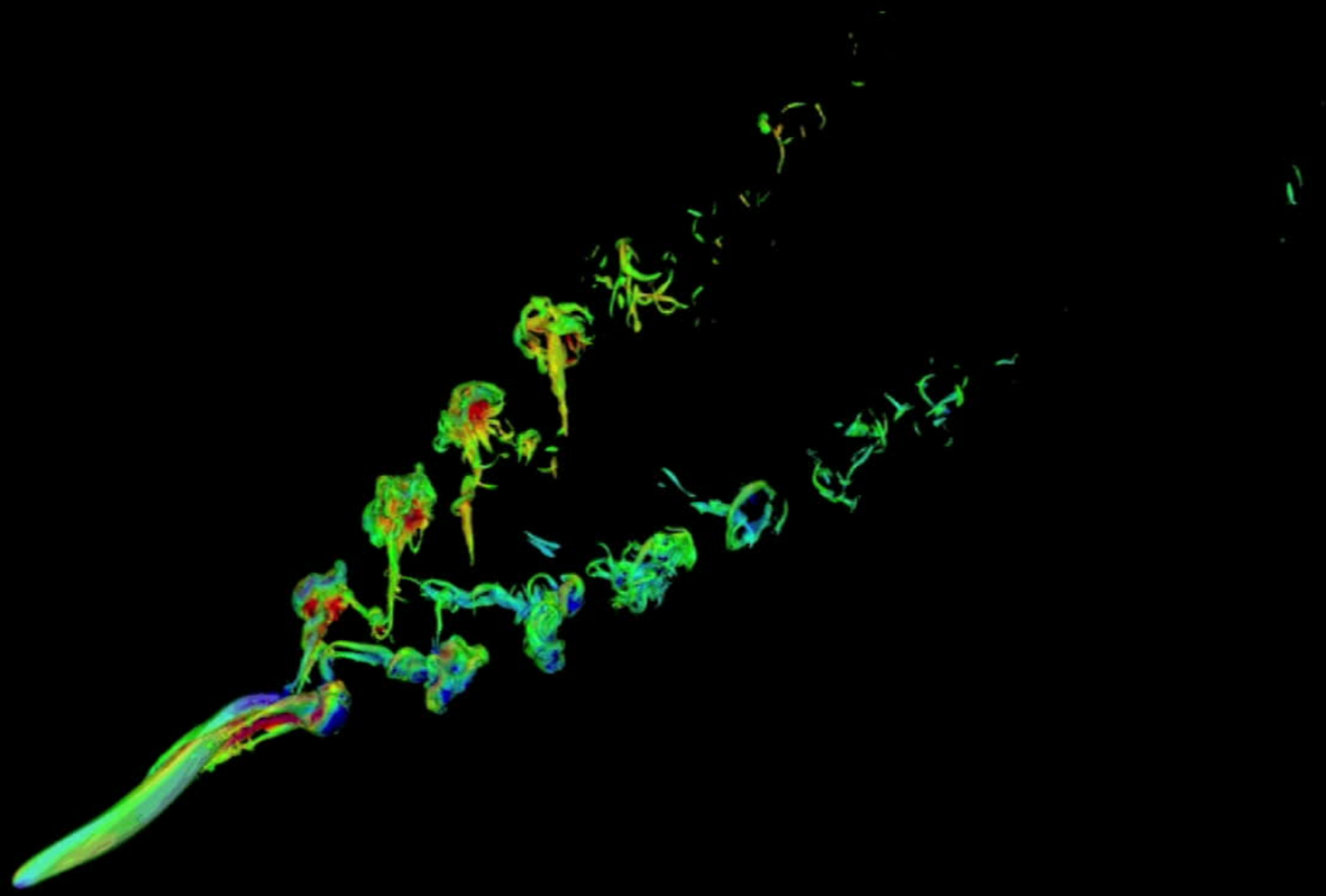
Amneet Bhalla (San Diego State) and Neelesh Patankar (Northwestern)



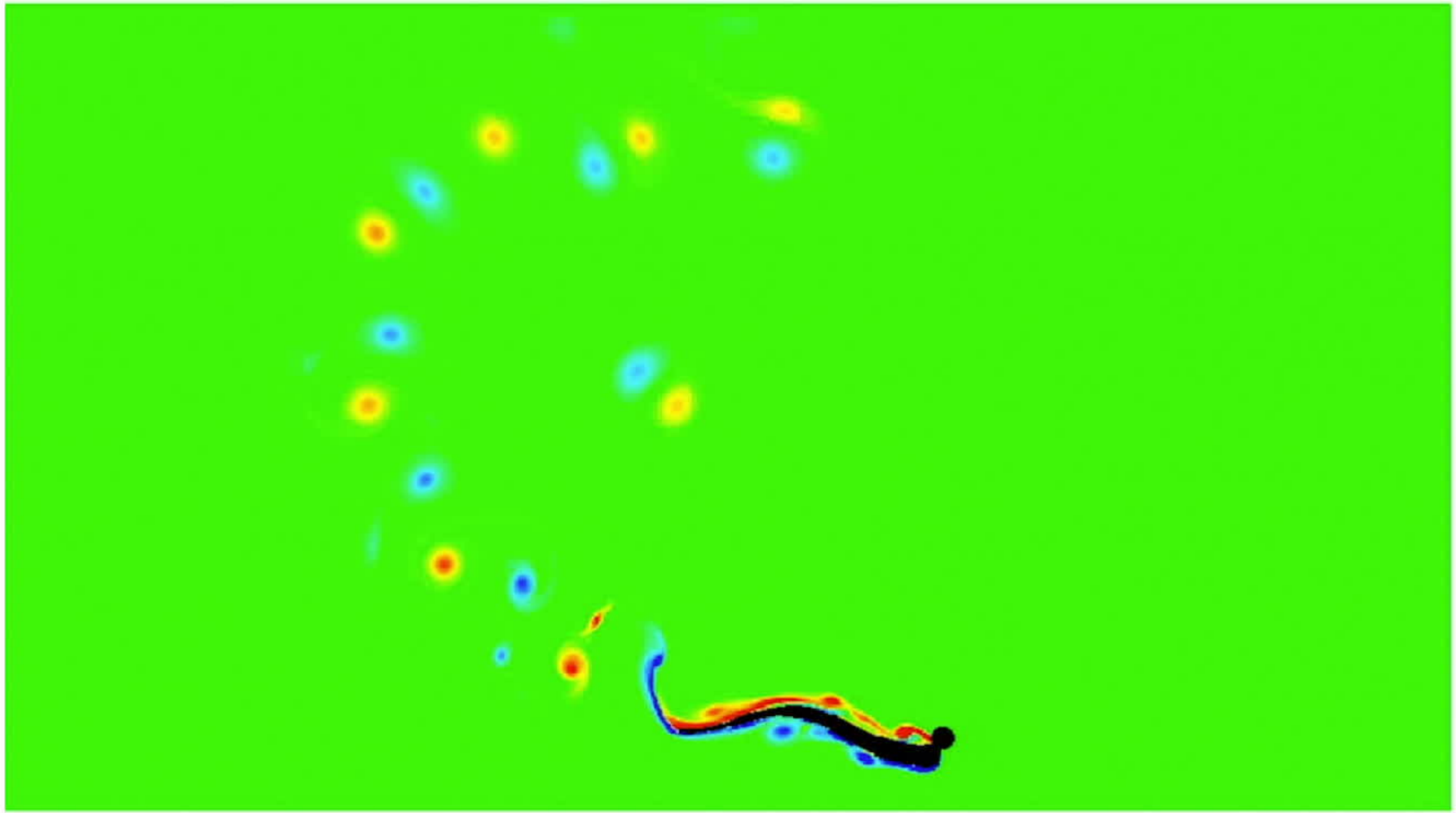
Amneet Bhalla (San Diego State) and Neelesh Patankar (Northwestern)



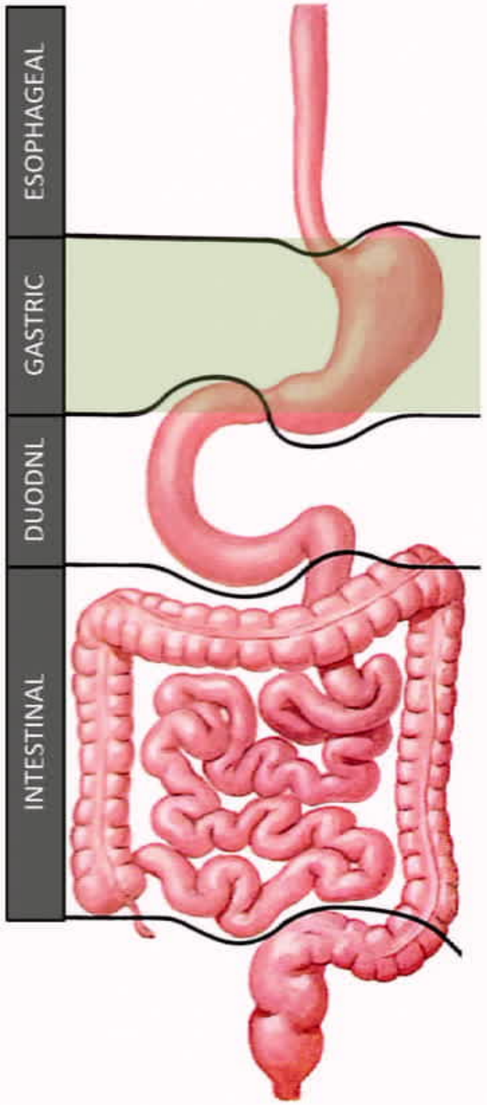
Amneet Bhalla (San Diego State) and Neelesh Patankar (Northwestern)

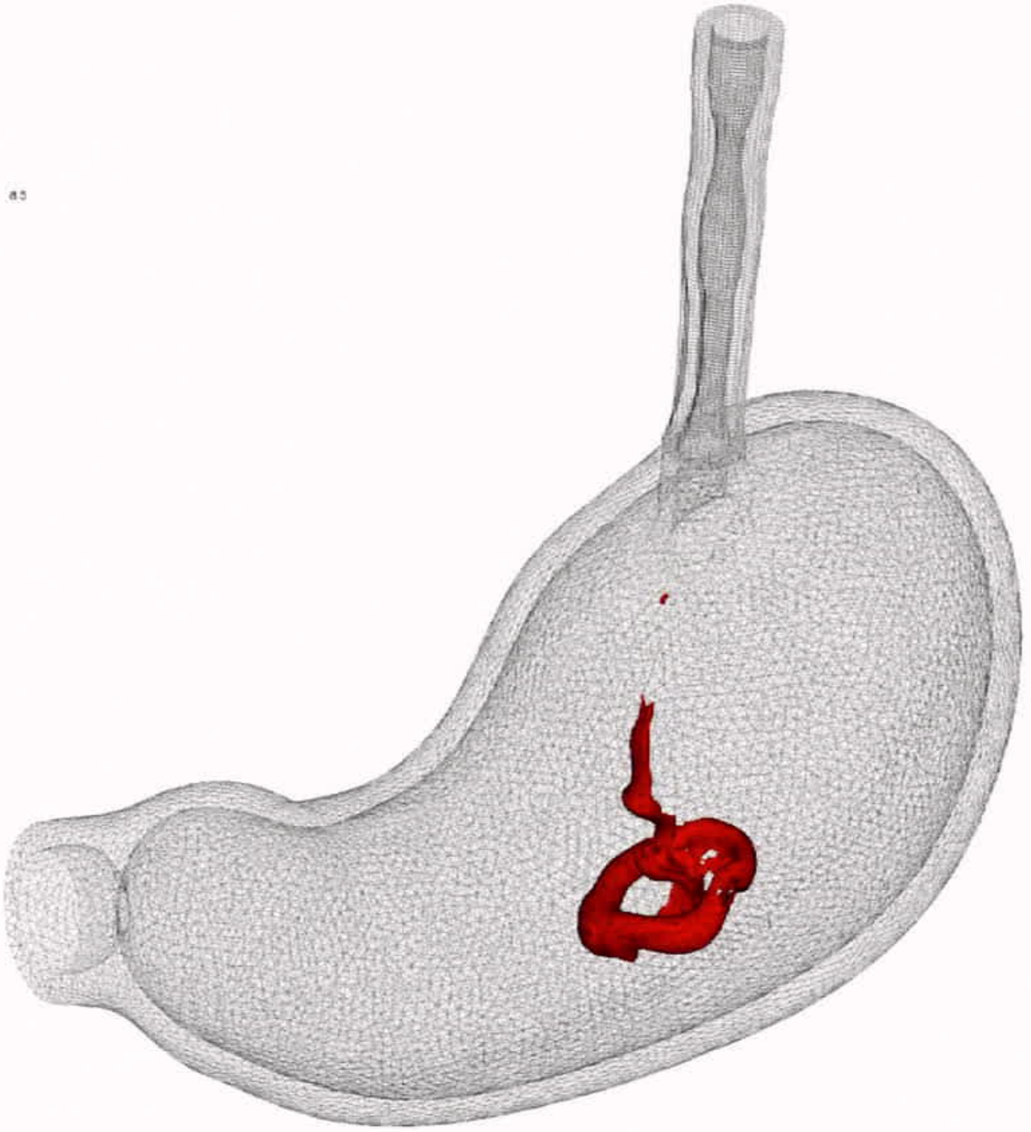


Amneet Bhalla (San Diego State) and Neelesh Patankar (Northwestern)

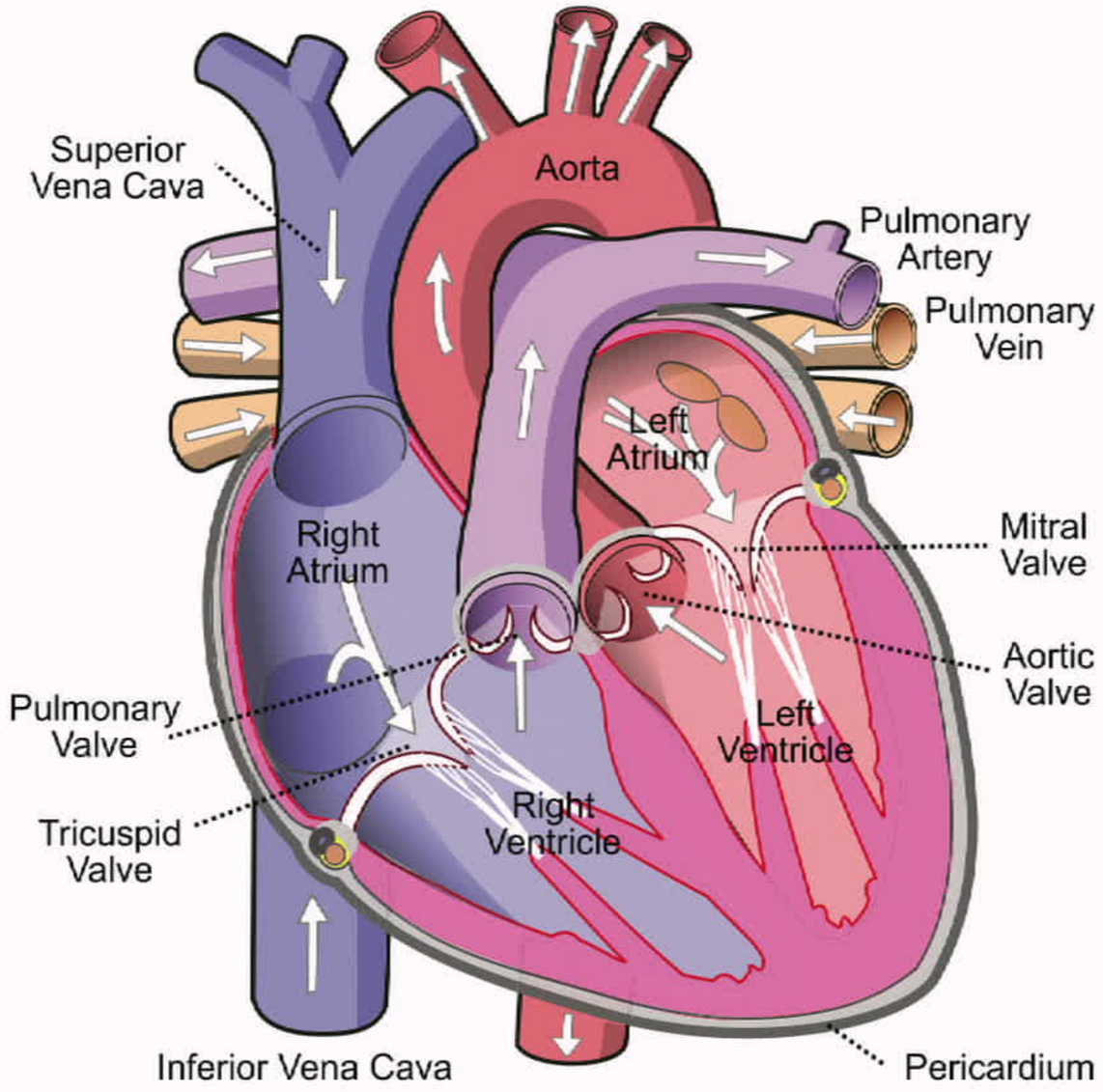


Amneet Bhalla (San Diego State) and Neelesh Patankar (Northwestern)

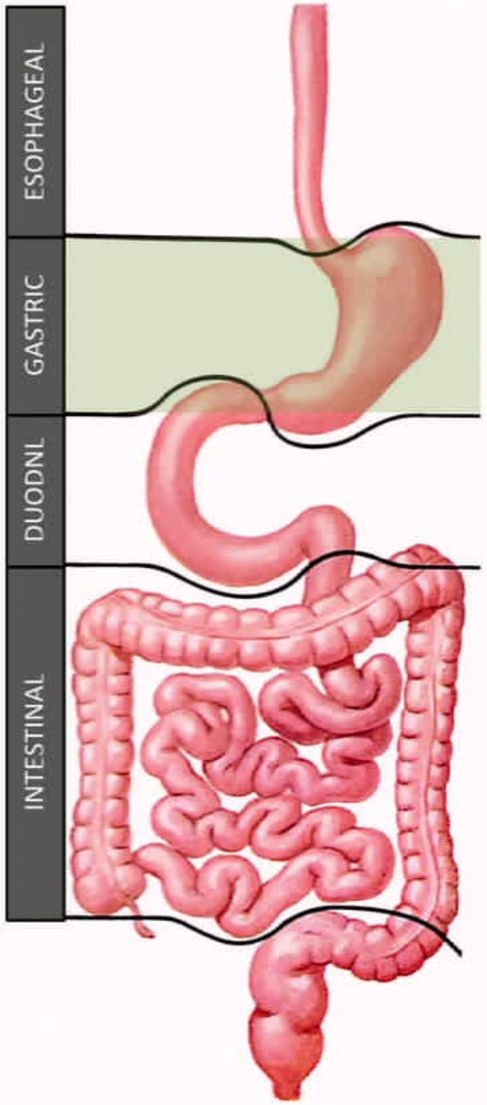


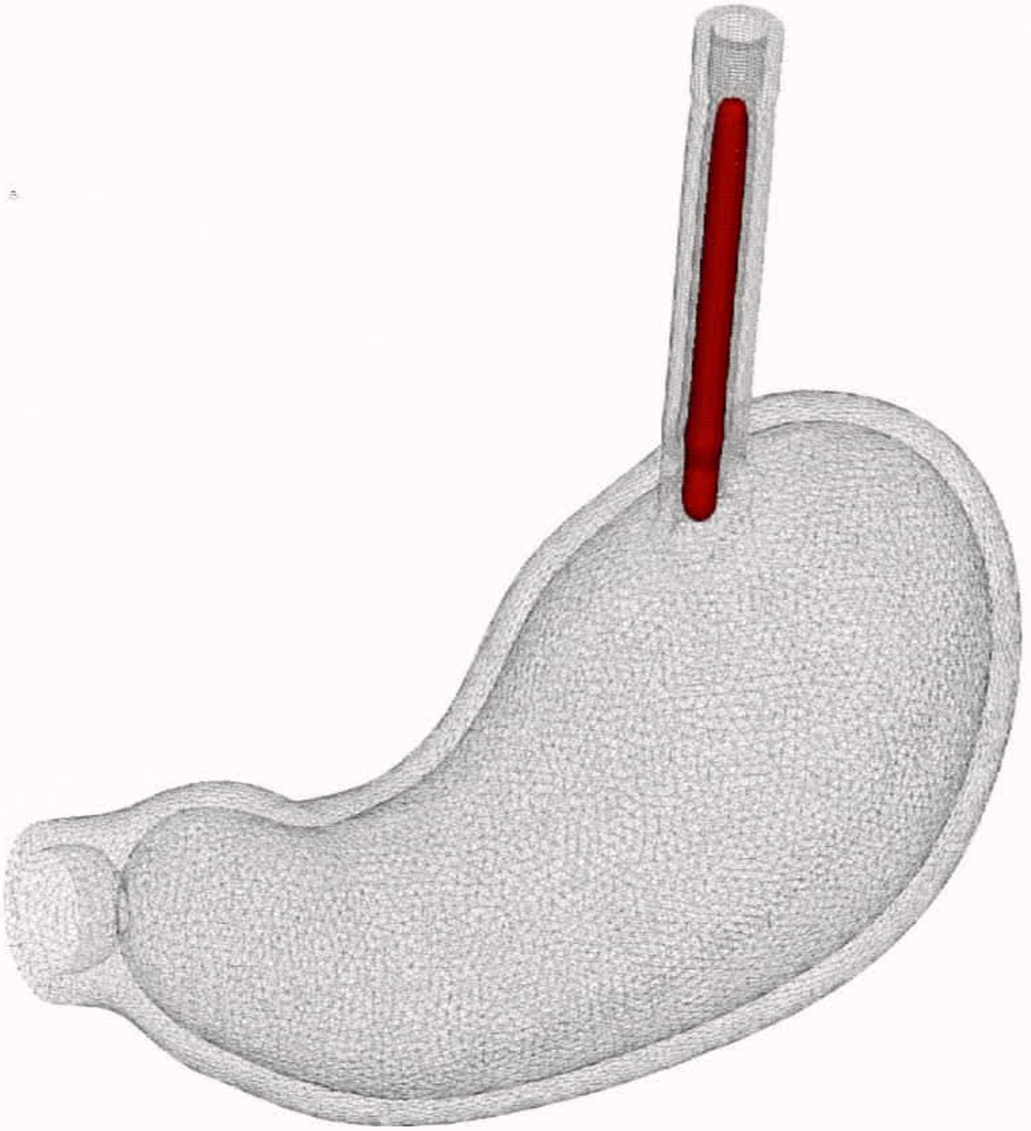


Shashank Achraya, Wenjun Kou, and Neelesh Patankar (Northwestern)

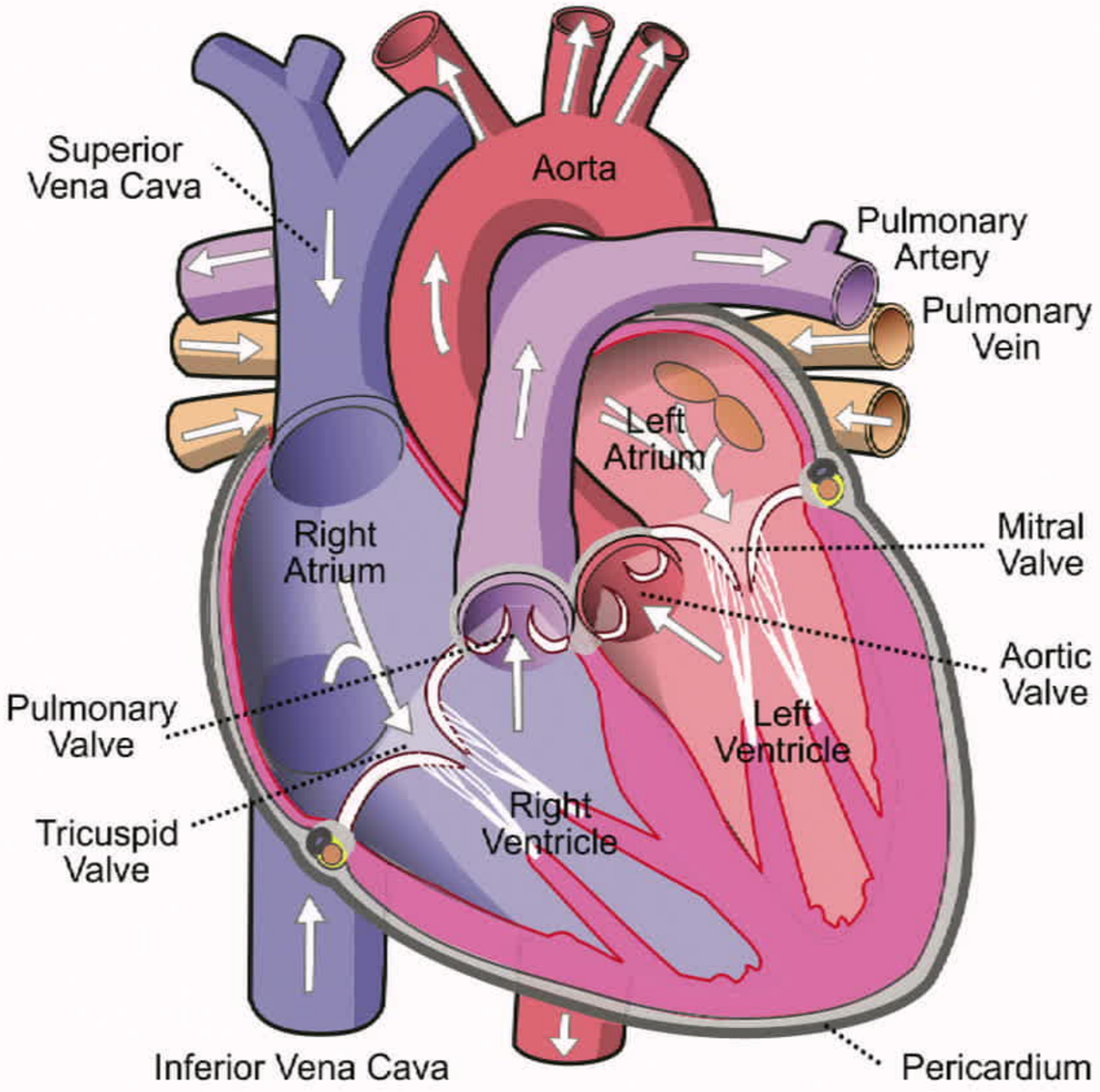


Wikimedia Commons (https://commons.wikimedia.org/w/index.php?curid=830253)

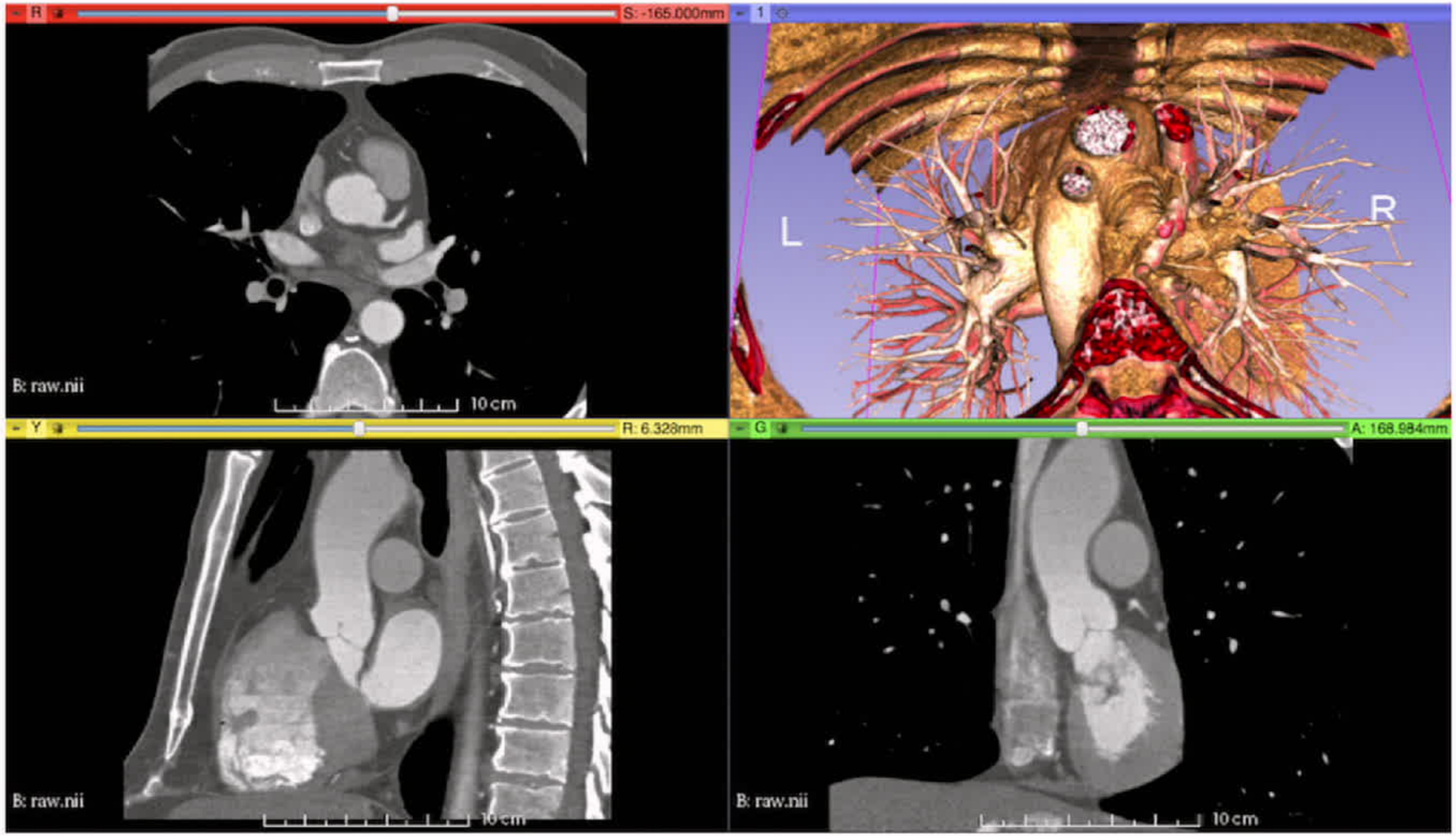




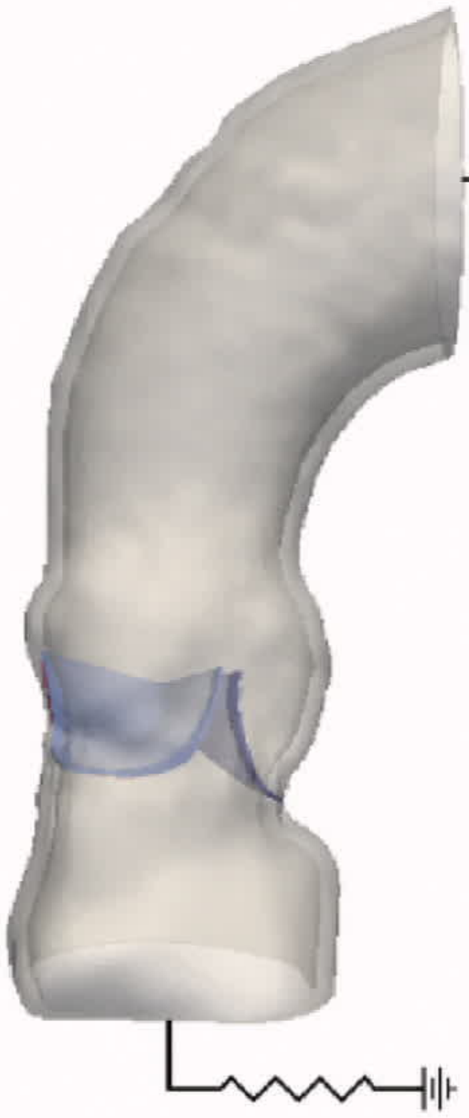
Shashank Achraya, Wenjun Kou, and Neelesh Patankar (Northwestern)



Wikimedia Commons (`https://commons.wikimedia.org/w/index.php?curid=830253`)



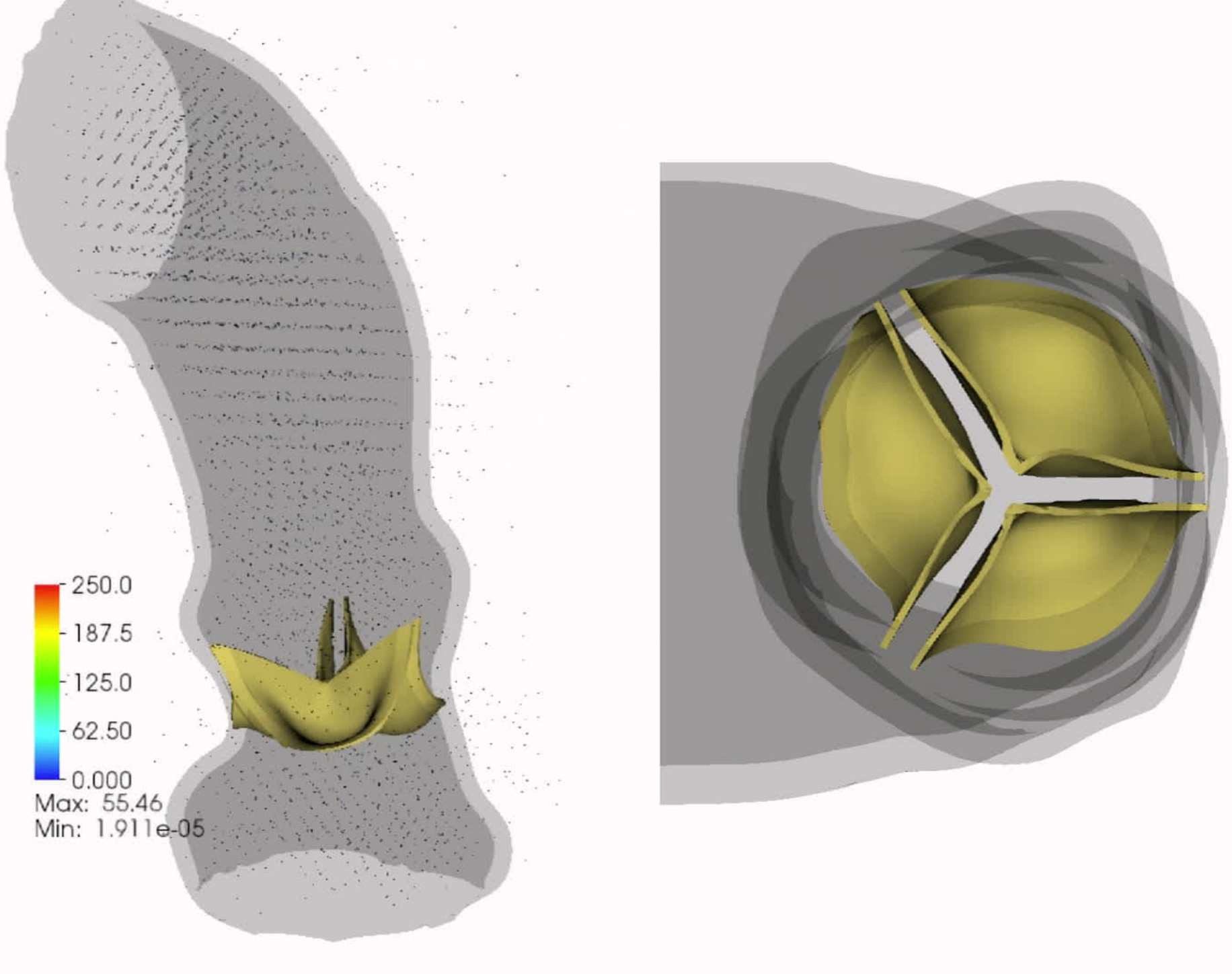
Ali Hasan (UNC-Chapel Hill Undergrad → Duke BME PhD student)
and Tommy Caranasos and John Vavalle (UNC School of Medicine)



downstream loading via a three-element Windkessel model

boundary condition models fit to clinical data from healthy subjects (Murgo et al., 1980)

upstream driving via a prescribed left ventricular pressure waveform


250.0
187.5
125.0
62.50
0.000
Max: 55.46
Min: 1.911e-05

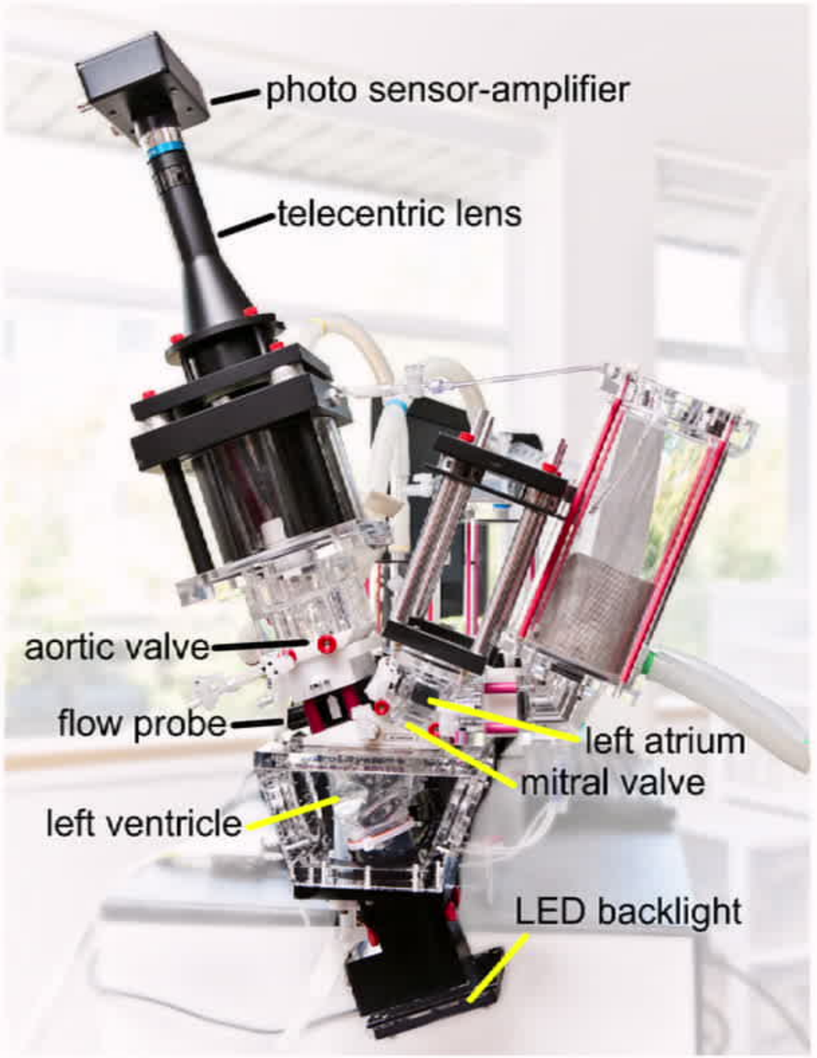
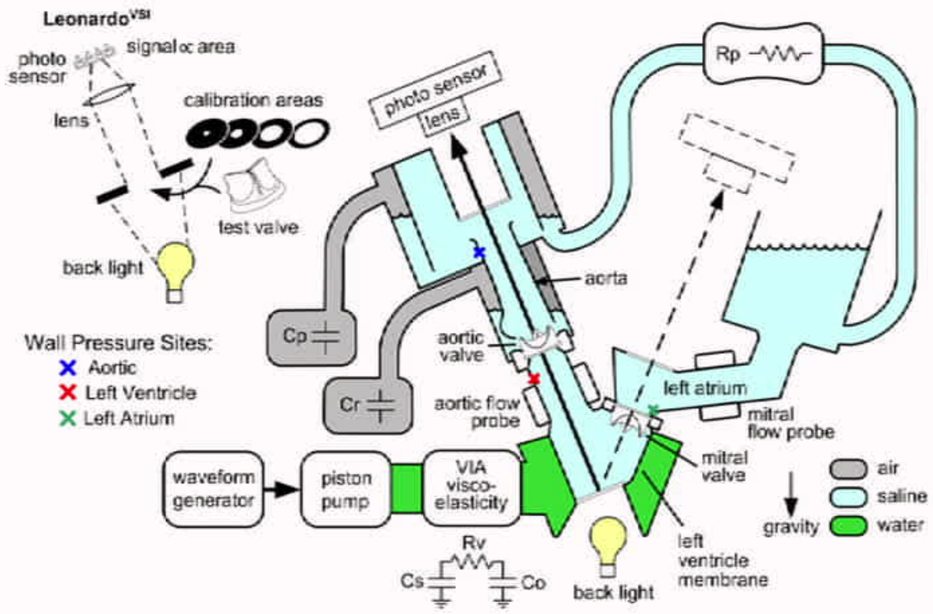
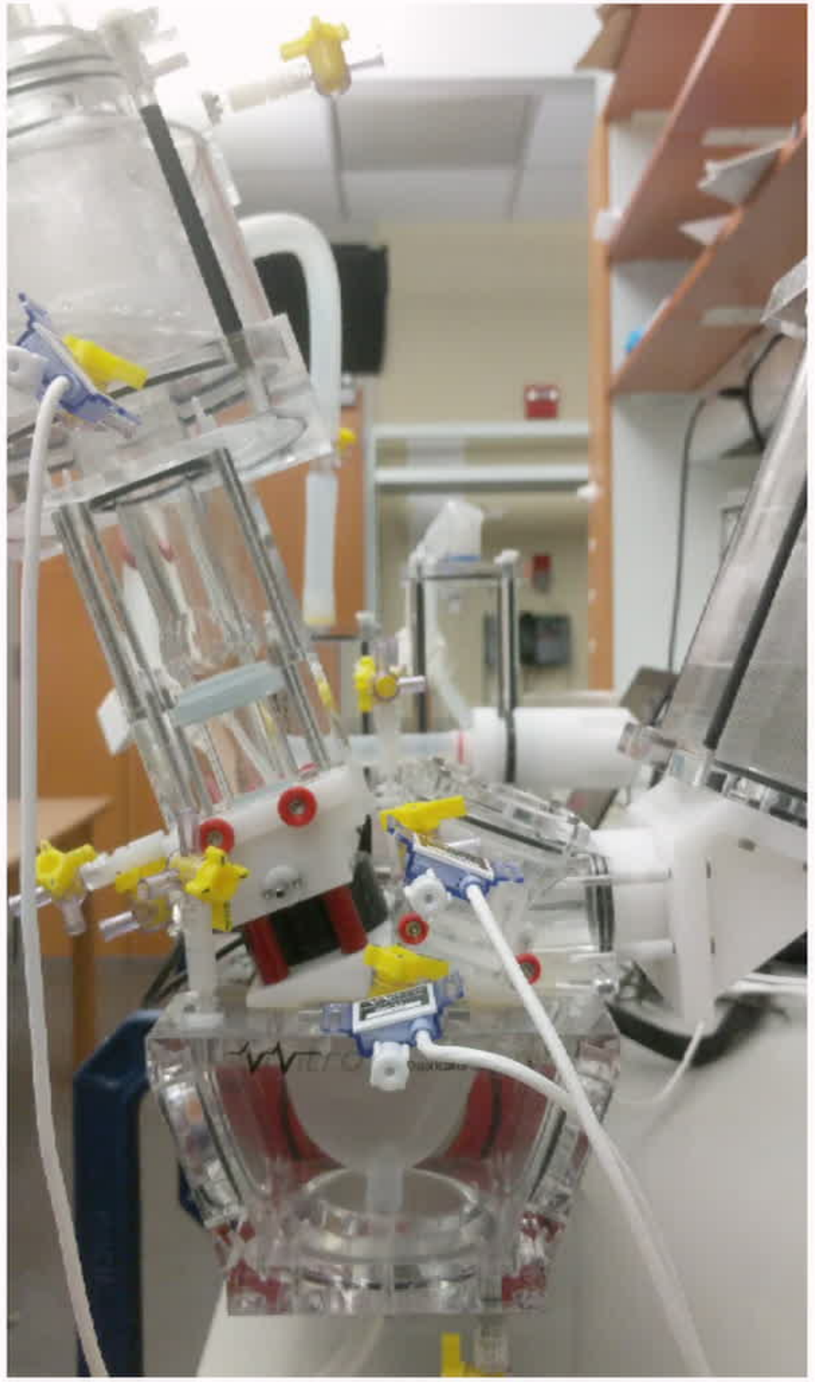
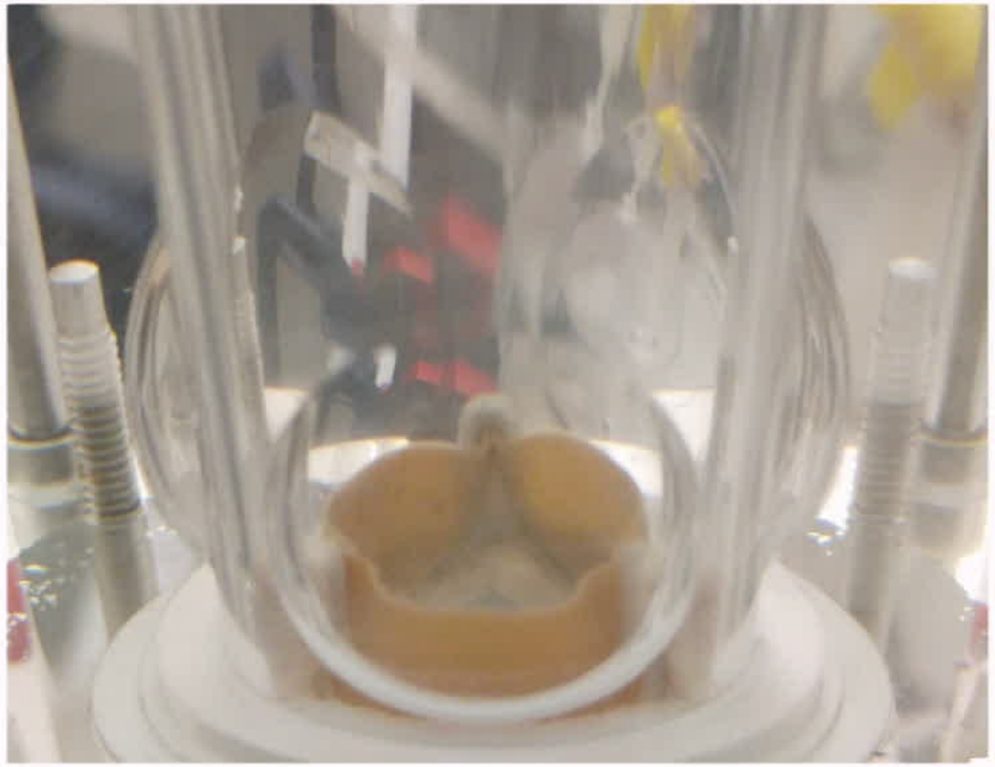


photo sensor-amplifier
telecentric lens
aortic valve
flow probe
left atrium
mitral valve
left ventricle
LED backlight


Leonardo VSI
photo sensor
signal
lens
calibration areas
test valve
back light
Wall Pressure Sites:
Aortic
Left Ventricle
Left Atrium
photo sensor
lens
Rp
aorta
Cp
aortic valve
Cr
aortic flow probe
left atrium
mitral flow probe
mitral valve
waveform generator
piston pump
VIA visco-elasticity
Rv
Cs
Co
back light
left ventricle membrane
gravity
air
saline
water



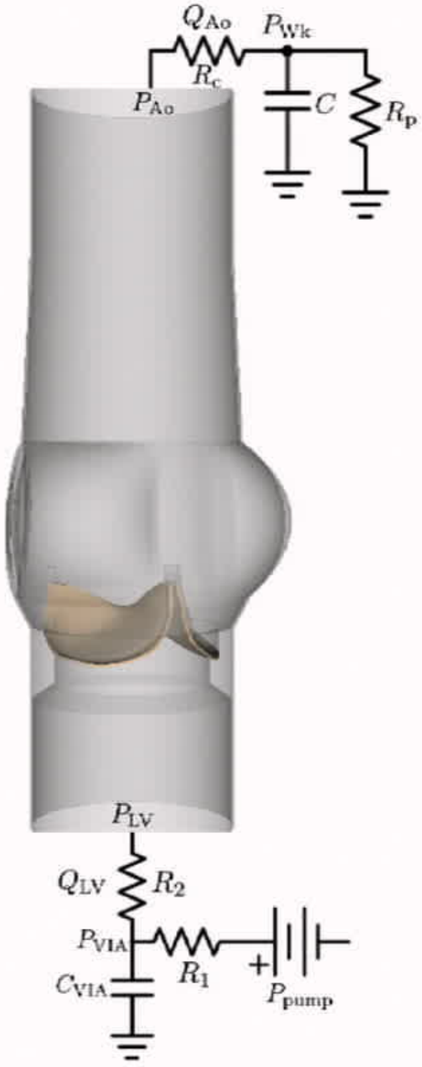

Pulse Duplicator SD2001-1



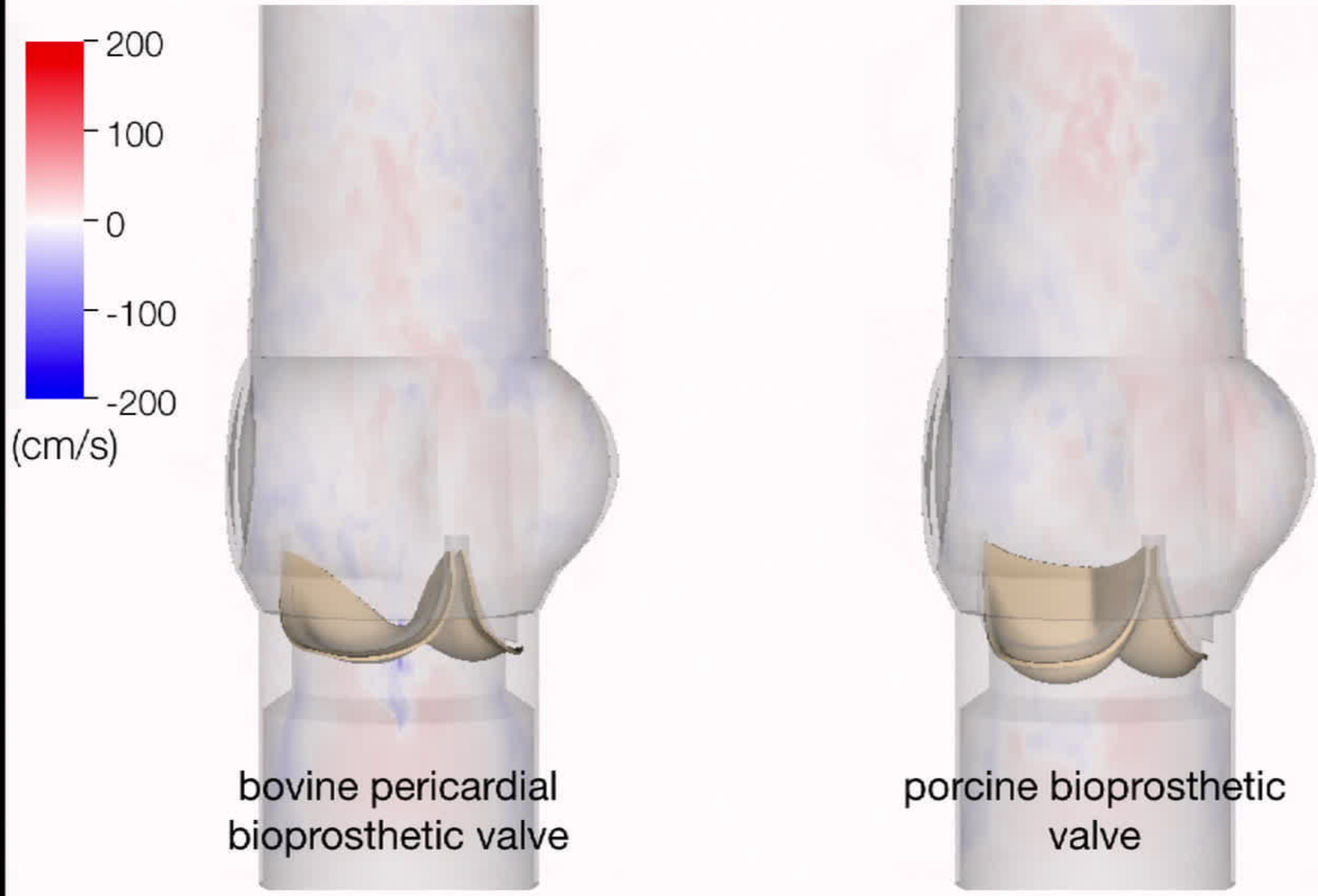

Pulse Duplicator SD2001-1

bileaflet mechanical valve (St. Jude)

porcine bioprosthetic valve

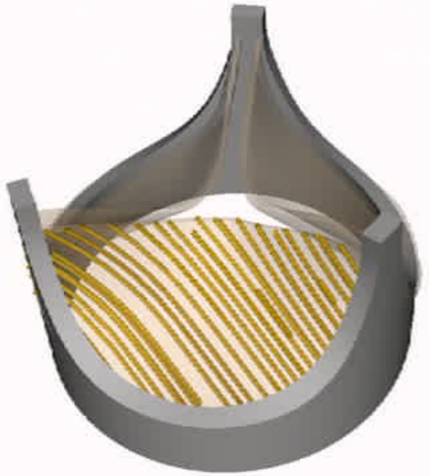


bioprosthetic valve in aortic test section

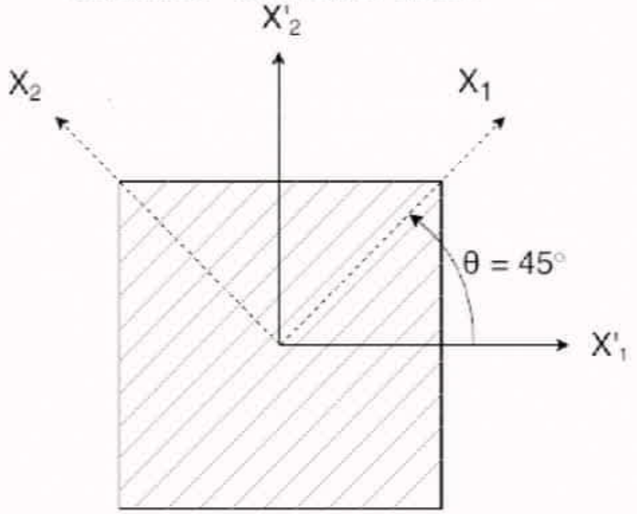


Larry Scotten (LNS Consulting), Mike Lee and Robert Hunt (UNC-Chapel Hill),
Amin Kolahdouz (UNC-Chapel Hill and FDA), and Brent Craven (FDA) and co-workers

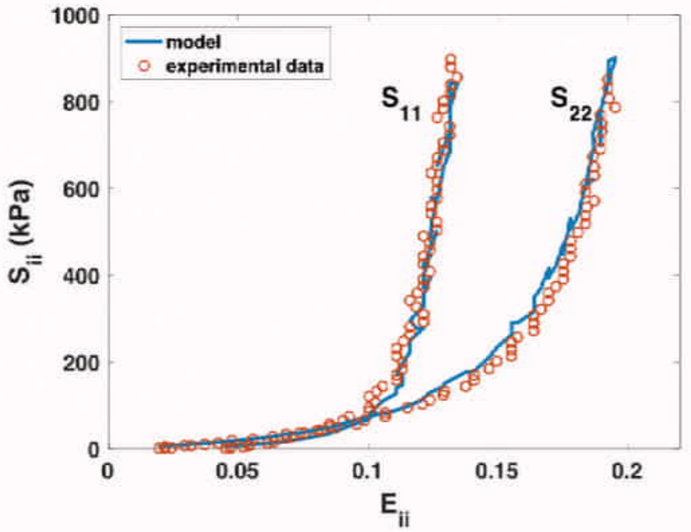
bovine pericardial bioprosthetic valve



biaxial tensile test



model fit



Data by Duraiswamy from Kim et al., *Ann Biomed Eng*, 2007

Constitutive model:

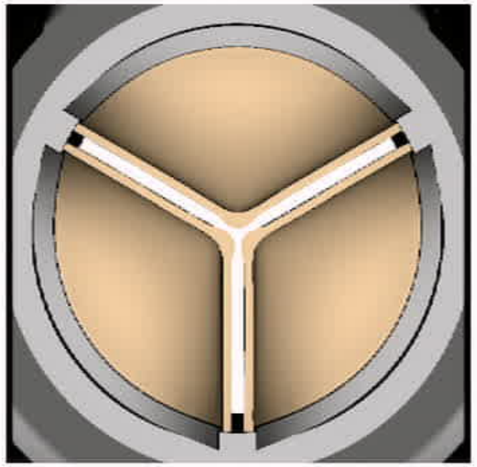
$$W = W_{\text{matrix}} + W_{\text{fiber}}$$

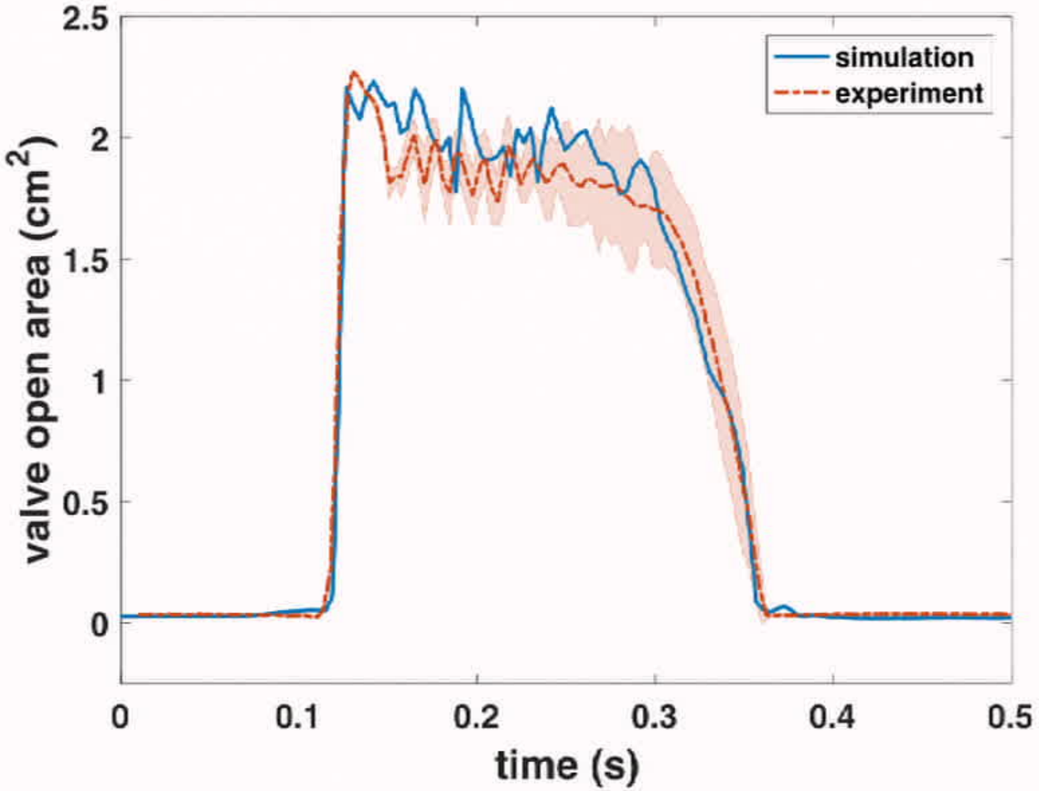
$$W_{\text{matrix}} = \frac{a}{2b}\left\{\exp[b(I_1 - 3)] - 1\right\}$$

$$W_{\text{fiber}} = \frac{c}{2d}\left\{\exp[d(\kappa I_1 + (1 - 3\kappa)I_4 - 1)^2] - 1\right\}$$

- $I_1 = \text{tr}(\mathbb{F}^T\mathbb{F})$
- $I_4 = \lambda_f^2$ is squared fiber stretch
- κ describes fiber dispersion

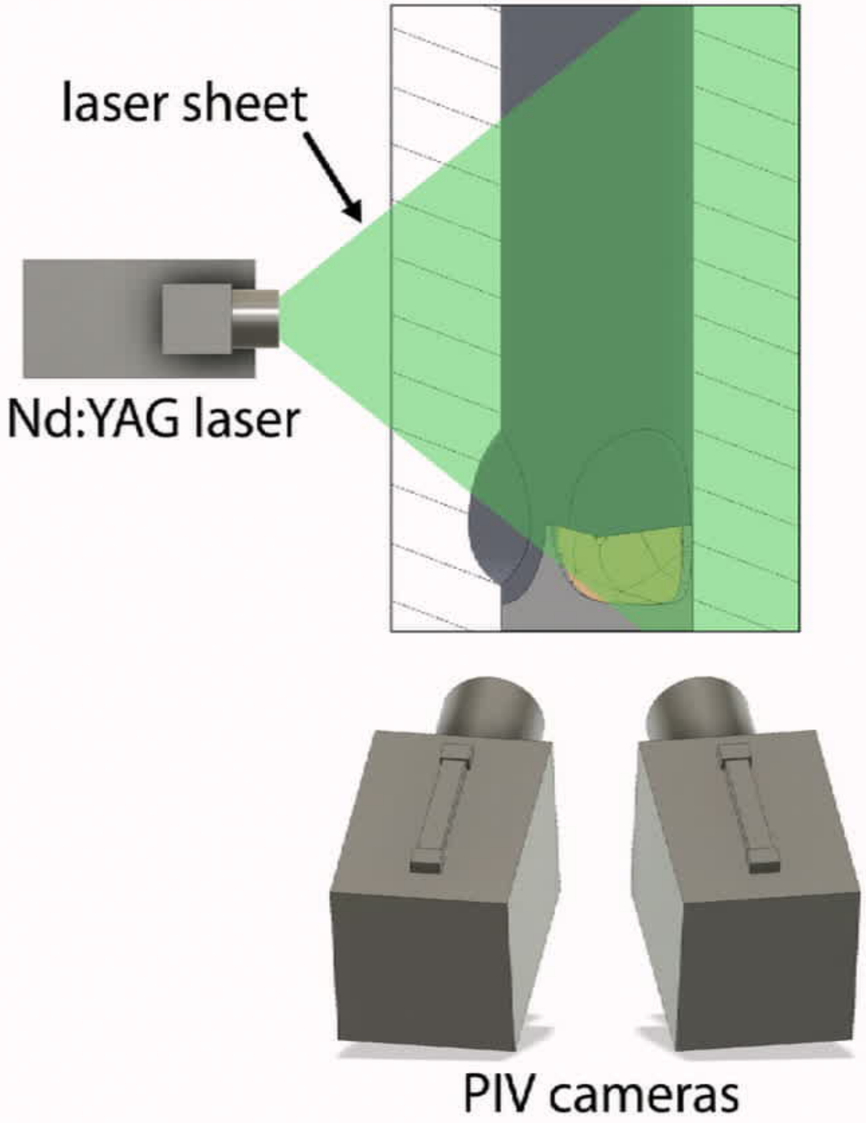
Porcine bioprosthetic valve: Comparing computational and experimental dynamics

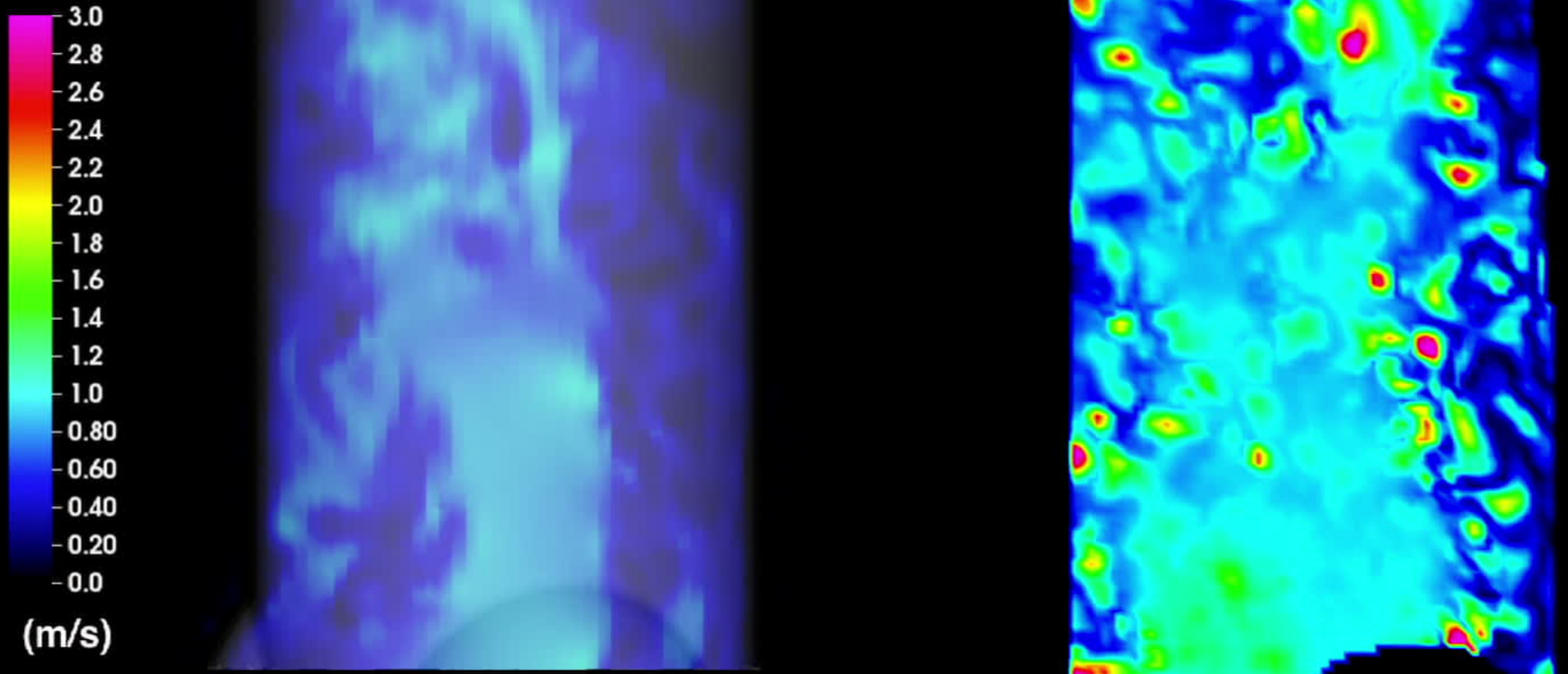


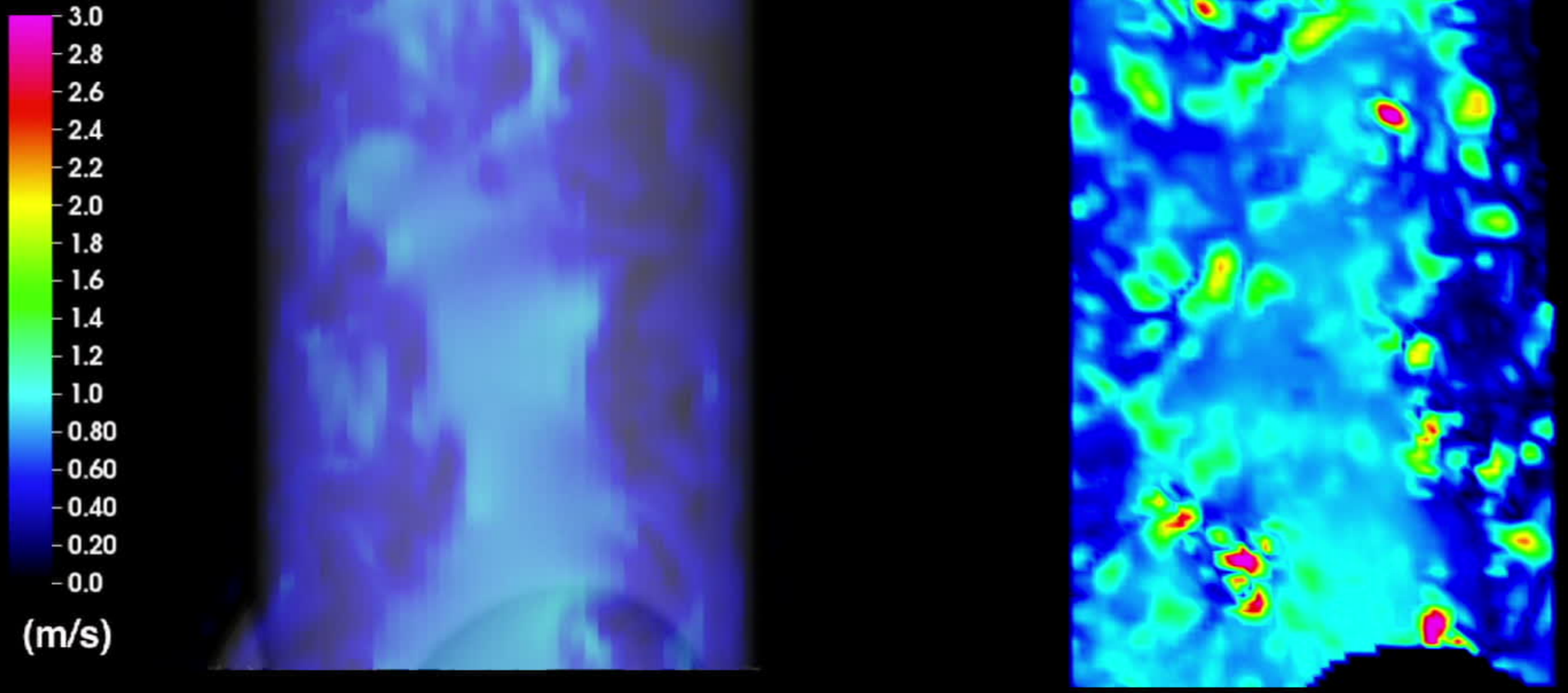


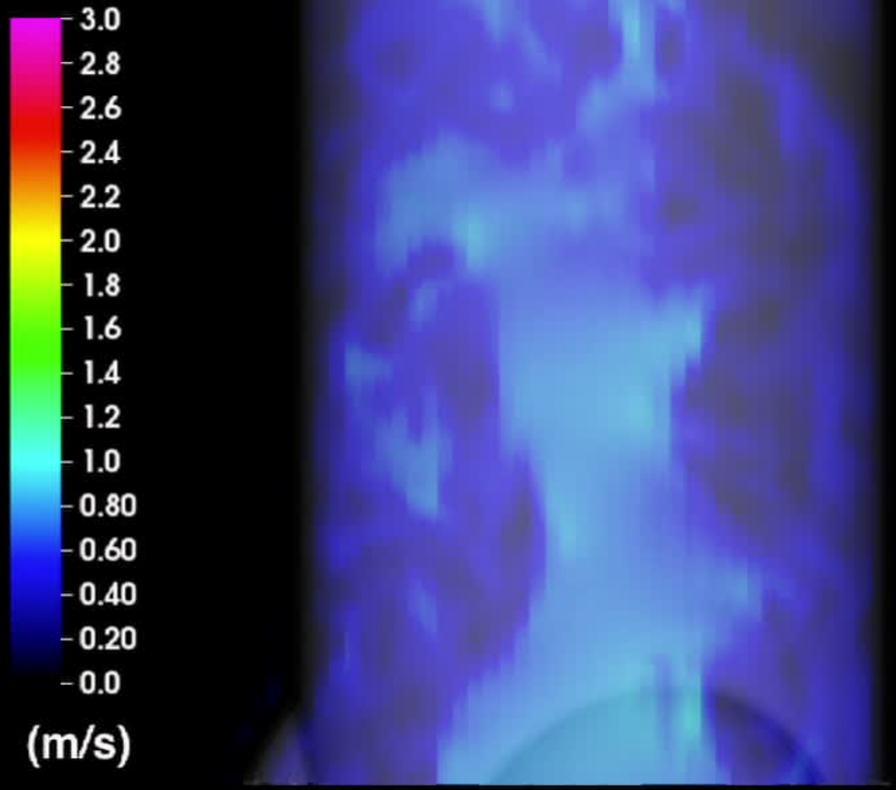
Scatter in leaflet kinematic quantification reflects complex flow dynamics.

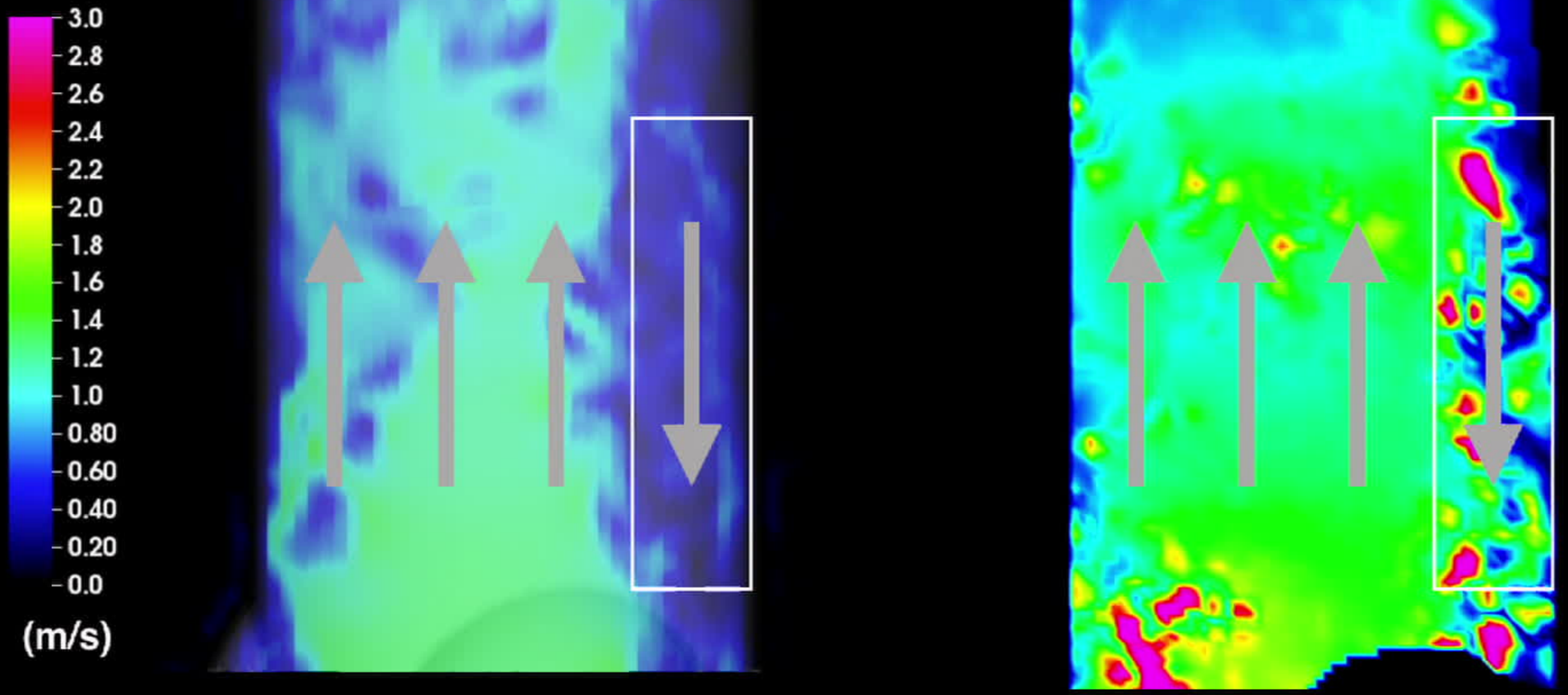
Particle Image Velocimetry (PIV)

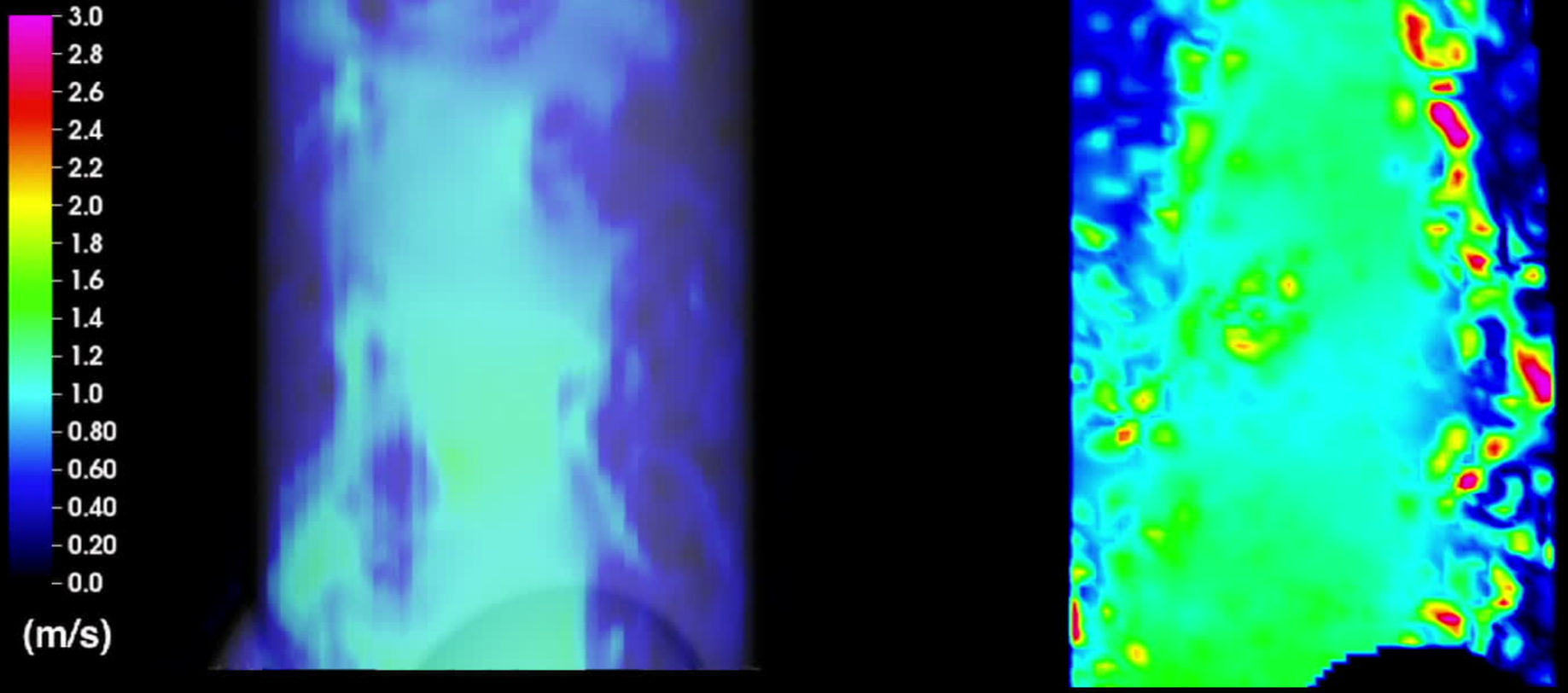


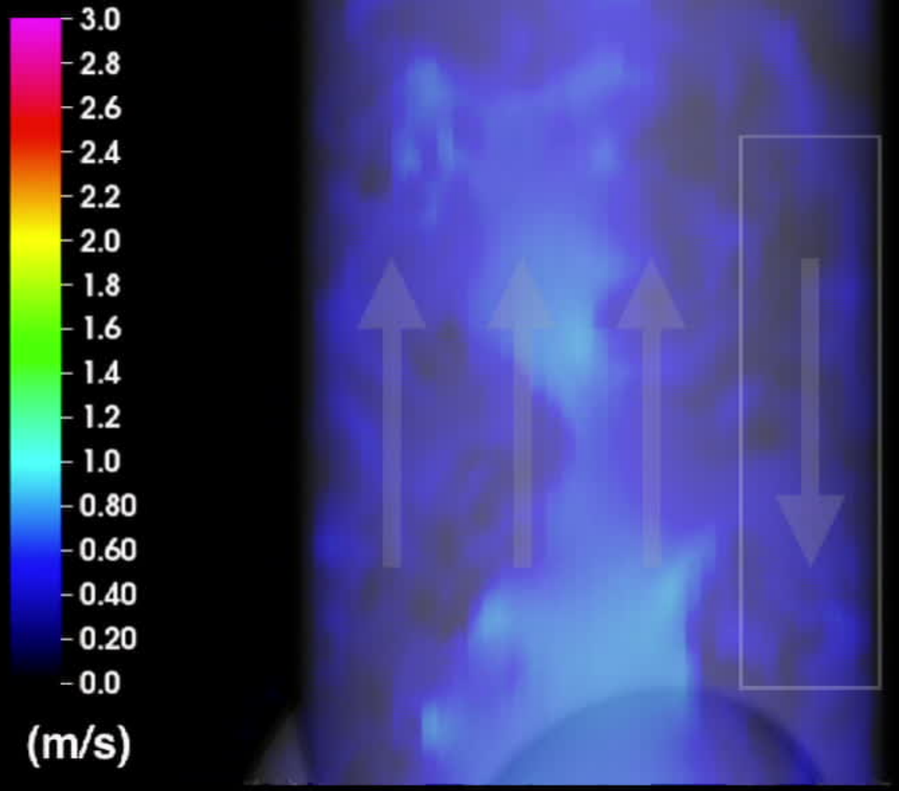

3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.80
0.60
0.40
0.20
0.0
(m/s)

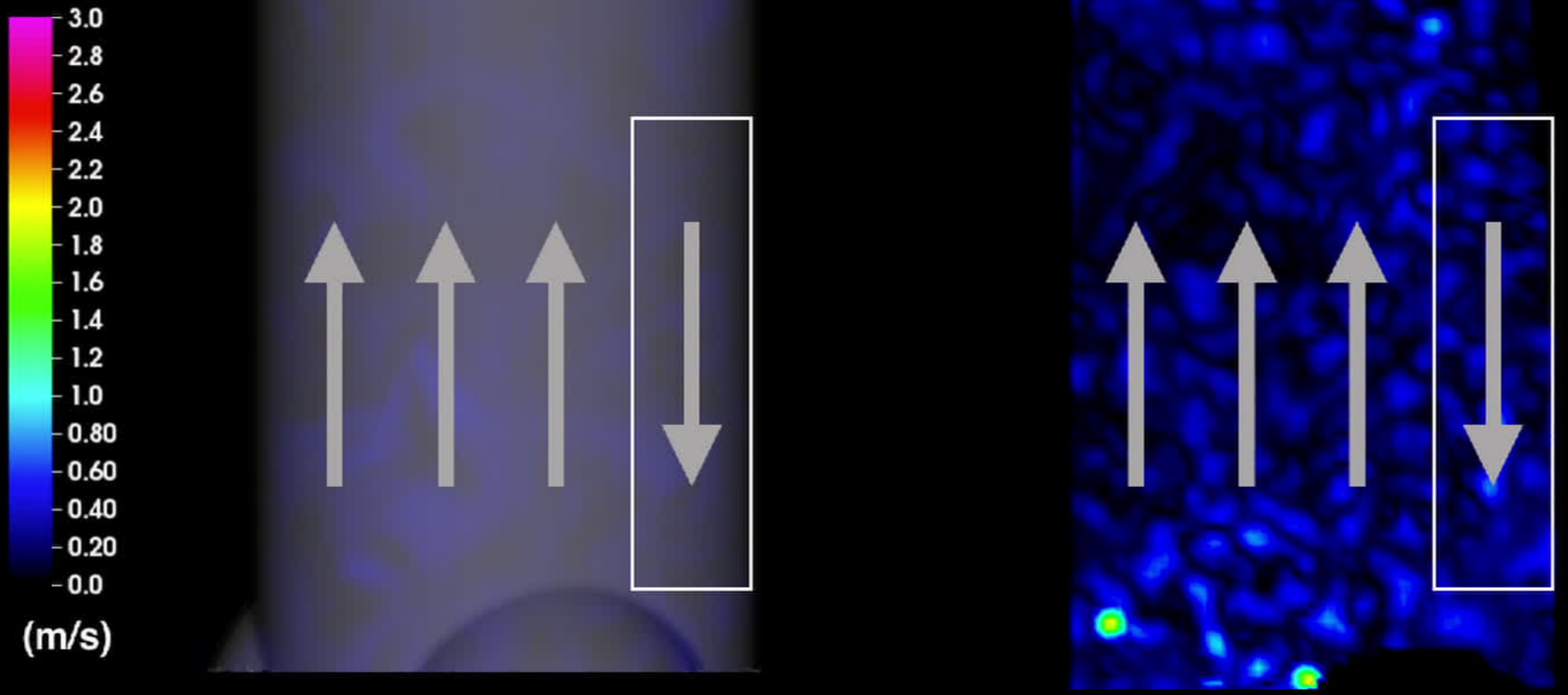

3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.80
0.60
0.40
0.20
0.0
(m/s)

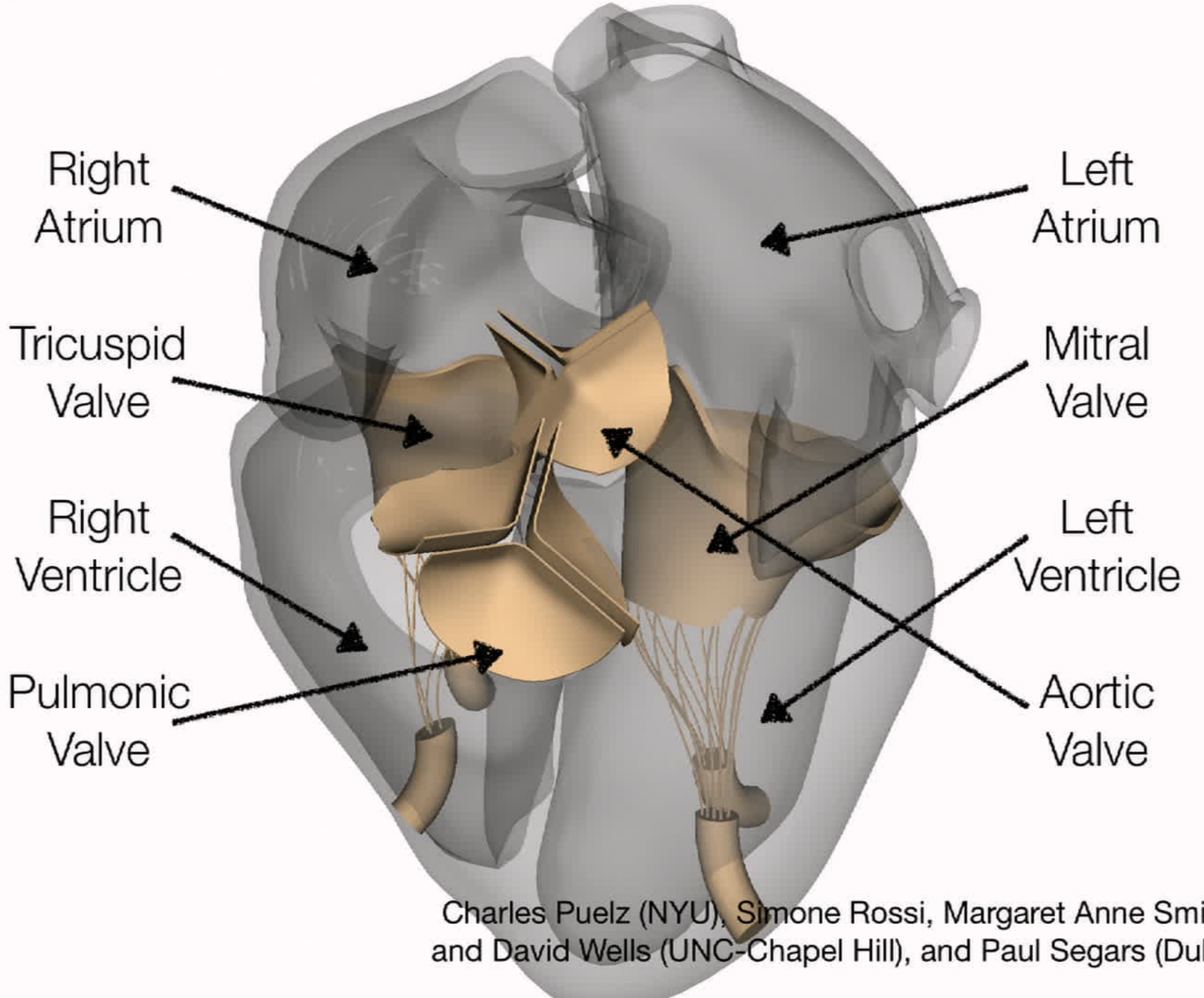

3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.80
0.60
0.40
0.20
0.0
(m/s)


3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.80
0.60
0.40
0.20
0.0
(m/s)


3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.80
0.60
0.40
0.20
0.0
(m/s)

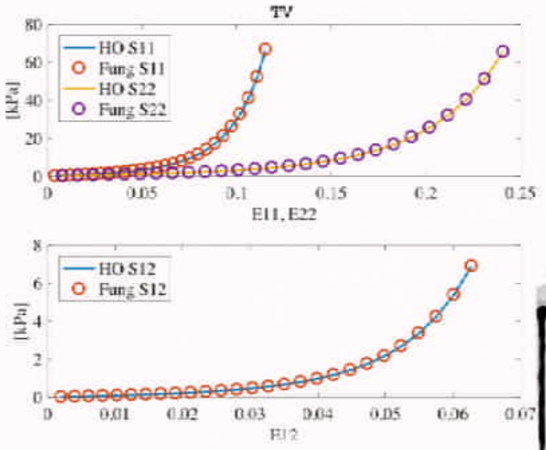

3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.80
0.60
0.40
0.20
0.0
(m/s)

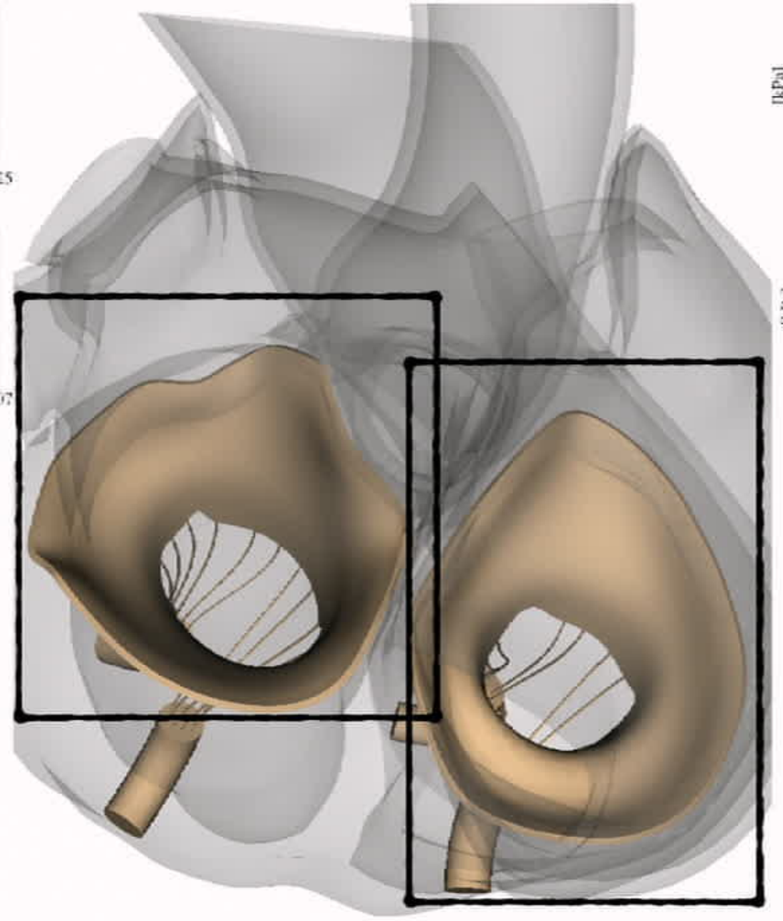

3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.80
0.60
0.40
0.20
0.0
(m/s)



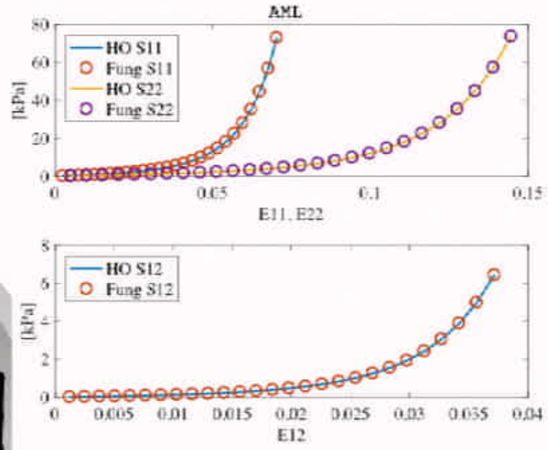
Charles Puelz (NYU), Simone Rossi, Margaret Anne Smith,
and David Wells (UNC-Chapel Hill), and Paul Segars (Duke)

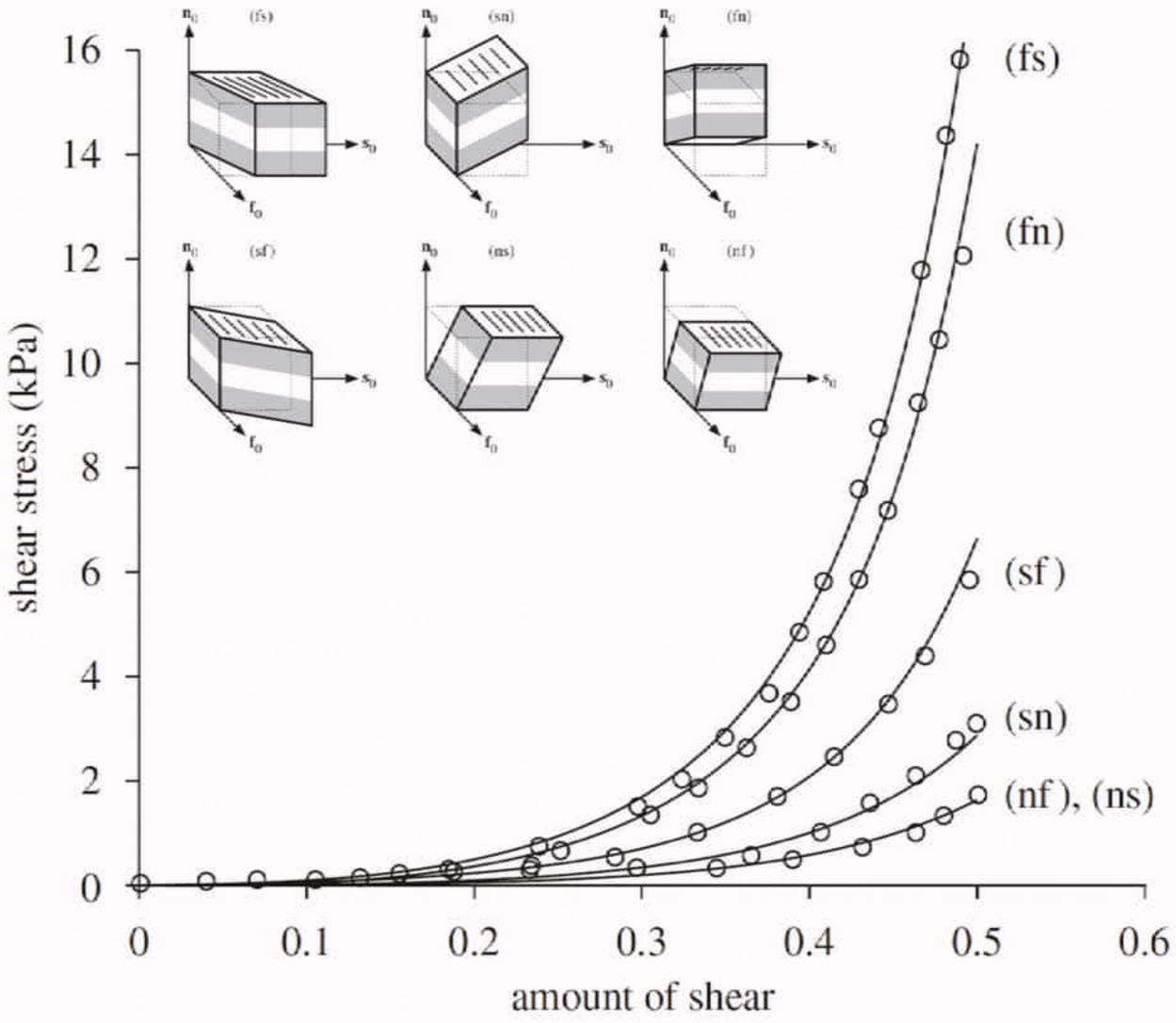
Tricuspid



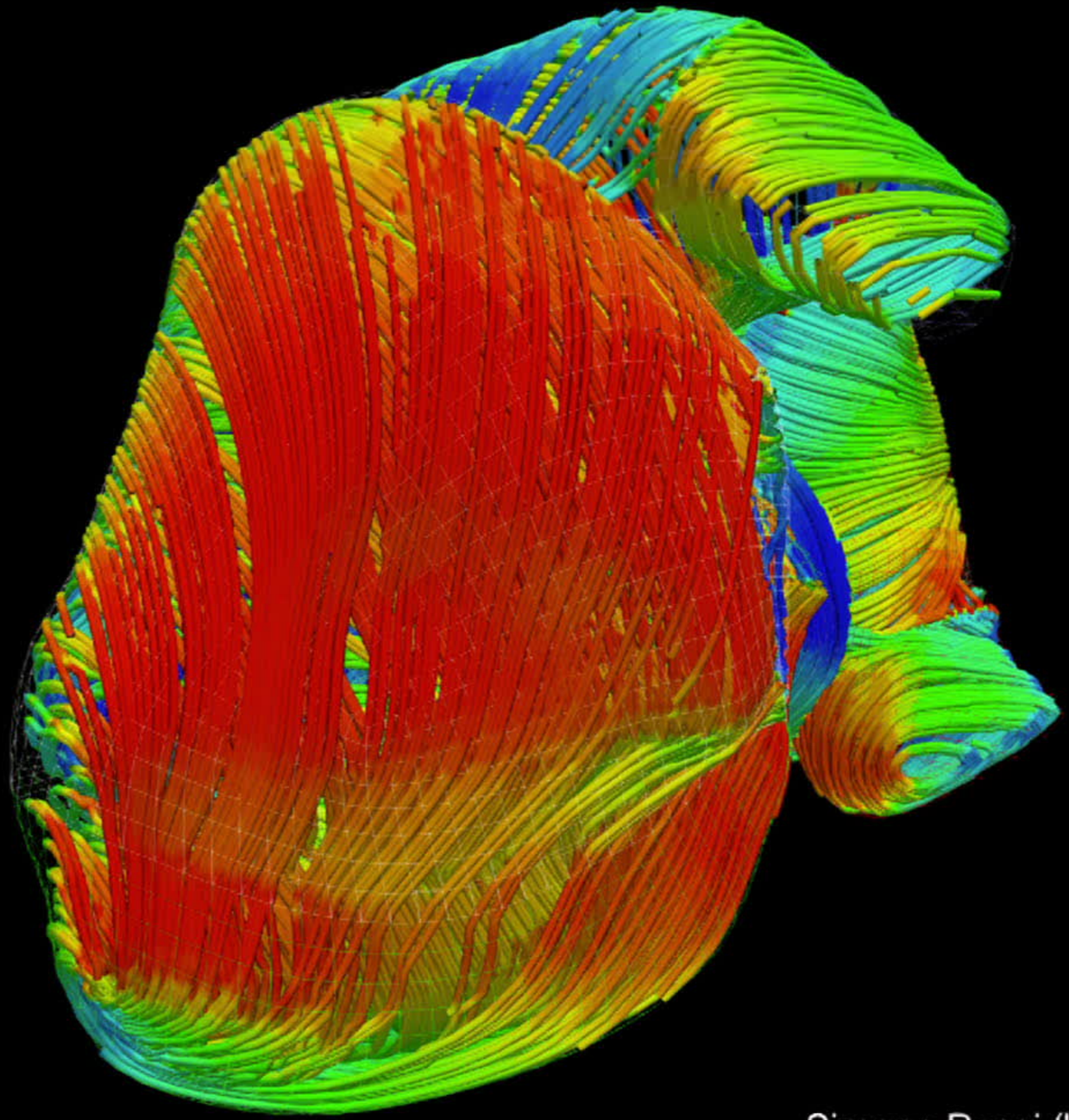


Mitral

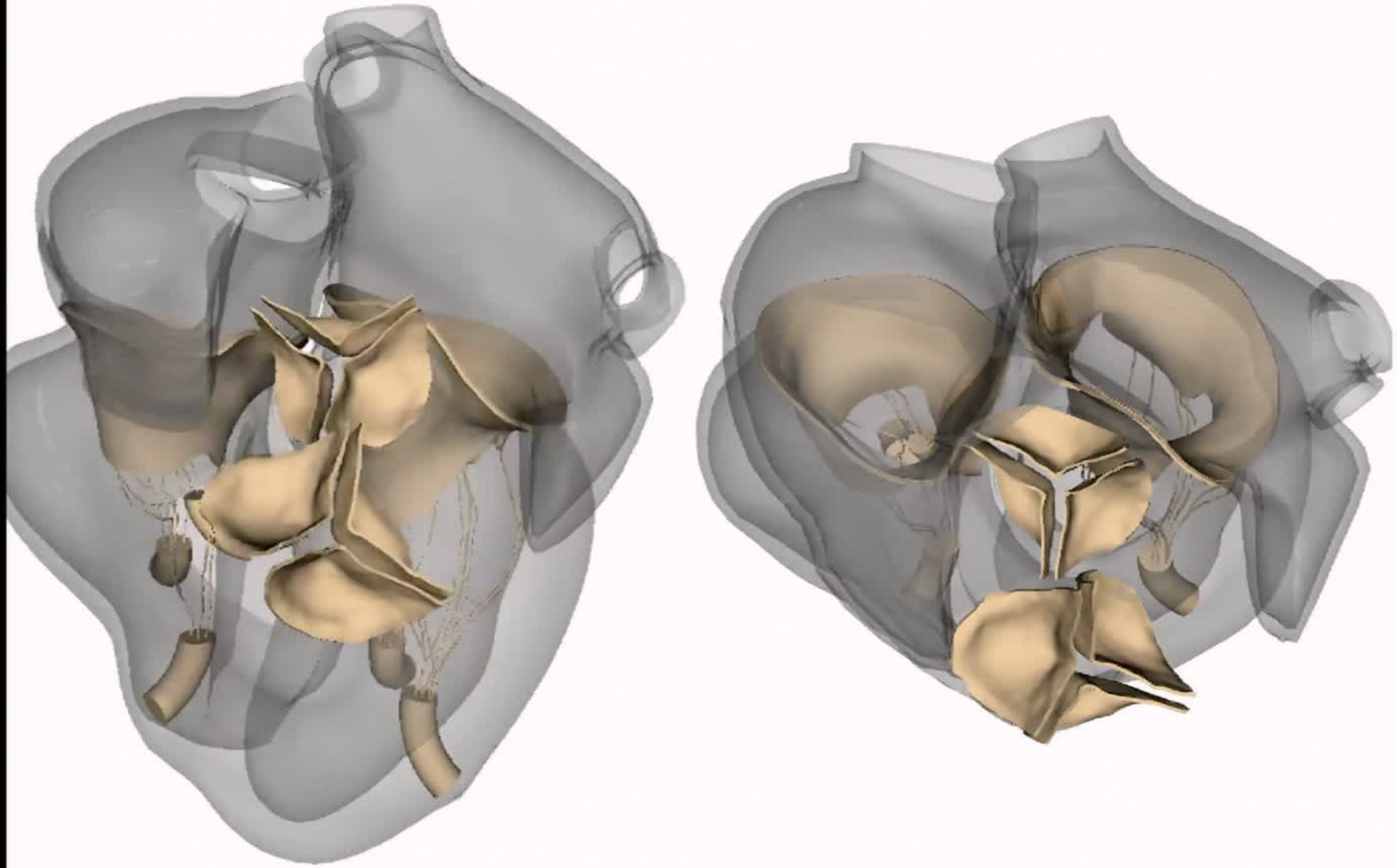




From Holzapfel and Ogden, *Phil Trans R Soc A*, 2009



Simone Rossi (UNC-Chapel Hill)



Acknowledgements

Griffith Research Group
Aaron Barrett
Jordan Brown
Ali Hasan (now at Duke)
Robert Hunt
Amin Kolahdouz (joint w/FDA)
Yanni Lai
Jae Ho Lee
Saad Qadeer
Simone Rossi
Margaret Anne Smith
Charles Talbot
Benjamin Vadala-Roth
David Wells

UNC-Chapel Hill
Thomas Caranasos
Daphne Klotsa
Laura Miller
John Vavalle

Akron
Alexander Hoover

Buffalo
Matthew Knepley

Duke
Paul Segars

Food and Drug Administration
Brent Craven
Nandini Duraiswamy
Amin Kolahdouz (joint w/UNC)
Stephen Retta
Alex Rygg

LNS Consulting
Larry Scotten

New York University
Aleks Donev
David McQueen
Charles Peskin
Charles Puelz

Northwestern
Neelesh Patankar
Shashank Acharya
Wenjun Kou
Sourav Halder
Nishant Nangia

San Diego State
Amneet Bhalla

NIH
HL117063 HL143336

NSF
CBET 1757193
DMS 1016554/1460368
DMS 1664645
OAC 1047734/1460334
OAC 1450327
OAC 1652541