FFR_{CT}: Beyond FFR

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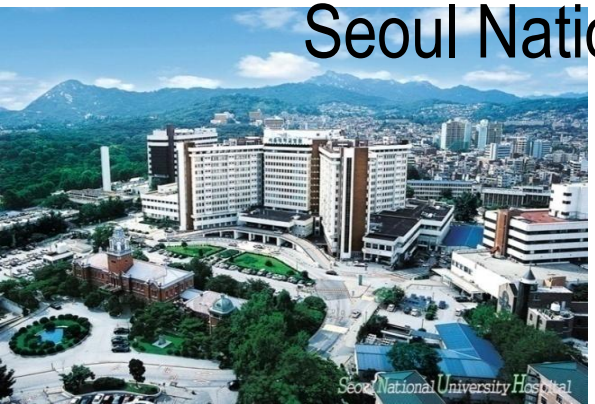
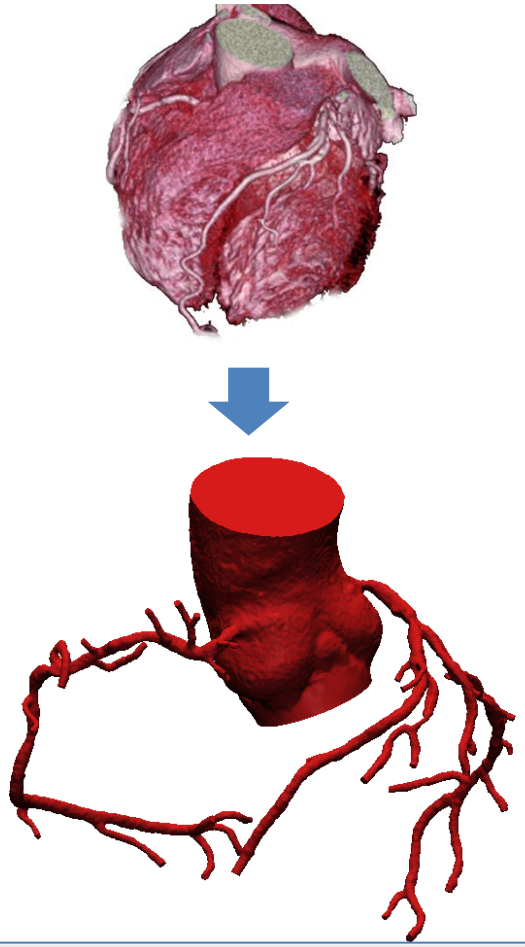


SNUH *Seoul National University Hospital*
Cardiovascular Center

Patient-specific non-invasive coronary hemodynamic assessment

Non-invasive, Pt-specific

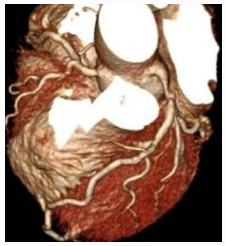


Hemodynamics

- **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
- ……..

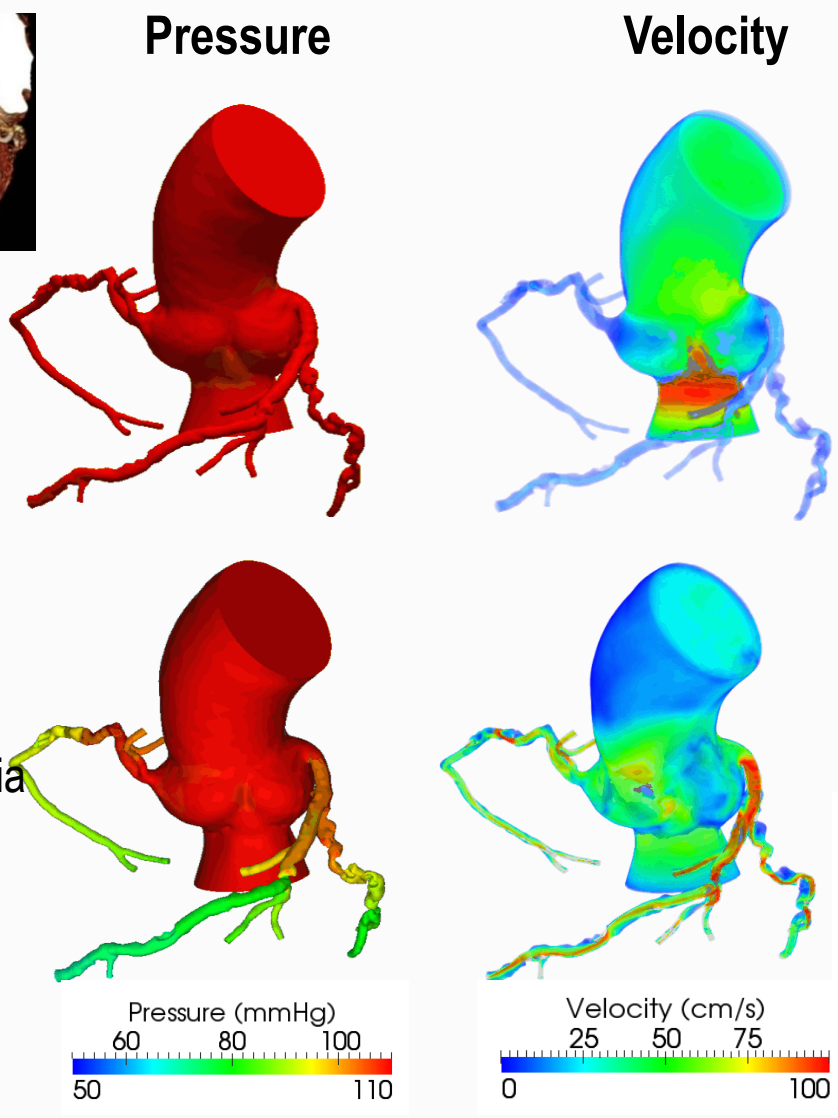
- Static
- Pulsatile
- Resting
- Hyperemic
- Exercise – mild, moderate, peak

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



Rest

Hyperemia



Hemodynamics

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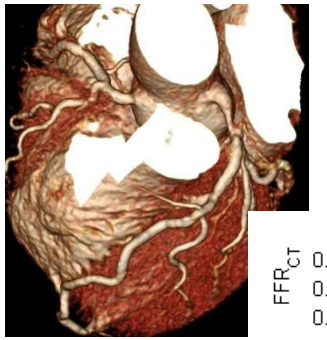
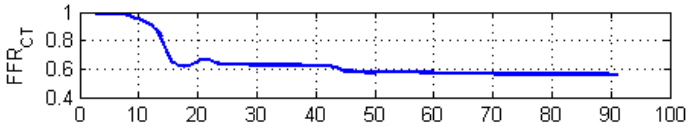
  - Pressure recovery
  - FFR
- Flow velocity
- **Flow rate**
- **Shear rate**
- **Shear stress – average, peak, gradient**
- **Traction**
- **Oscillatory shear index**
- **Particle residence time**
- **Turbulent kinetic energy**
- ……

Image-based computerised modelling of coronary circulation: ***Potentials***



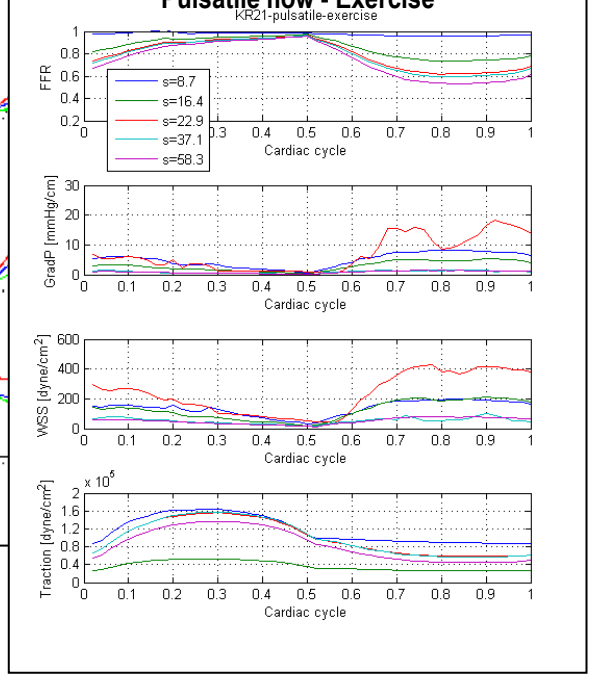
Static flow - hyperemic



Pulsatile flow - rest

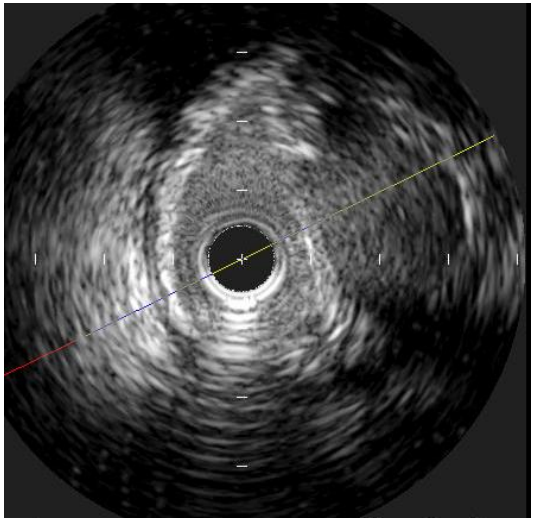
Pulsatile flow - Hyperemia

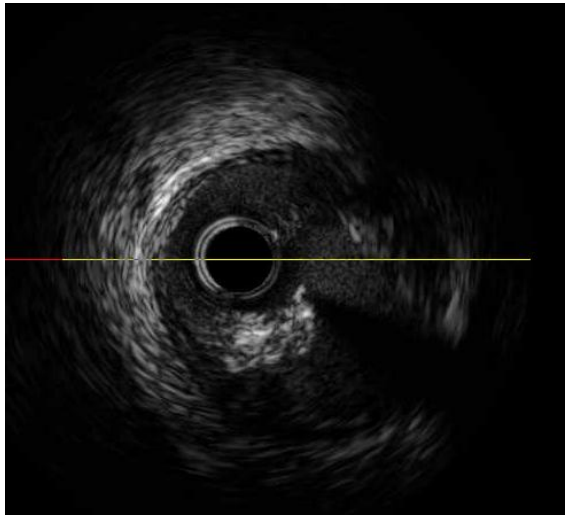
Pulsatile flow - Exercise

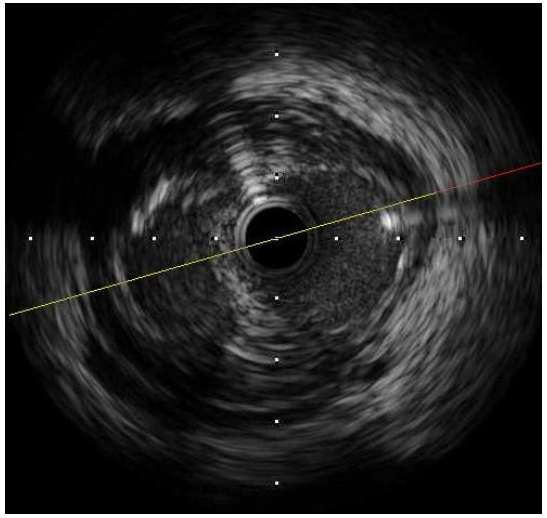


Why Does the Plaque Rupture?

Mechanistic link between Hemodynamics and Acute Coronary Syndrome

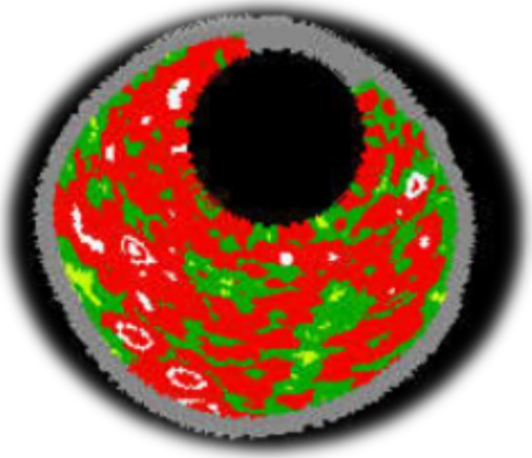


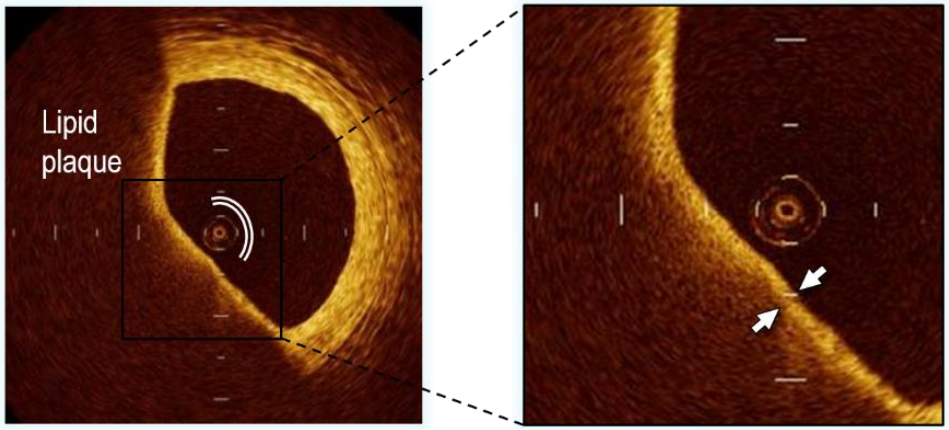




We already know….

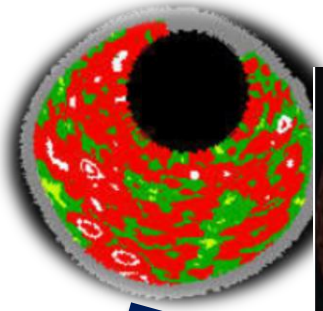
- Coronary plaque rupture is a critical event that triggers the initiation of acute coronary syndrome (ACS).
- Risk assessment for ACS
  - **Plaque Vulnerability**: cap thickness, lipid core, inflammation, neovascularization, posterior attenuation…….

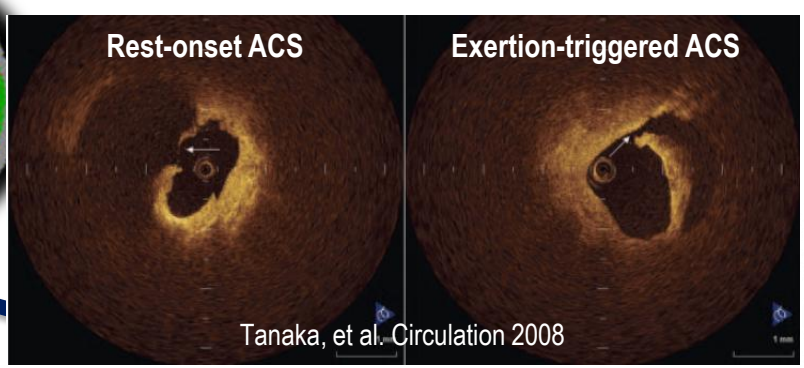




Why does the plaque rupture?
:Mechanism of material failure

Durability = Vulnerability



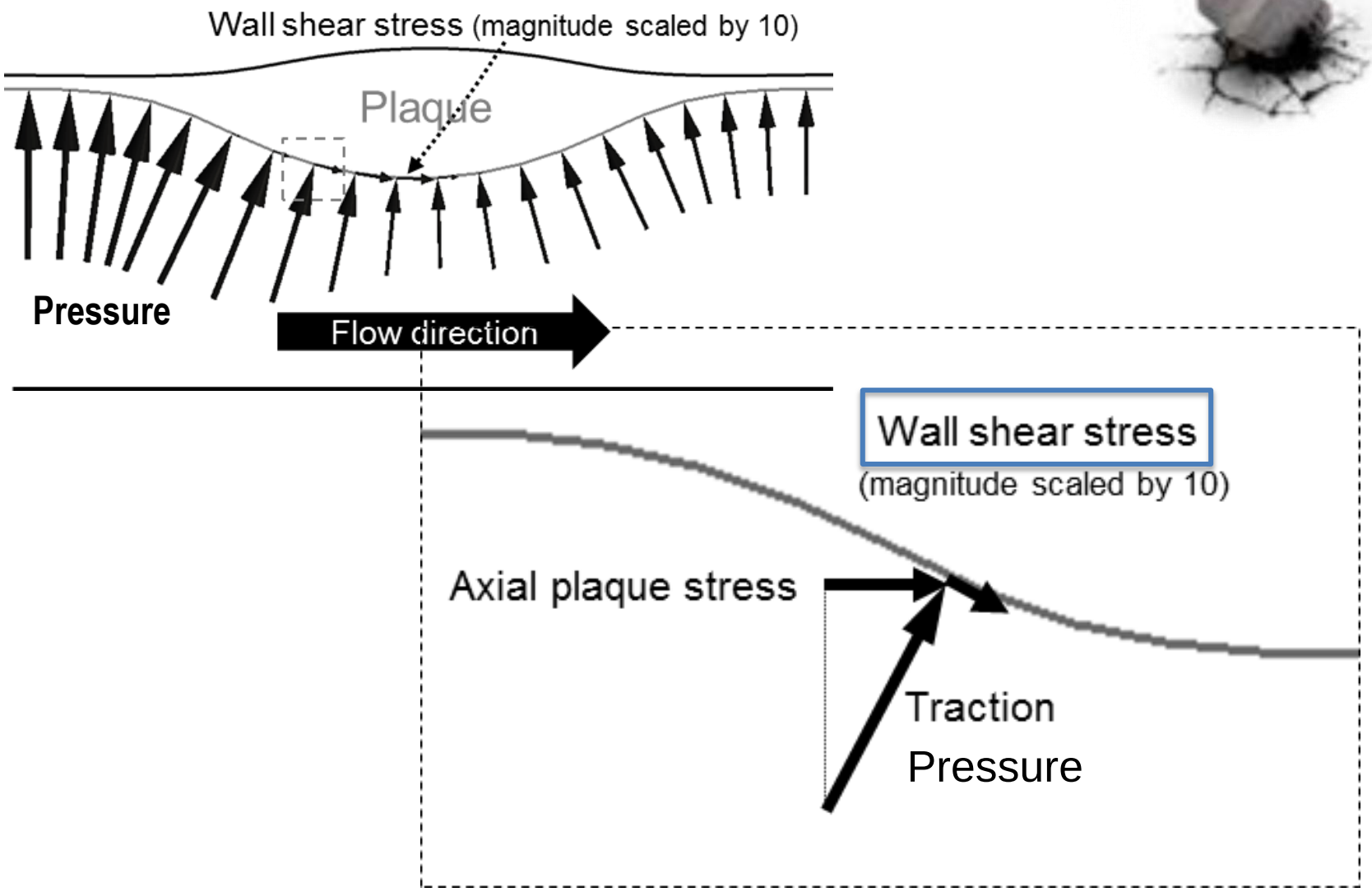


The broken cap was much thinner in the rest-onset group than in the exertion group (50 vs. 90 μm, *P*<0.01)

External force

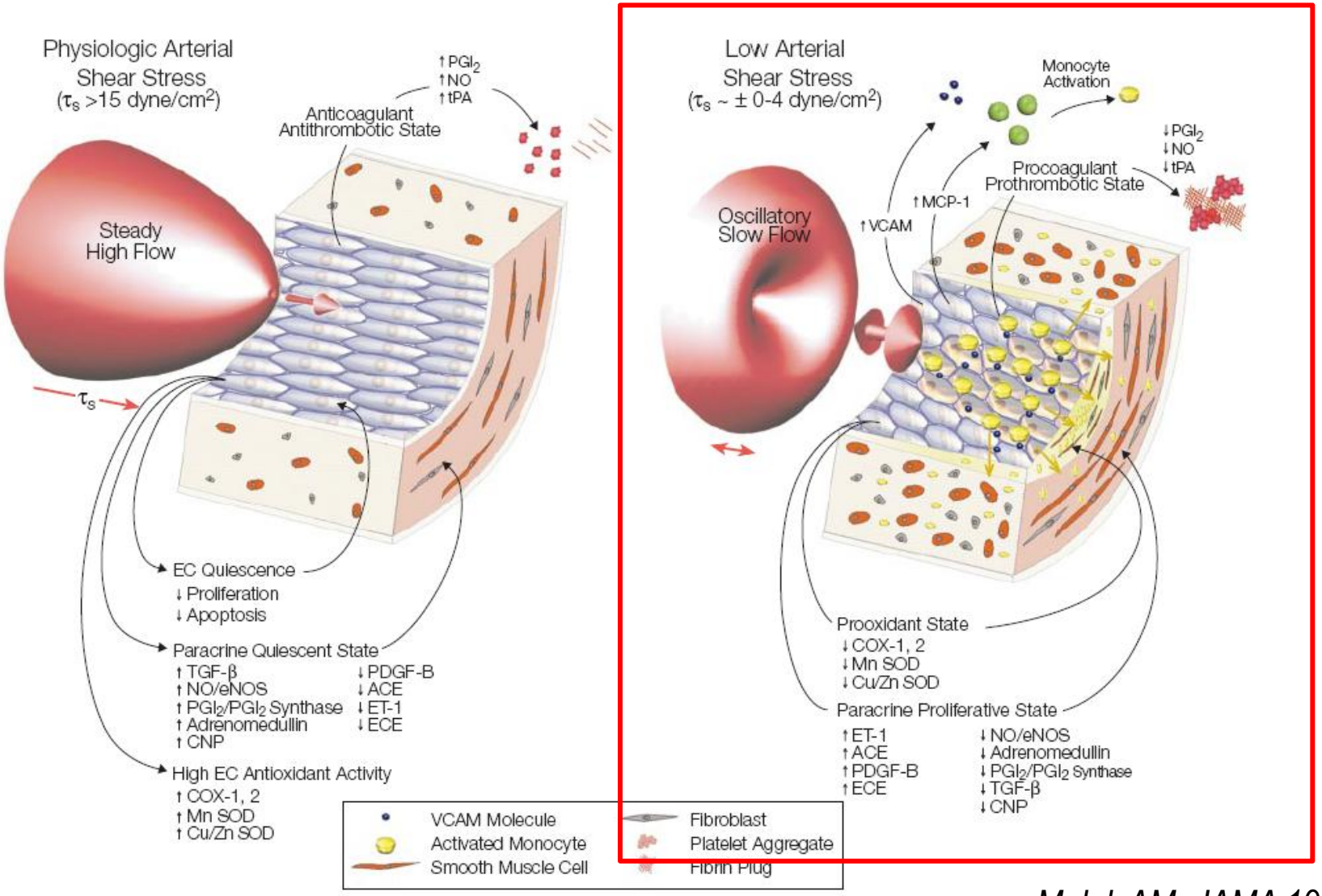
Information on external force in addition to vulnerability can lead to better discrimination of the risk of plaque rupture.

What kind of forces are acting on the plaque?



Low wall shear stress

→ Proliferative, pro-inflammatory, pro-thrombotic stimulus



Malek AM, JAMA 1999

Very high WSS vs. Vulnerability

Annals of Biomedical Engineering, Vol. 41, No. 7, July 2013 *(© 2012)* pp. 1411–1427
DOI: 10.1007/s10439-012-0695-0

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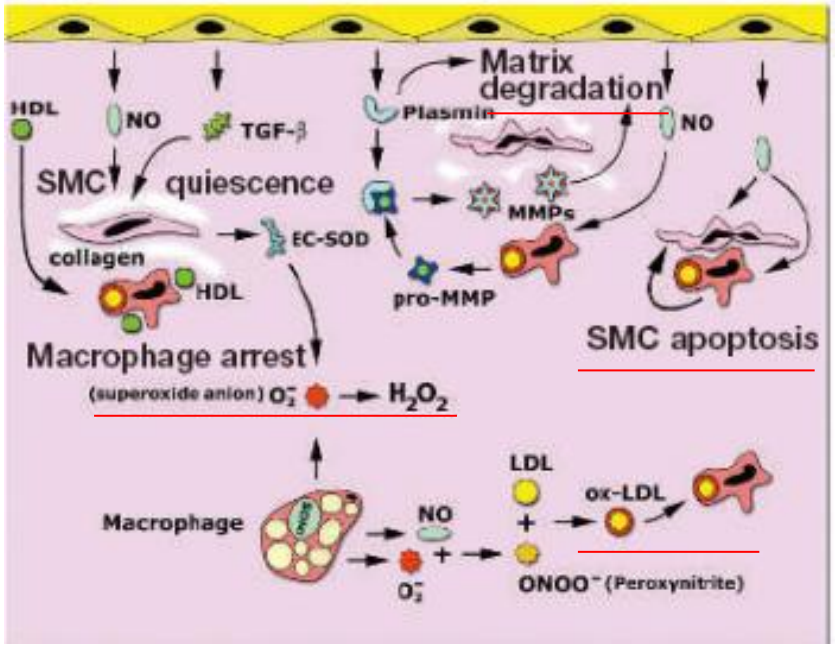
High Wall Shear Stress and Spatial Gradients in Vascular Pathology: A Review

JENNIFER M. DOLAN,[1,3,4] JOHN KOLEGA,[1,3,4] and HUI MENG[1,2,3,5]

Abstract—Cardiovascular pathologies such as intracranial aneurysms (IAs) and atherosclerosis preferentially localize to bifurcations and curvatures where hemodynamics are complex. While extensive knowledge about low wall shear stress (WSS) has been generated in the past, due to its strong relevance to atherogenesis, high WSS (typically >3 Pa) has emerged as a key regulator of vascular biology and pathology as well, receiving renewed interests. As reviewed here, chronic high WSS not only stimulates adaptive outward remodeling, but also contributes to saccular IA formation (at bifurcation apices or outer curves) and atherosclerotic plaque destabilization (in stenosed vessels). Recent advances in understanding IA pathogenesis have shed new light on the

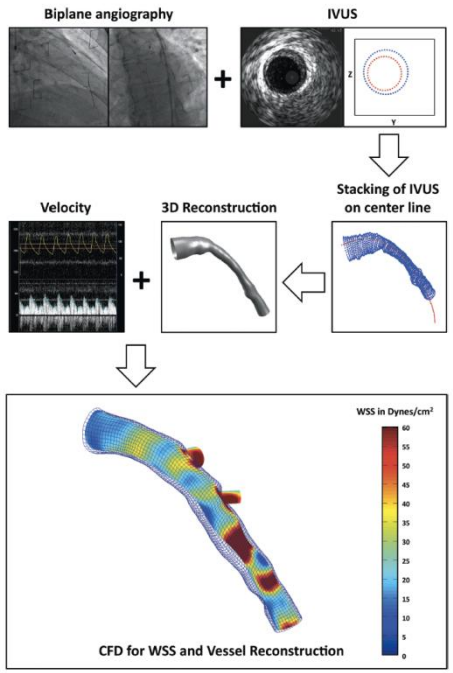
Very High SS

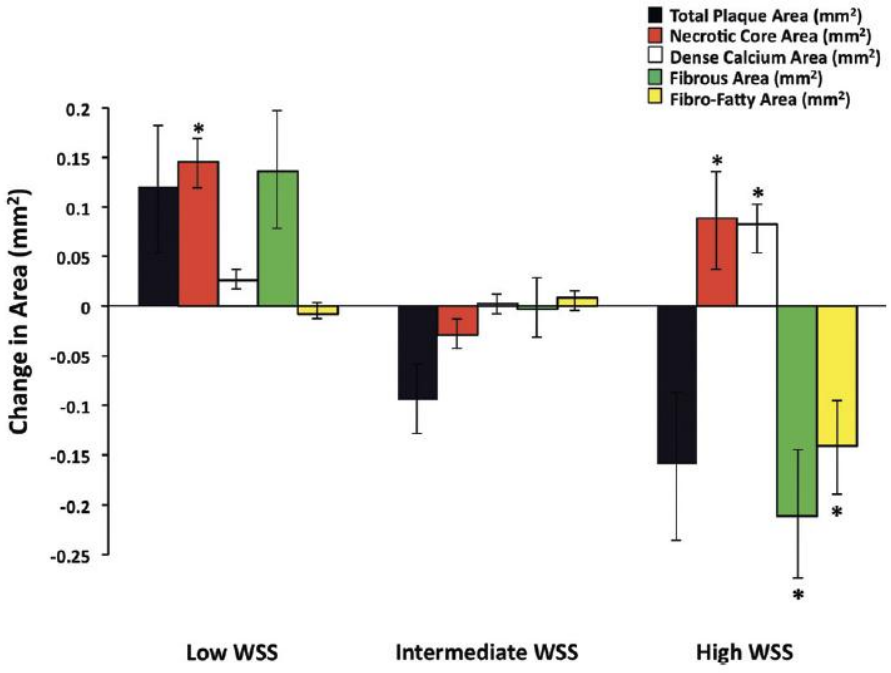


Slager, et al. Nature Clin Pract 2005

Coronary Artery Wall Shear Stress Is Associated With Progression and Transformation of Atherosclerotic Plaque and Arterial Remodeling in Patients With Coronary Artery Disease

Habib Samady, MD; Parham Eshtehardi, MD; Michael C. McDaniel, MD; Jin Suo, PhD; Saurabh S. Dhawan, MD; Charles Maynard, PhD; Lucas H. Timmins, PhD; Arshed A. Quyyumi, MD; Don P. Giddens, PhD

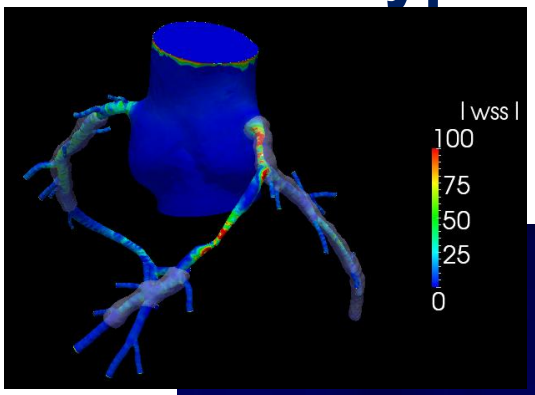


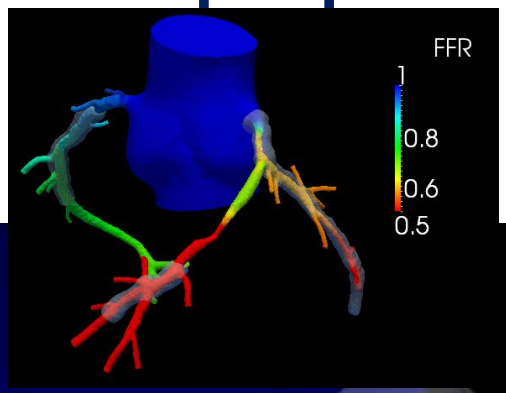


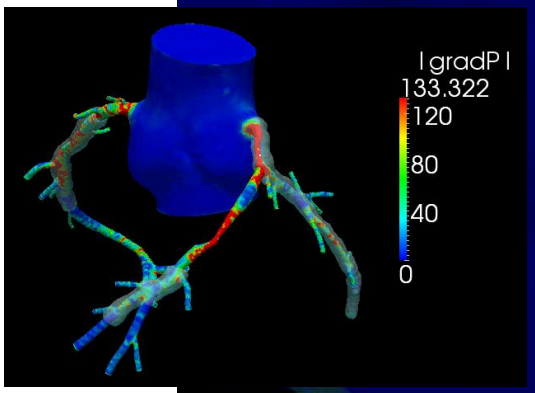
Conclusions—Compared with intermediate-WSS coronary segments, low-WSS segments develop greater plaque and necrotic core progression and constrictive remodeling, and high-WSS segments develop greater necrotic core and calcium progression, regression of fibrous and fibrofatty tissue, and excessive expansive remodeling, suggestive of transformation to a more vulnerable phenotype.

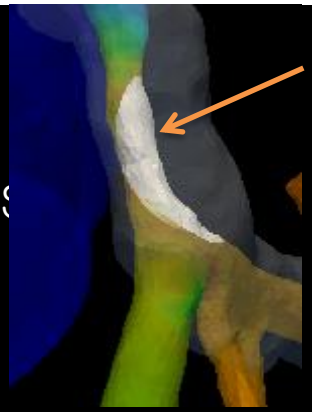
Circulation 2011

Prototype: Total plaque force model (May 29, 2013)

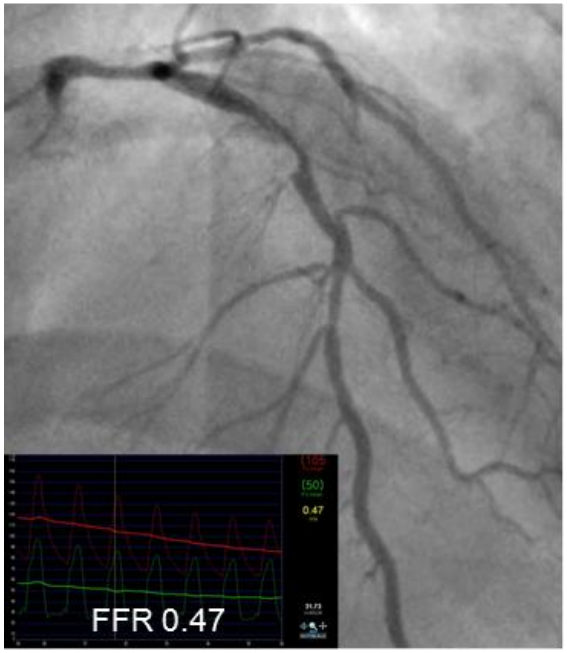


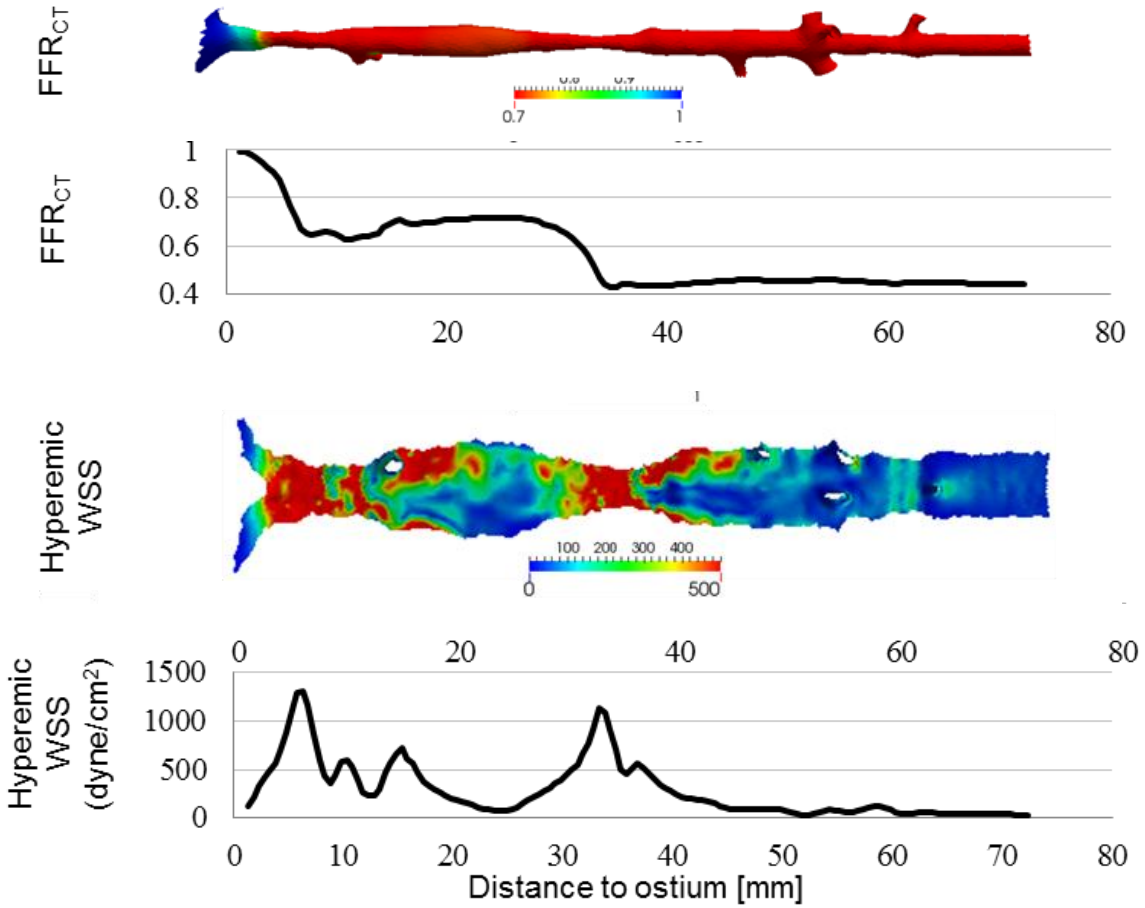






Measurement of hemodynamic parameters in a patient using cCTA and computational fluid dynamics

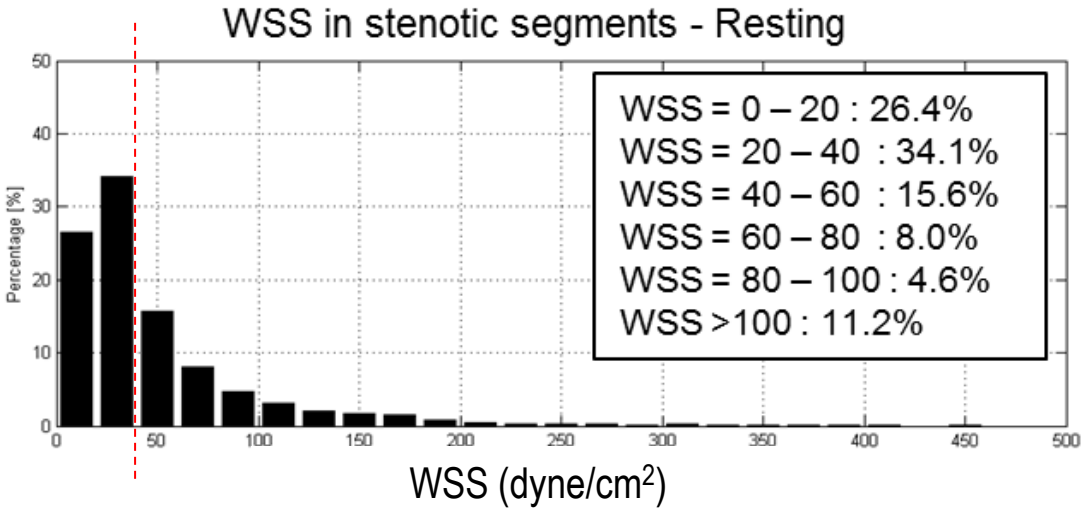


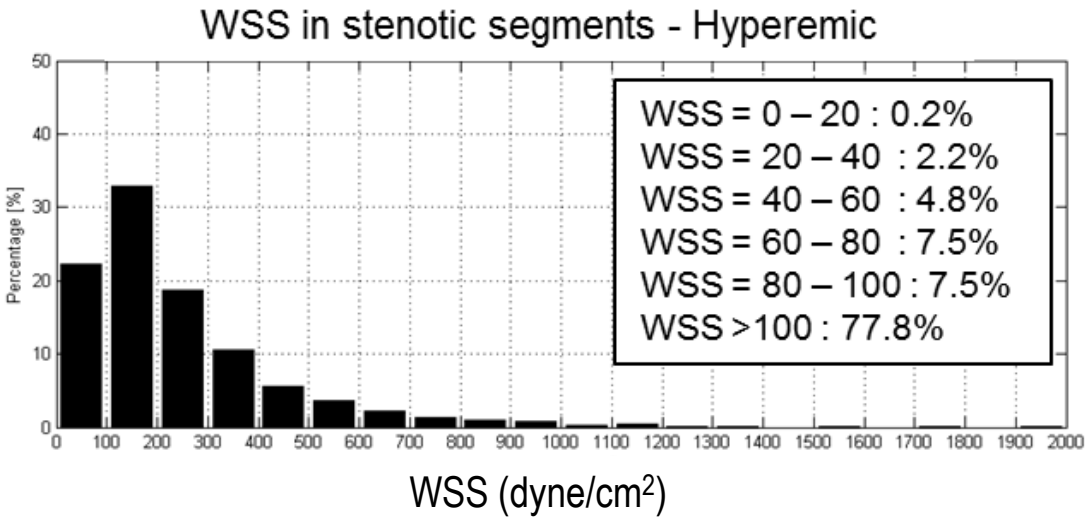


Koo BK. International Symposium on Biomechanics 2014

WSS in clinically relevant lesions

- 80 patients
- Clinically driven invasive coronary angiography and CT angiography
- Average % diameter stenosis: 52.3±12.4%





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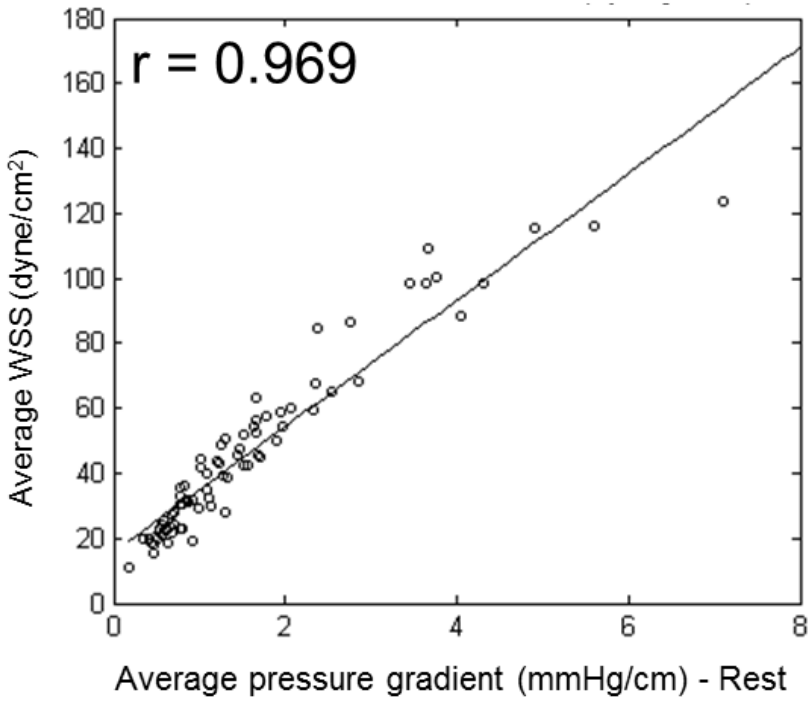
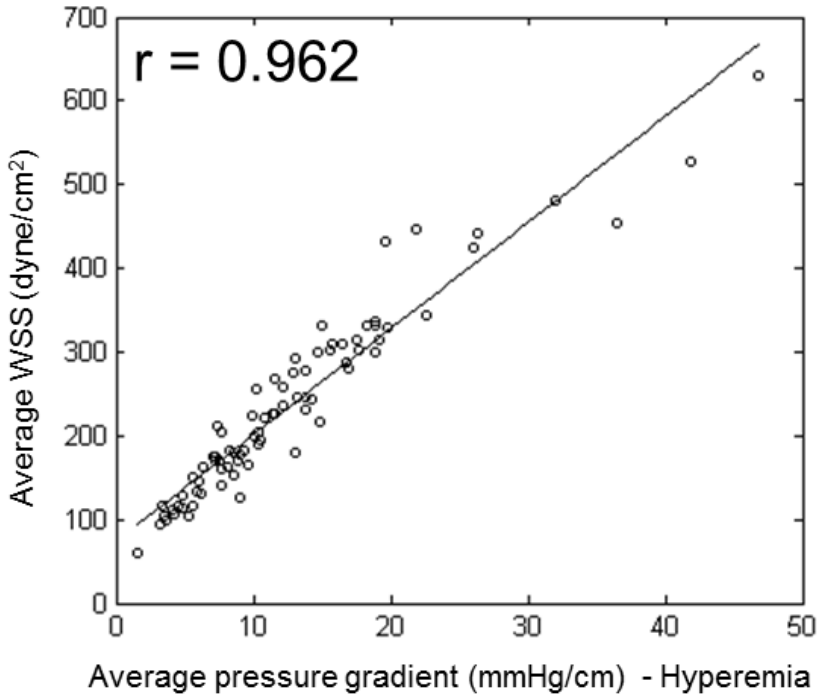
Relationship between WSS and pressure gradient





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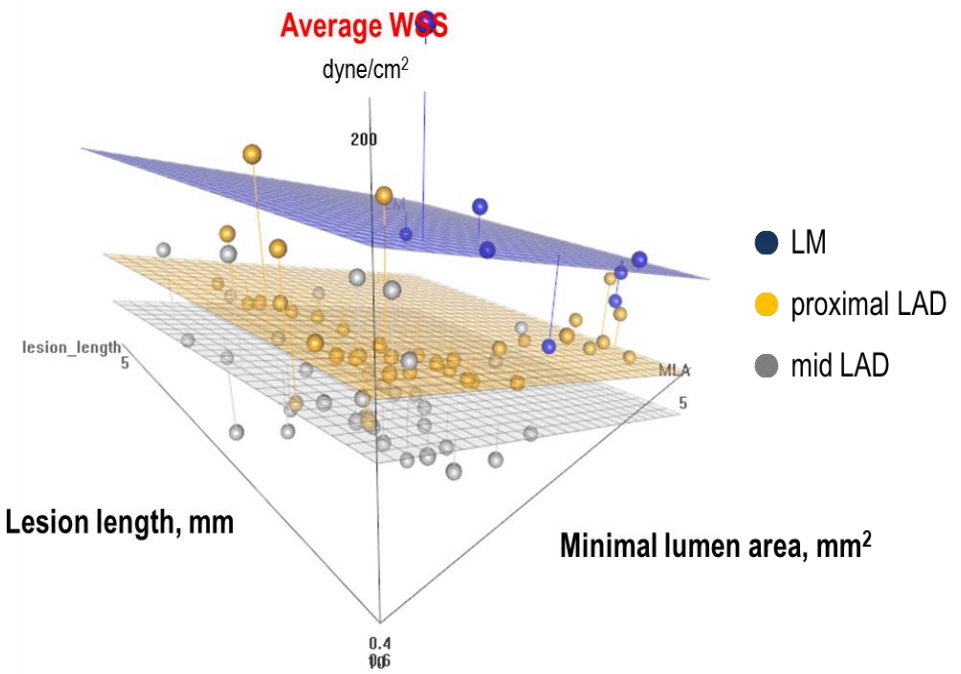
Relationship between WSS and lesion characteristics

Determinants	β	95% CI	p
Pressure Gradient	1.281	0.35 – 2.25	0.007
Blood flow	0.683	0.34 – 1.02	<0.001
Distance from LM ostium	-0.298	-0.56 – -0.04	0.024
Minimal lumen area	-1.676	-2.44 – -0.92	<0.001
Lesion length	-1.157	-1.81 – -0.51	<0.001



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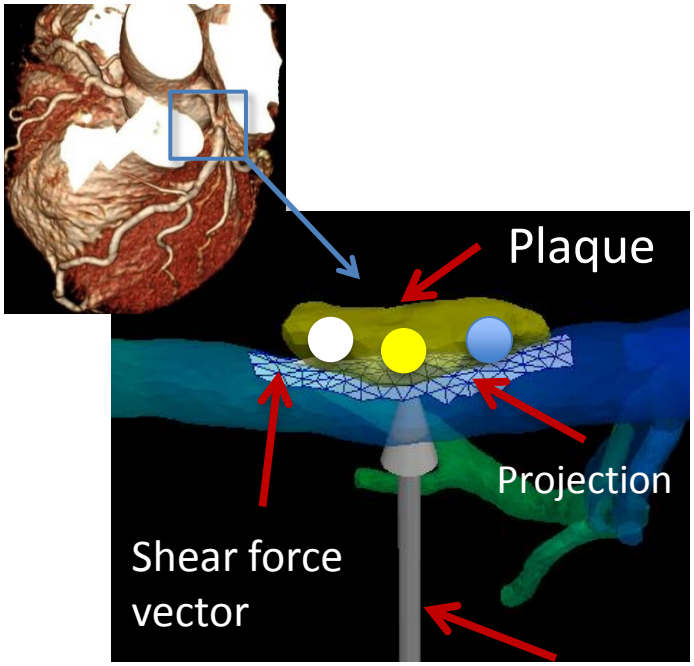
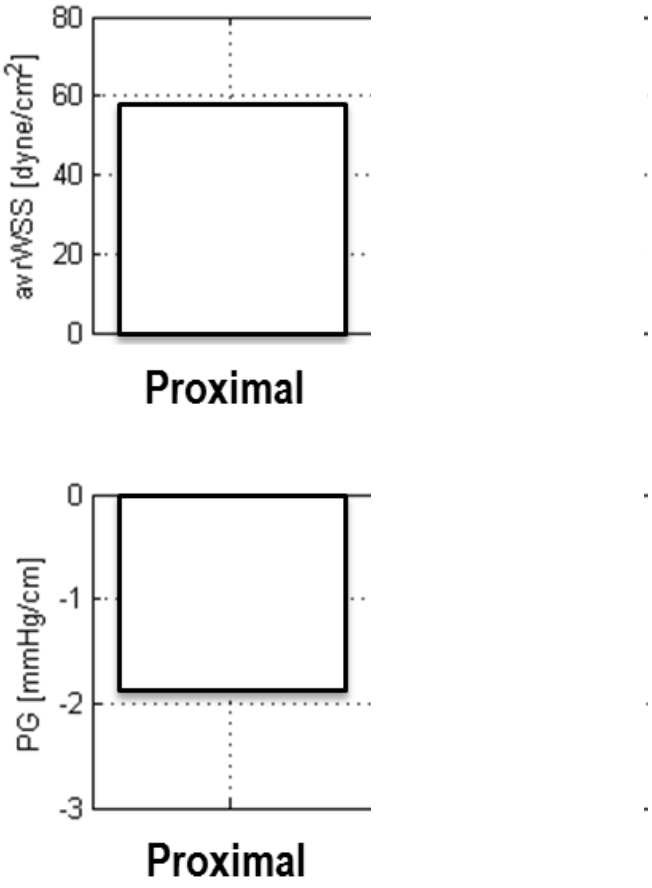
Regional distribution of hemodynamic forces
: Pressure gradient vs. WSS





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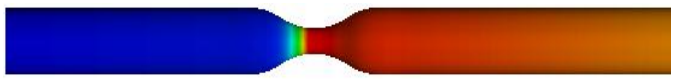
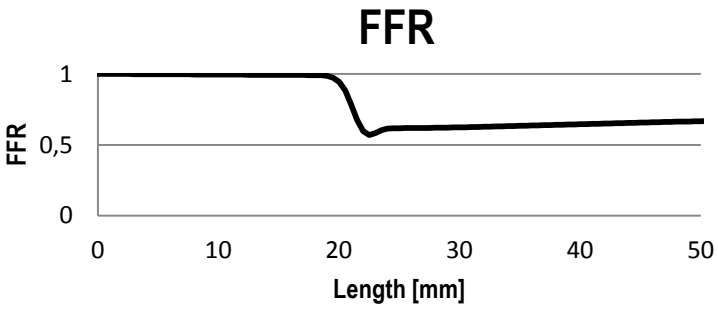
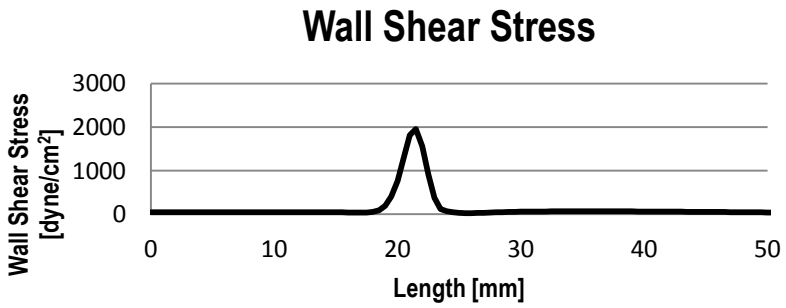
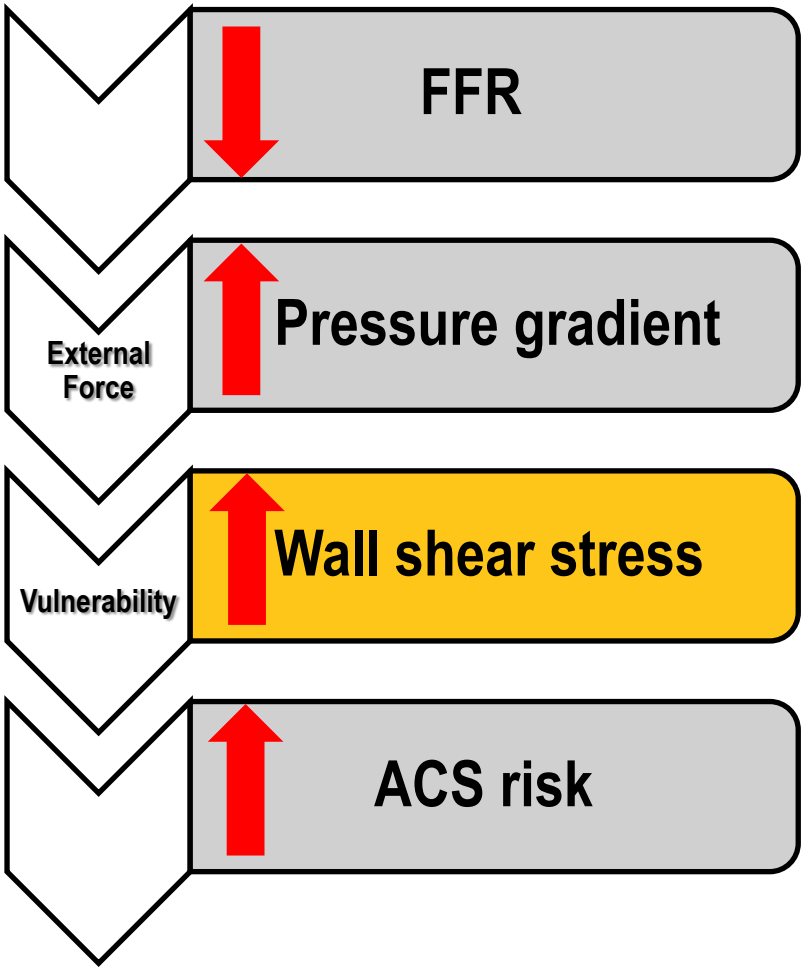
FFR vs. ACS









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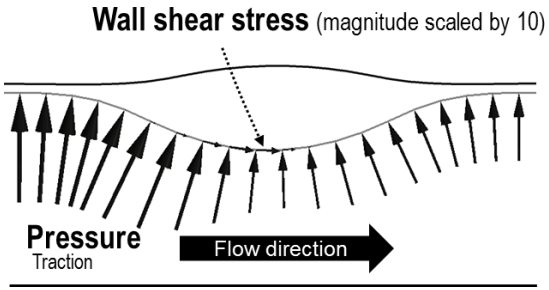
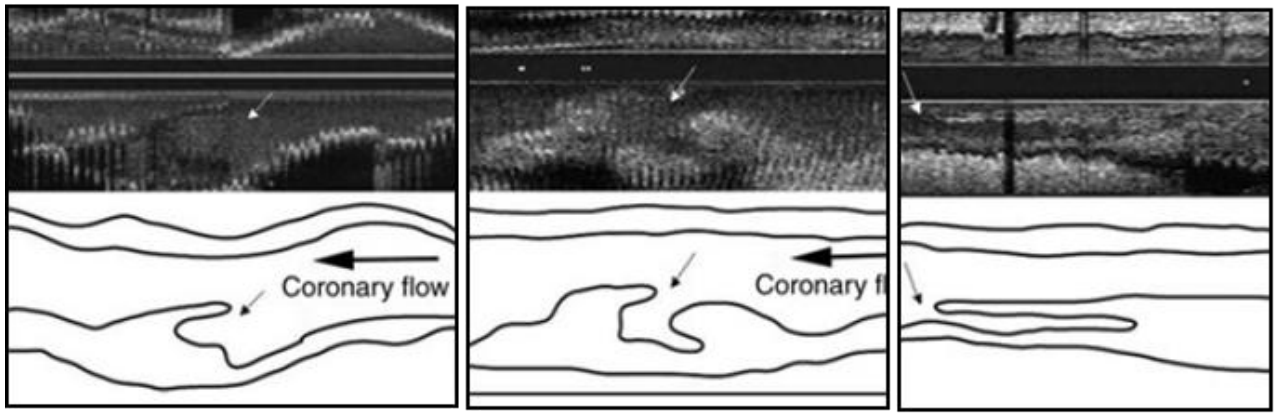
WSS and pressure, are they enough?



Location of rupture



Tanaka, et al. Eur Heart J 2008;29:38-44

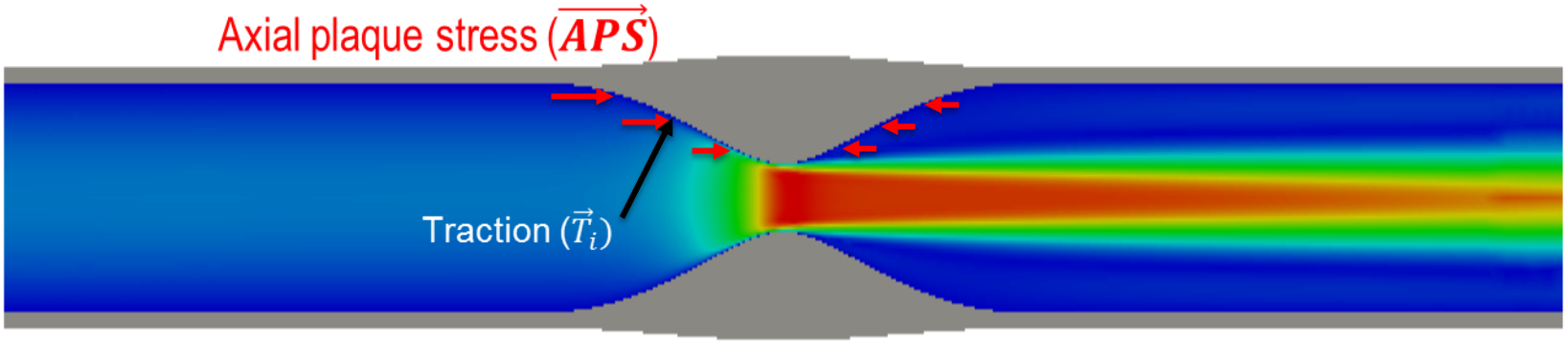
Pressure, FFR and WSS are high at the *upstream segment* of a plaque. Therefore, these parameters cannot explain the occurrence of *downstream rupture*.

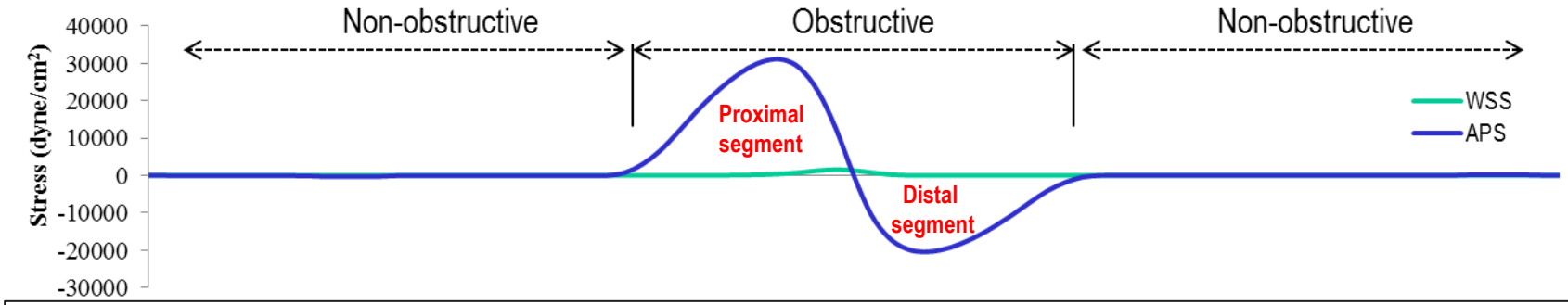
WSS and pressure, then what else?

- Traction is the total force (stress) acting on vessel wall (plaque), and can be decomposed

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

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

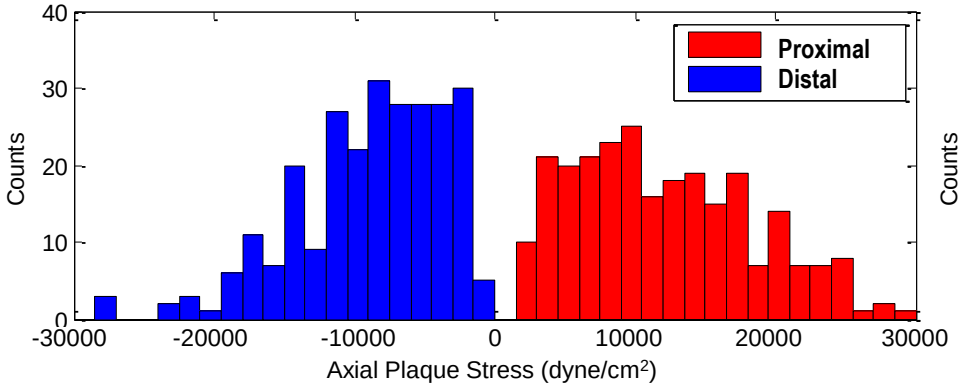




Axial plaque stress is much larger than WSS and uniquely characterizes the upstream and downstream segments of coronary stenosis.

Distribution of "Axial Plaque Stress"

Idealized stenosis models (n=264)



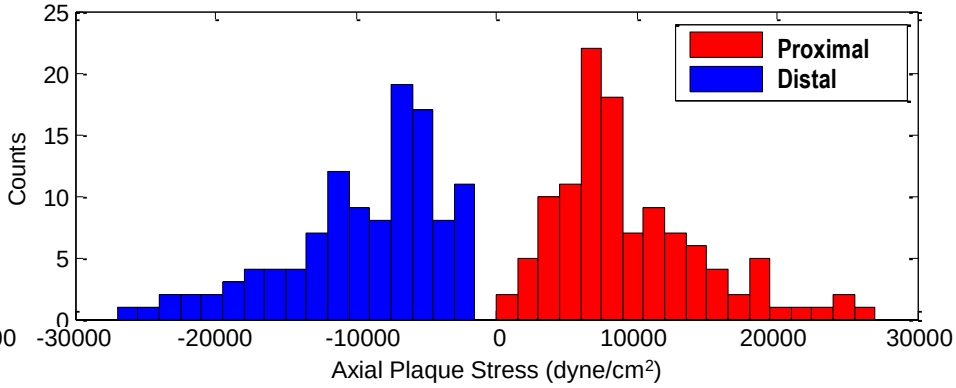
Distal segment

- N=264
- **Median: -7801.3dyne/cm²**
- IQR: -11954.3, - 4603.1

Proximal segment

- N=264
- **Median: 11629.4 dyne/cm²**
- IQR: 11954.3, 4603.2

Patients' lesions (n=114)



Distal segment

- N=114
- **Median: -7912.4dyne/cm²**
- IQR: -12366.7, - 5632.7

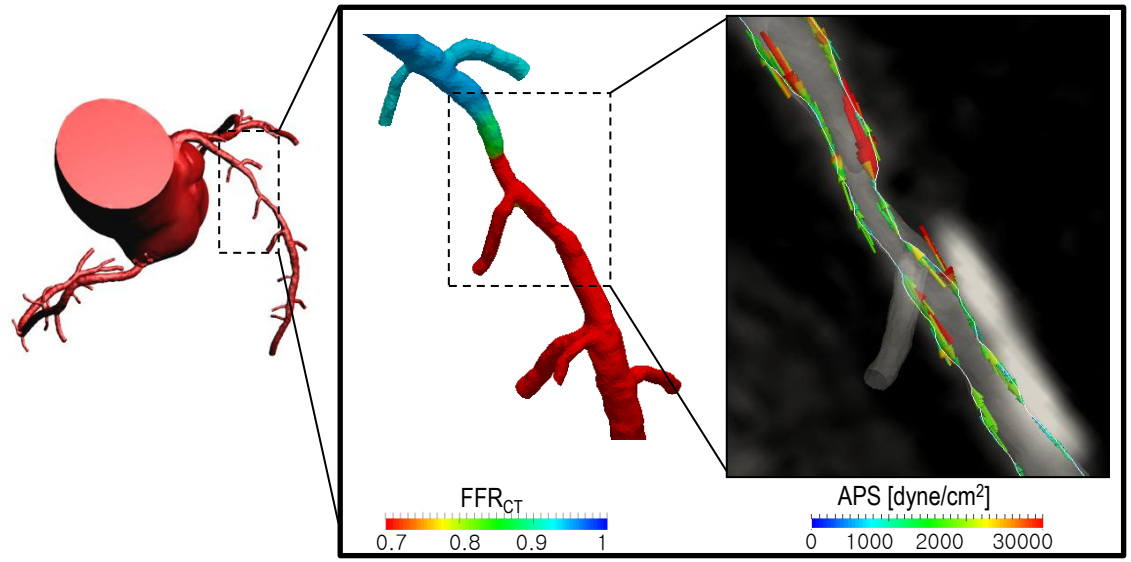
Proximal segment

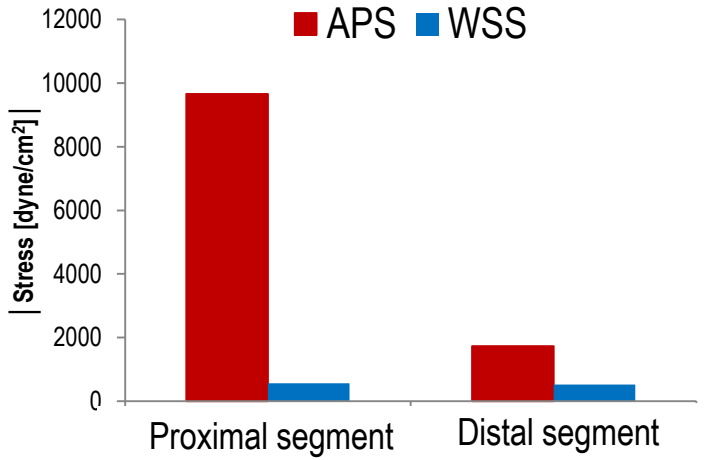
- N=114
- **Median: 7885.66 dyne/cm²**
- IQR: 6055.9, 12707.9

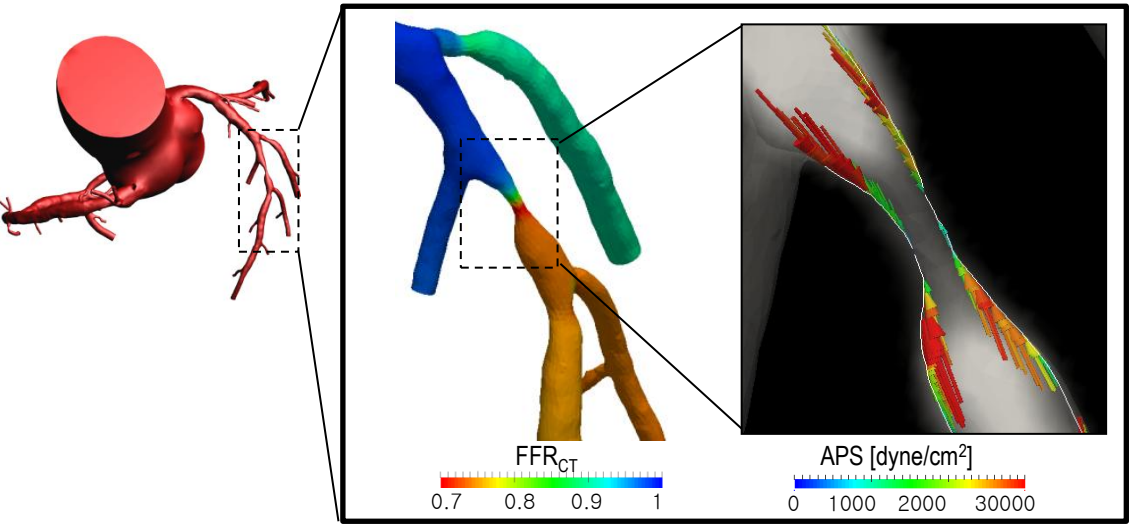
Distribution of axial plaque stress is similar between idealized models and patients lesions.

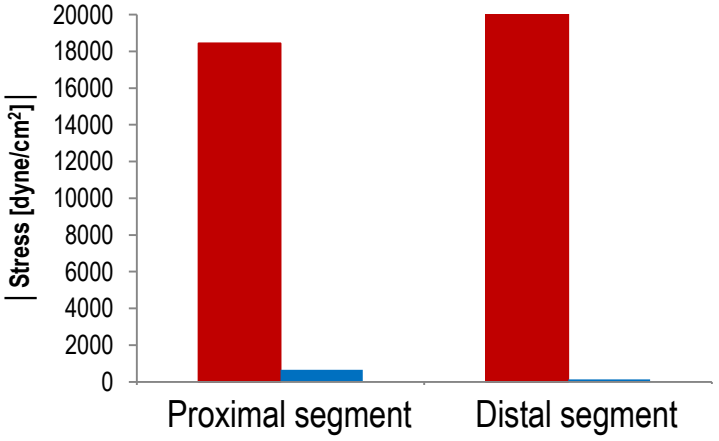
JACC imaging 2015, in press

Distribution of Axial Plaque Stress in patients



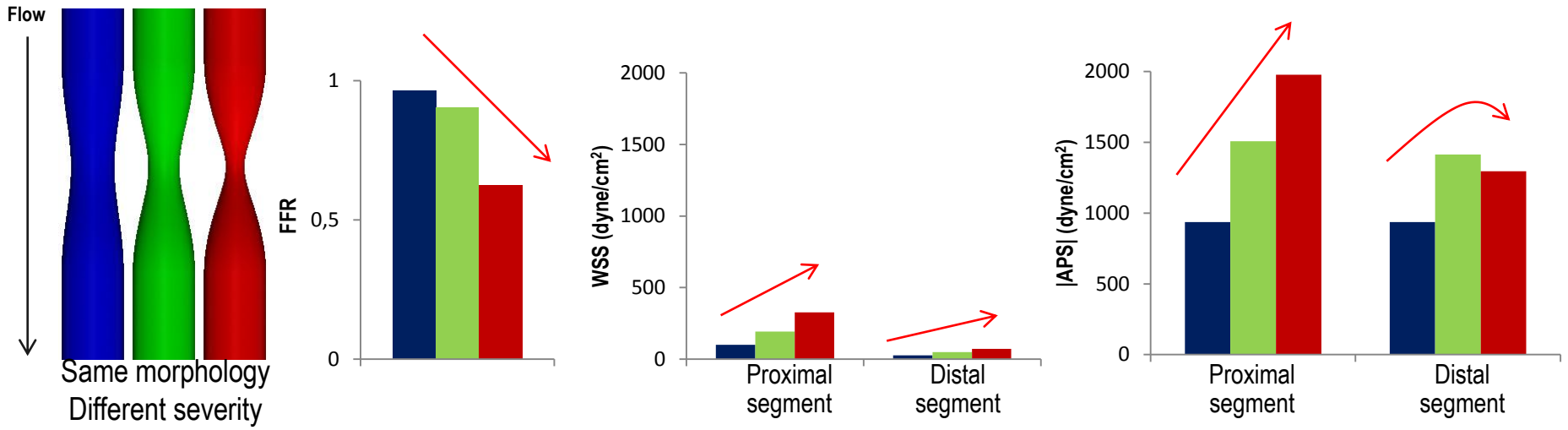


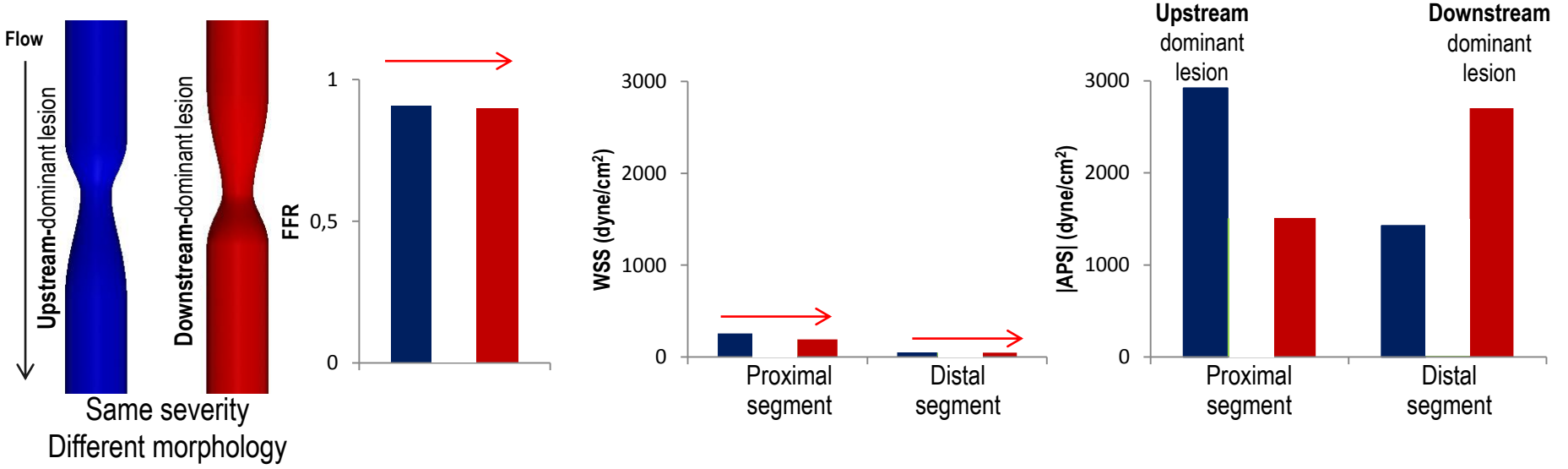




JACC imaging 2015, in press

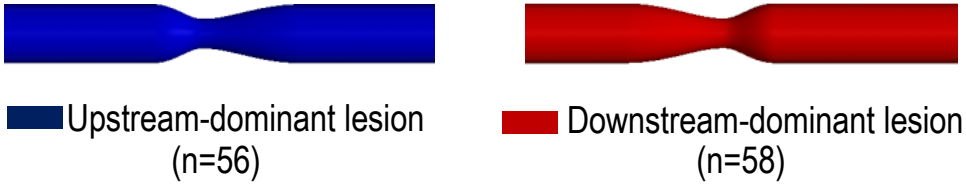
Lesion geometry vs. Hemodynamic forces



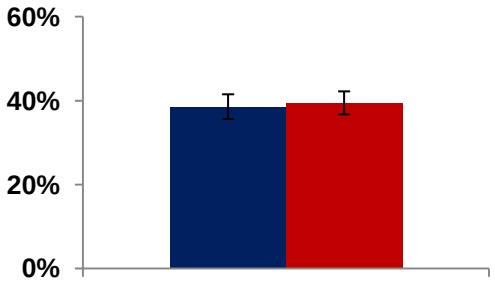


JACC imaging 2015, in press

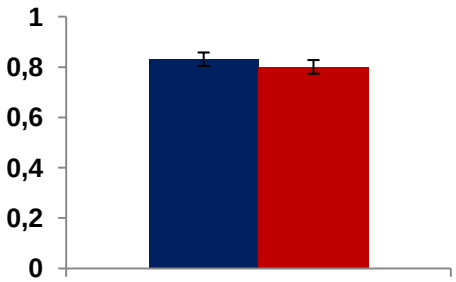
Influence of "Lesion Shape" on Hemodynamic Parameters (n=114)



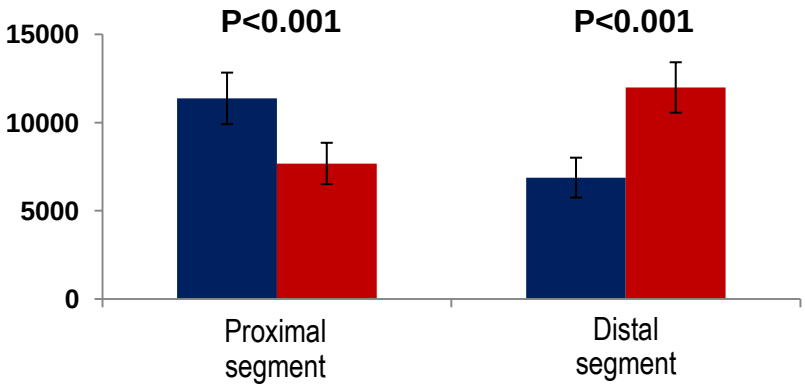
% Diameter Stenosis



FFR_{CT}



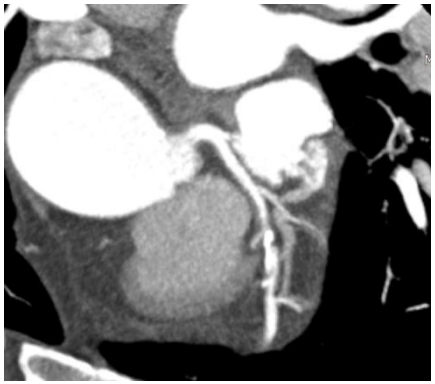
| Axial Plaque Stress | (dyne/cm^2)



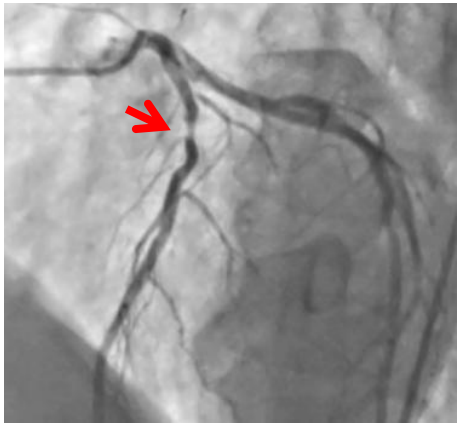
JACC imaging 2015, in press

Future perspective

2011-04 CT, Asymptomatic

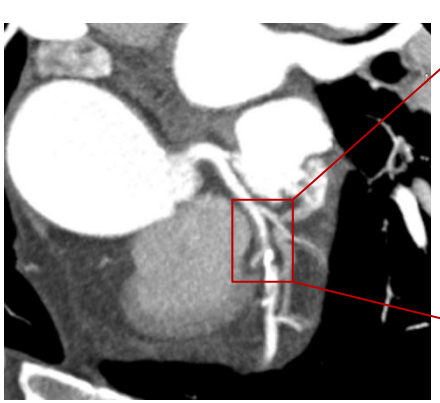


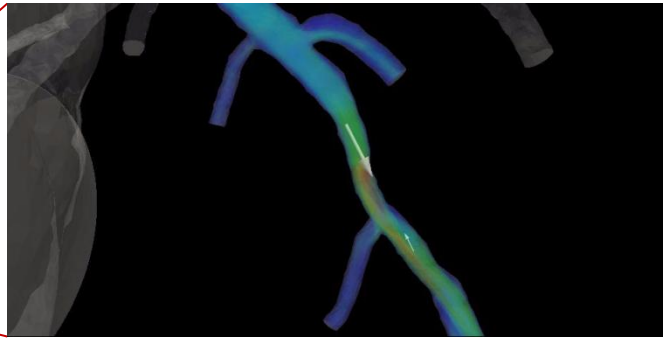
2012-06 Acute MI

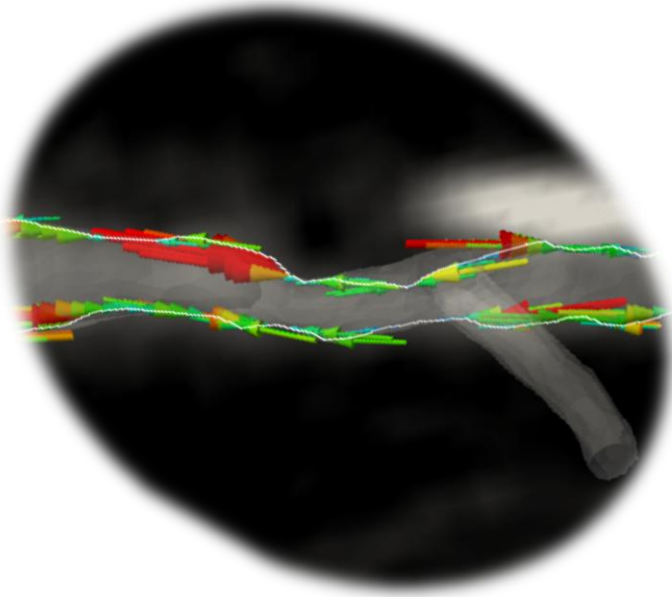


Future perspective

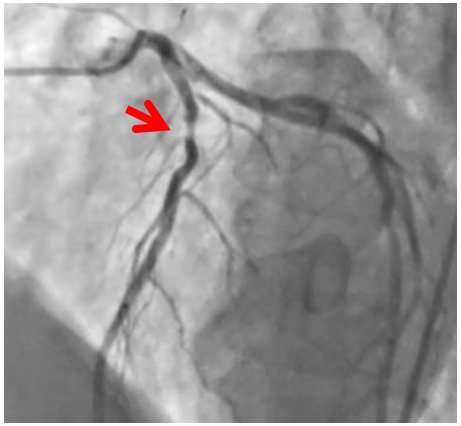
2011-04 CT, Asymptomatic



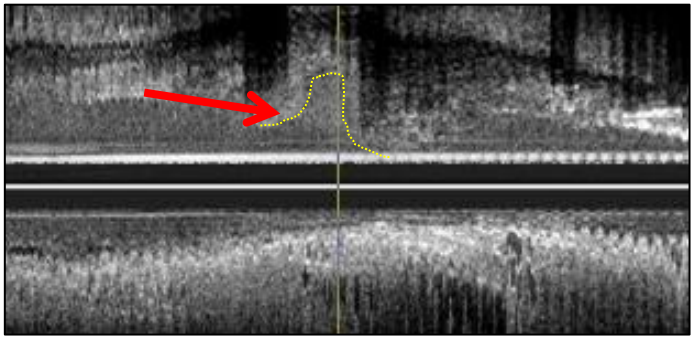




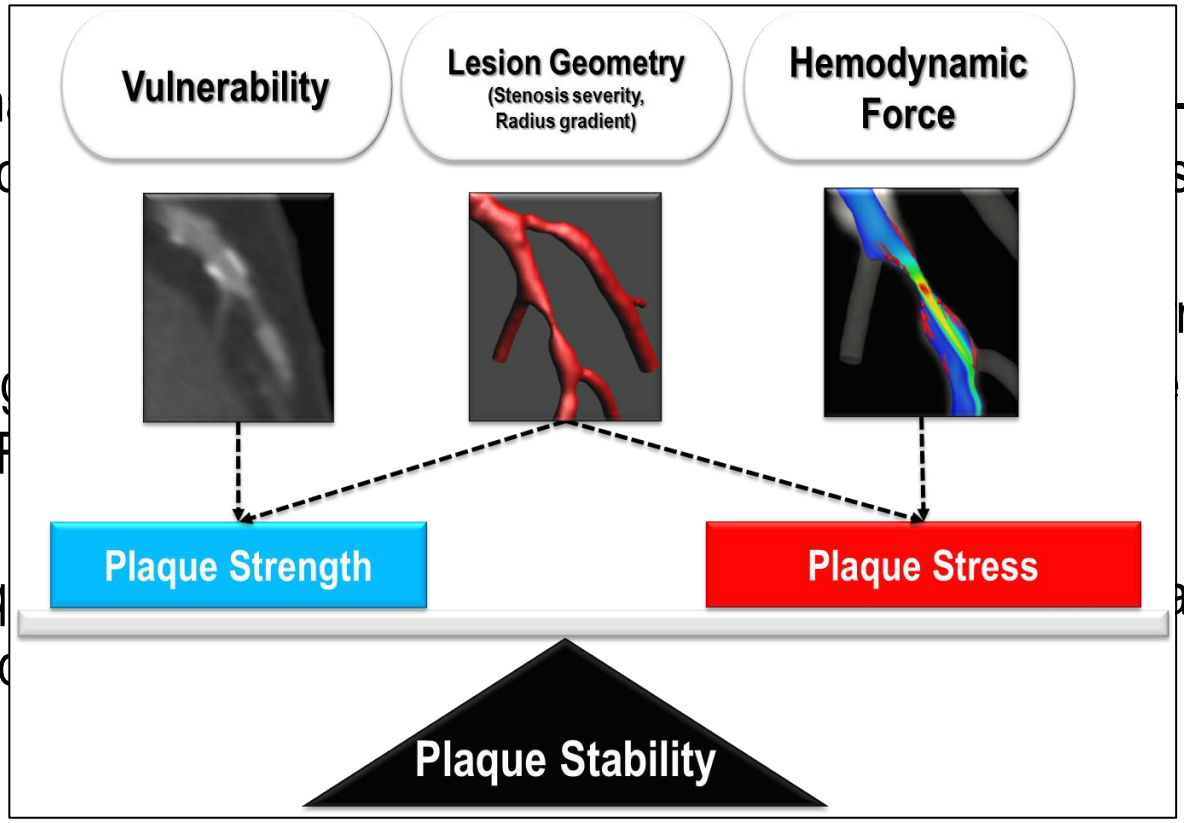
2012-06 Acute MI



	APS
Upstream	**9960 dyne/cm^2**
Downstream	1740 dyne/cm^2



Conclusion



- Hemodyn -invasively using cor s.
- Very high mined by pressure the link between
- Axial plaq and can provide a
- Clinical application of these non-invasive hemodynamic parameters can be helpful to assess the future risk of plaque related clinical events.