Hemodynamic Force and Coronary Plaque

:Theoretical Evaluation of Mechanistic Effect

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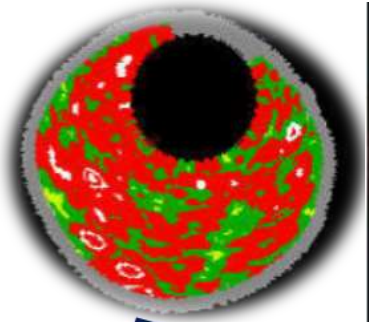
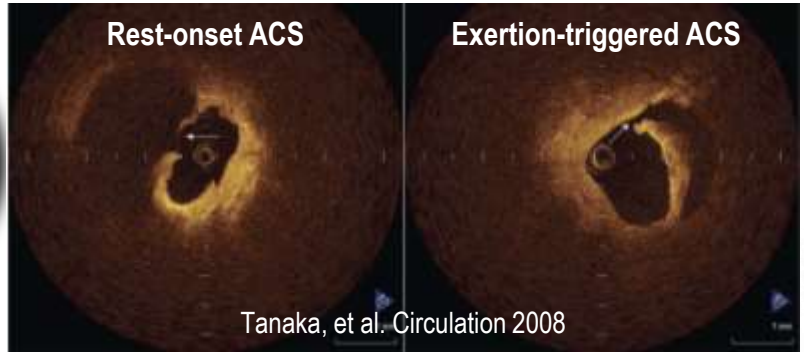
Why does the plaque rupture?

:Mechanism of material failure

Durability = Vulnerability





The broken cap was much thinner in the rest-onset group than in the exertion group (50 vs. 90 μm, *P*<0.01)

External force

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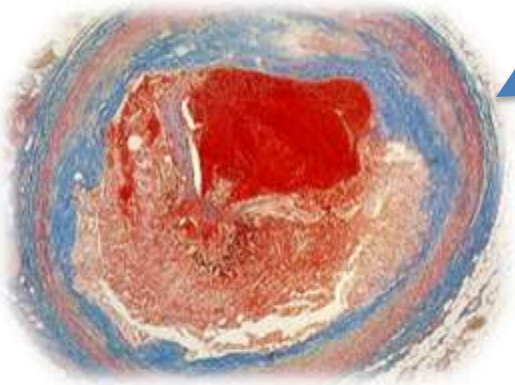


?

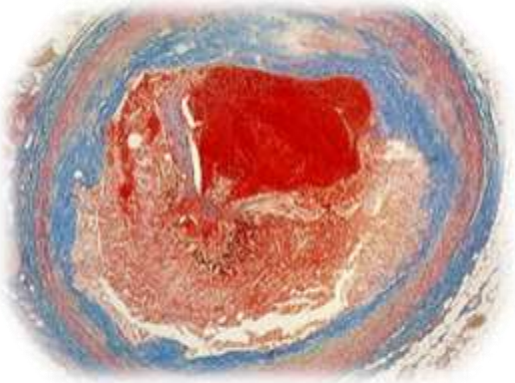
ACS (with rupture)

Pressure gradient (FFR)

Fractional Flow Reserve (FFR)

- Surrogate for “ischemia”
- Prognostic indicator for coronary artery disease

Looking for the links between FFR and ACS…



ACS (with rupture)

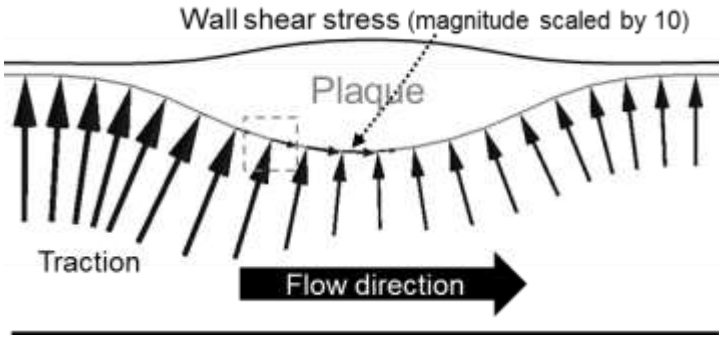
Platelet activation
Thrombosis

Plaque Stress

Plaque vulnerability

Pressure gradient (FFR)

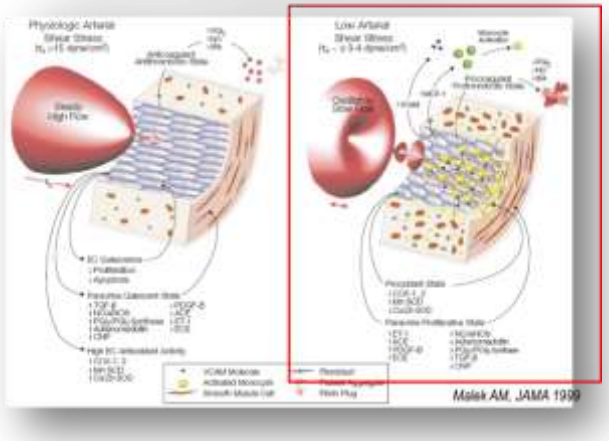
Wall shear stress: Small, but important!



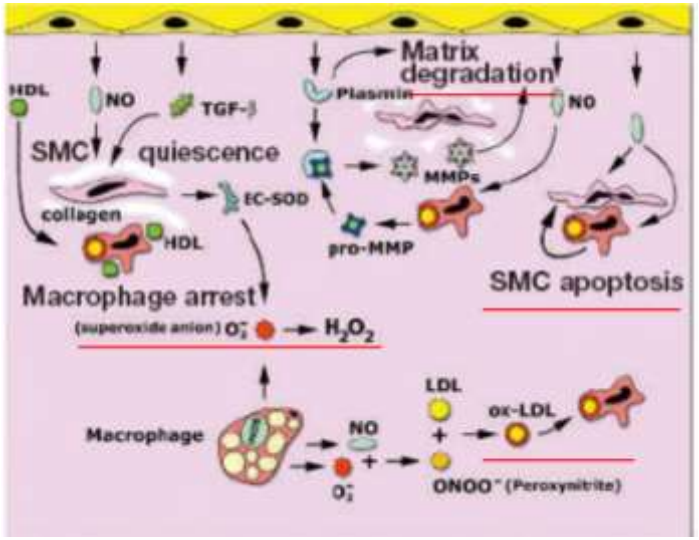
WSS: Tiny tangential force of flowing blood on endothelial surface

Low wall shear stress

→ Proliferative, pro-inflammatory, pro-thrombotic stimulus



Very high WSS (> 30 dyne/cm^2)



- Activation of MMP
- Smooth muscle cell apoptosis
- Suppress matrix production
- Acceleration of downstream atherosclerosis
- Positive remodeling
- Increase necrotic core
- Platelet activation

Slager CJ, et al. Nature Clin Pract 2005
Sheriff J, et al. Ann Biomed Eng 2010
Samady H, et al. Circulation 2011

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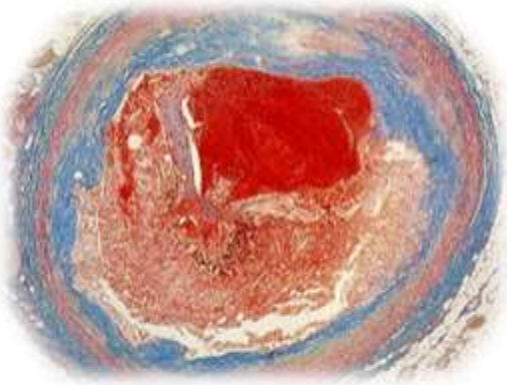


ACS (with rupture)

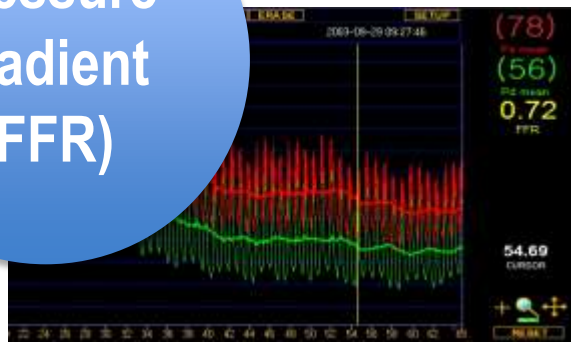
Plaque Stress

Platelet activation
Thrombosis

High WSS
High WSS gradient

Plaque vulnerability

Pressure gradient (FFR)

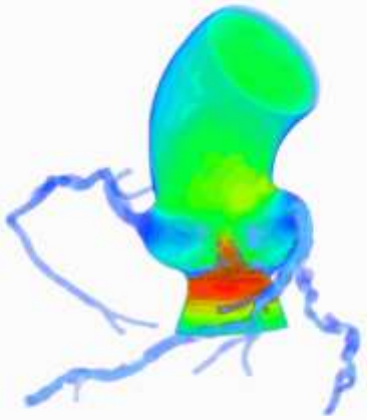


Non-invasive hemodynamic parameter measurement using computational fluid dynamics and cCTA

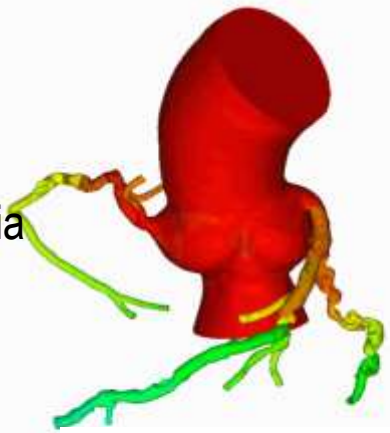
Pressure

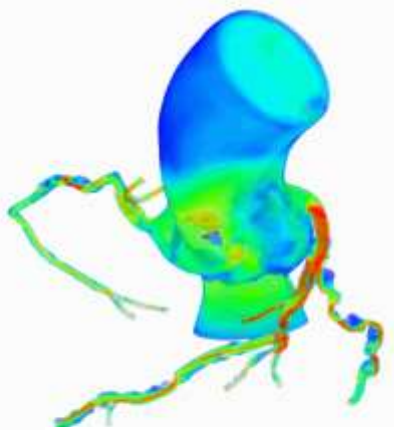
Velocity

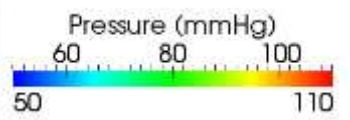
Rest

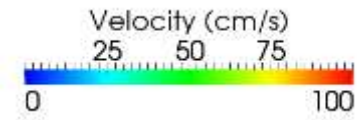


Hyperemia





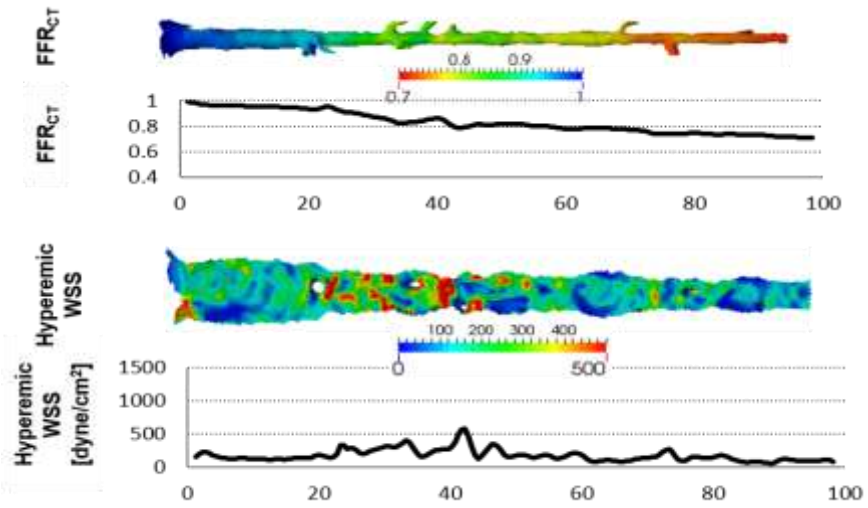


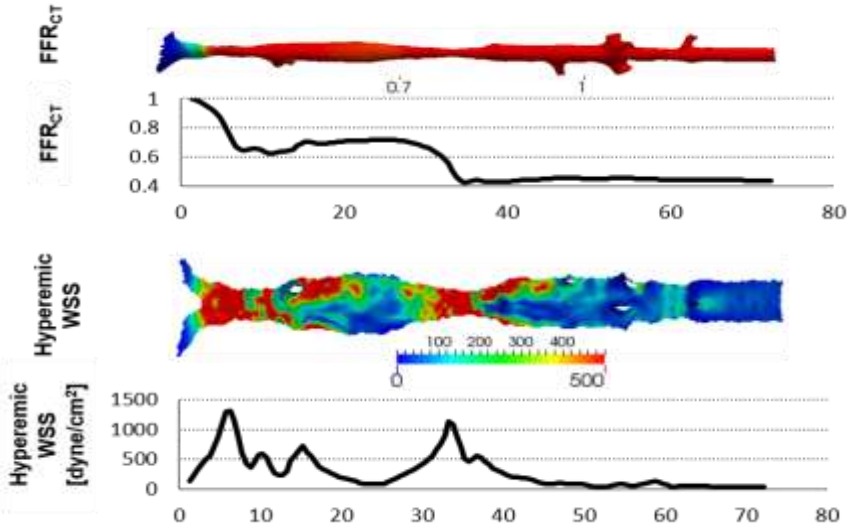


Hemodynamics

- Pressure
  - Pressure difference
  - Pressure gradient
  - Pressure recovery
  - FFR
- Flow velocity
- **Flow rate**
- **Shear rate**
- **Shear stress – average, peak, gradient**
- **Traction**
- **Oscillatory shear index**
- **Particle residence time**
- **Turbulent kinetic energy**
- ……..

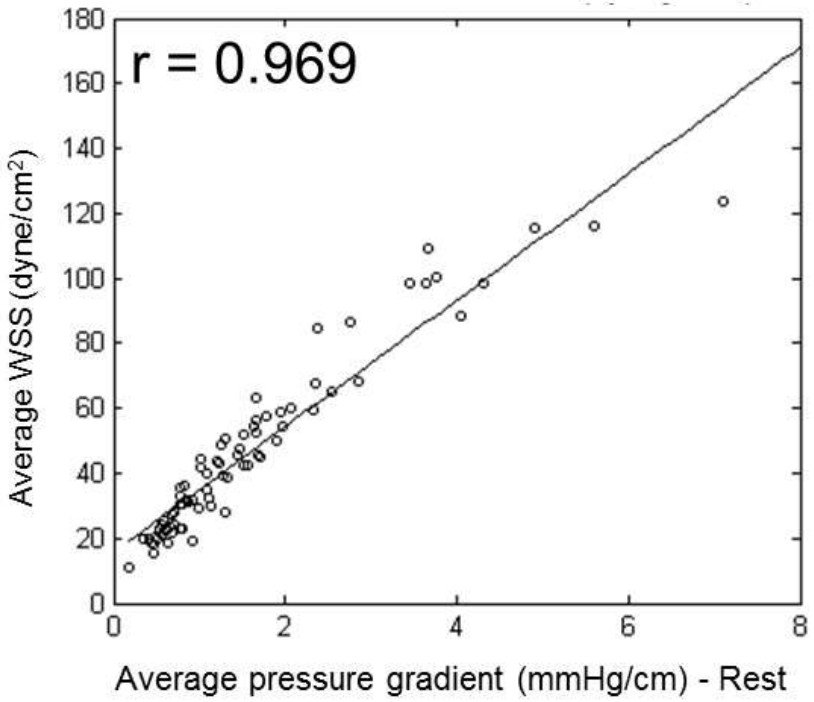
Non-invasive WSS assessment using cCTA and computational fluid dynamics

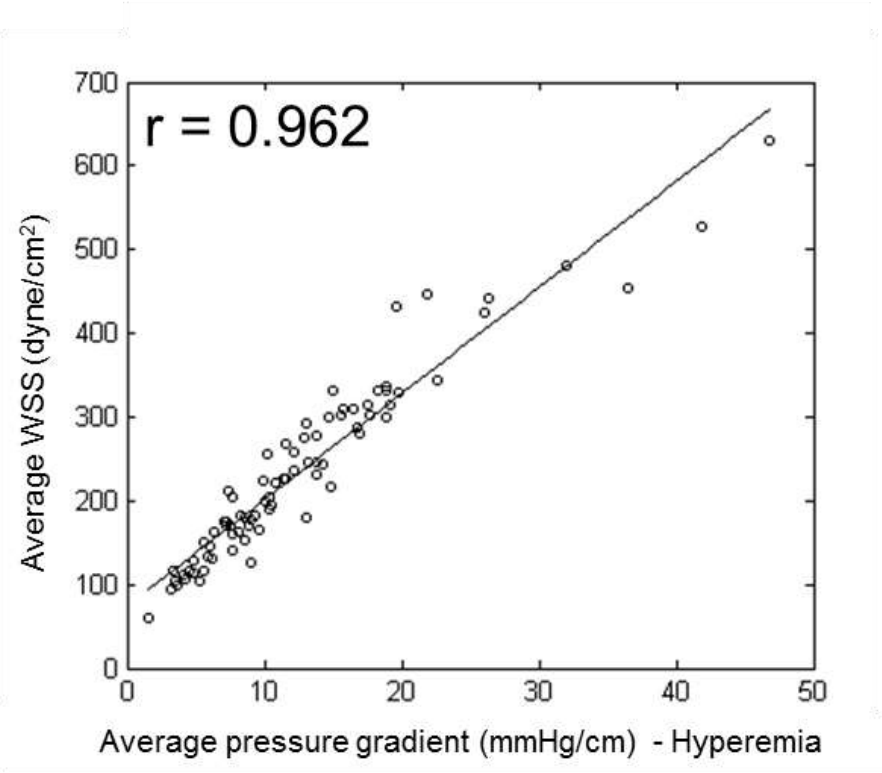




Koo BK. International Symposium on Biomechanics 2014

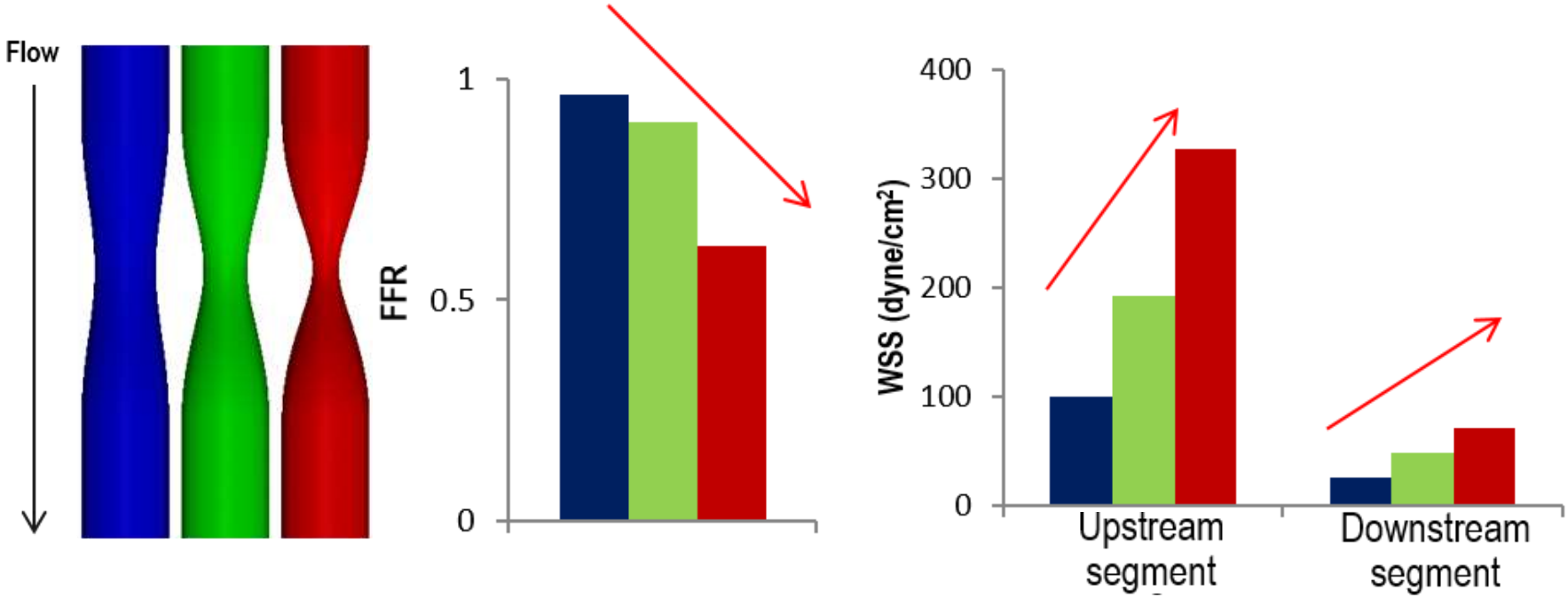
Relationship between WSS and pressure gradient





Park JB, et al. Under revision

FFR vs. WSS


Flow
FFR
1
0.5
0
WSS (dyne/cm²)
400
300
200
100
0
Upstream segment
Downstream segment

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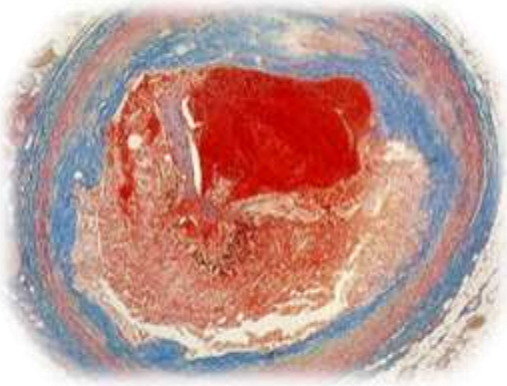
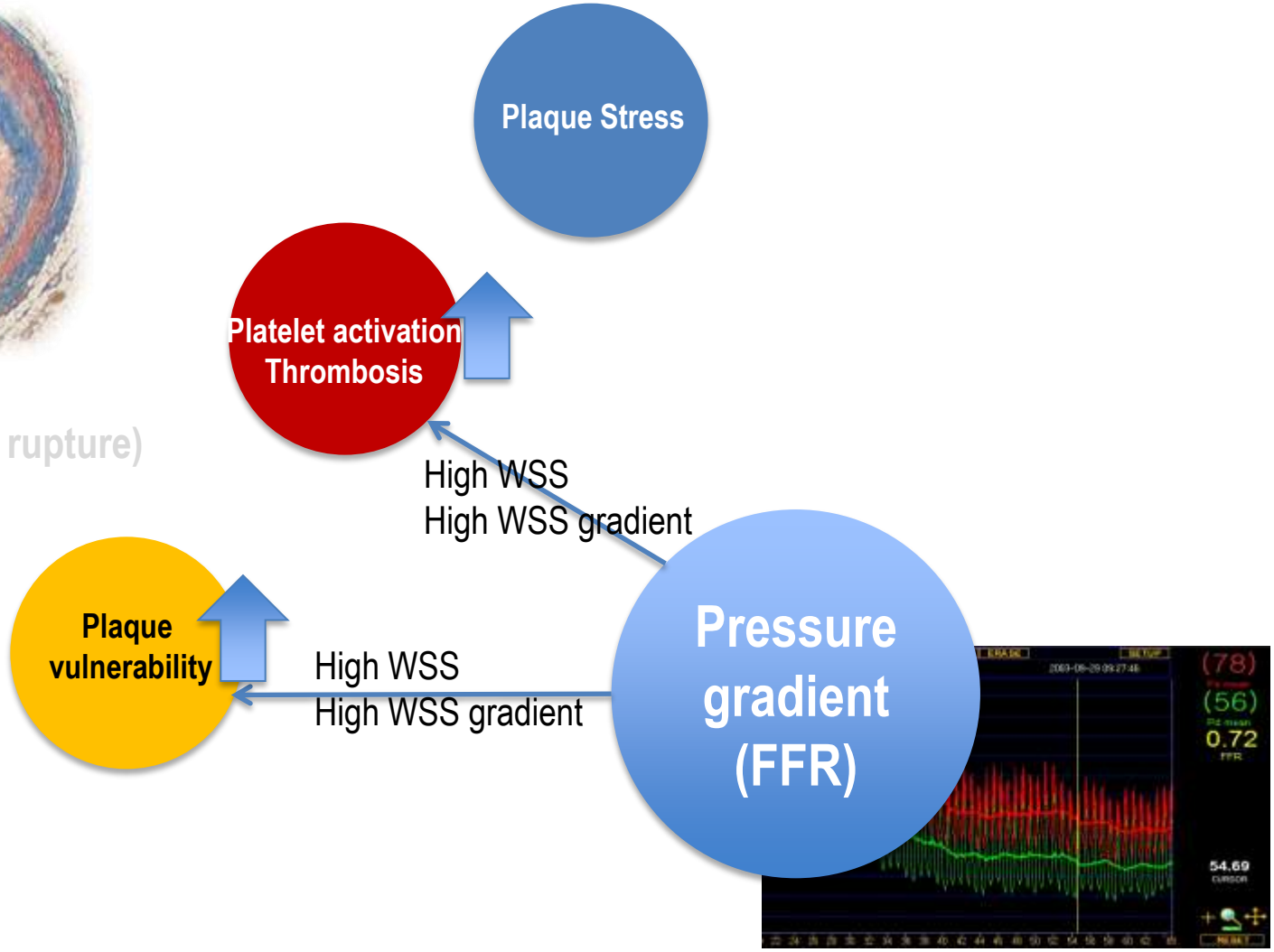
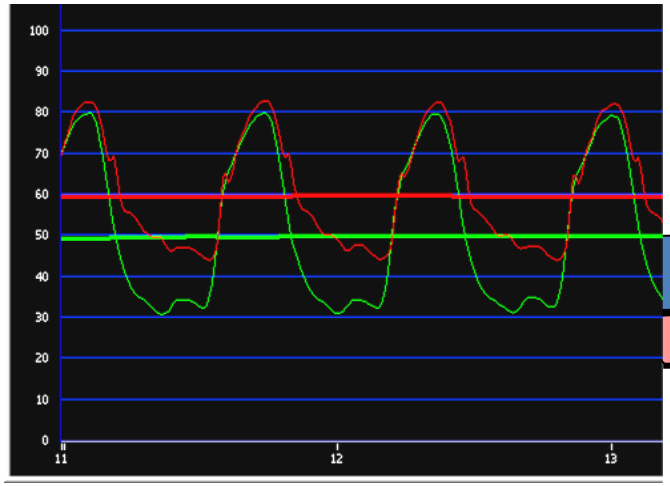


ACS (with rupture)



Mechanical constraints on coronary stenoses

40.000.000 / year



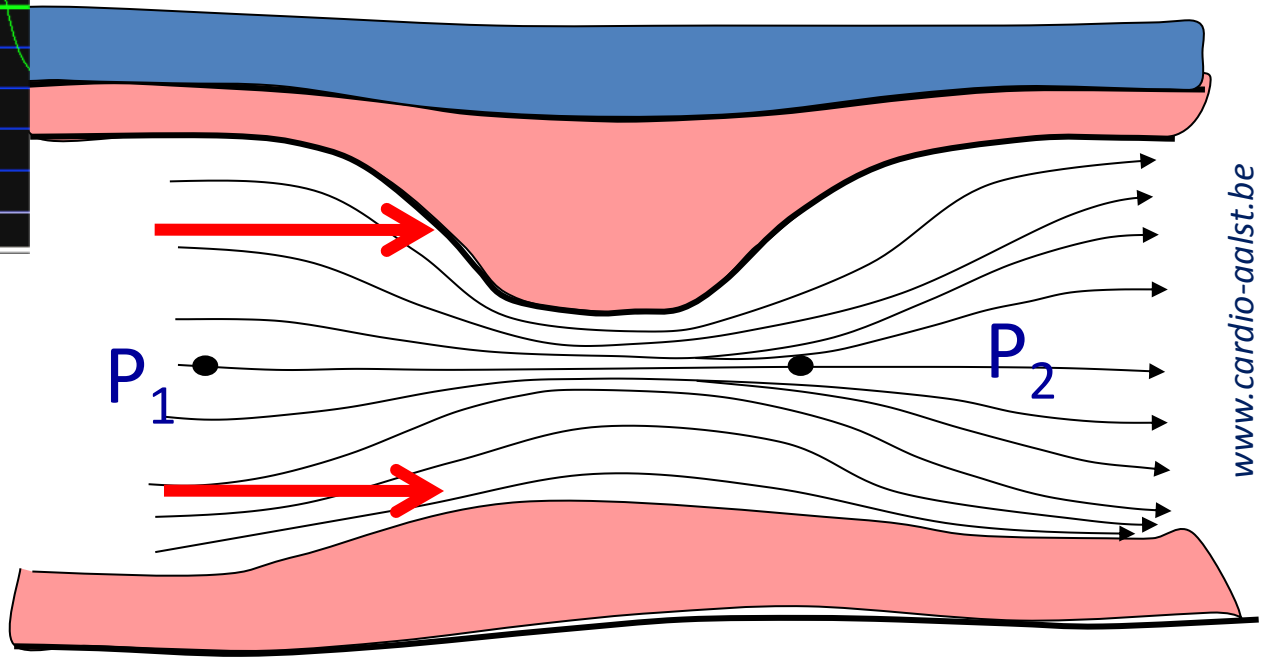
Pressure wave

↓

Slicing forces

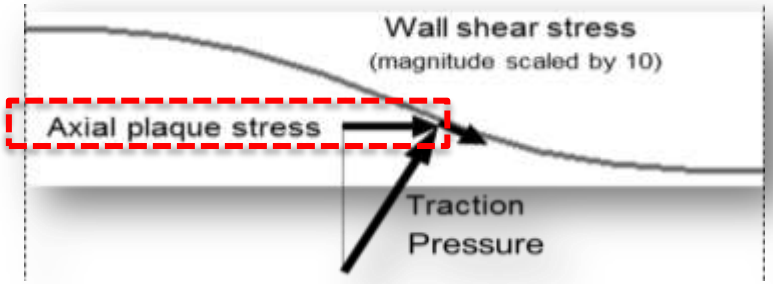
↓

Plaque fatigue



Courtesy of Bernard de Bruyne, MD, PhD

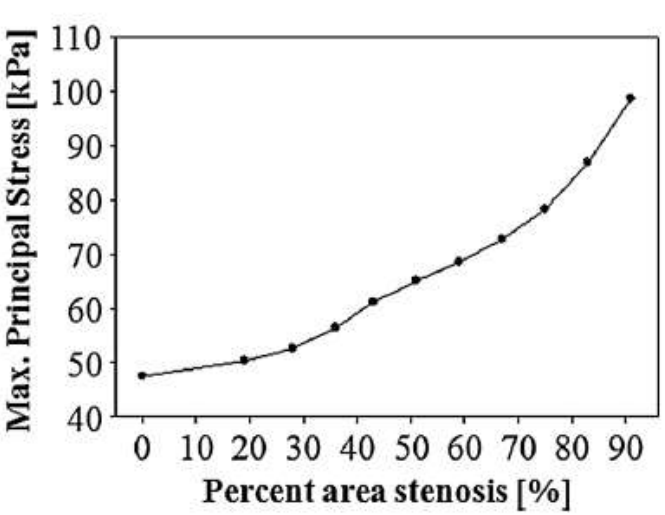
WSS and pressure, then what else?

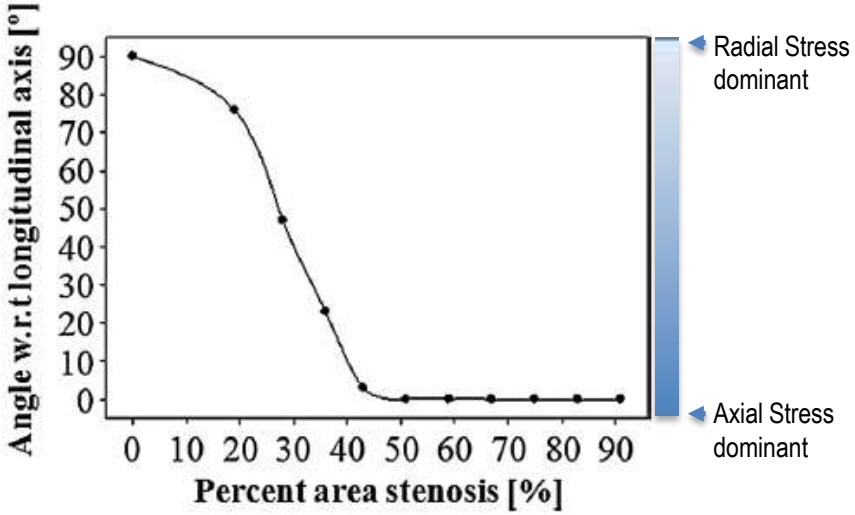


- Traction is the total force acting on vessel wall , and can be decomposed

In relation to lumen surface: $\|\mathbf{Traction}\|^2 = \|\mathbf{WSS}\|^2 + \|\mathbf{Pressure}\|^2$

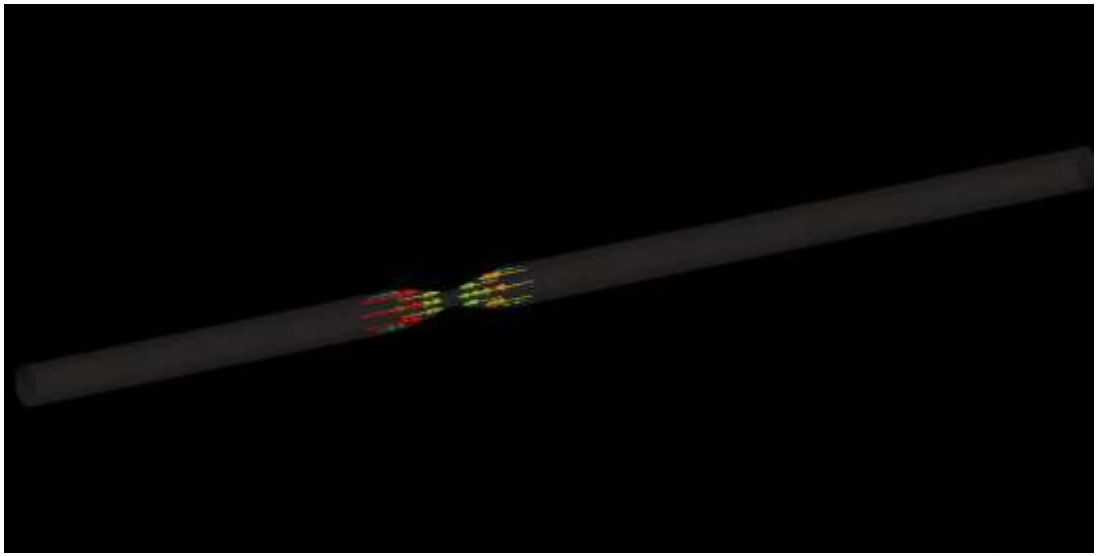
In relation to centerline: $\|\mathbf{Traction}\|^2 = \|\mathbf{Axial\ Stress}\|^2 + \|\mathbf{Radial\ Stress}\|^2$





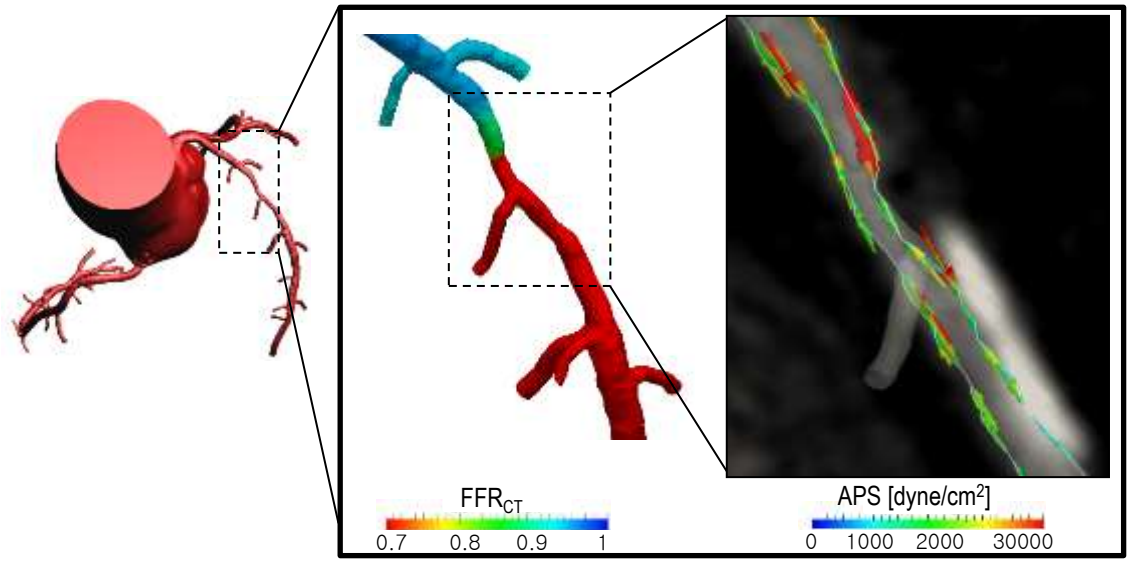
Pagiatakis C, et al. Med Biol Eng Comput 2015

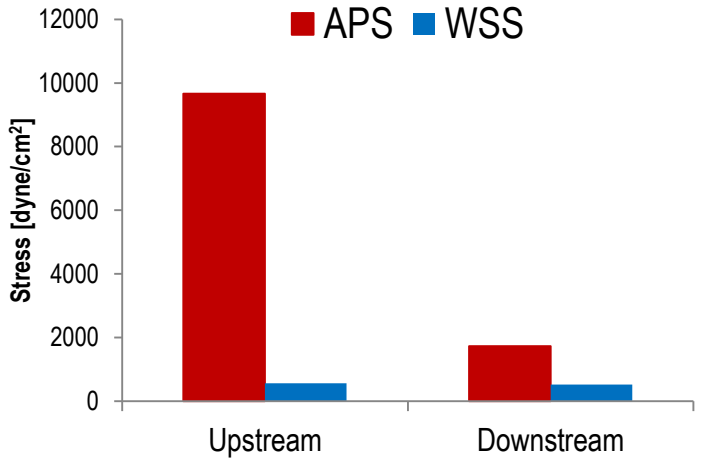
Novel hemodynamic index: Axial Plaque Stress

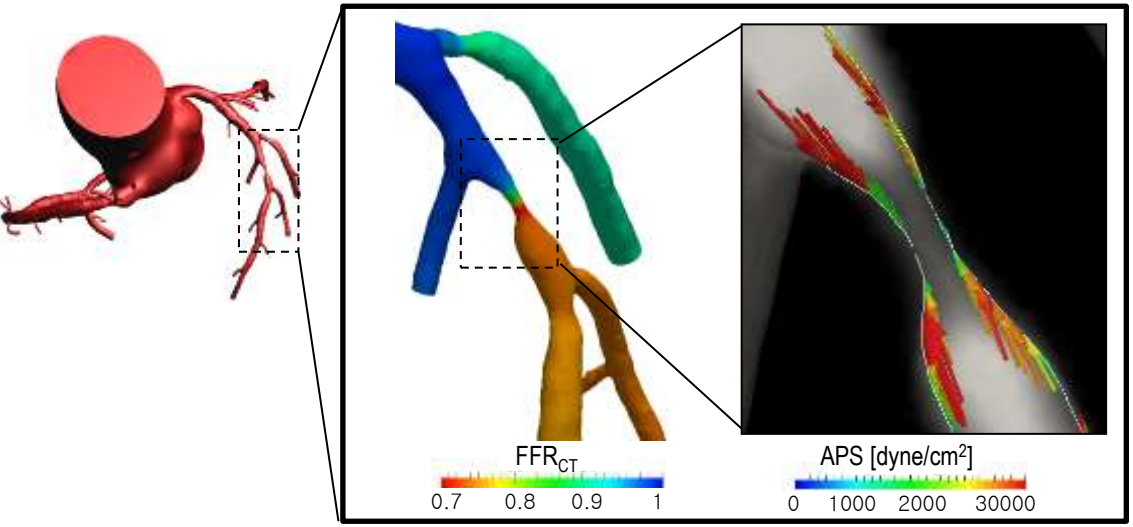


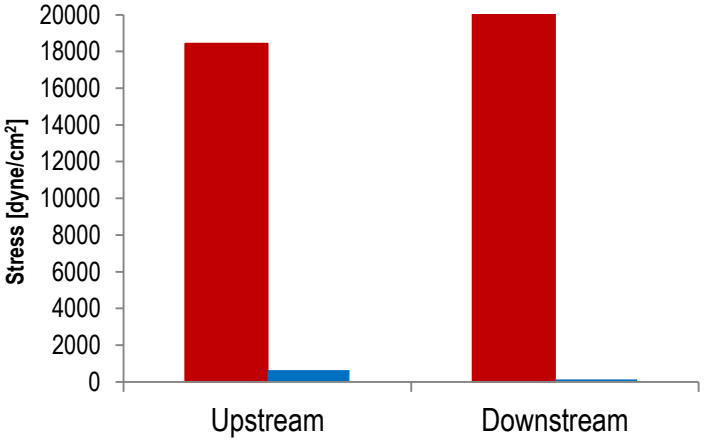
- **Axial plaque stress** uniquely characterizes the diseased segment of both upstream and downstream.
- **Axial plaque stress** is much higher than wall shear stress.

Distribution of Axial Plaque Stress in patients







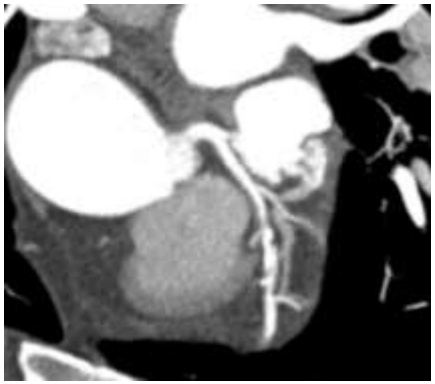


Choi GW…Koo BK. JACC imaging 2015

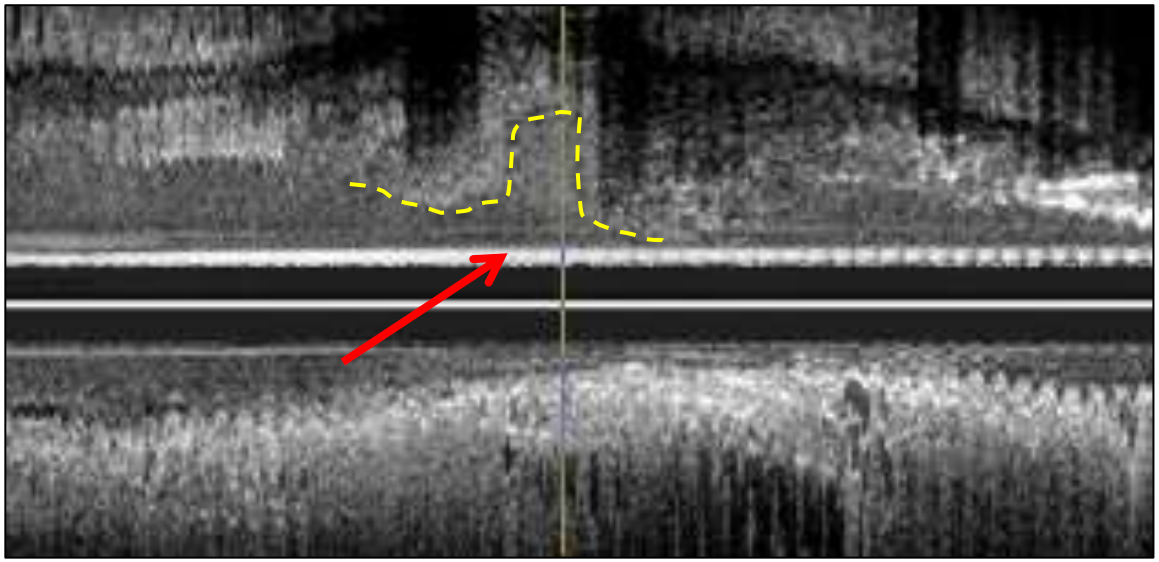
Axial Plaque Stress and Clinical Event

Why the rupture is there?

2011-04 CT, Asymptomatic



2012-06 Acute MI



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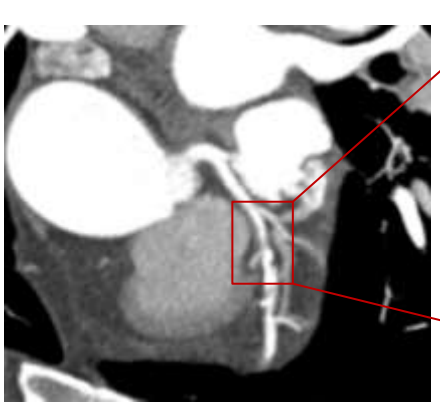
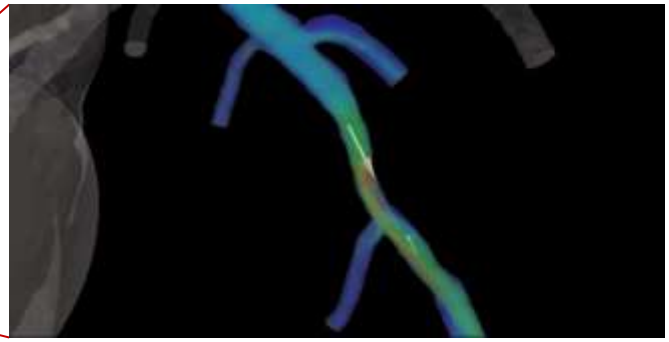
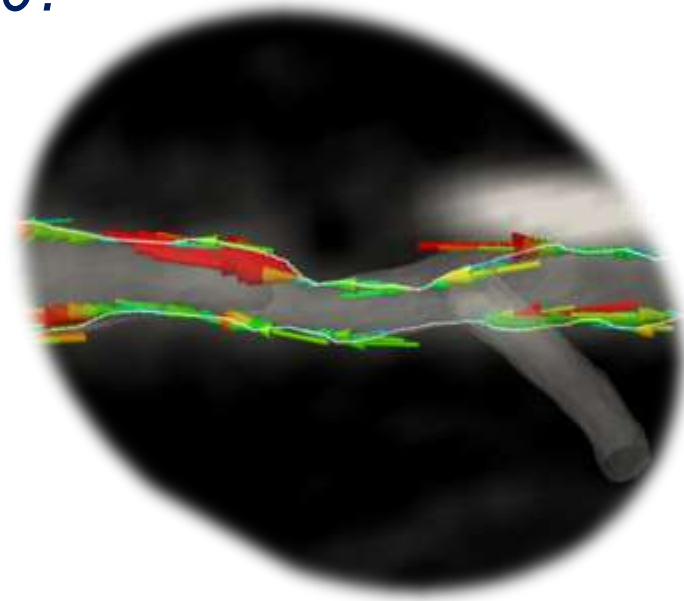
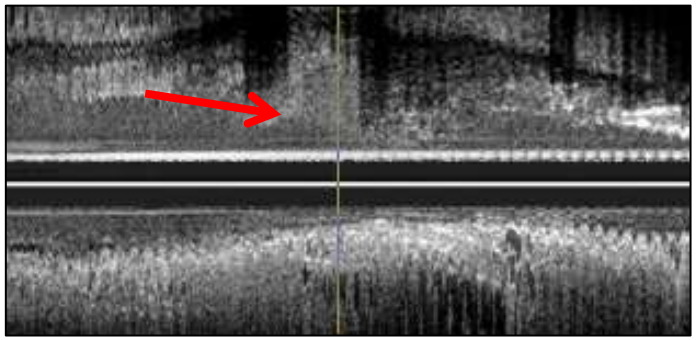






	Axial plaque stress
Upstream	**9960 dyne/cm^2**
Downstream	1740 dyne/cm^2

2012-06 Acute MI

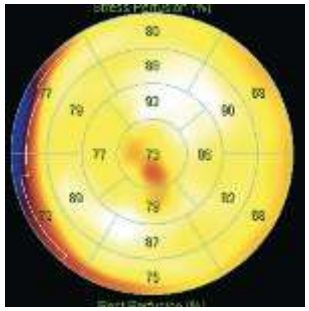


Choi GW…Koo BK. JACC imaging 2015

Axial Plaque Stress and Clinical Event

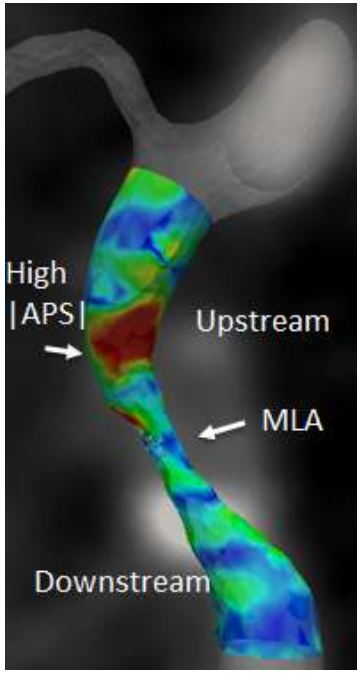
M/52, Asymptomatic

Rb-82 myocardial perfusion scan



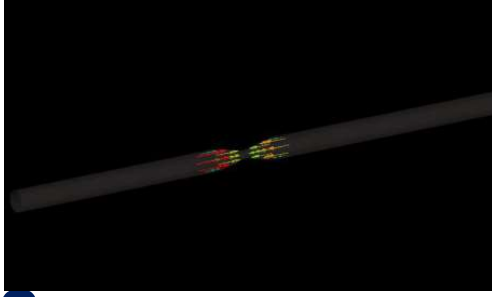
No perfusion decrease

1 year later, after strenuous exercise…..

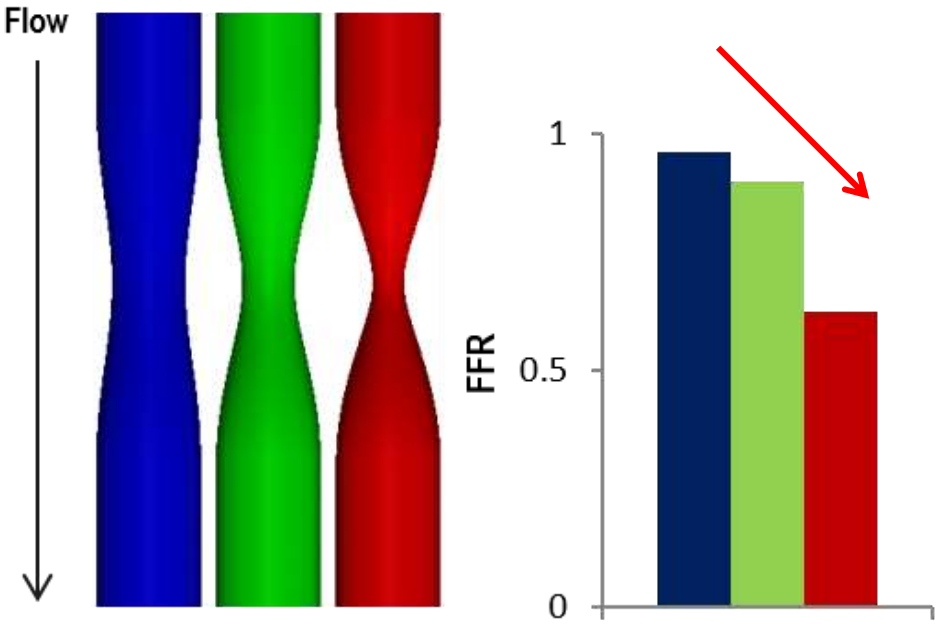


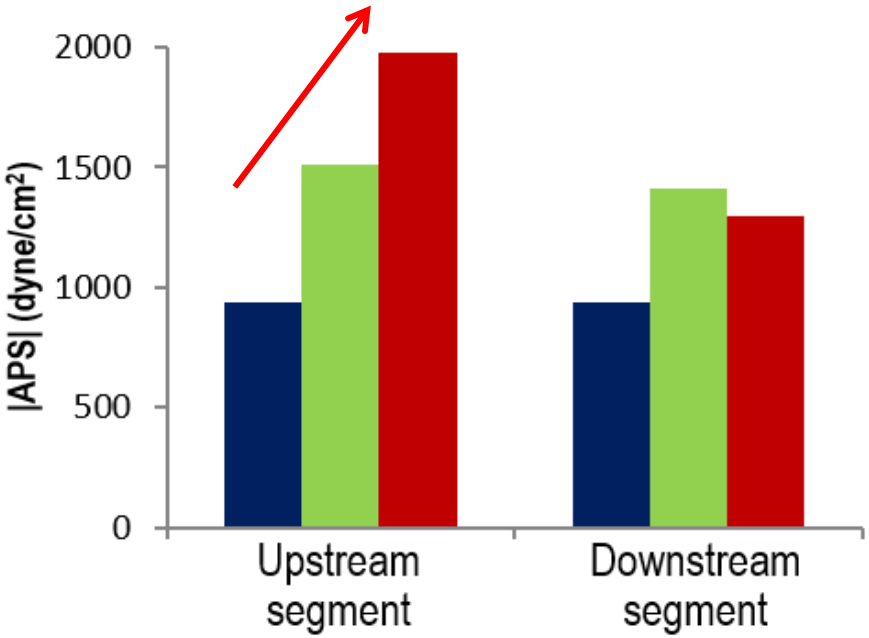
	Upstream segment	Downstream segment
APS (dyne/cm^2)	17200	-11732
WSS (dyne/cm^2)	325	209

Courtesy of Bjarne L. Norgaard, MD, PhD



FFR vs. Axial plaque stress





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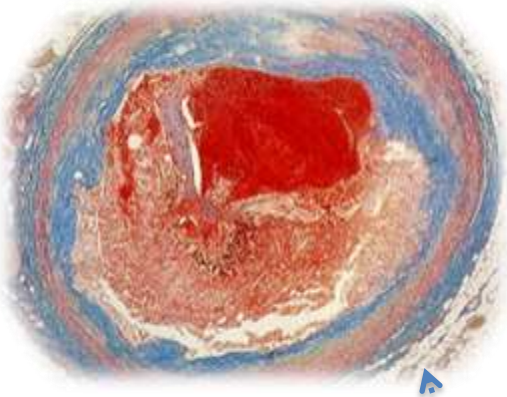


ACS (with rupture)

Plaque Stress

Platelet activation
Thrombosis

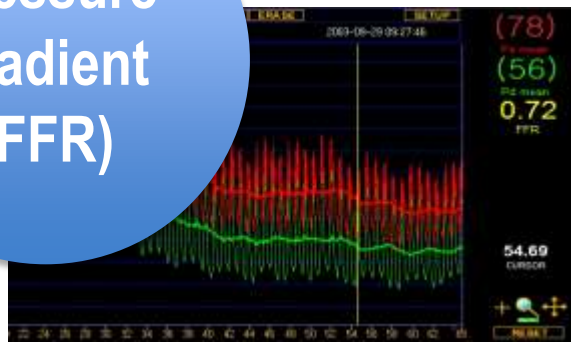
High External force

High WSS
High WSS gradient

Plaque vulnerability

High WSS
High WSS gradient

Pressure gradient (FFR)



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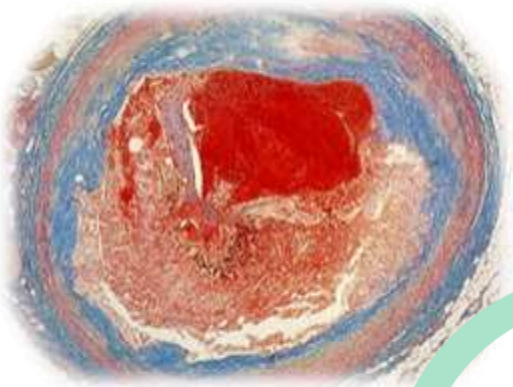

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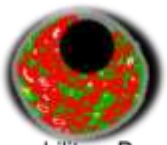


Vulnerability = Durability

External force

Thrombosis

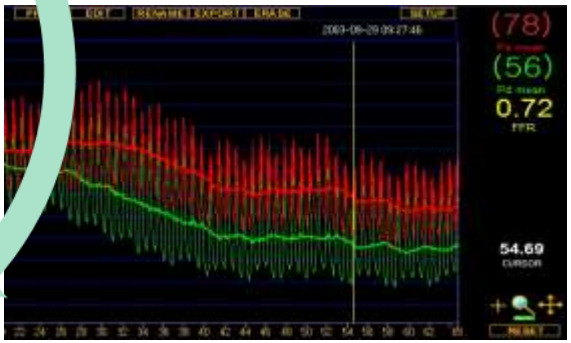
High WSS
High WSS gradient

Plaque vulnerability

High WSS
High WSS gradient

Pressure gradient (FFR)

High axial plaque force (External force)



In addition to define ischemia, FFR can tell the risk of ACS through the interaction with biomechanical forces.