13th Annual Angioplassty Summit
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Fluid dynamics and rheology in bifurcation lesions

Gérard Finet MD PhD

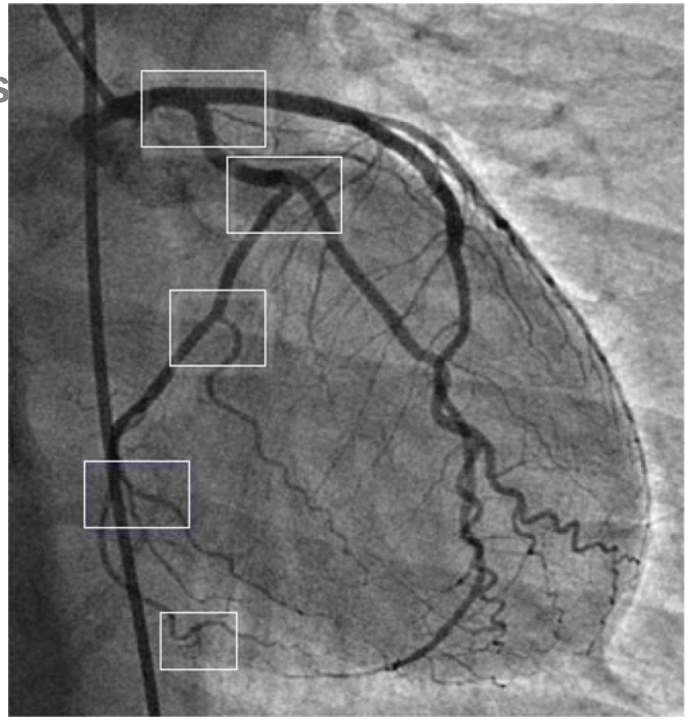
Department of Hemodynamics and Interventional Cardiology
Cardiovascular Hospital - Hospices Civils de Lyon
INSERM Unit 886
Claude Bernard University Lyon 1
Lyon - France

gerard.finet@univ-lyon1.fr

Inserm
Institut national de la santé et de la recherche médicale

The geometry of Nature

Coronary artery bifurcations



Finet G. et al. EuroIntervention 2007

Vascular branching :

- ***distributive function***
- ***hemodynamic function***

Multi-scale analysis

Quantification of coronary artery bifurcations according to mother-vessel diameter
Values obtained on quantitative coronary bifurcation angiography

	For all
# of bifurcation	**173**
D_m (mean7DS)	**3.339 ± 0.948**
$D_{d\text{-larger}}$ (mean7DS)	**2.708 ± 0.774**
$D_{d\text{-smaller}}$ (mean7DS)	**2.236 ± 0.689**
Reduction in mm (mean7DS)	**0.631 ± 0.365**
% reduction	**18.9**
Mean ratio	**0.678**

Variables are presented as mean ± SD
D in mm
D_m: Diameter of the mother vessel
$D_{d\text{-larger}}$: Diameter of the larger daughter vessel
$D_{d\text{-smaller}}$: Diameter of the smaller daughter vessel
Reduction: difference between the diameter of mother vessel and the diameter of the larger daughter vessel
Ratio: $D_m / (D_{d\text{-larger}} + D_{d\text{-smaller}})$

$$R = \frac{D_{mother}}{D_{daughter\ 1} + D_{daughter\ 2}}$$

Finet G. et al. EuroIntervention 2007;3:1-9.

For an incompressible fluid,

The continuity formula is: **Qo1+Qo2=Qi**

Q=SV

If V=constant then :

$$\pi\frac{D_i^2}{4} = \pi\frac{D_{o1}^2}{4} + \pi\frac{D_{o2}^2}{4}$$

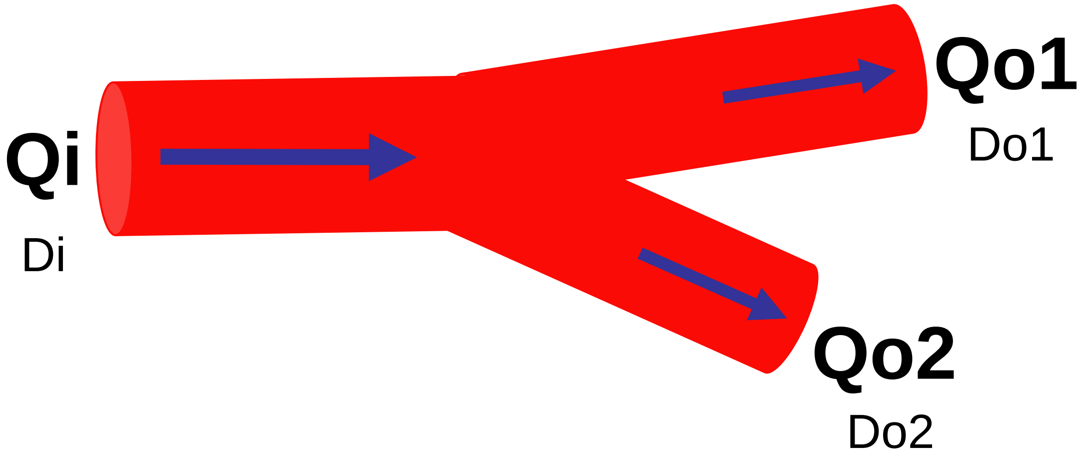
$$D_i = \sqrt{D_{o1}^2 + D_{o2}^2}$$

$$D_{o1}^2 = D_{o2}^2 = D_o$$

$$D_i = \sqrt{2D_o^2} = \sqrt{2}D_0$$

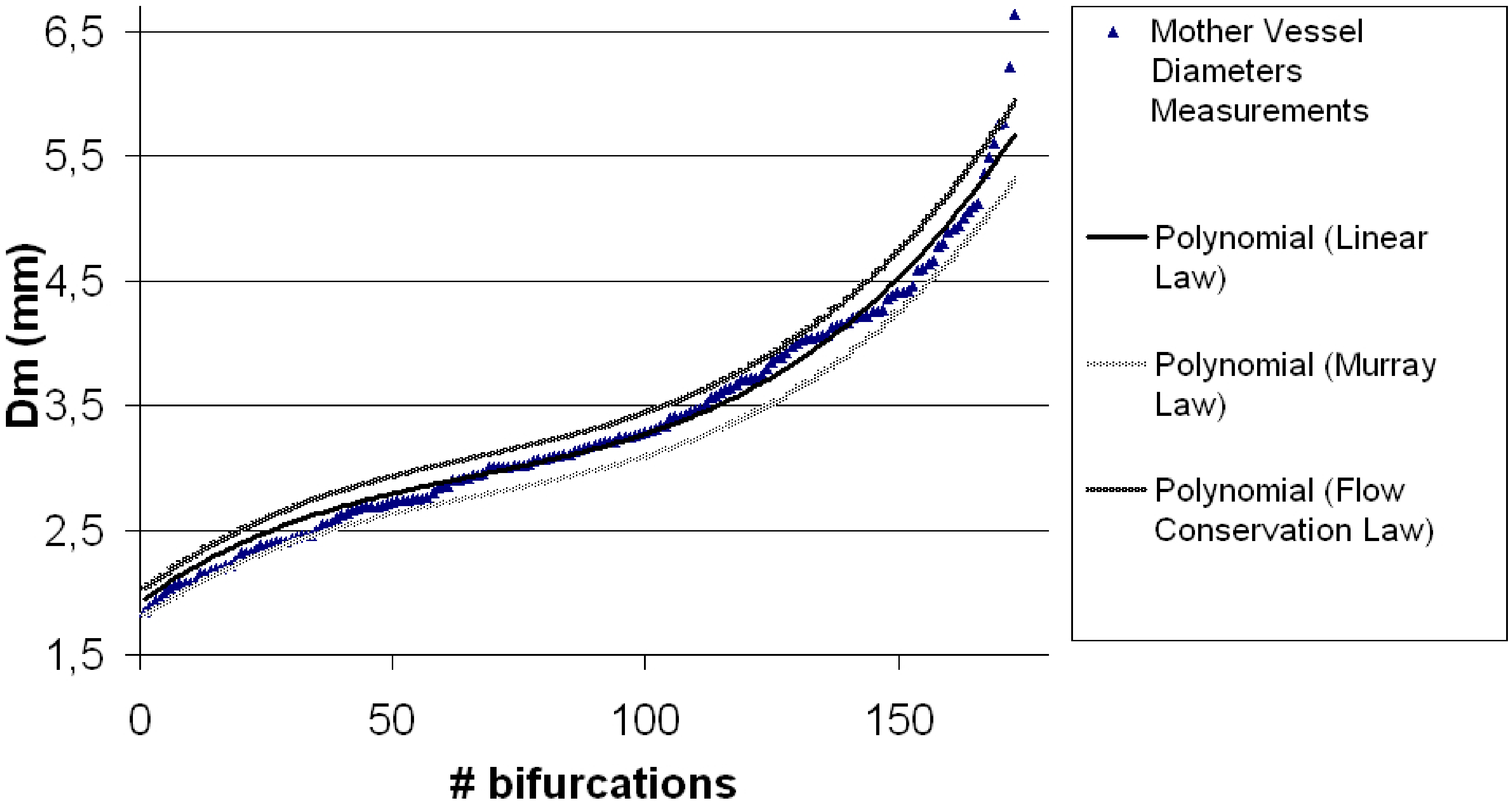
$$D_i = \sqrt{2}D_0 = \frac{\sqrt{2}}{2}(D_{o1} + D_{o2})$$

$$\frac{\sqrt{2}}{2} = 0.707 \quad \# \mathbf{0.678}$$



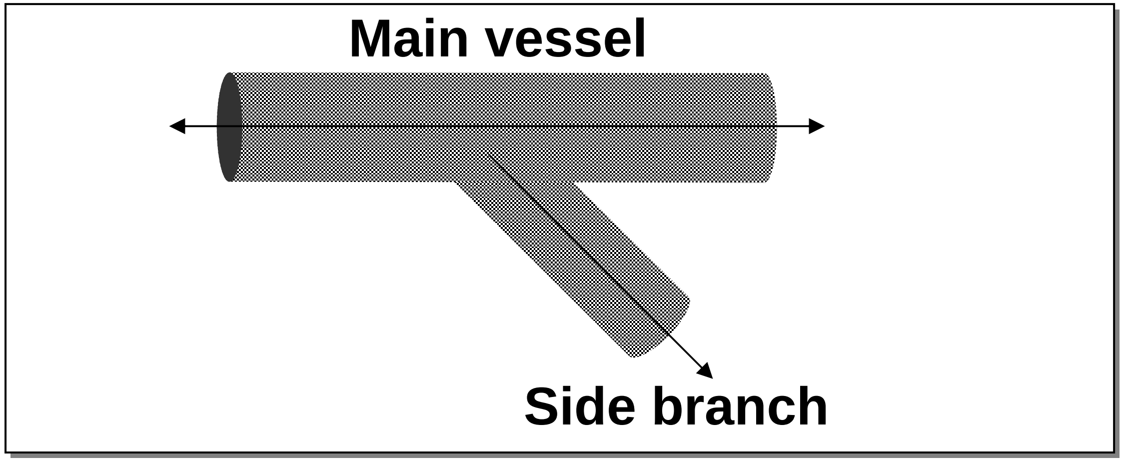
Distribution of the 173 sets of mother-vessel diameters, as measured and calculated according to the 3 laws

The linear law (R=0.678) is found to be the most exact: the flow conservation law overestimates and Murray's law underestimates the calculated mother-vessel diameter

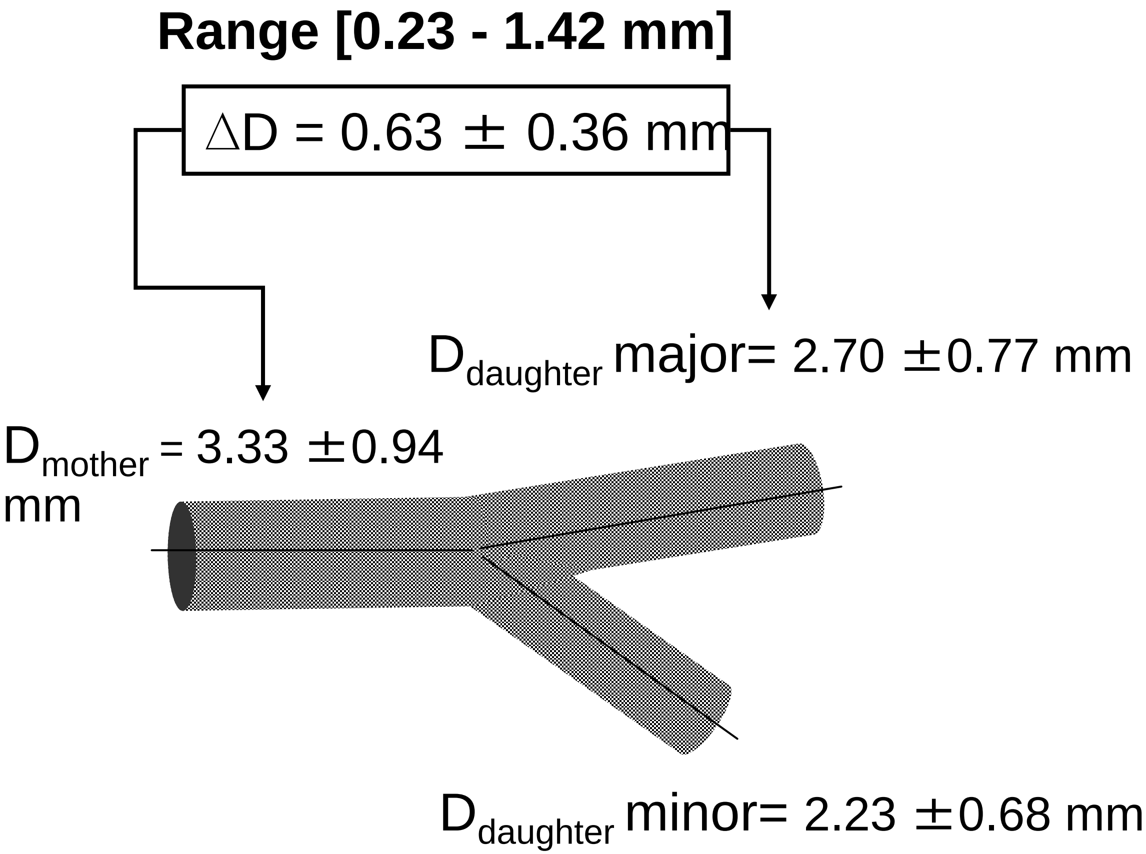


Tanaka et al. Am J Physiol Heart Circ Physiol 1999; 276:2262-2267
Murray CD. Proc Natl AcadSci USA 1926:12:207-214
Suwa N. Principle of pathomorphology. Tokyo, Iwanami 1981

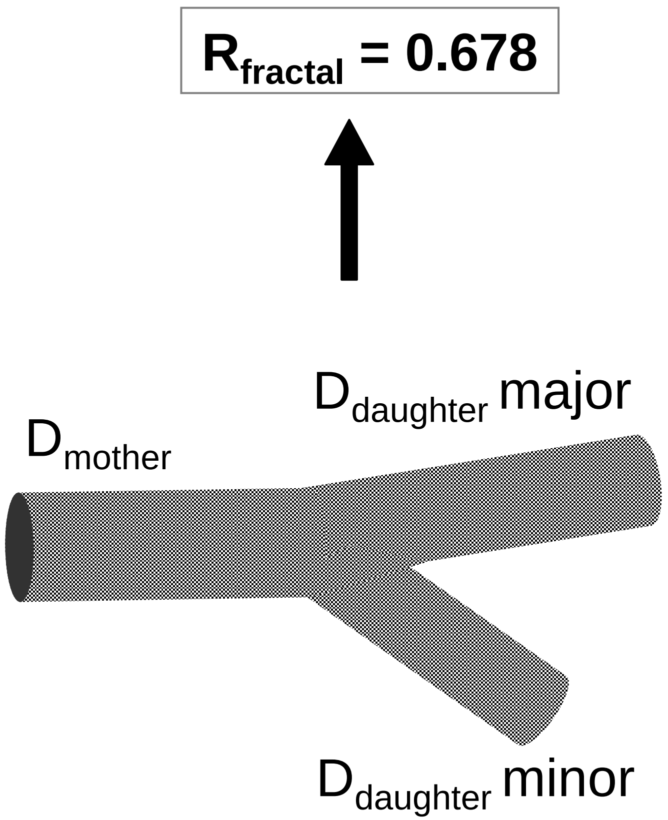
Finet G. et al. EuroIntervention 2007;3:1-9.



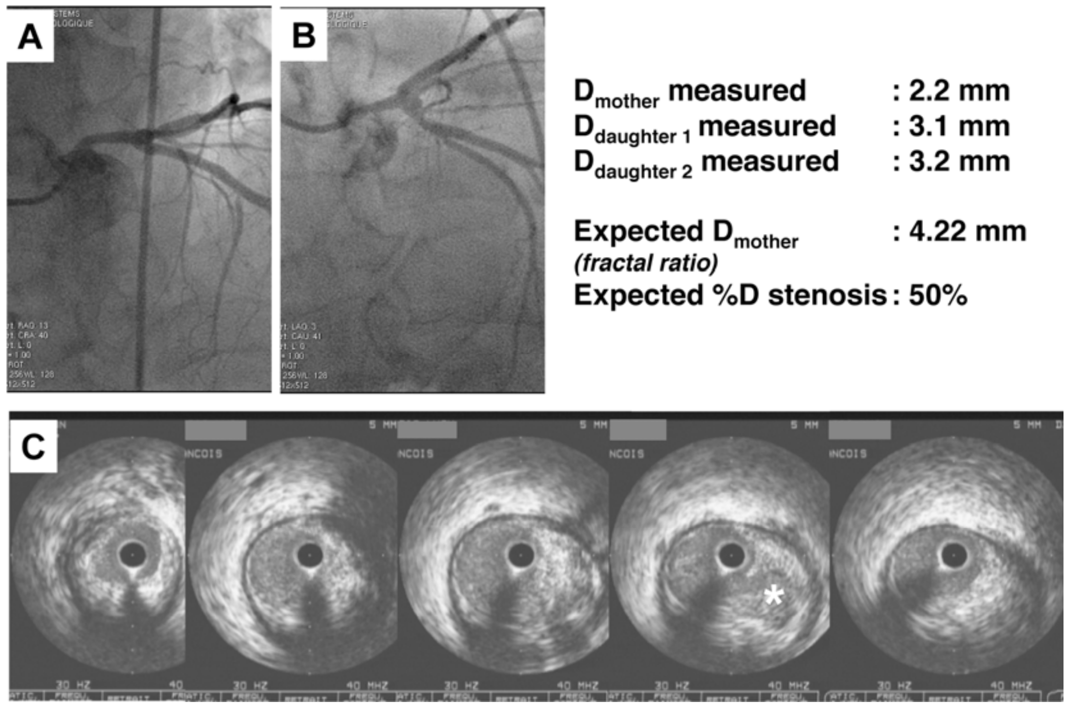
Main vessel
Side branch



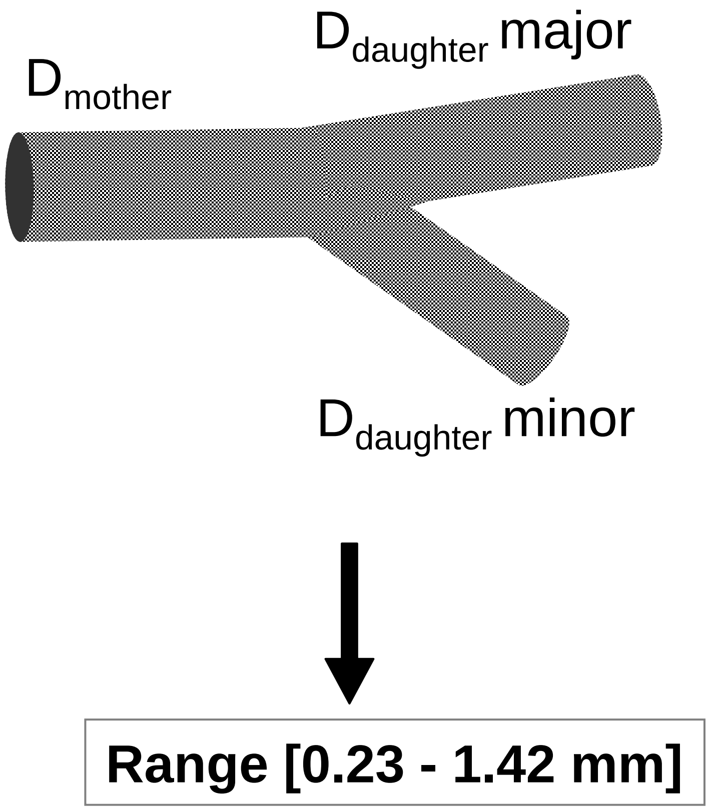
Range [0.23 - 1.42 mm]
ΔD = 0.63 ± 0.36 mm
$D_{daughter}$ major= 2.70 ±0.77 mm
D_{mother} = 3.33 ±0.94 mm
$D_{daughter}$ minor= 2.23 ±0.68 mm

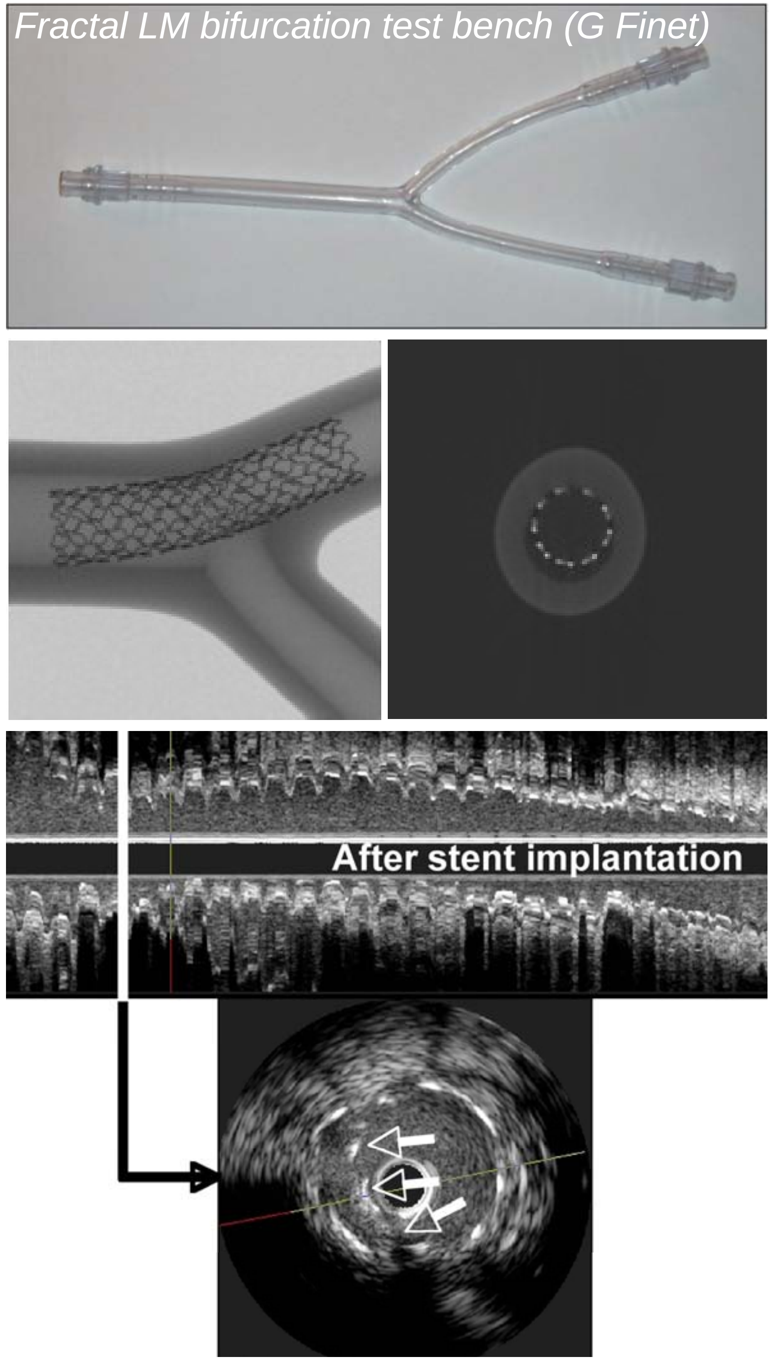


R_fractal = 0.678
D_mother
D_daughter major
D_daughter minor



A
B
C
D_mother measured : 2.2 mm
D_daughter 1 measured : 3.1 mm
D_daughter 2 measured : 3.2 mm
Expected D_mother : 4.22 mm
(fractal ratio)
Expected %D stenosis : 50%
*

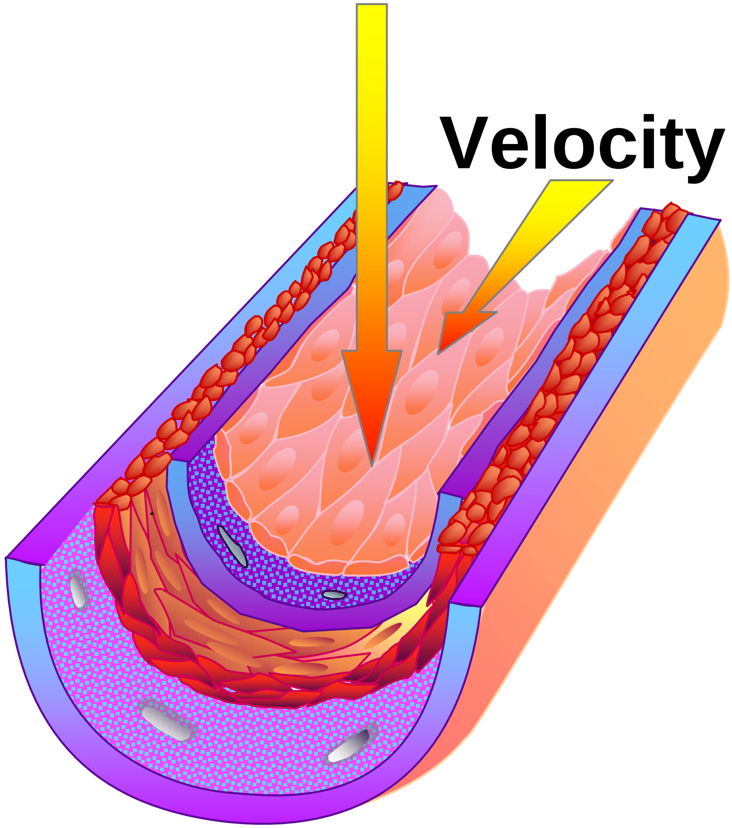

D$_{mother}$
D$_{daughter}$ major
D$_{daughter}$ minor
Range [0.23 - 1.42 mm]


Fractal LM bifurcation test bench (G Finet)
After stent implantation

Mechanical forces in the vascular wall

Pressure → **Circumferential stress** (kPa)

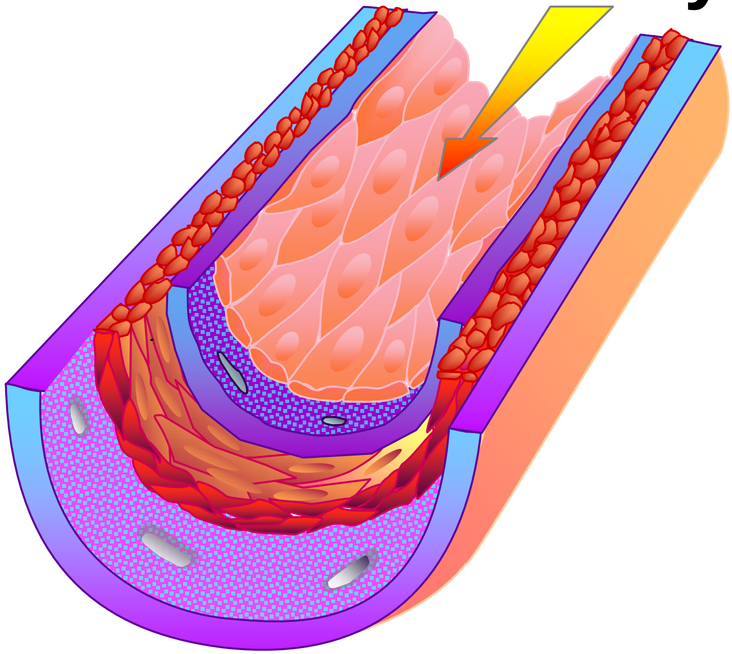
Velocity → **Wall shear stress** (N/m^2)

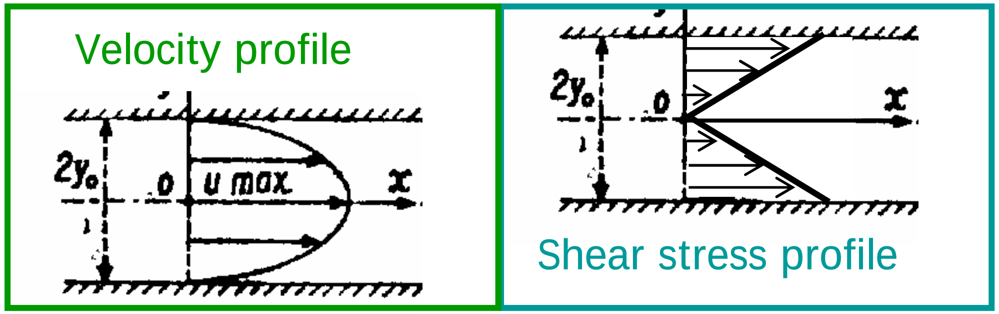


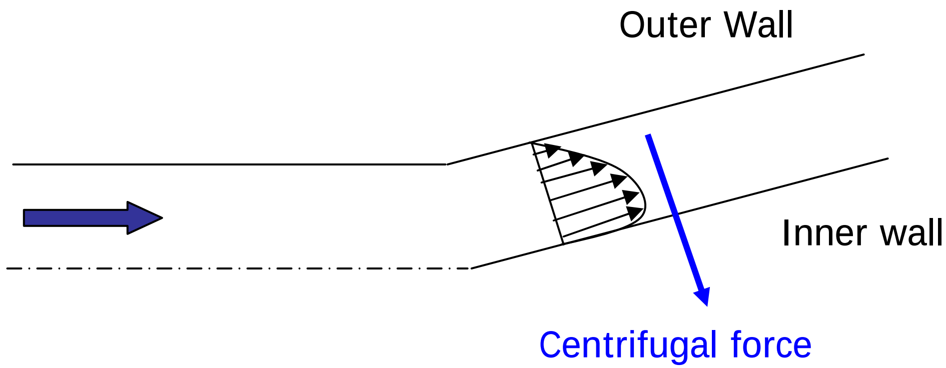
Tanaka et al. Am J Physiol Heart Circ Physiol 276:2262-2267, 1999.

Wall shear stress

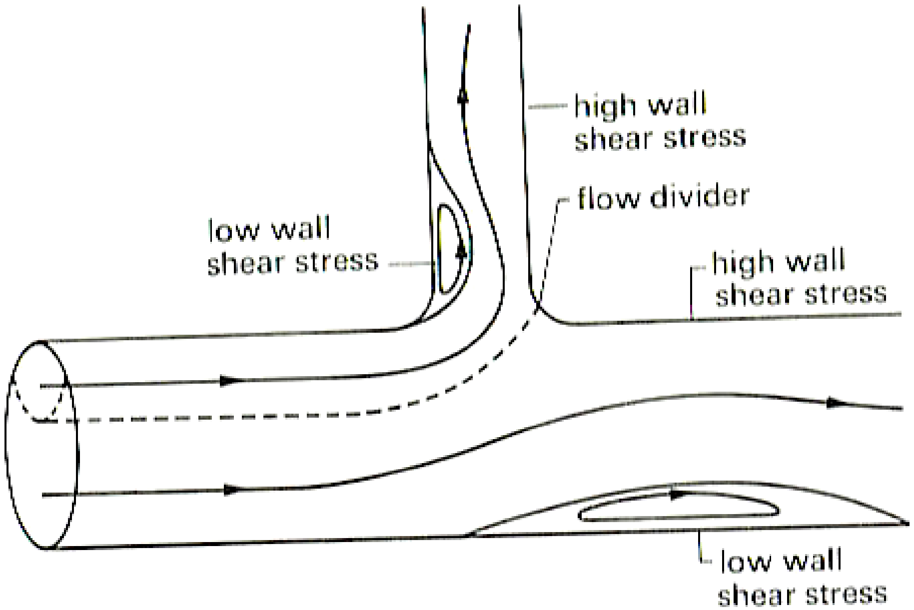
Velocity → **Wall shear stress (N/m^2)**



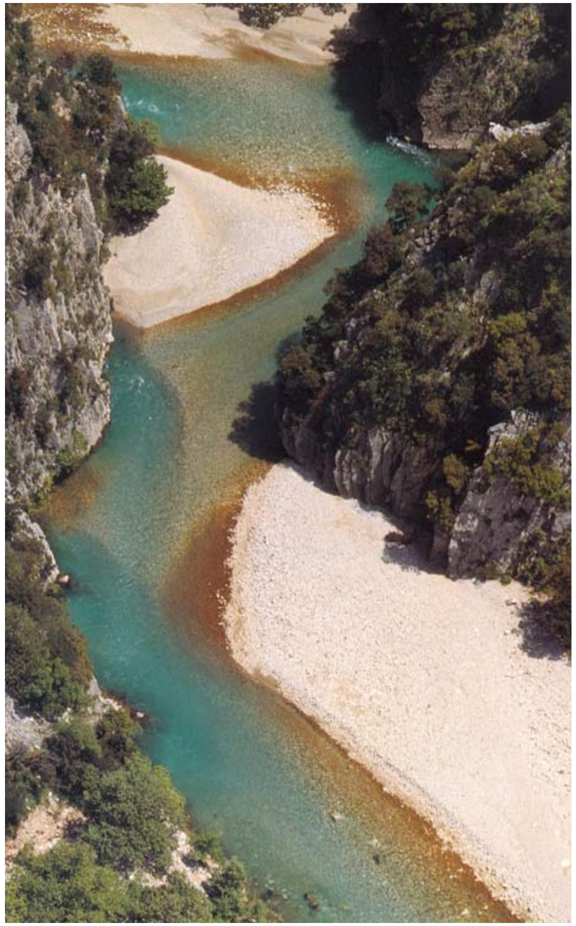




Wall shear stress distribution in bifurcation



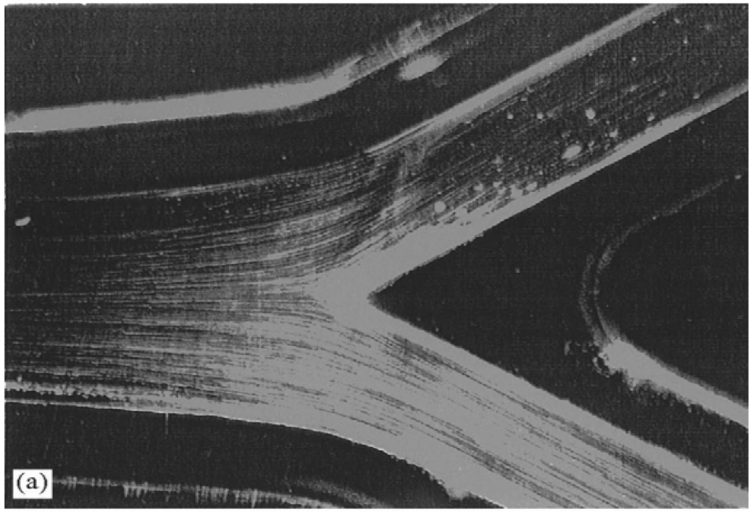
Taken from Caro et al, 1978

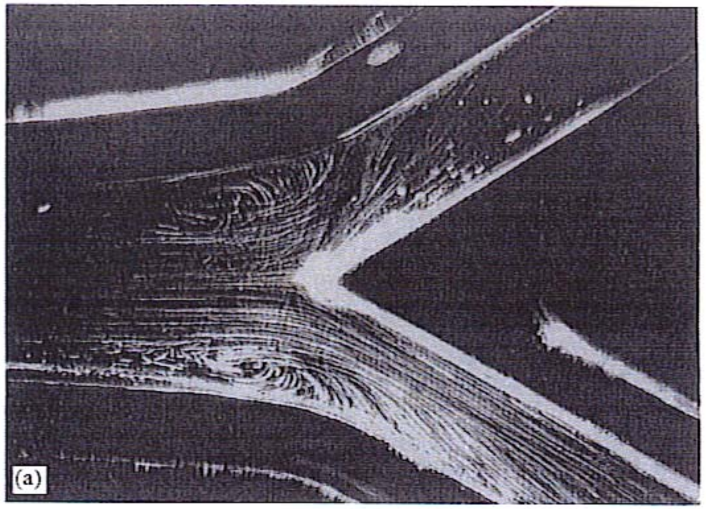


Taken from G. Giannakoulas (EBC 2008)

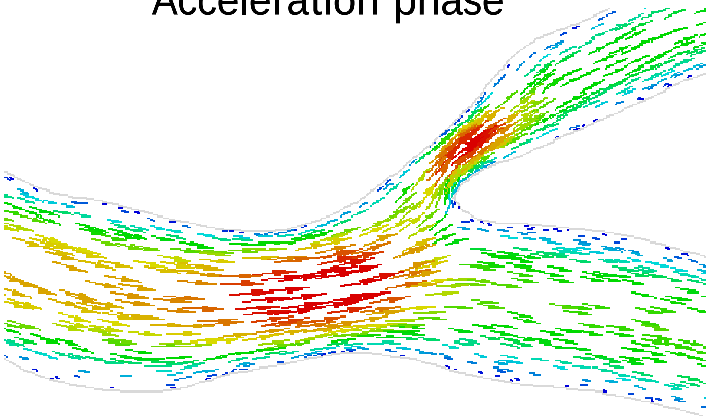
Flow behaviour in an normal bifurcation

Fabregues et al, 1998

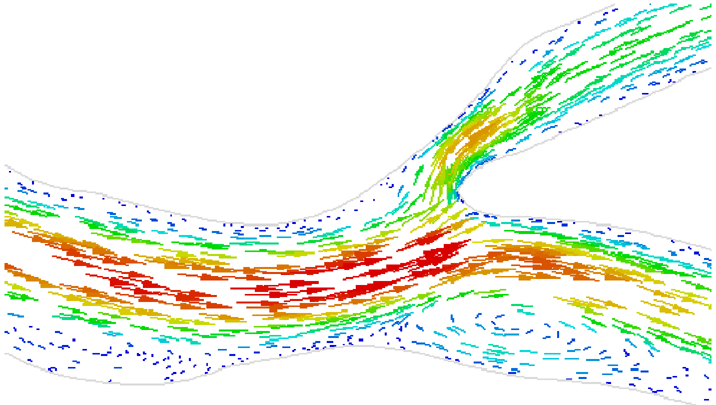




Acceleration phase



Deceleration phase

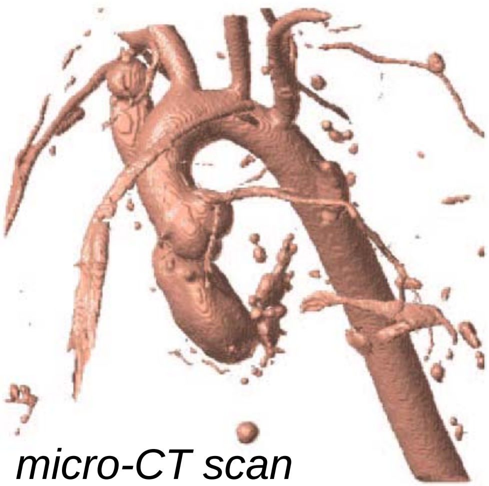


- **High WSS at flow divider**

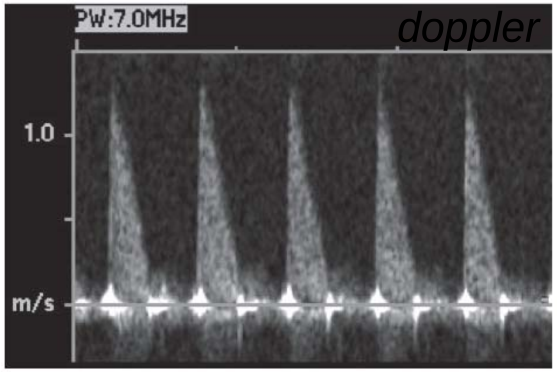
- **Low WSS at lateral walls**

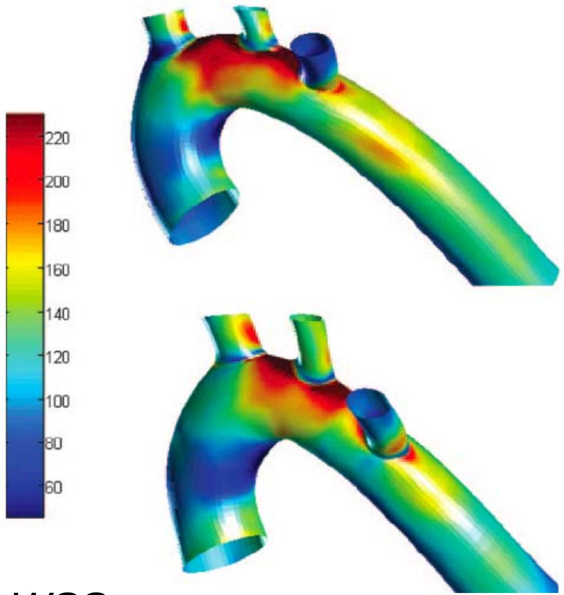
G. Giannakoulas, G. Giannoglou, 2007

Hemodynamic Shear Stresses in Mouse Aortas
Implications for Atherogenesis



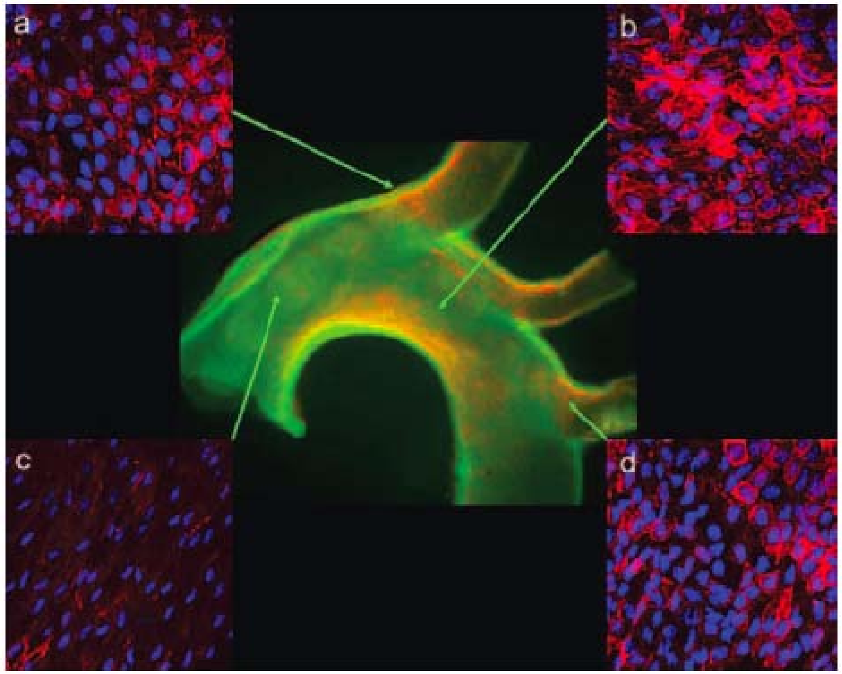
micro-CT scan





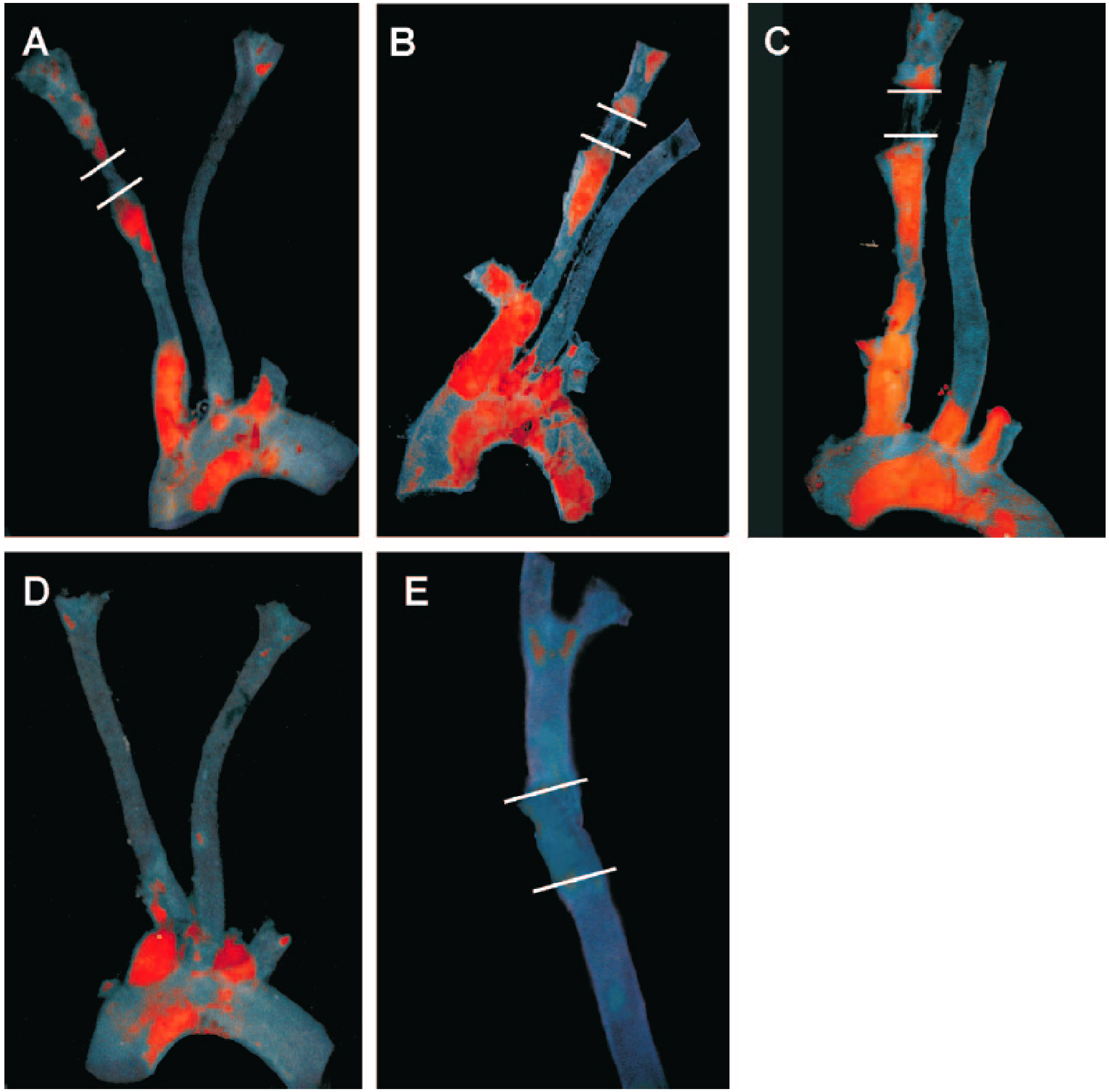
WSS maps

The differential localization
of VCAM-1 protein expression



Suo et al. Atheroscler Thromb Vasc Biol 2007;27:346.

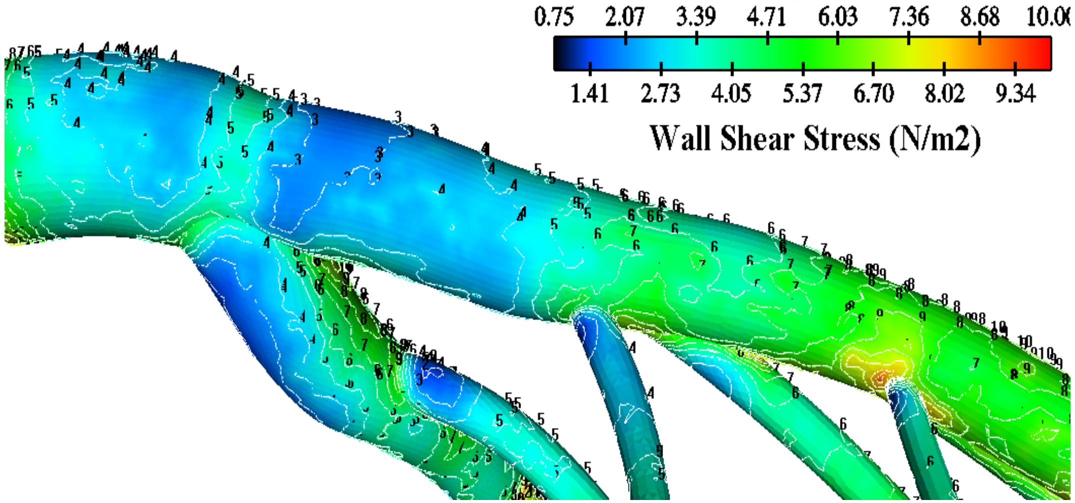
Atherosclerotic lesion size and vulnerability are determined by patterns of fluid shear stress



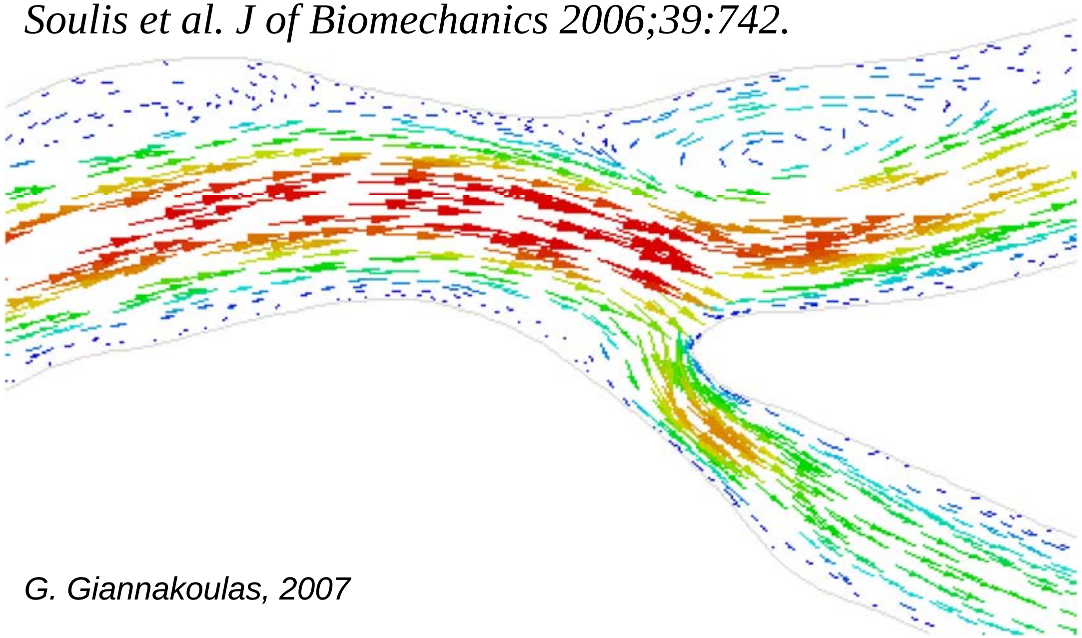
Cheng et al. Circulation 2006;113:2744-53.

The distribution of the low WSS values is in accordance with the localization of atherosclerosis lesion

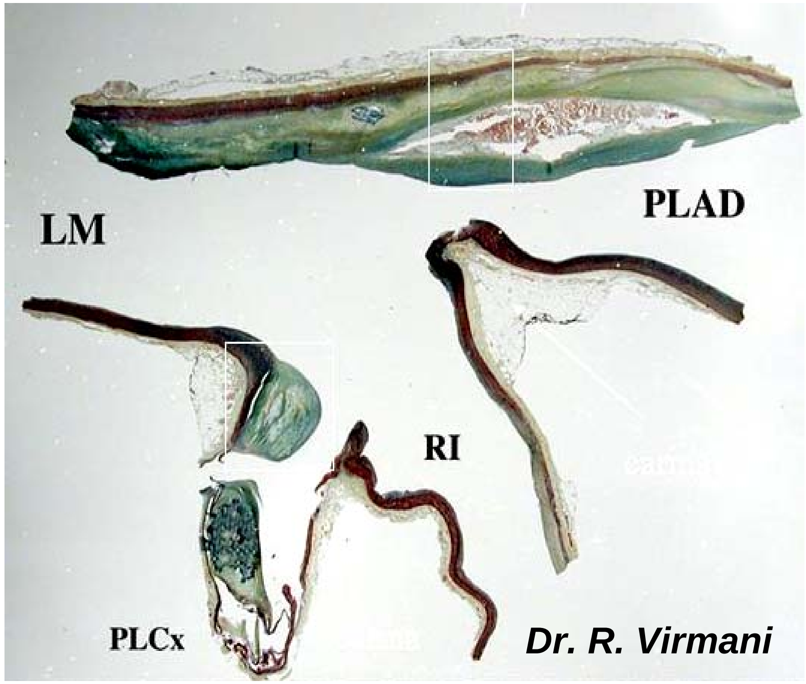
(LM bifurcation)

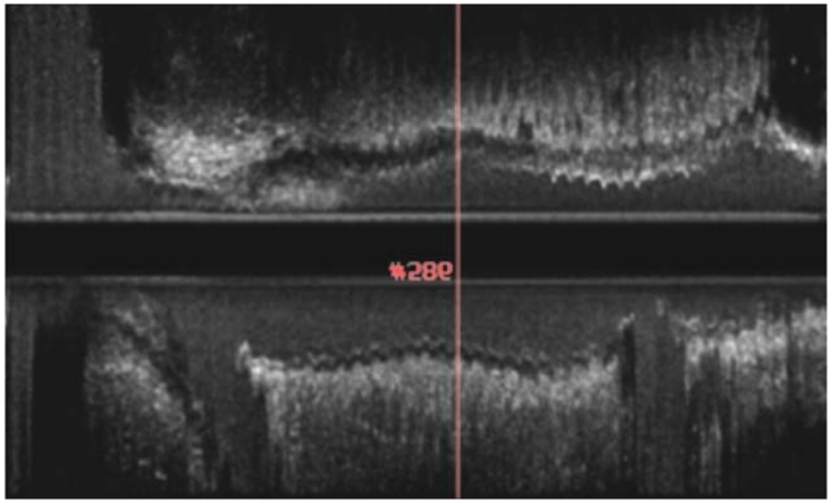


Soulis et al. J of Biomechanics 2006;39:742.

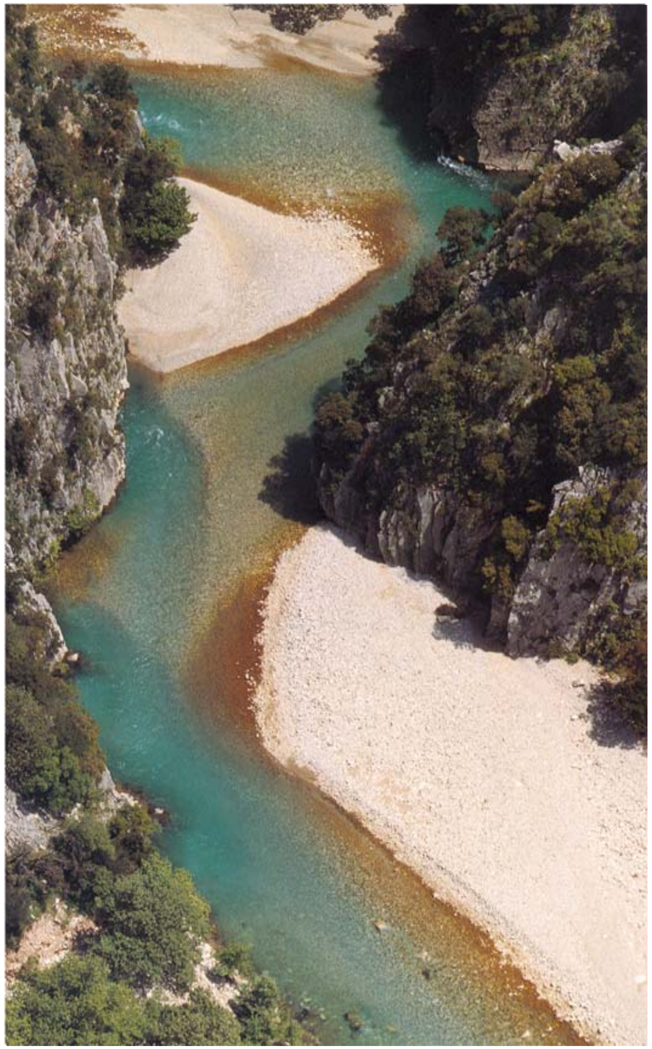


G. Giannakoulas, 2007





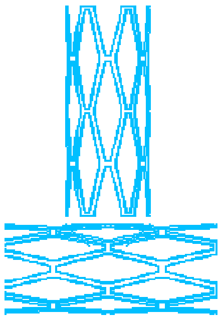
Plaque formation and Plaque progression

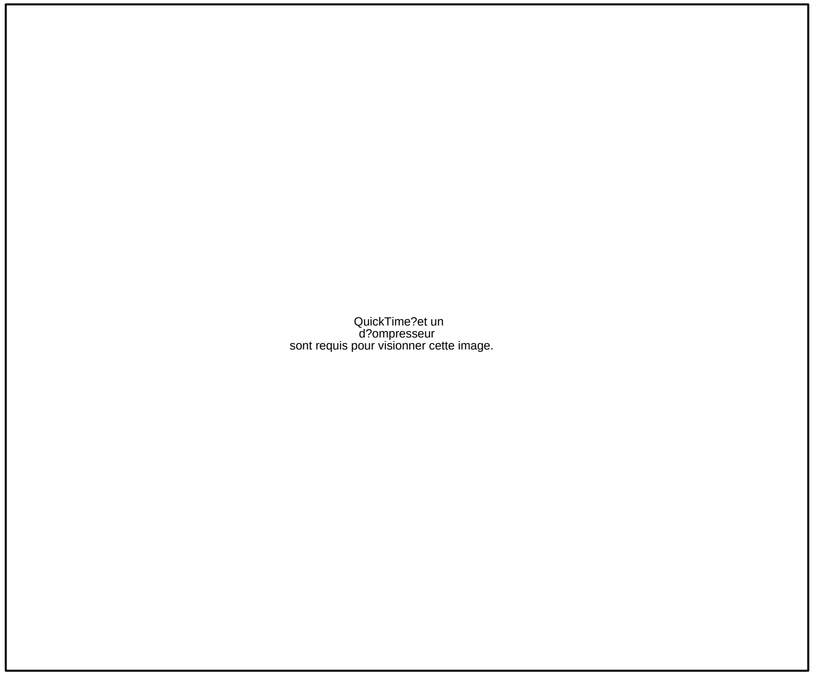


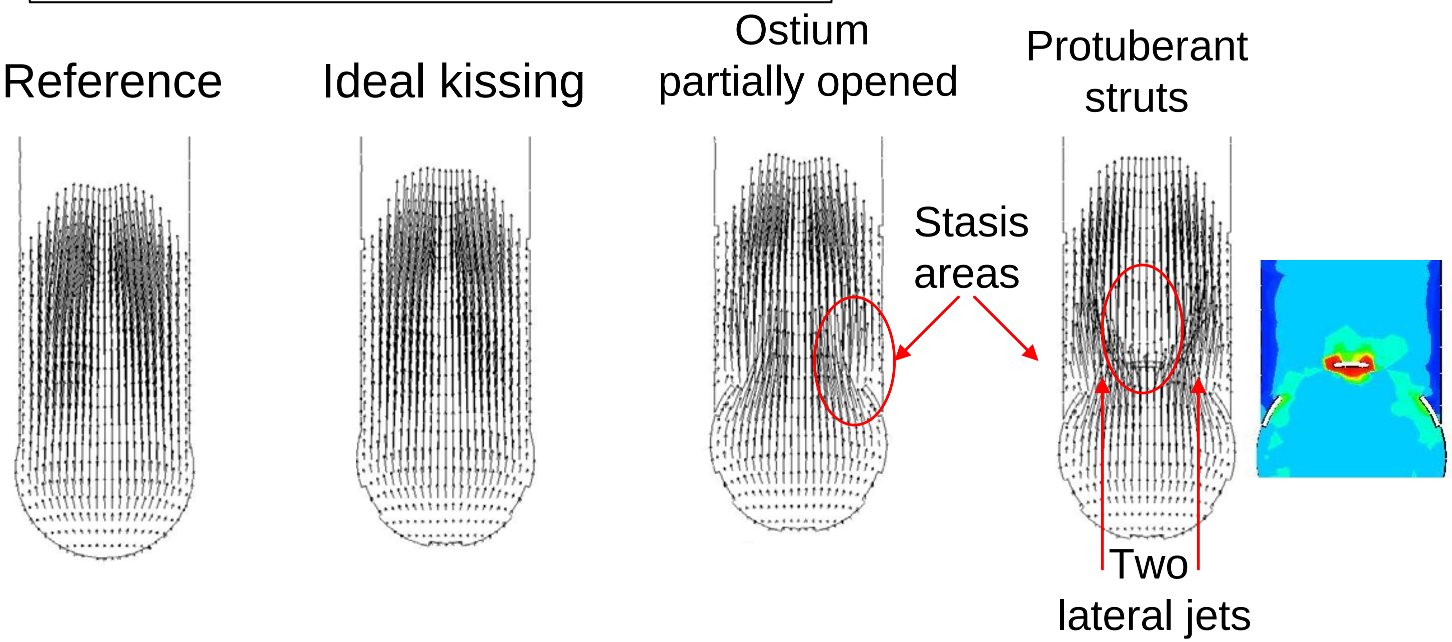
adapted from G. Giannakoulas (EBC 2008)

Flow behaviour in a **stented** coronary bifurcation

Courtesy of Valérie Deplano



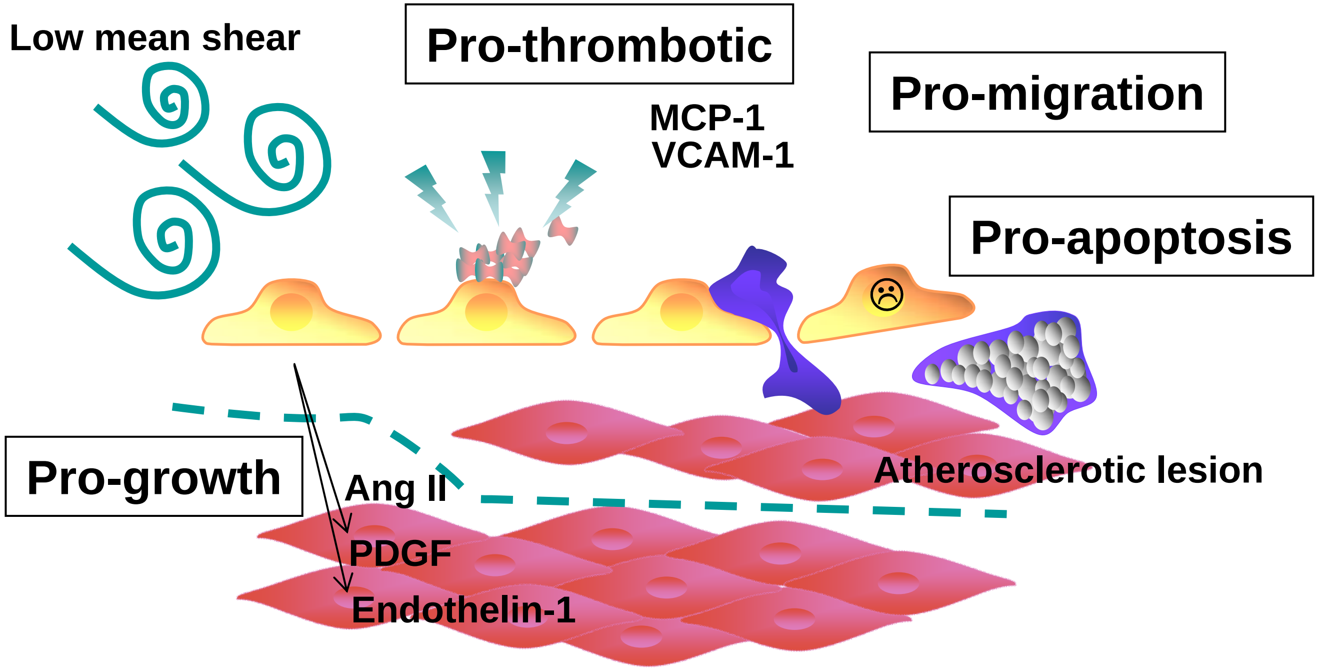




Deplano et al, 2004

- Recirculating zone and/or low Flow <u>Favor</u> Atherosclerosis or NIH

Traub & Berk, ATVB 1998
Wentzel, 2001



- **Struts protruding into the lumen generate very high stent shear stress (swss) values**
  Concomitant areas of high and low swss values <u>favor</u>:
  - Platelet activation & deposition (Moake, 1988, Spijker, 2003)
  - Thromboembolic complications (Bluestein, 2002)

Arterial bifurcation is *a morphological singularity of the vascular tree*

Despite its seeming complexity the vascular bifurcation tree turns out to be a sophiticated solution: *a maximum cost/benefit ratio*

Coronary bifurcation geometry is invariable whatever the observation scale and precisely described by a *fractal ratio*, this ratio can be very useful in our daily practice of angiography and angioplasty

$$D_{mother\ vessel} = \underline{0.678}\ (D_{daughter\ vessel\ 1} + D_{aughter\ vessel2})$$

Flow dynamics, rheology, and geometry interact

The occurrence of atherogenesis, atherosclerosis, and thrombosis are closely linked to local hemodynamic factors

Stented bifurcation can become focus of flow disturbances and complications