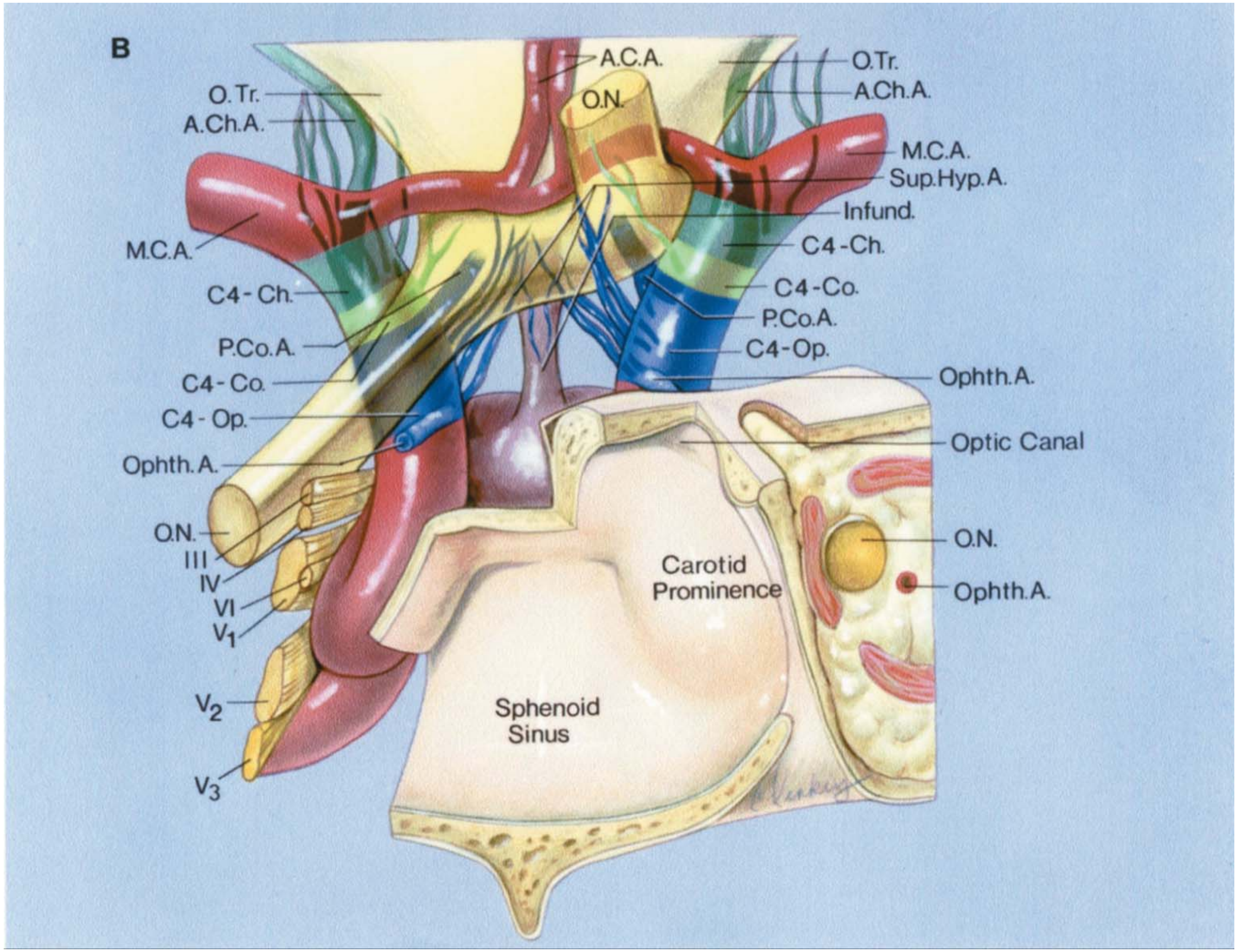
Hemodynamic Therapy of Middle Cerebral Artery Vasospasm Guided by a Multiphase Model of Oxygen Transport

Steven A. Conrad[1,3], Prashant Chittiboina[2], Bharat Guthikonda[2]

[1]Division of Critical Care Medicine, and [2]Department of Neurosurgery, LSU Health Sciences Center – Shreveport

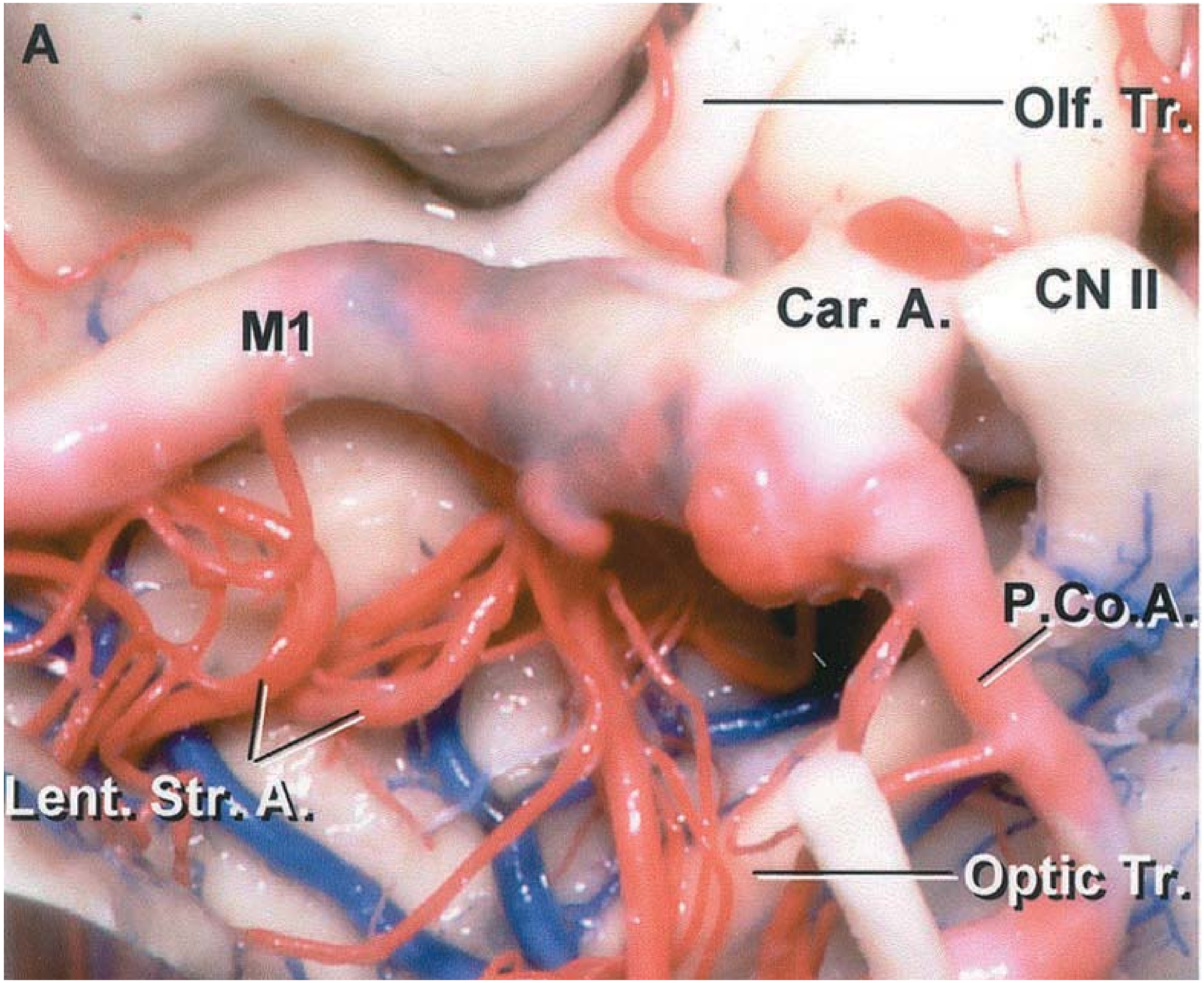
[3]Department of Biomedical Engineering
Louisiana Tech University, Ruston, LA

Middle Cerebral Artery



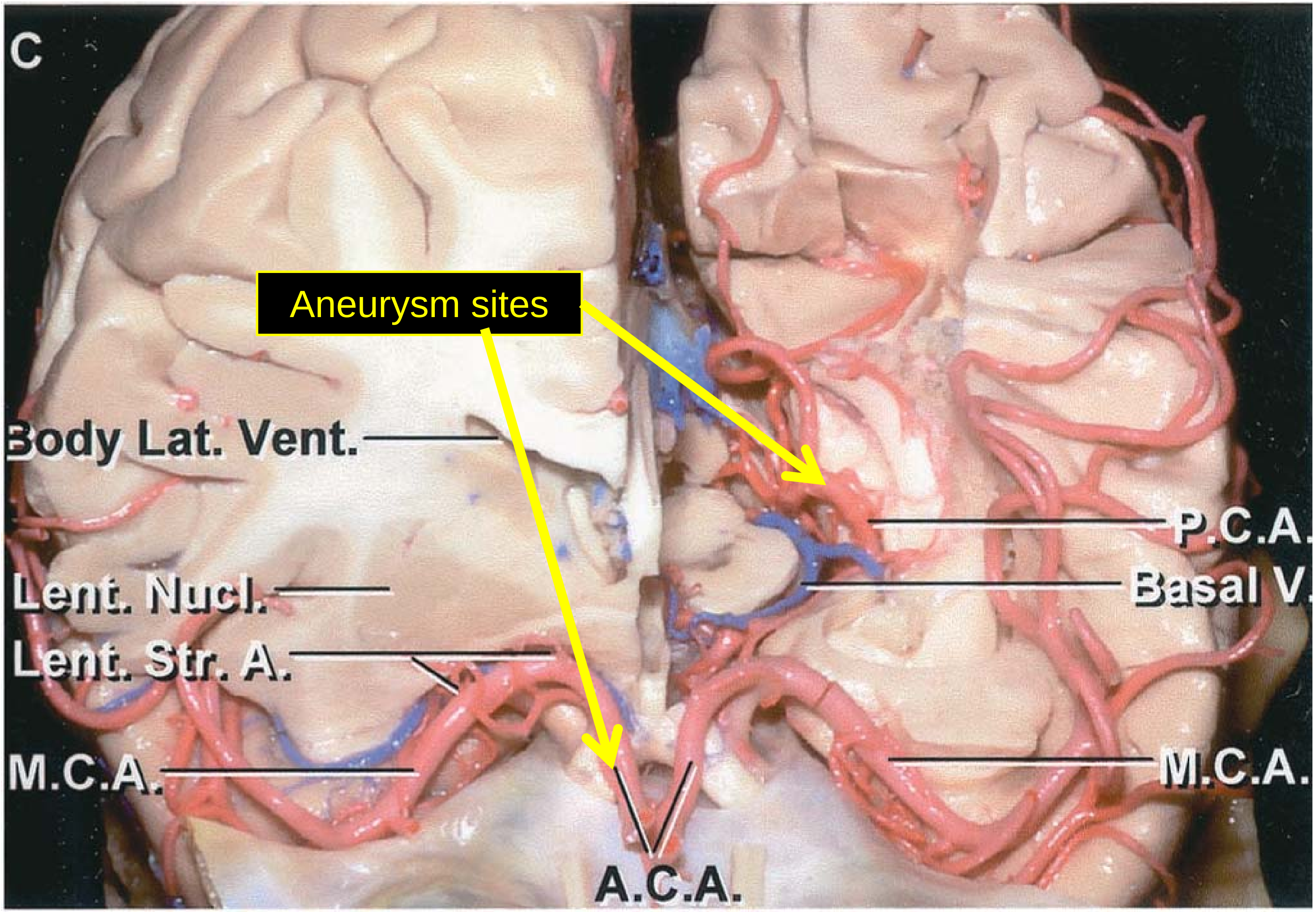
Rhoton AL: *Neurosurgery* 2002; 51[Suppl 1]:53-120

M1 Segment of the MCA



Rhoton AL: *Neurosurgery* 2002; 51[Suppl 1]:53-120

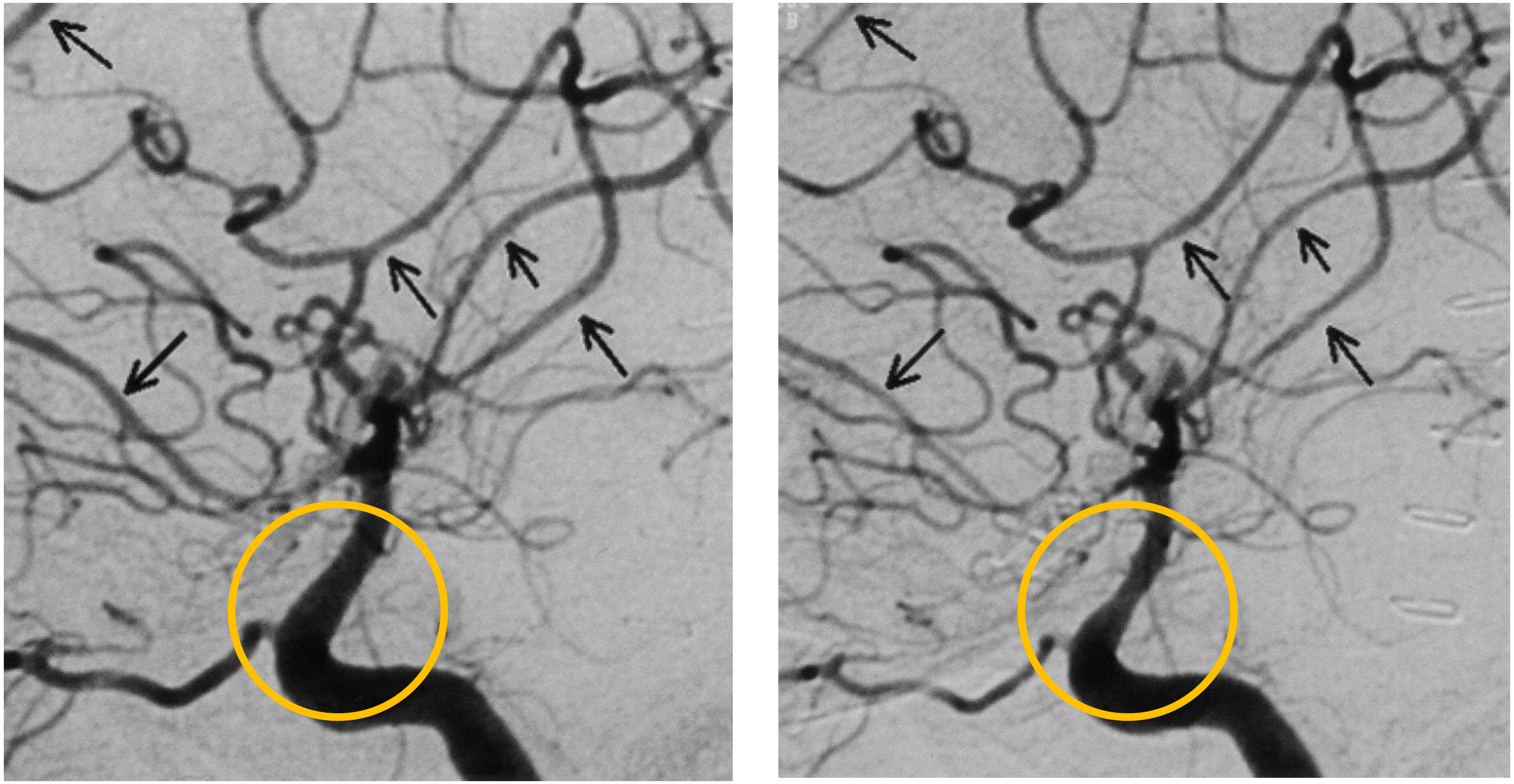
Distribution of the MCA



Aneurysm sites

Rhoton AL: *Neurosurgery* 2002; 51[Suppl 1]:53-120

Cerebral Vasospasm



Mainstay of Therapy

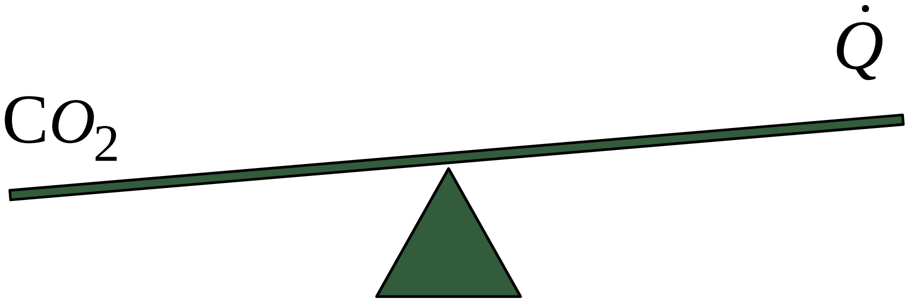
- ‘Triple H’ therapy
  - Hypertension – increase flow through pressure
  - Hemodilution – increase flow through viscosity
  - Hypervolemia – supports goals of above two

- Potential problem
  - Hemodilution decreases oxygen content

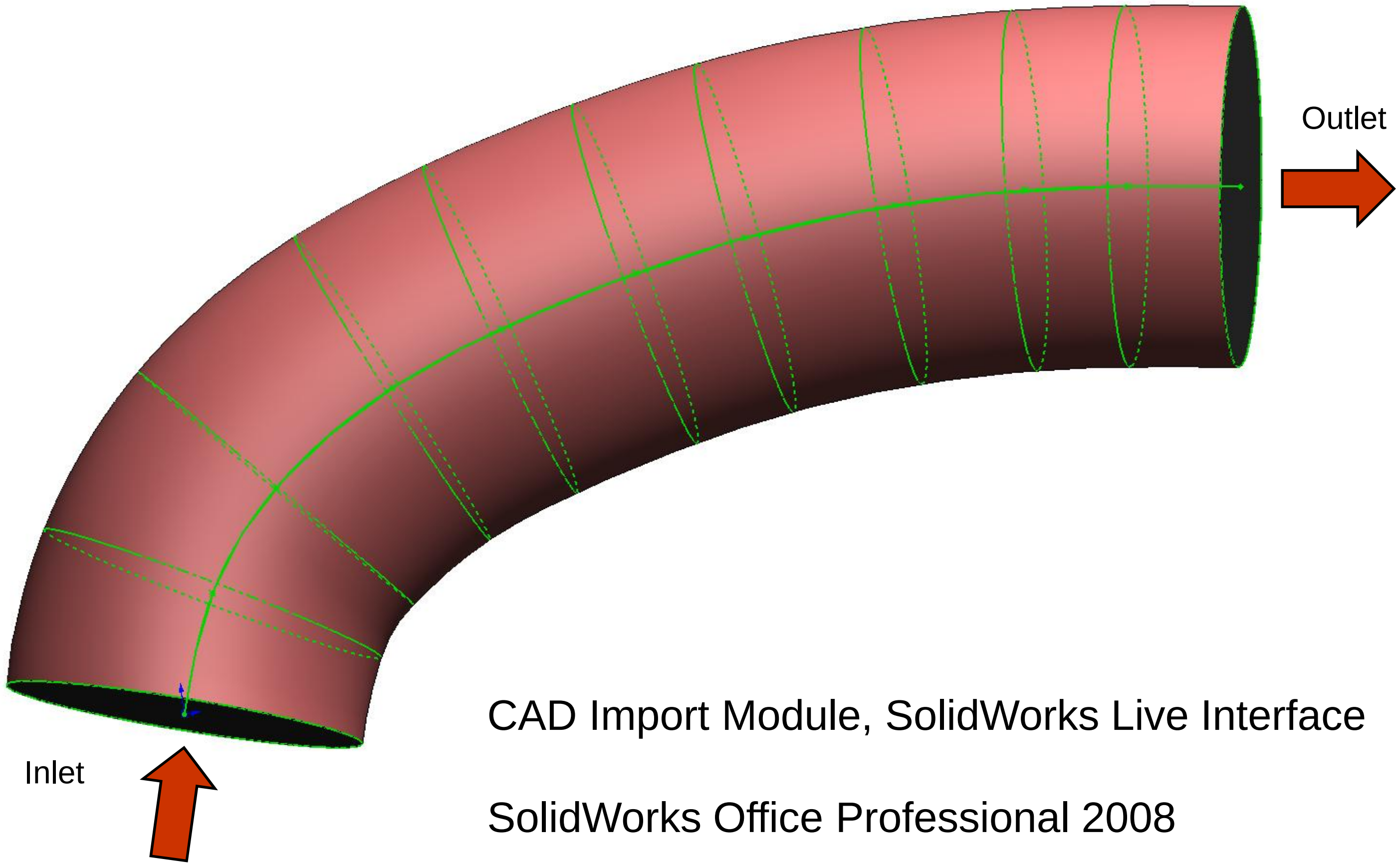
$$\boxed{\mathrm{DO}_2 = \mathrm{CO}_2 \cdot \dot{Q}}$$

Complexity of the Problem

- Blood viscosity is a non-linear, complex function of hematocrit (fraction of blood volume occupied by red cells, normal 0.45, target 0.30)
- Oxygen content is a linear function of hemoglobin concentration (and saturation, here assumed = 1)
- Blood is a non-Newtonian fluid
- The MCA geometry may be additional confounding variable



M1 Segment Geometry

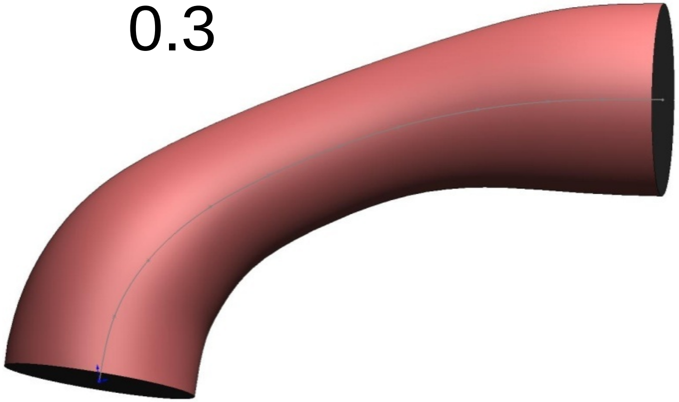


CAD Import Module, SolidWorks Live Interface

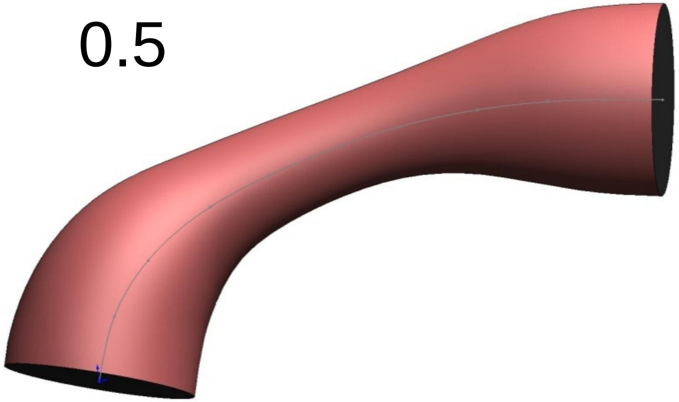
SolidWorks Office Professional 2008

Example Stenotic Geometries

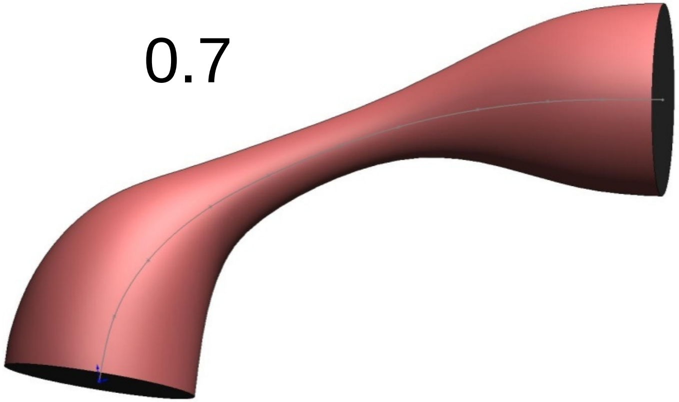
0.3



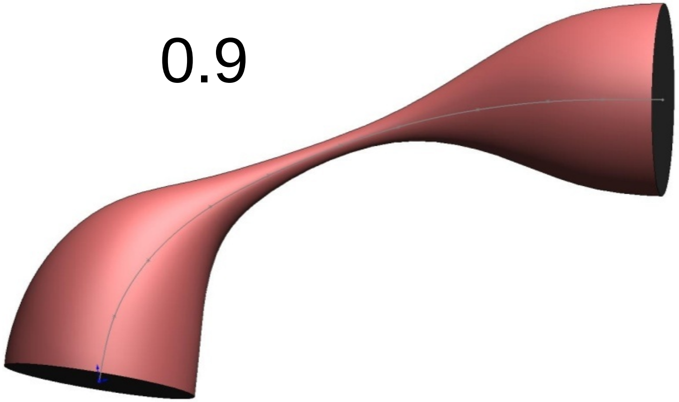
0.5



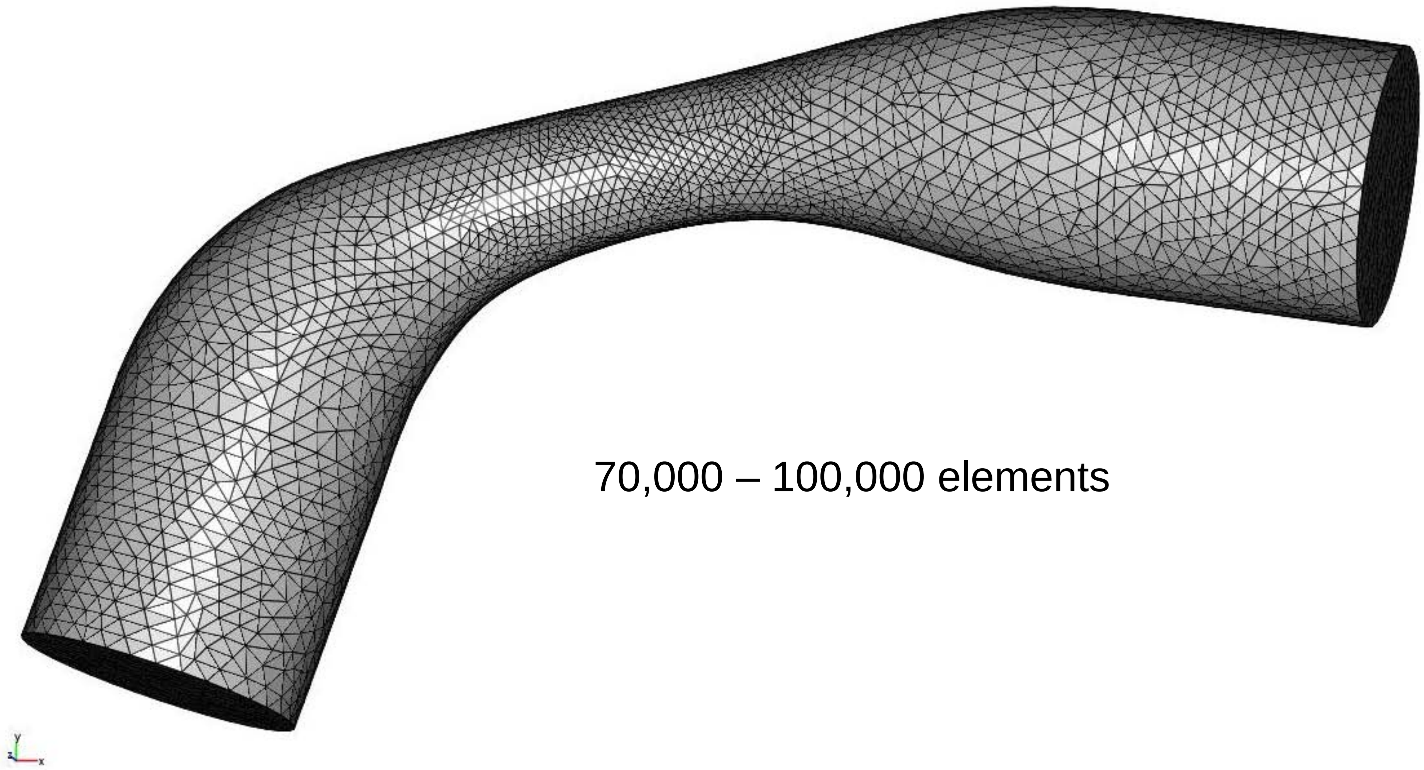
0.7



0.9



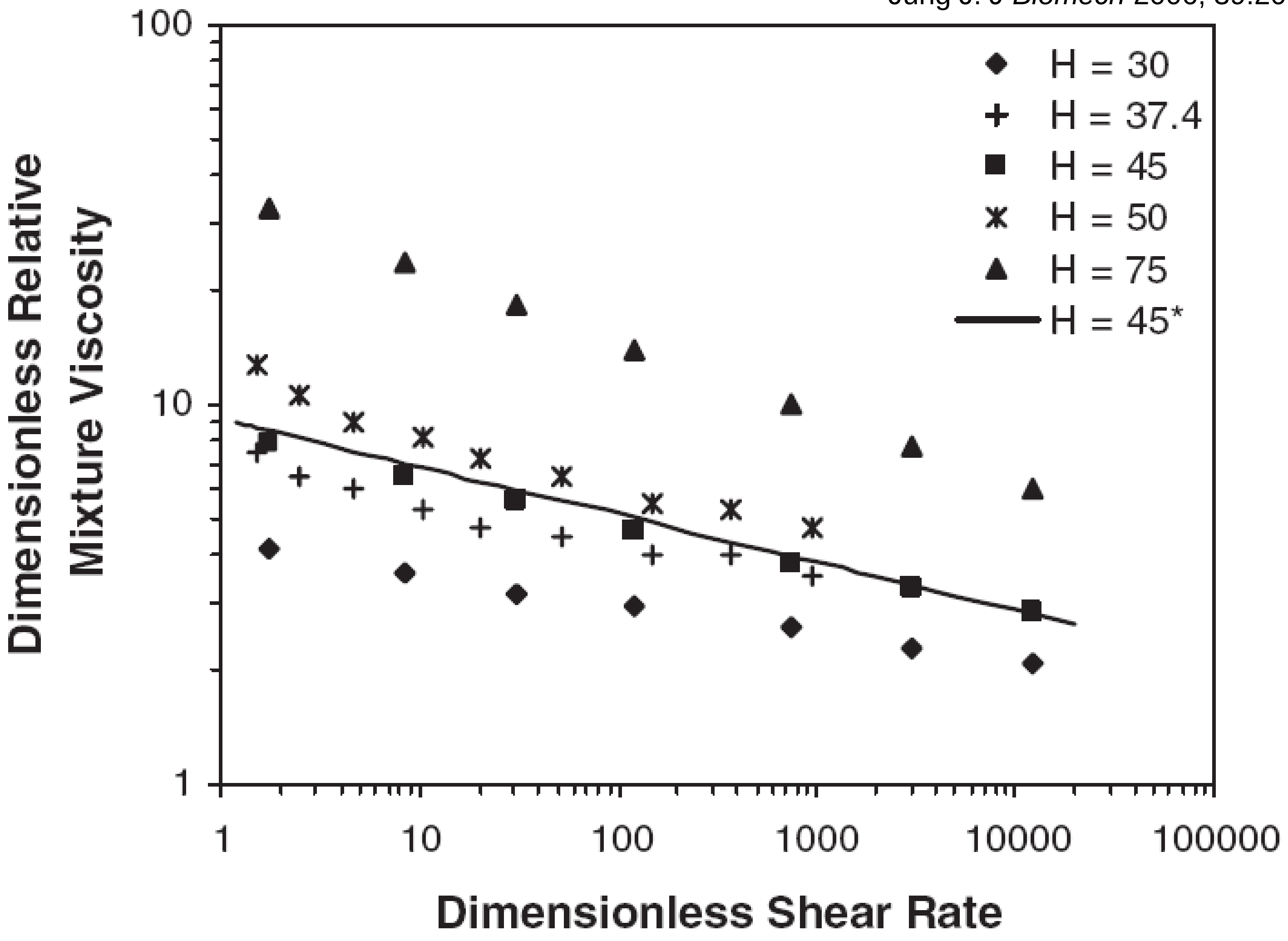
Unstructured Mesh



70,000 – 100,000 elements

Experimental Values of Blood Viscosity

Jung J: *J Biomech* 2006; 39:2064-73



Carreau-Yasuda Viscosity Model

$$\eta = m\left[1+\left(\lambda\dot{\gamma}\right)^2\right]^{\frac{n-1}{2}}$$

$$m = 122.28\varepsilon_{rbc}^3 - 51.213\varepsilon_{rbc}^2 + 16.30\varepsilon_{rbc} + 1$$

$$n = 0.8092\varepsilon_{rbc}^3 - 0.8246\varepsilon_{rbc}^3 - 0.3503\varepsilon_{rbc} + 1$$

Jung J: *J Biomech* 2006; 39:2064-73

Volume-Averaged Blood Density

$$\rho_{blood} = \varepsilon_{rbc}\rho_{rbc} + \varepsilon_{plasma}\rho_{plasma}$$

Single Phase Governing Equations

$$\rho\left(\mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p\mathbf{I} + \nabla\left(\eta\left[\nabla\mathbf{u} + \left(\nabla\mathbf{u}\right)^{T}\right]\right) + \mathbf{F}$$

$$\nabla\mathbf{u} = 0$$

COMSOL Incompressible Navier-Stokes Application Mode (ChemEng)

Two Phase Mixture Model (Eulerian-Eularian)

$$\rho\left(\mathbf{u}\cdot\nabla\mathbf{u}\right)=\nabla p-\nabla\left(\rho\theta_d\rho_d/\rho\left(1-\theta_d\rho_d/\rho\right)\mathbf{u}_{slip}\mathbf{u}_{slip}\right)$$

$$+\nabla\left(\eta\left[\nabla\mathbf{u}+\left(\nabla\mathbf{u}\right)^T\right]\right)+\rho\mathbf{g}+\mathbf{F}$$

$$\left(\rho_c-\rho_d\right)\left[\nabla\left(\theta_d\left(1-\theta_d\rho_d/\rho\right)\mathbf{u}_{slip}\right)+m_{dc}\rho_d\right]+\rho_c\left(\nabla\mathbf{u}\right)=0$$

$$\nabla\left[\theta_d\mathbf{u}+\theta_d\left(1-\theta_d\rho_d/\rho\right)\mathbf{u}_{slip}\right]=m_{dc}/\rho_d$$

COMSOL Multiphase Mixture Model Application Mode (ChemEng)
Liquid dispersed and continuous phases

Two Phase Slip Model (Schiller-Naumann)

$$\frac{3}{4} C_d \frac{\rho_c \left|\mathbf{u}_{slip}\right| \mathbf{u}_{slip}}{d_d} = -\frac{\rho - \rho_d}{\rho \nabla p}$$

$$C_d = \left| \begin{array}{ll} \dfrac{24}{\mathrm{Re}_p}\left[1+0.15\,\mathrm{Re}_p^{0.687}\right] & \mathrm{Re}_p < 1000 \\ 0.44 & \mathrm{Re}_p \geq 1000 \end{array} \right.$$

$$\mathrm{Re}_p = \frac{d_d \rho_c \left|\mathbf{u}_{slip}\right|}{\eta}$$

Mixture viscosity model same as for single phase flow
(Carreau-Yasuda viscosity model based on hematocrit)

Calculation of Oxygen Delivery

$$DO_2 = \int \mathbf{u} \cdot CO_2$$

$$CO_2 = \mathrm{hct} \cdot \mathrm{MCHC} \cdot 1.34\ \mathrm{mL/g}$$

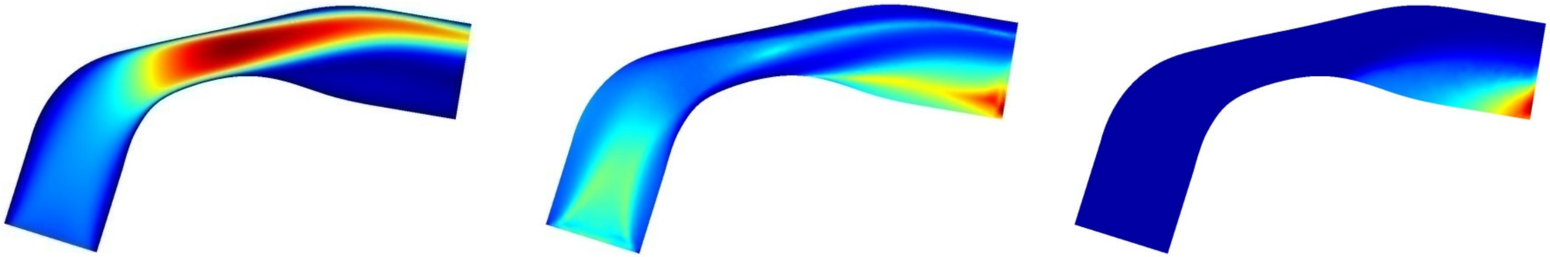
$$\mathrm{MCHC} = 33\ \mathrm{g/dL}$$

hct = hematocrit (single phase) or *phid* (two phase)

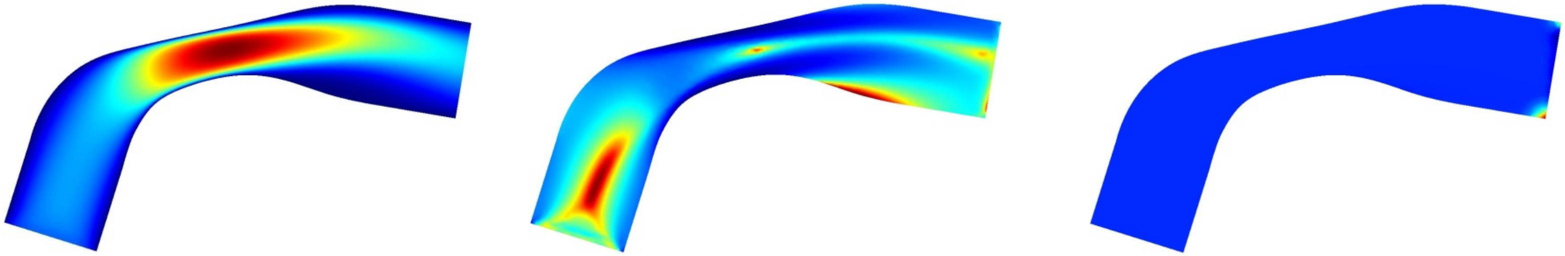
MCHC = mean corpuscular hemoglobin concentration

Sample Visualizations, 0.5 Stenosis

Mixture Velocity | Dynamic Viscosity | Mixture Density

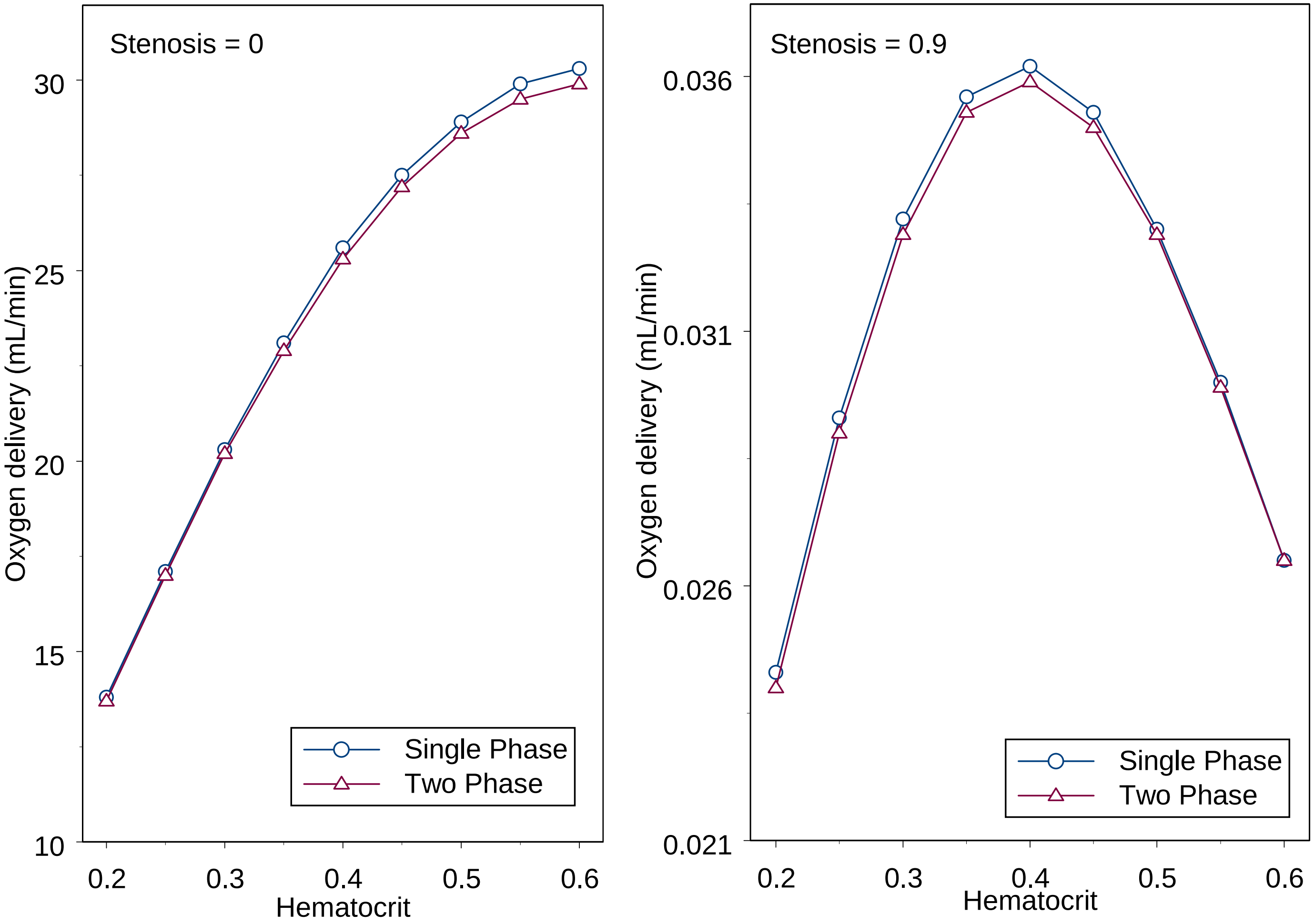


hct = 0.2

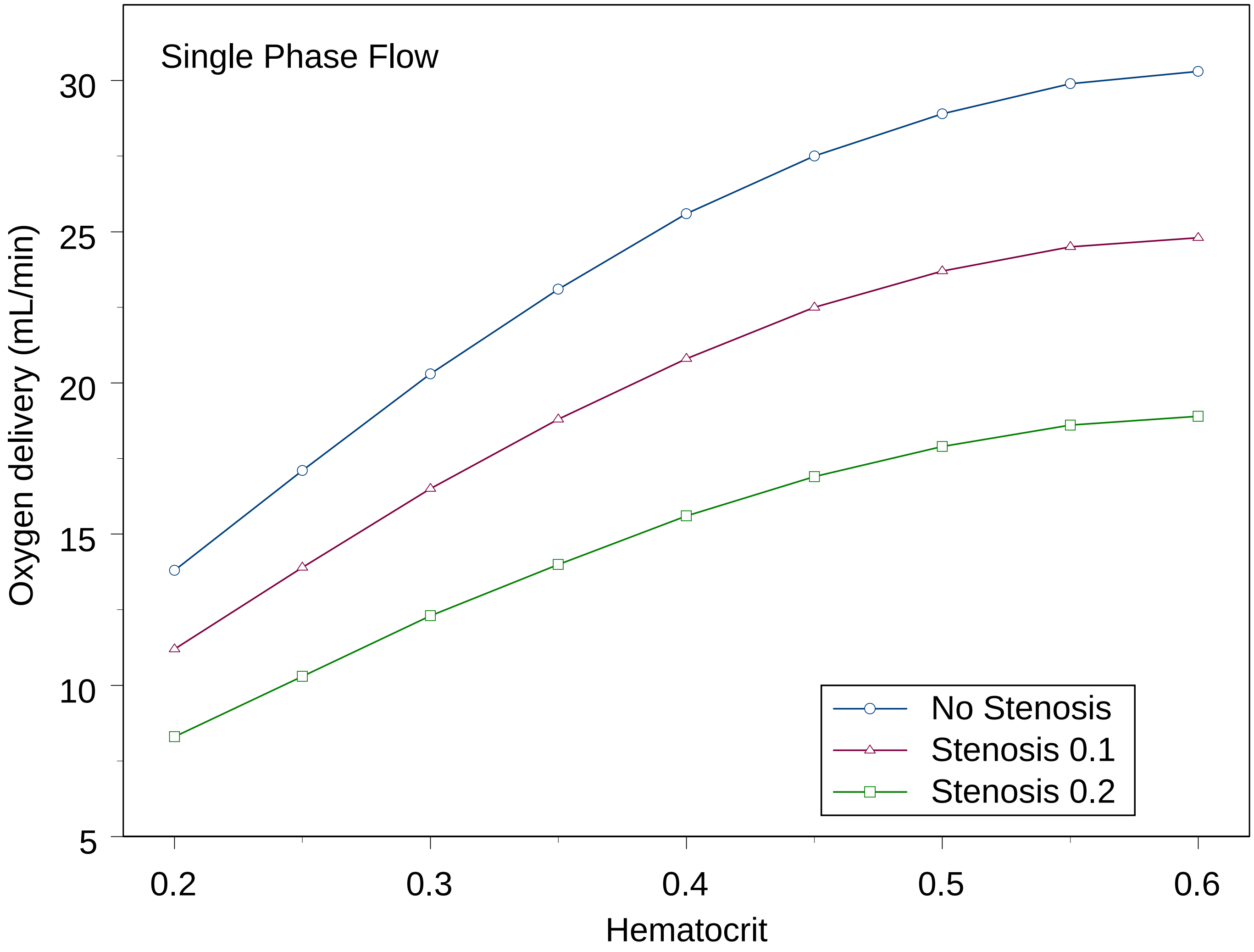


hct = 0.6

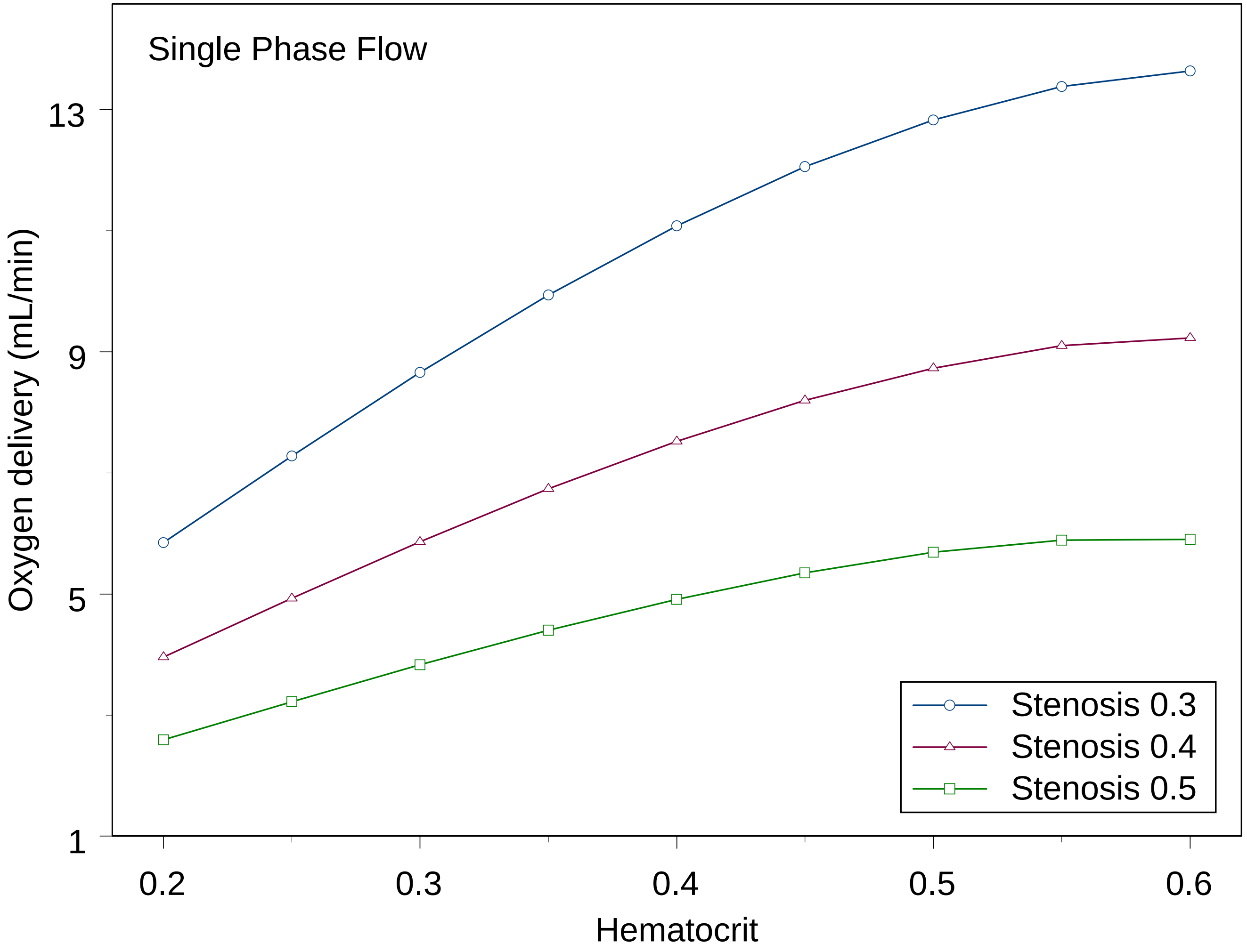
Single Phase vs Two Phase Results



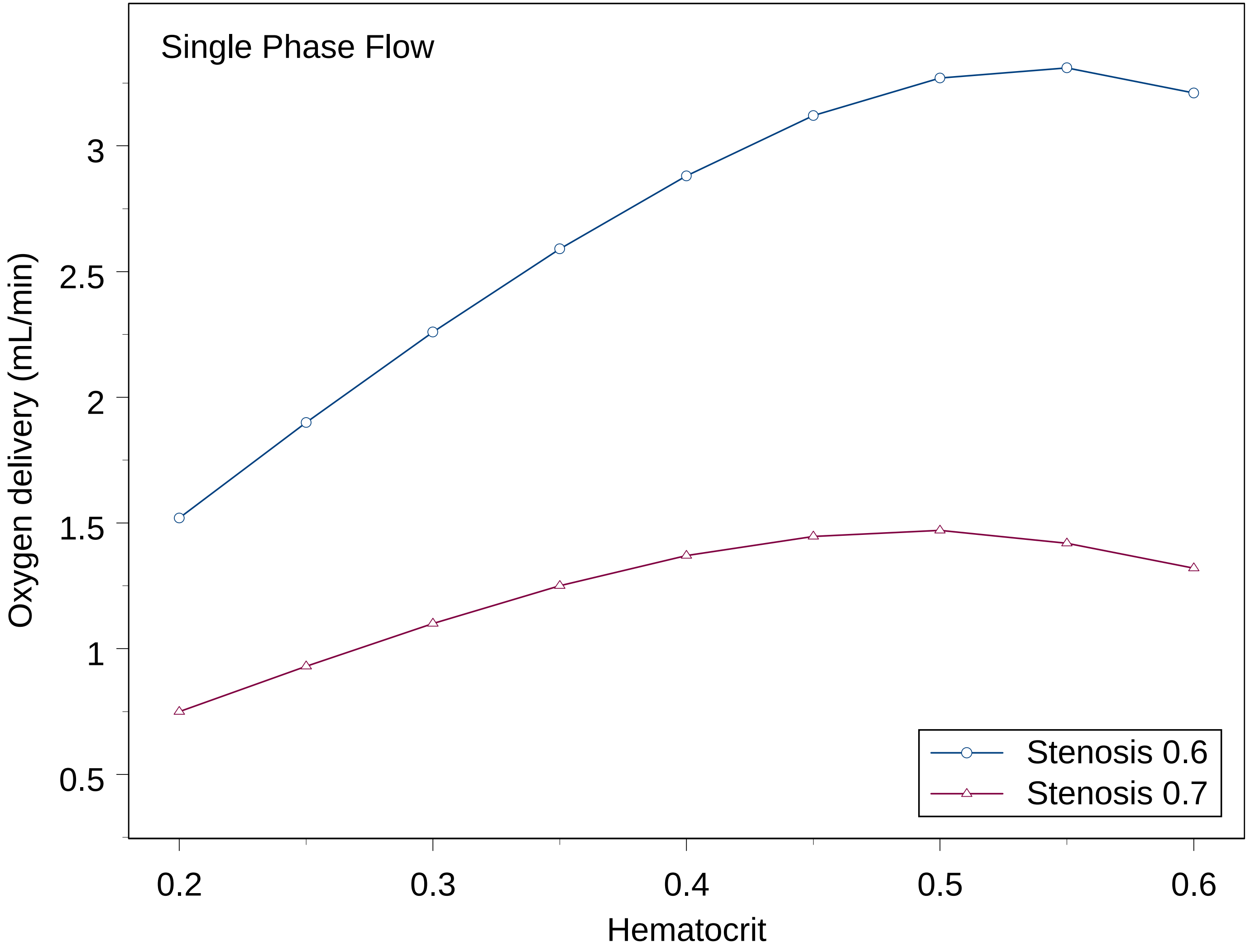
Effect of Hematocrit with Mild Stenosis



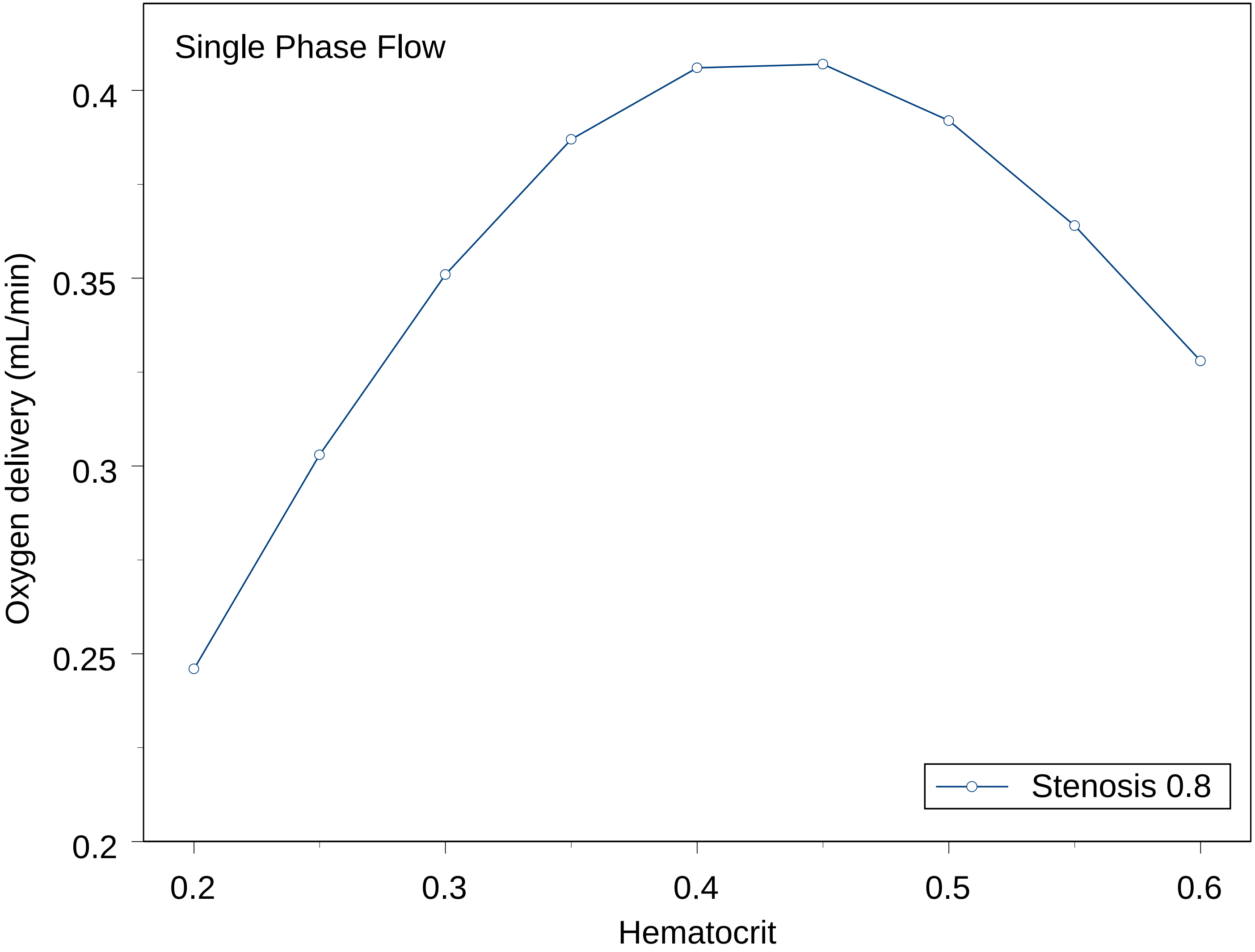
Moderate to Severe Stenoses



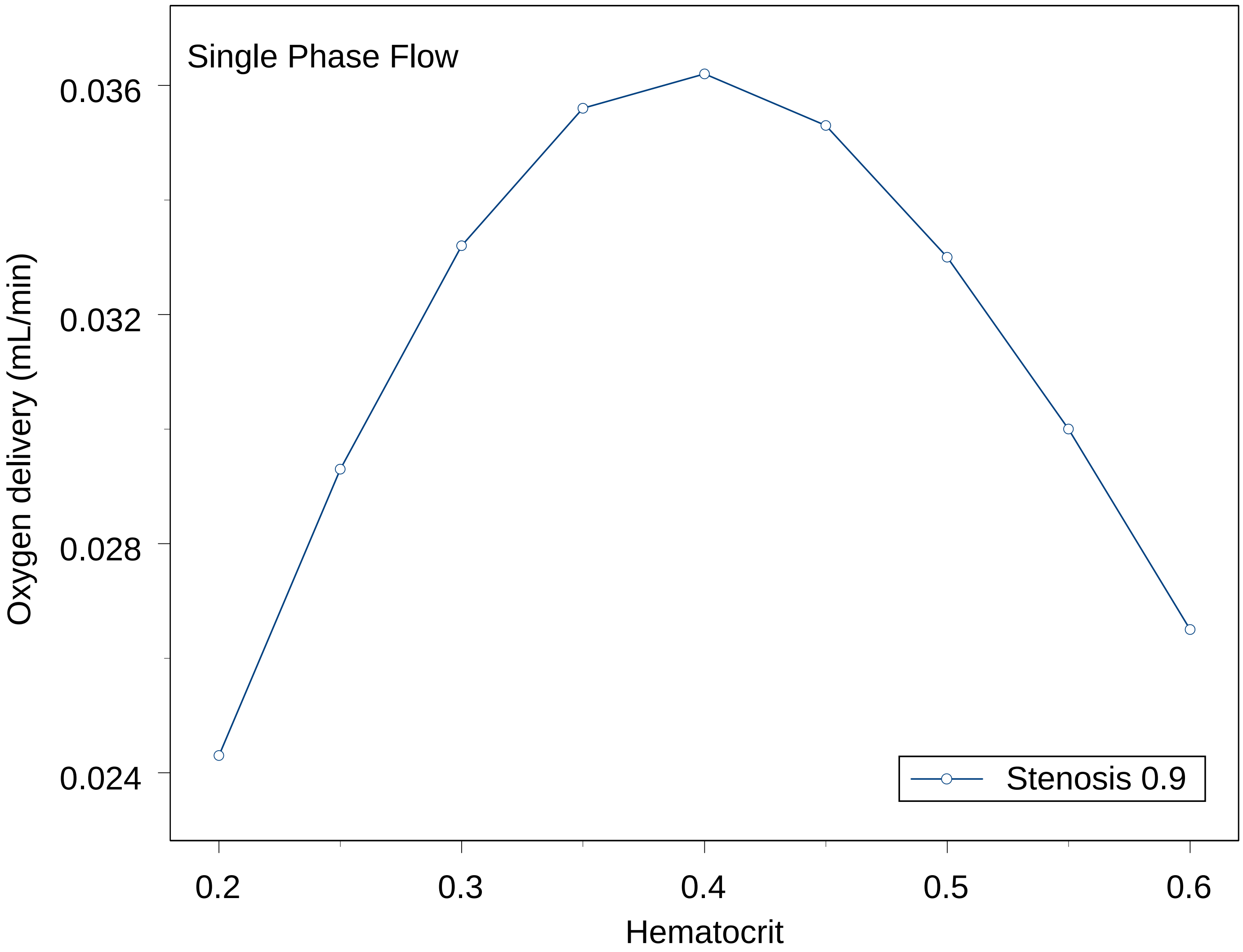
Very Severe Stenoses



Stenosis 0.8


Single Phase Flow
Oxygen delivery (mL/min)
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6
Hematocrit
Stenosis 0.8

Stenosis 0.9


Single Phase Flow
Oxygen delivery (mL/min)
0.036
0.032
0.028
0.024
0.2
0.3
0.4
0.5
0.6
Hematocrit
Stenosis 0.9

Conclusions

- In this model, single phase and two phase approaches yielded comparable results
- In mild to critical stenoses, where therapy may impact outcome, hemodilution may worsen oxygen delivery and contribute to ischemia
- In very severe stenoses (0.9 and above), hemodilution may improve oxygen delivery, but blood flow is so low (3 orders of magnitude lower) that it would not likely have any clinical impact
- These results assume no change in downstream impedance to blood flow, but are likely still clinically generalizable to the problem at hand