From CTA to CT-FFR

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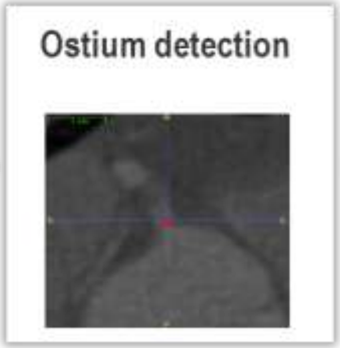
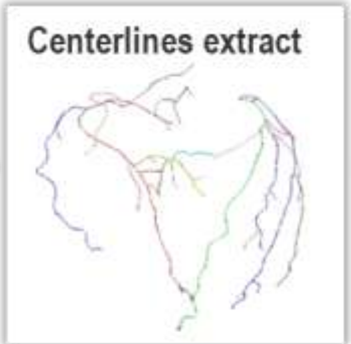
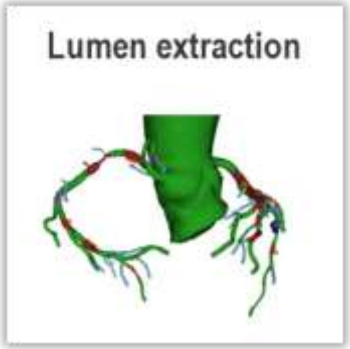
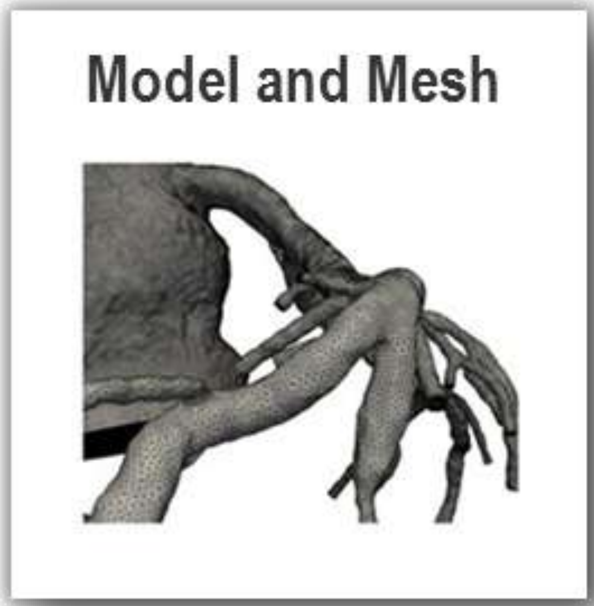
How to assess hemodynamics from static image?

Step #1 3-dimensional anatomic modelling

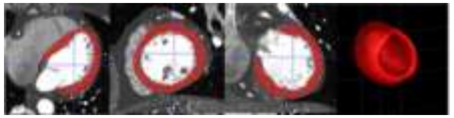








How to assess hemodynamics from static image?



2. Resistance: *Resistance of microcirculatory vascular bed at rest is inversely proportional to size of feeding vessel*

: $P=QR$ and $Q \propto d^k$, then $R \propto d^{-k}$

How to assess hemodynamics from static image?

2. Resistance: *Resistance of microcirculatory vascular bed at rest is inversely proportional to size of feeding vessel*

: P=QR and Q $\propto$ d^k, then R $\propto$ d^{-k}

Mass Conservation (1 equation):

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0$$

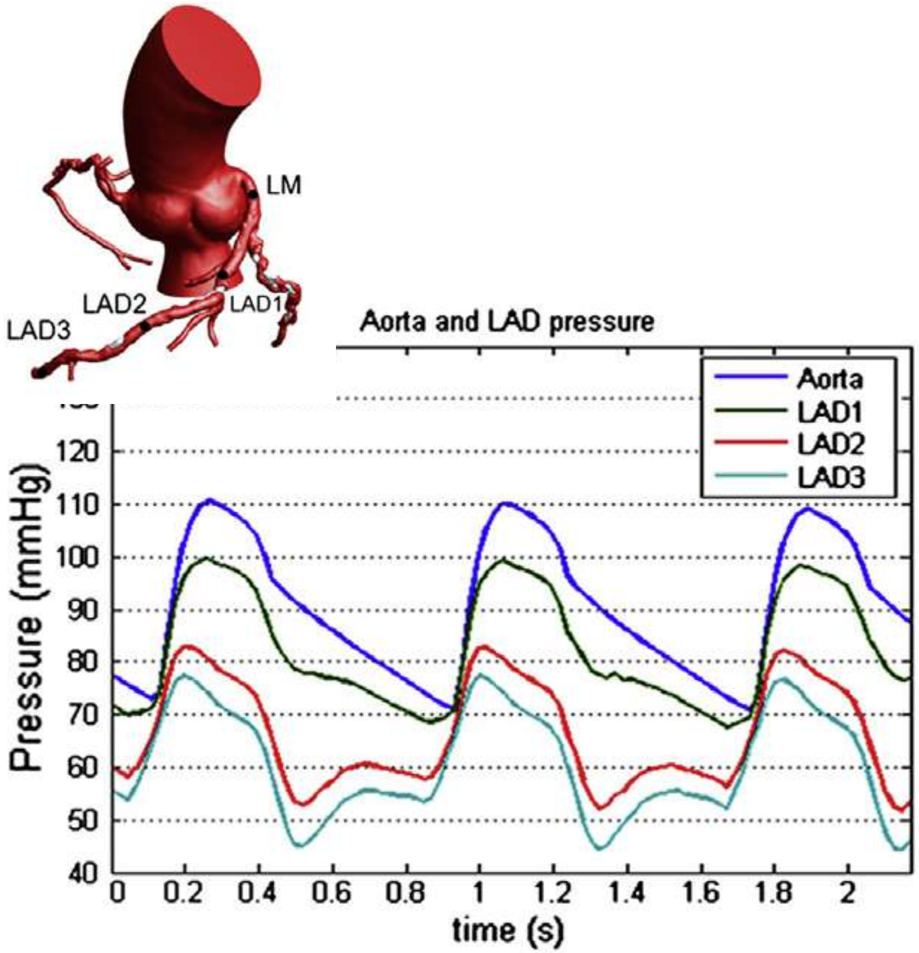
Momentum Balance (3 equations):

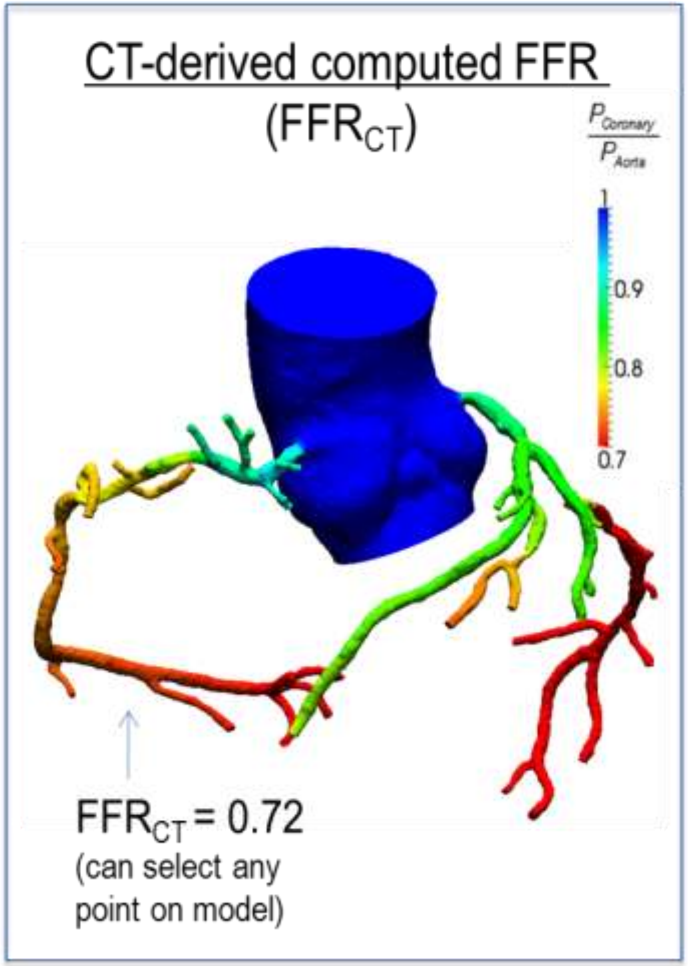
$$\rho\frac{\partial v_x}{\partial t}+\rho\left(v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}+v_z\frac{\partial v_x}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right)$$

$$\rho\frac{\partial v_y}{\partial t}+\rho\left(v_x\frac{\partial v_y}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_y}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right)$$

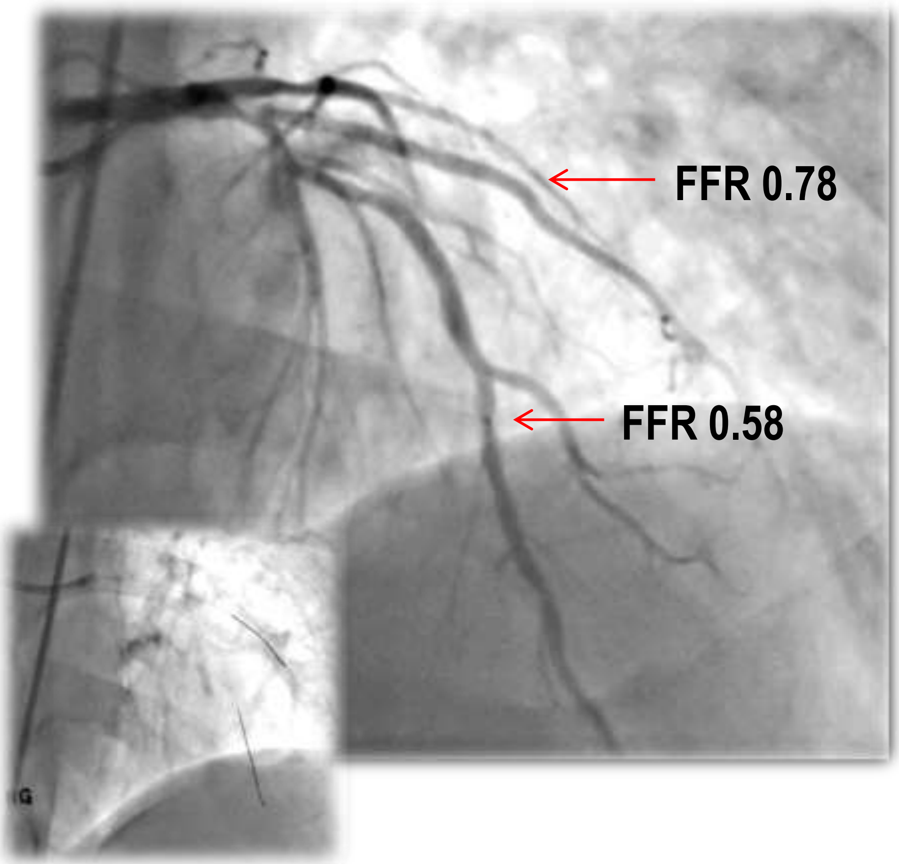
$$\rho\frac{\partial v_z}{\partial t}+\rho\left(v_x\frac{\partial v_z}{\partial x}+v_y\frac{\partial v_z}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right)$$

Hemodynamics from static image

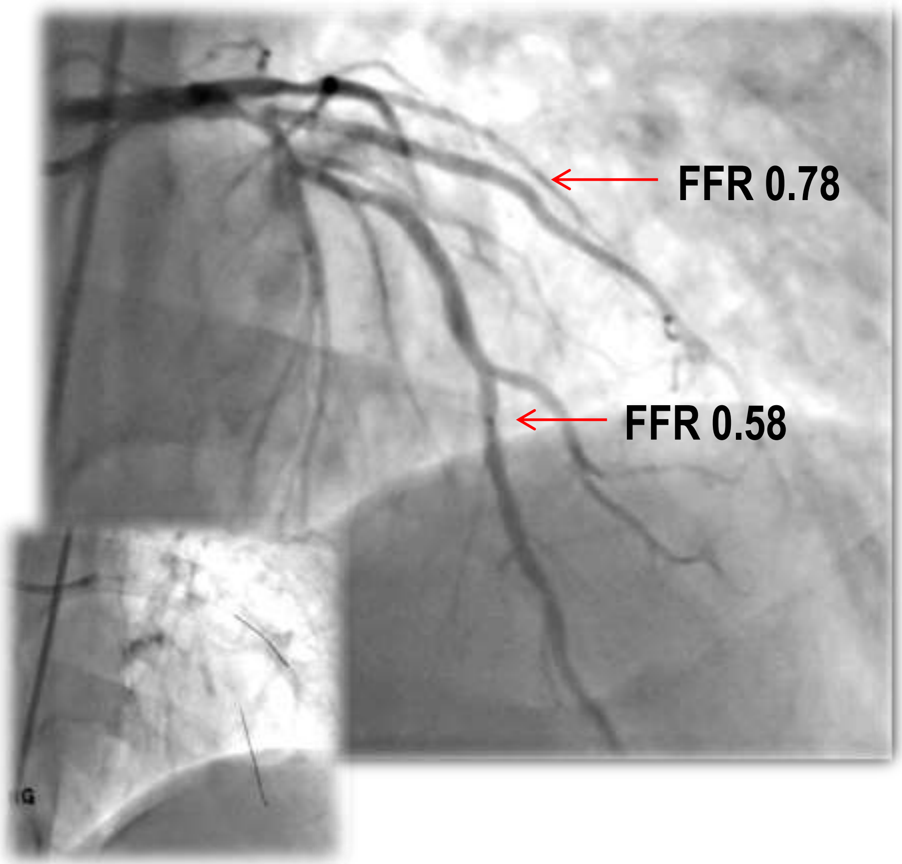


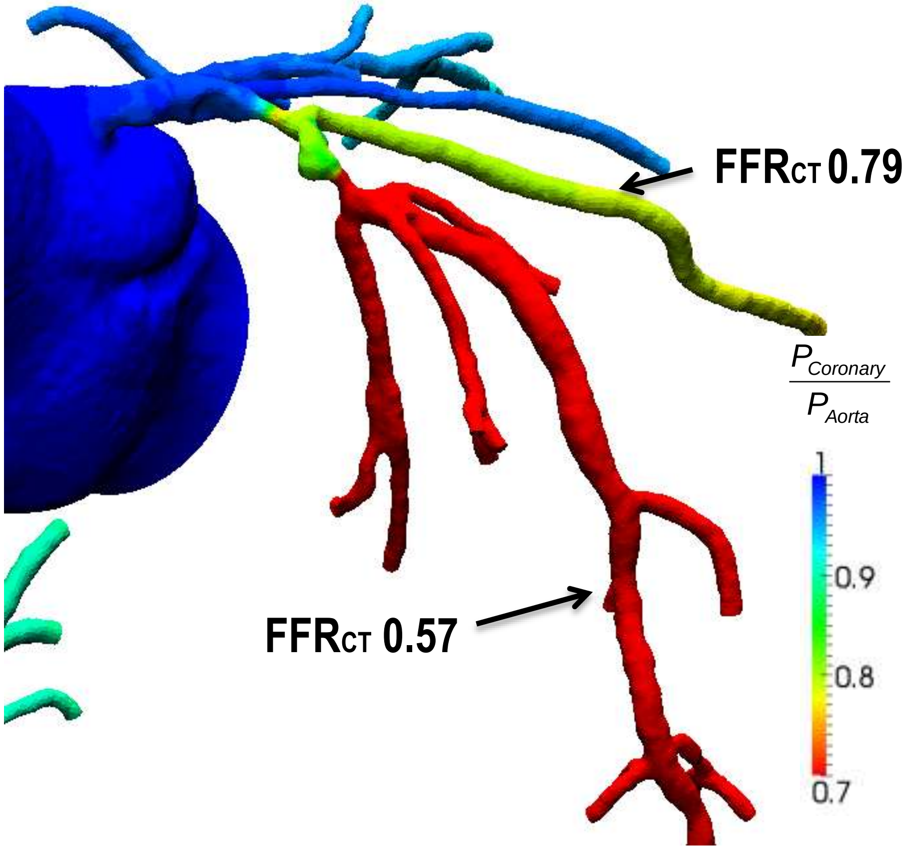


FFR vs. CT-derived computed FFR



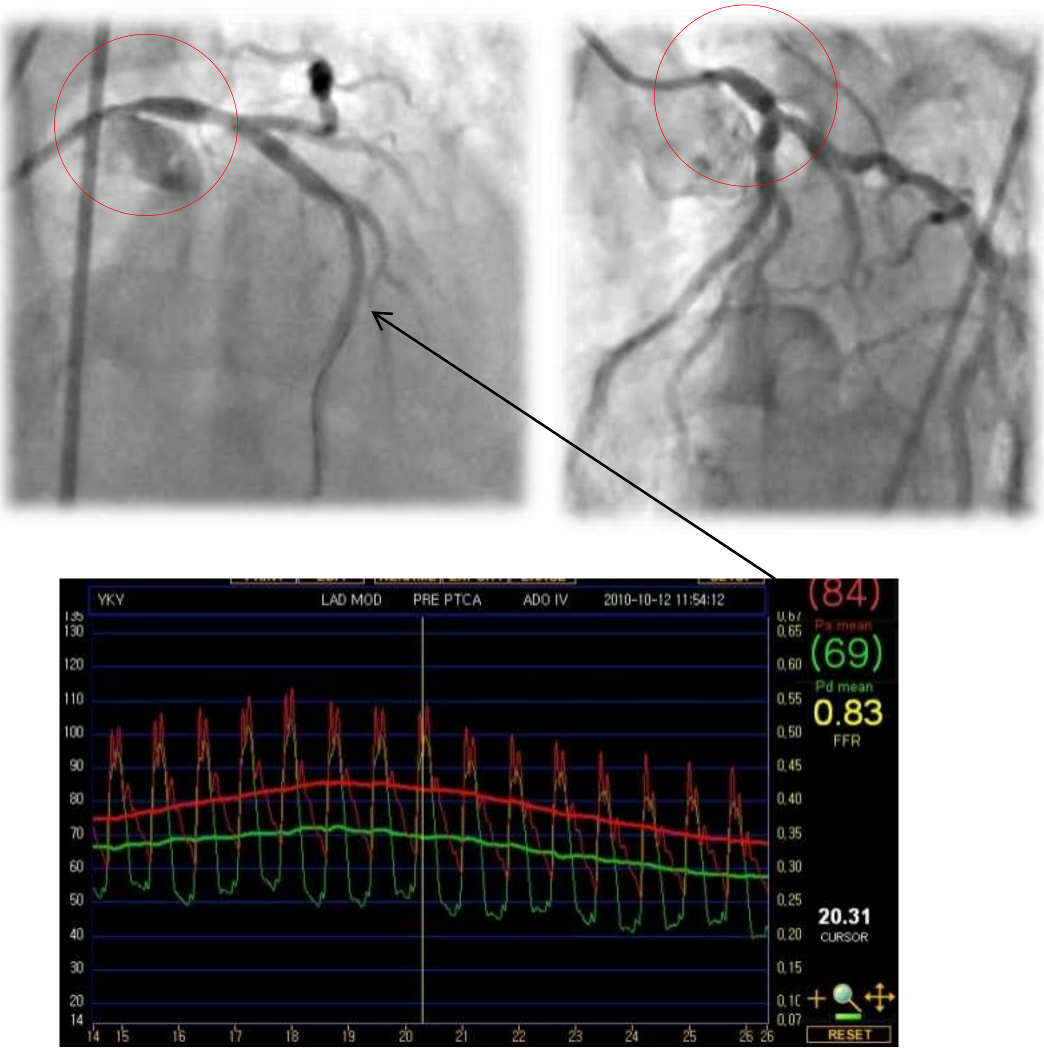
FFR vs. CT-derived computed FFR

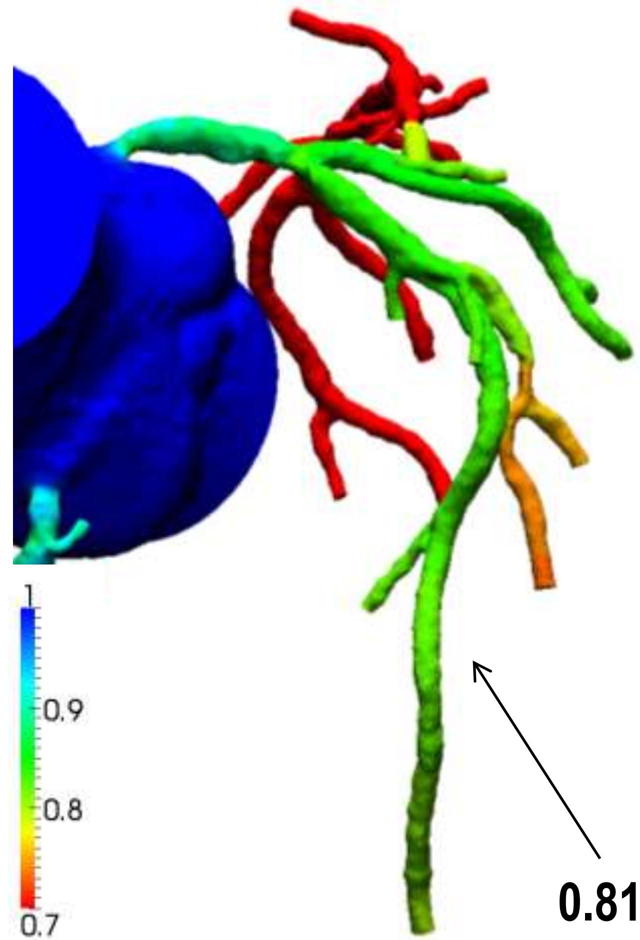




Without invasive procedure
Without pressure wire, without adenosine

FFR vs. CT-derived computed FFR





Clinical Evidences on Diagnostic Performance

- **DISCOVER-FLOW**
  - 5 center FIH clinical trial
  - Completed 2011
  - N=103 patients
  - Published in JACC
- **DeFACTO**
  - 17 center clinical trial
  - Completed 2012
  - N=252 patients
  - Published in JAMA
- **NXT**
  - 10 center clinical trial
  - Completed August, 2013
  - N=251 patients
  - Published in JACC

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doi:10.1016/j.jacc.2011.06.066

Cardiac Imaging

Diagnosis of Ischemia-Causing Coronary Stenoses by Noninvasive Fractional Flow Reserve Computed From Coronary Computed Tomographic Angiograms

Results From the Prospective Multicenter DISCOVER-FLOW (Diagnosis of Ischemia-Causing Stenoses Obtained Via Noninvasive Fractional Flow Reserve) Study

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Seoul and Goyang, South Korea; Riga, Latvia; Palo Alto, San Francisco, and Los Angeles, California; New York, New York; New Haven, Connecticut; and Vancouver, British Columbia, Canada

ORIGINAL CONTRIBUTION

ONLINE FIRST

Diagnostic Accuracy of Fractional Flow Reserve From Anatomic CT Angiography

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Laura Mauri, MD

Context Coronary computed tomographic (CT) angiography is a noninvasive anatomic test for diagnosis of coronary stenosis that does not determine whether a stenosis causes ischemia. In contrast, fractional flow reserve (FFR) is a physiologic measure of coronary stenosis expressing the amount of coronary flow still attainable despite the presence of a stenosis, but it requires an invasive procedure. Noninvasive FFR computed from CT (FFR_{CT}) is a novel method for determining the physiologic significance of coronary artery disease (CAD), but its ability to identify ischemia has not been adequately examined to date.

Objective To assess the diagnostic performance of FFR_{CT} plus CT for diagnosis of hemodynamically significant coronary stenosis.

Design, Setting, and Patients Multicenter diagnostic performance study involving 252 stable patients with suspected or known CAD from 17 centers in 5 countries who underwent CT, invasive coronary angiography (ICA), FFR, and FFR_{CT} between October 2010 and October 2011. Computed tomography, ICA, FFR, and FFR_{CT} were interpreted in blinded fashion by independent core laboratories. Accuracy of FFR_{CT} plus CT for diagnosis of ischemia was compared with an invasive FFR reference standard. Ischemia was defined by an FFR or FFR_{CT} of 0.80 or less, while anatomically obstructive CAD was defined by a stenosis of 50% or larger on CT and ICA.

Main Outcome Measures The primary study outcome assessed whether FFR_{CT} plus CT could improve the per-patient diagnostic accuracy such that the lower boundary of the 1-sided 95% confidence interval of this estimate exceeded 70%.

Results Among study participants, 137 (54.4%) had an abnormal FFR determined by ICA. On a per-patient basis, diagnostic accuracy, sensitivity, specificity, positive predictive value, and negative predictive value of FFR_{CT} plus CT were 73% (95% CI, 67%-78%), 90% (95% CI, 84%-95%), 54% (95% CI, 46%-83%), 67% (95% CI, 60%-74%), and 84% (95% CI, 74%-90%), respectively. Compared with obstructive CAD

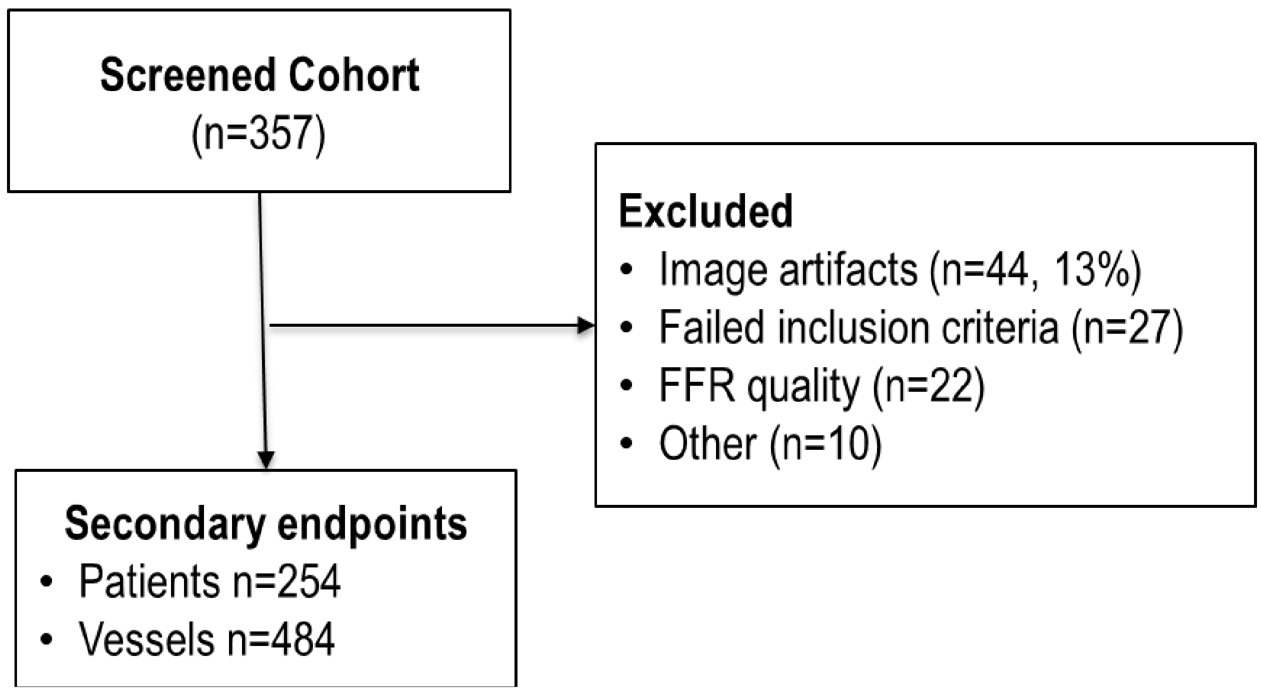
NXT study

Incorporates learning from previous FFR_{CT} trials:

- Newest generation of FFR_{CT} analysis software
- Strict CT acquisition protocol according to societal guidelines

CT Characteristics

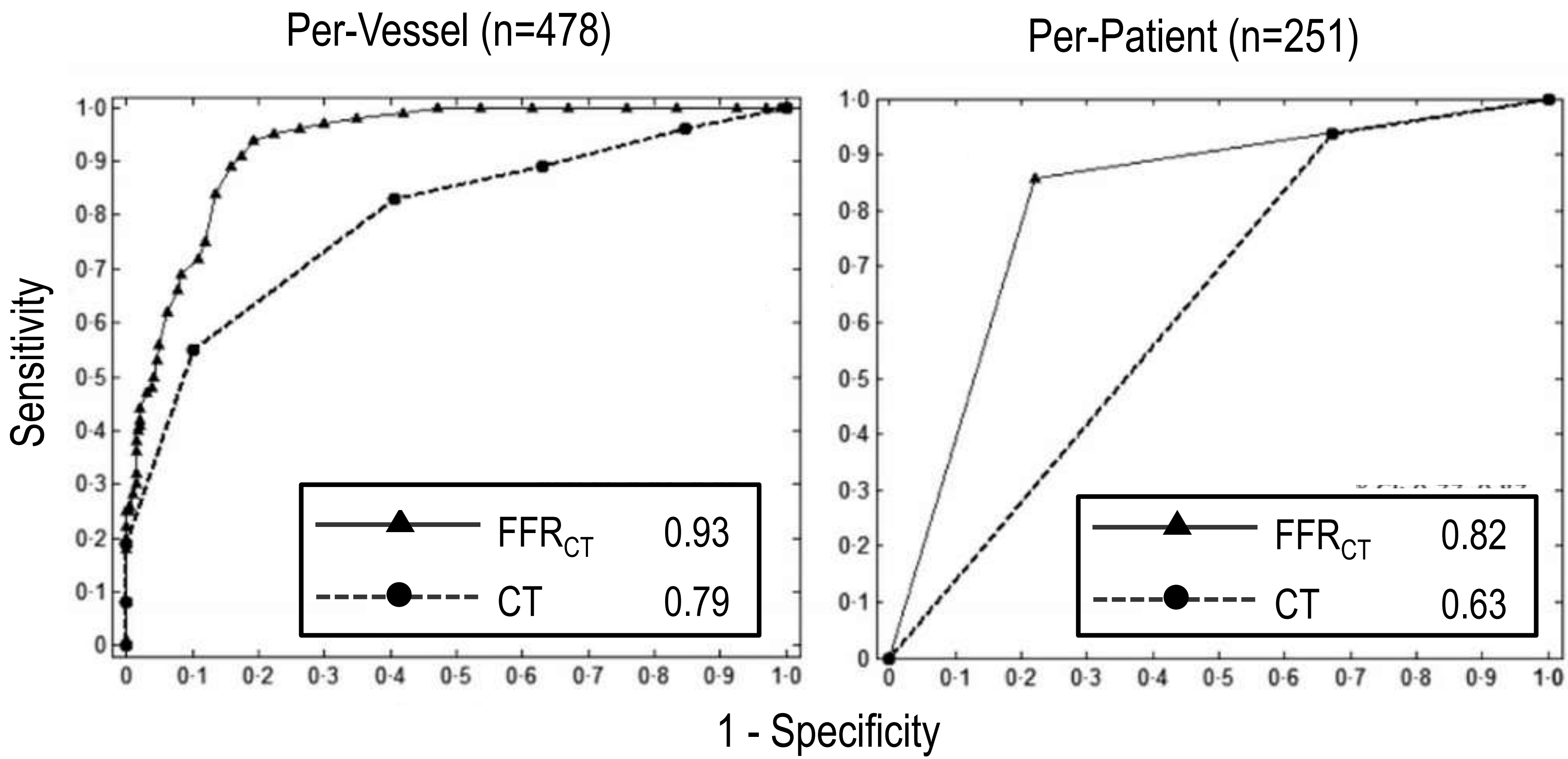
– Nitrates	99.6%
– Beta Blockers	78%
– Heart Rate (bpm)	63
Range	37-110
– Prospective	54%
mean dose (mSv)	3
– Retrospective	46%
mean dose (mSv)	14
– Calcium score*	
Mean	302
>400	26%



Nørgaard B, JACC 2014

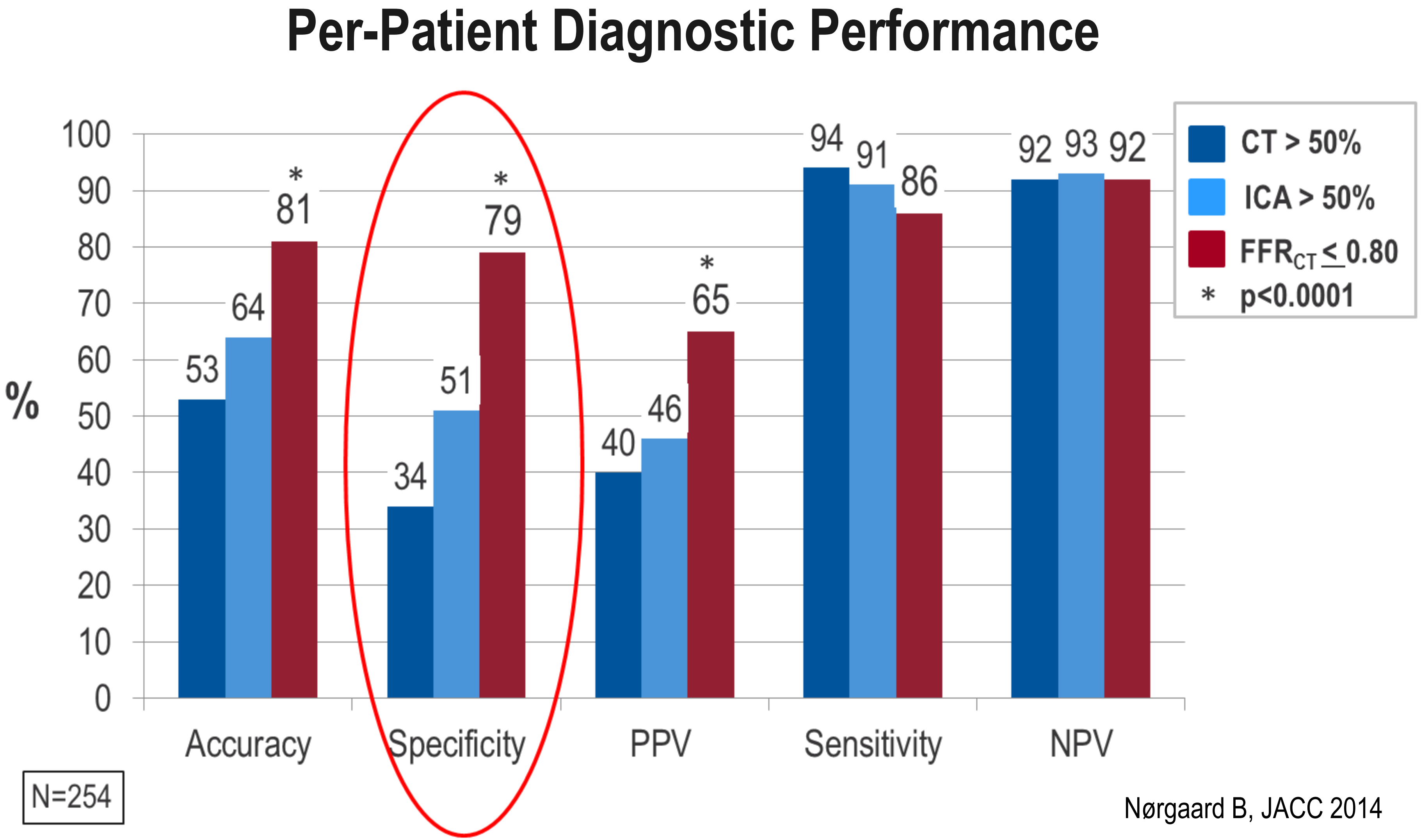
NXT study: RESULTS

Discrimination of Ischemia



Nørgaard B, JACC 2014

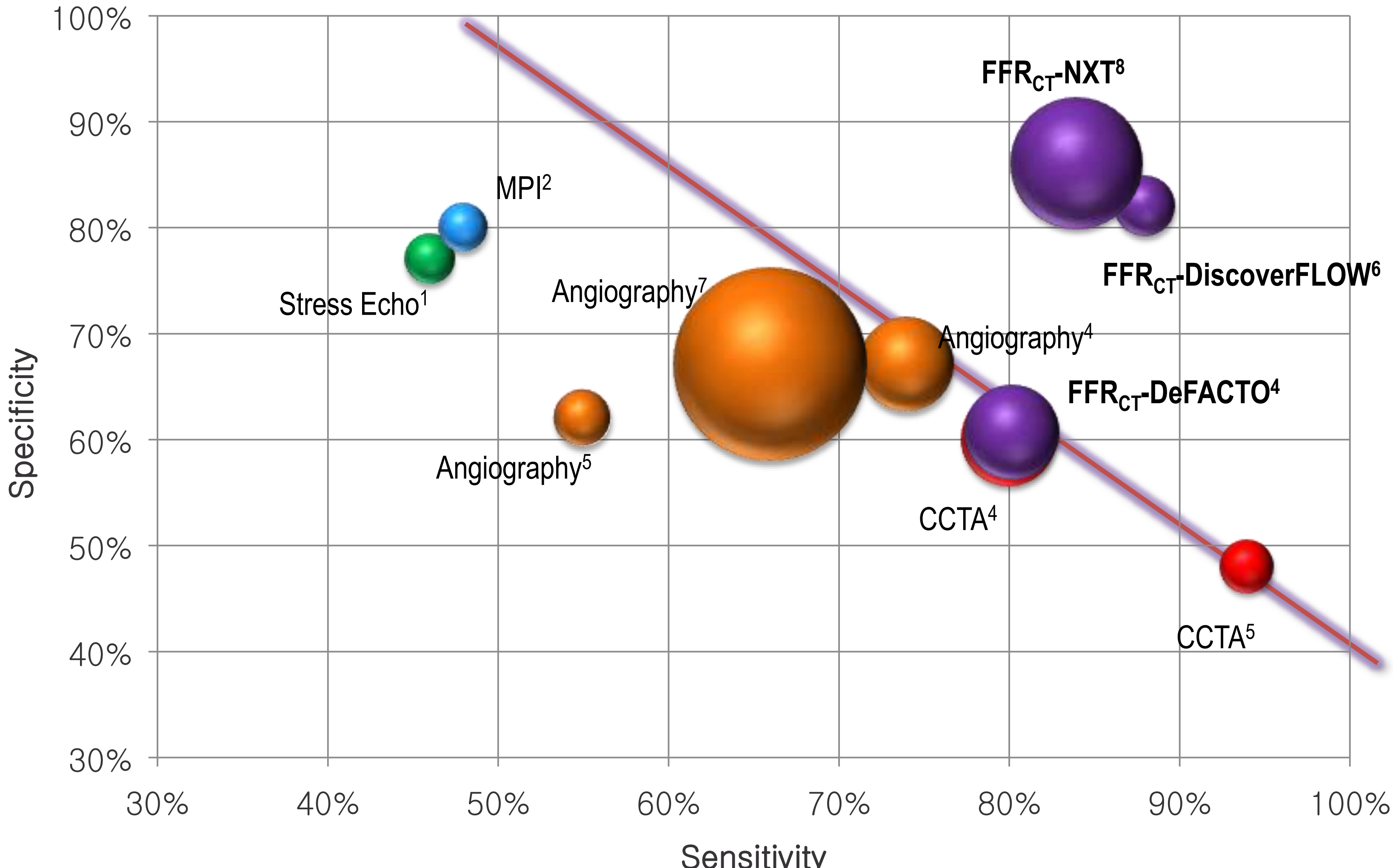
NXT study: RESULTS



N=254

Nørgaard B, JACC 2014

Non-invasive tests/FFR_{CT}/Angiography vs. FFR

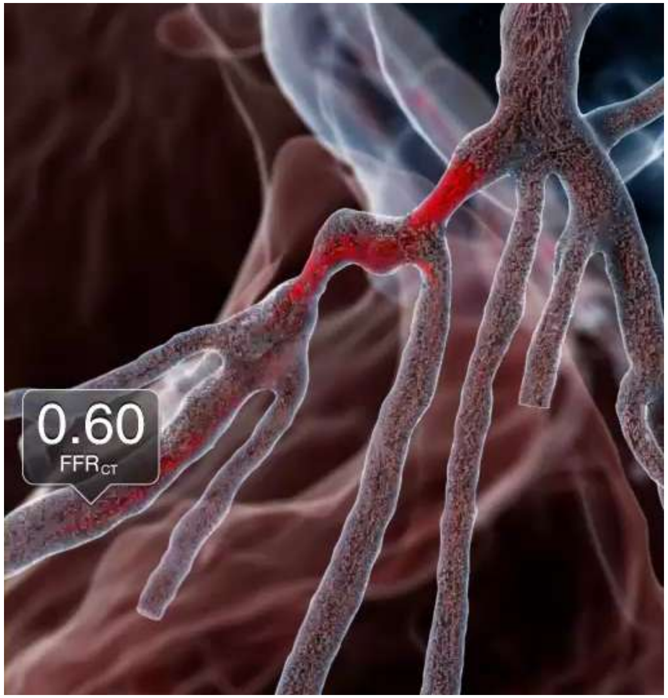


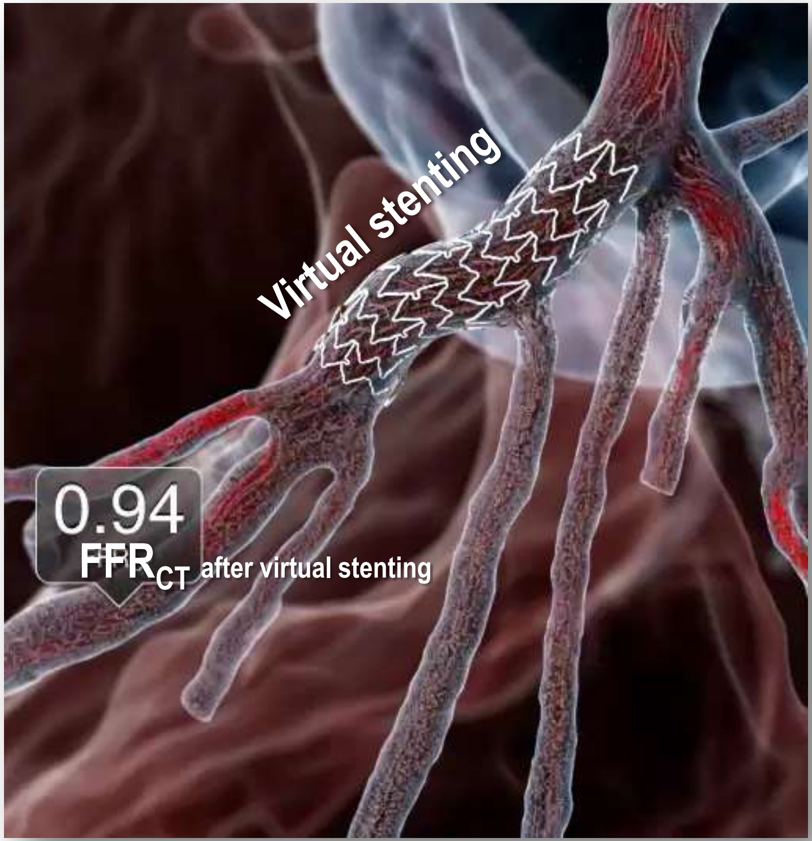
1. Jung et al. EHJ 2008;29:2536-2543.
2. Mellkian et al. JACC Intervention 2010;3:307-314
3. Muller et al. JACC Intervention 2011;4
4. Min et al. JAMA 2012;308:1237-1245
5. Meijboom et al. JACC 2008;52:636–43
6. Koo et al. JACC 2011;58:1989-97
7. Park et al. JACC 2012
8. Norgaard et a. JACC 2014

From CTA to CT-FFR and its beyond…

Planning the treatment strategy using

Virtual revascularization & CT-derived computed FFR



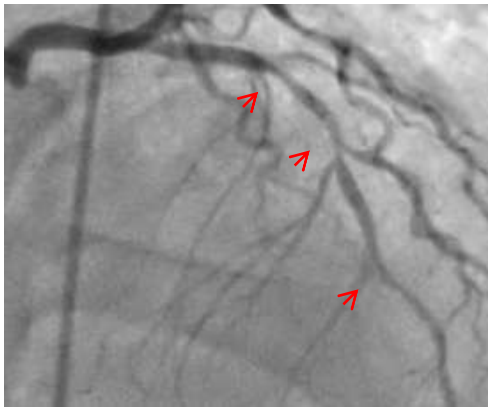


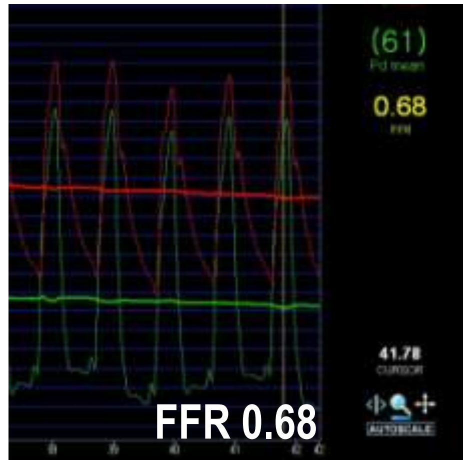
Angiography

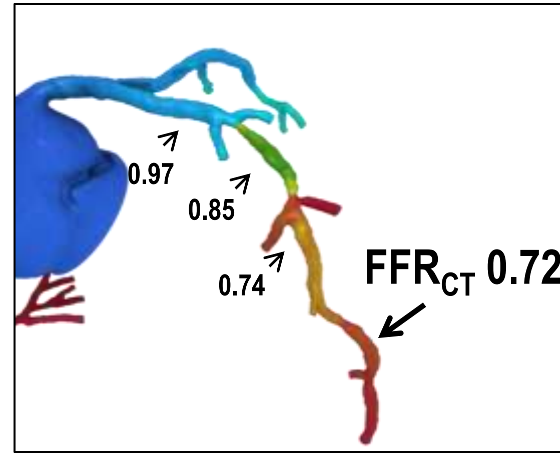
Invasive FFR

CT-derived computed FFR (FFR_{CT})

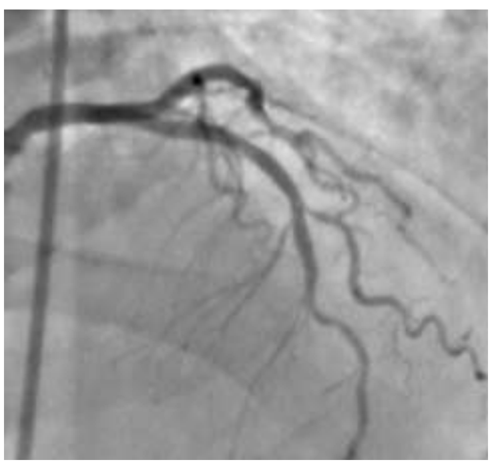
Before Stenting

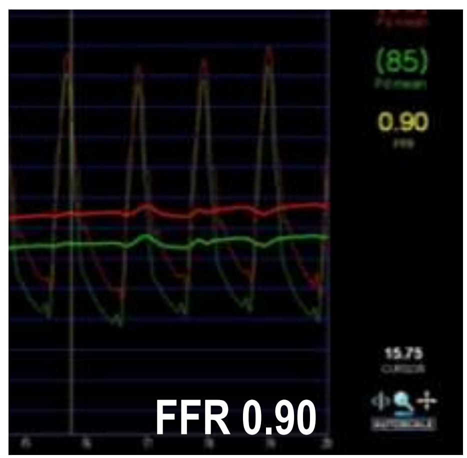


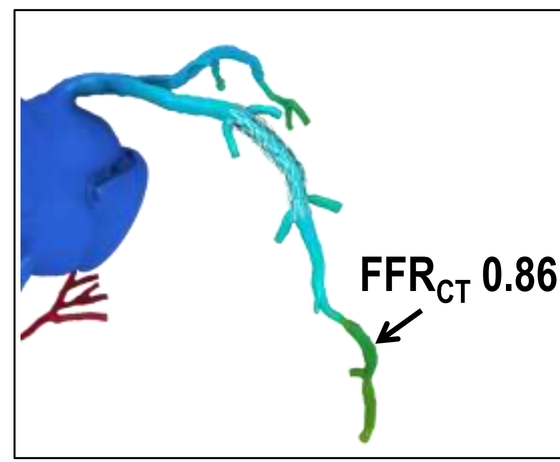


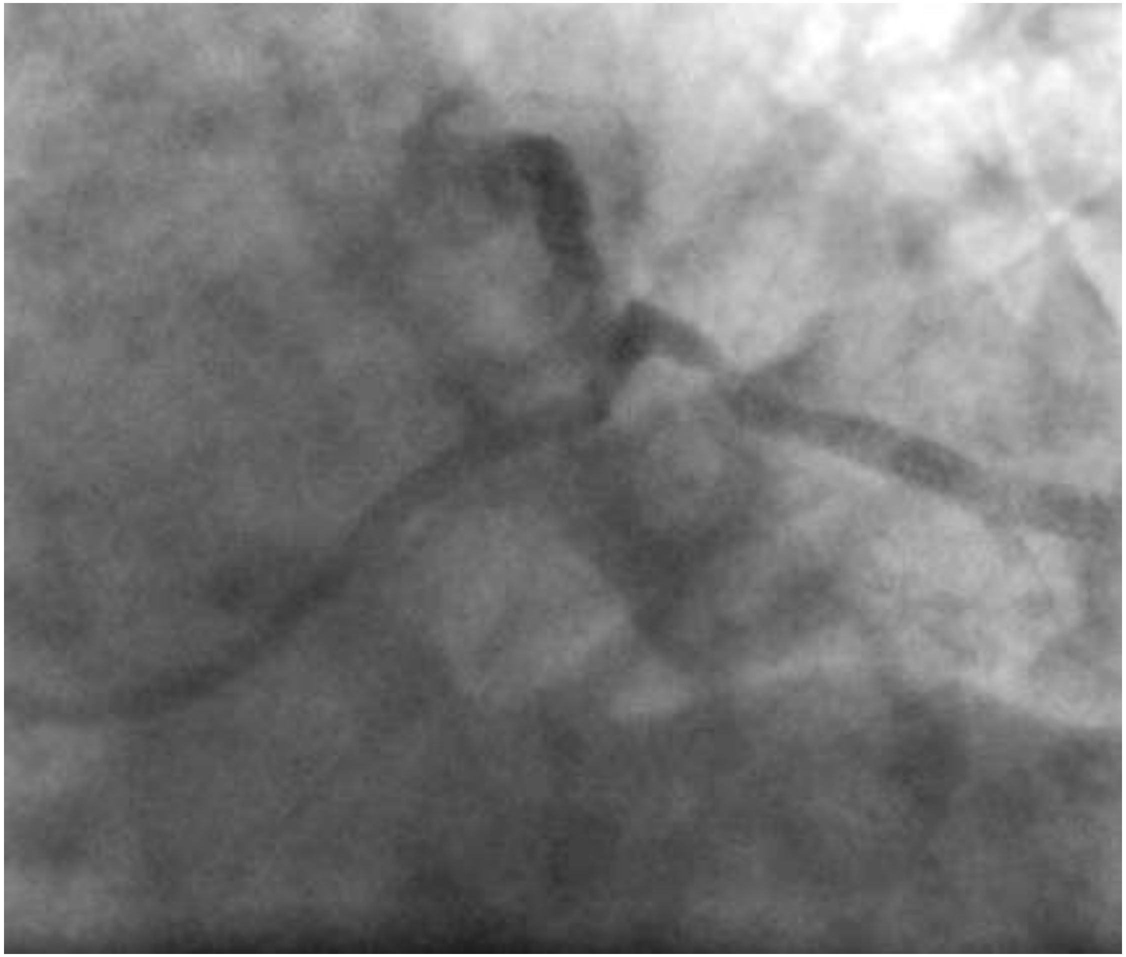


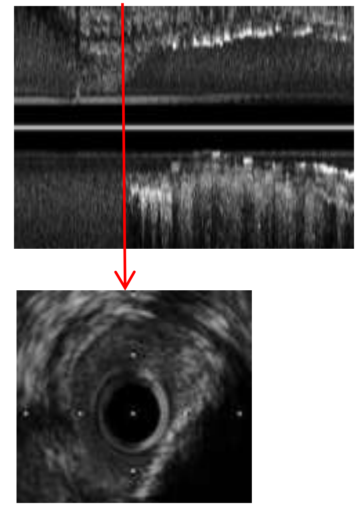
After Stenting

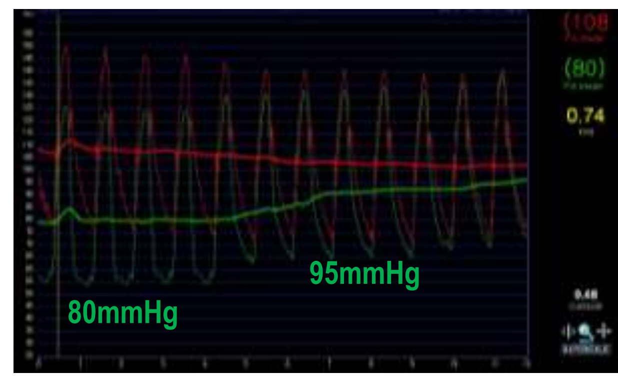






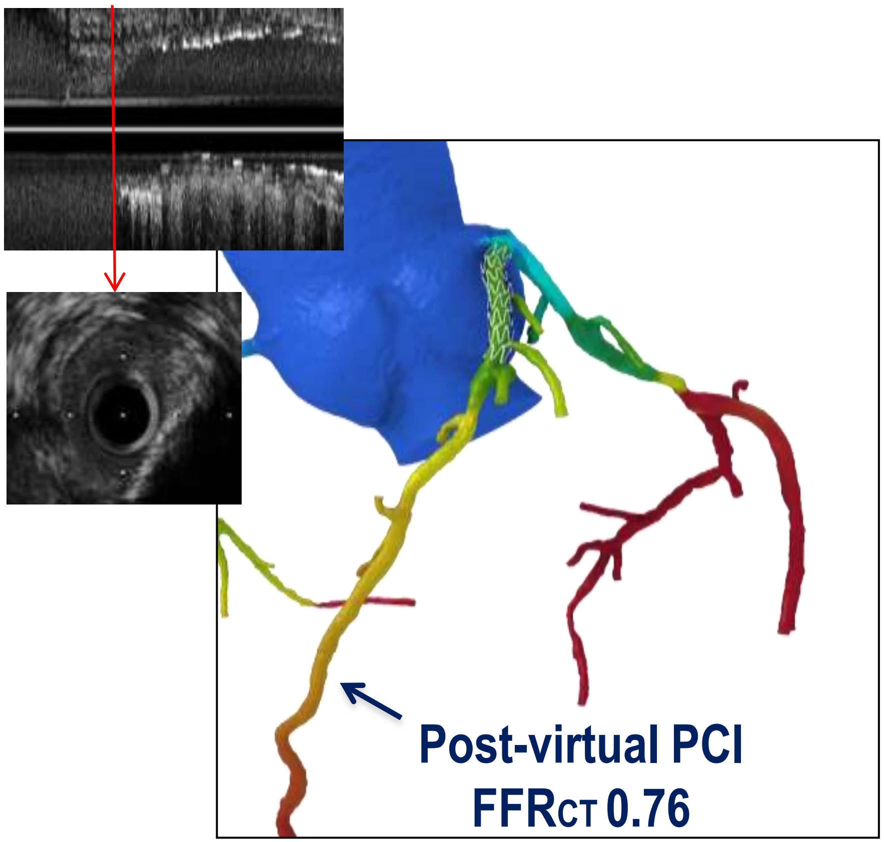




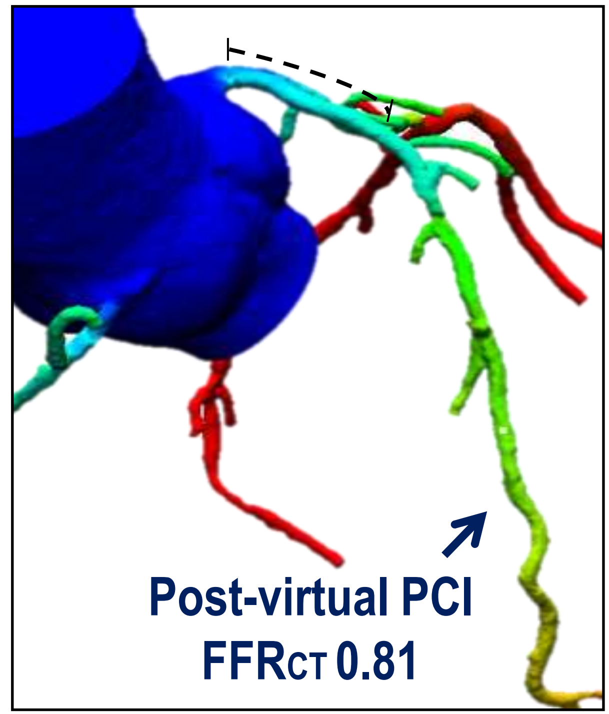


After Stenting of proximal LAD lesion

Cover LAD os or not, that's the question…..

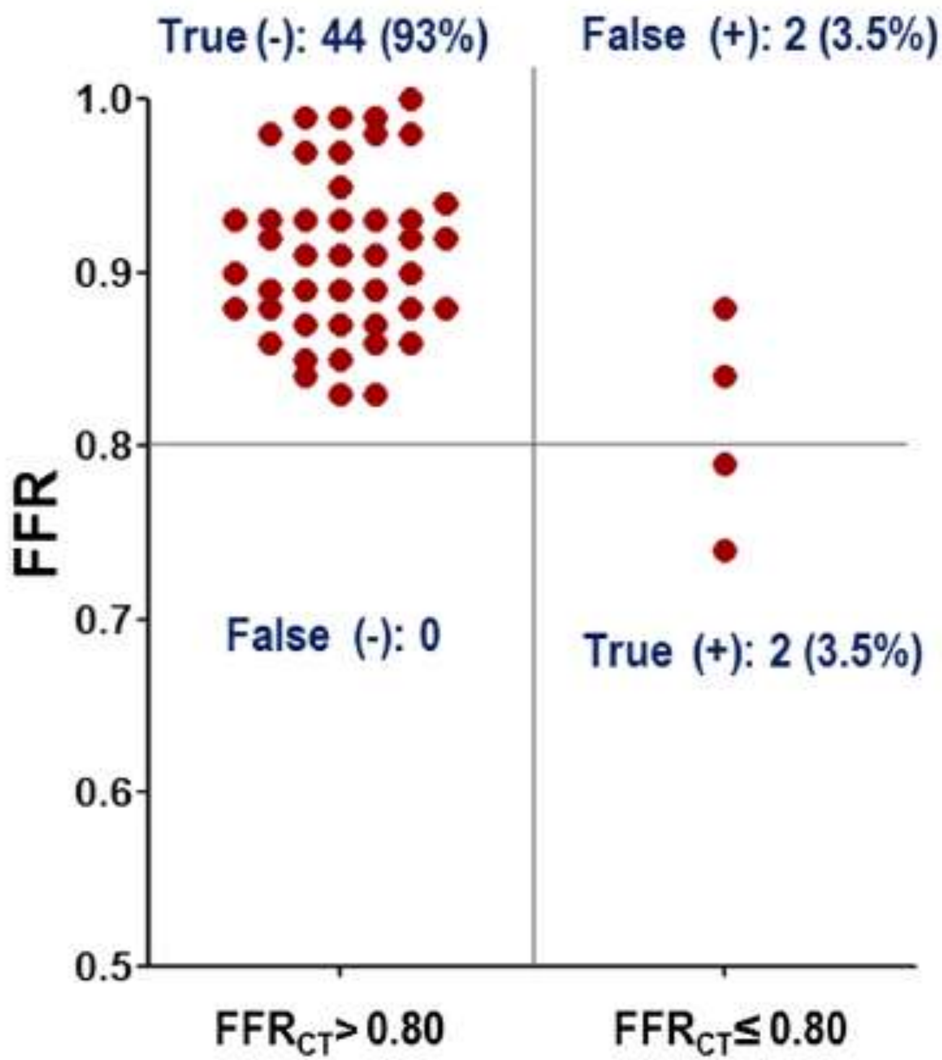


Residual ostial stenosis+



Stenting the ostial lesion

Diagnostic performance of FFR_{CT} after virtual stenting to predict the residual ischemia



Kim KH, Koo BK, et al. JACC interv 2014

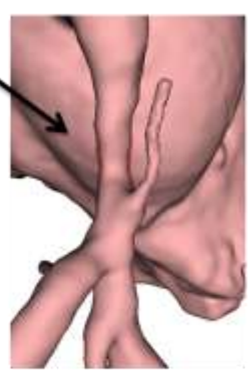
Image-based computerised modelling of coronary circulation: ***Potentials***

More patient-specific information using perturbation

Measured FFR 0.66

FFRCT 0.58

- KR-21
  - Image Quality Score = 0.0 (best)

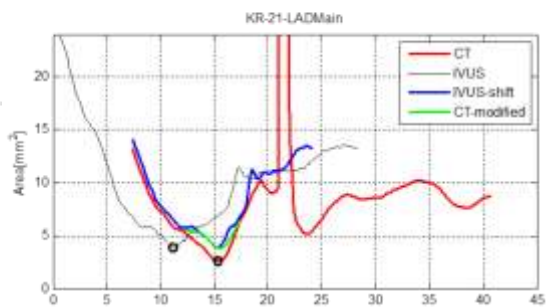


Red: IVUS-matched CT
46.7% area increase
(21.1% in diameter)

Adjust geometry using IVUS data

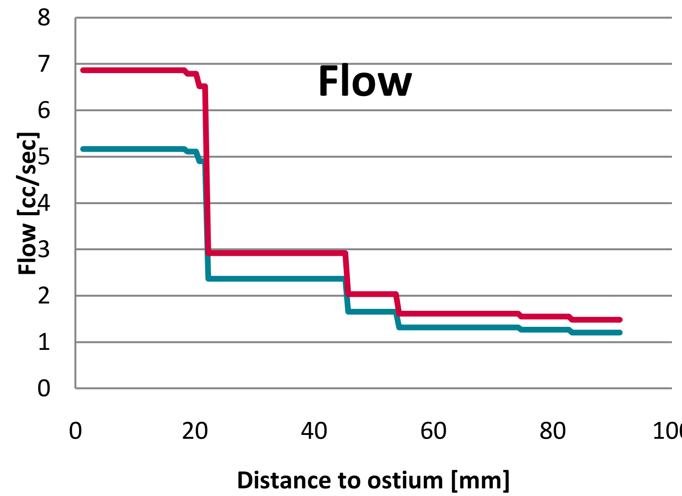
FFRCT 0.64

MLA at focal lesion was matched

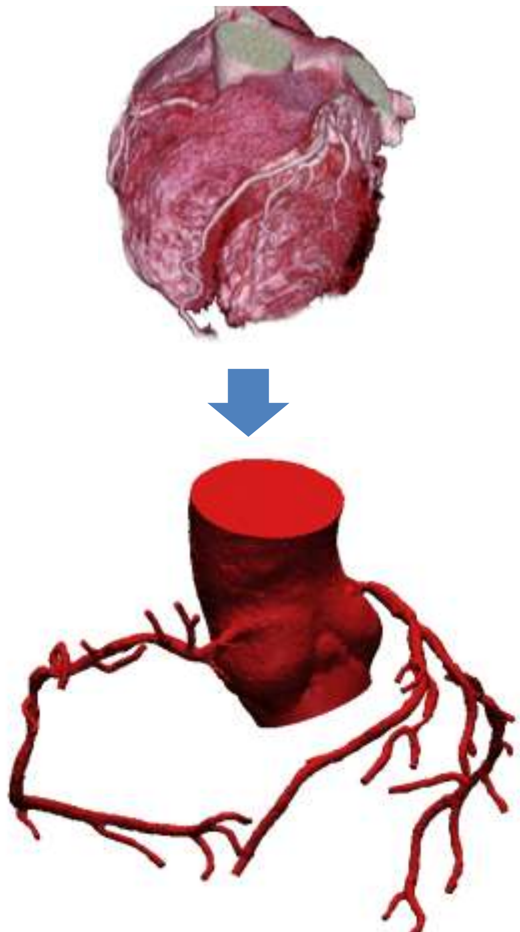


Adjust outlet resistance

FFRCT 0.66



3-D geometry from CCTA

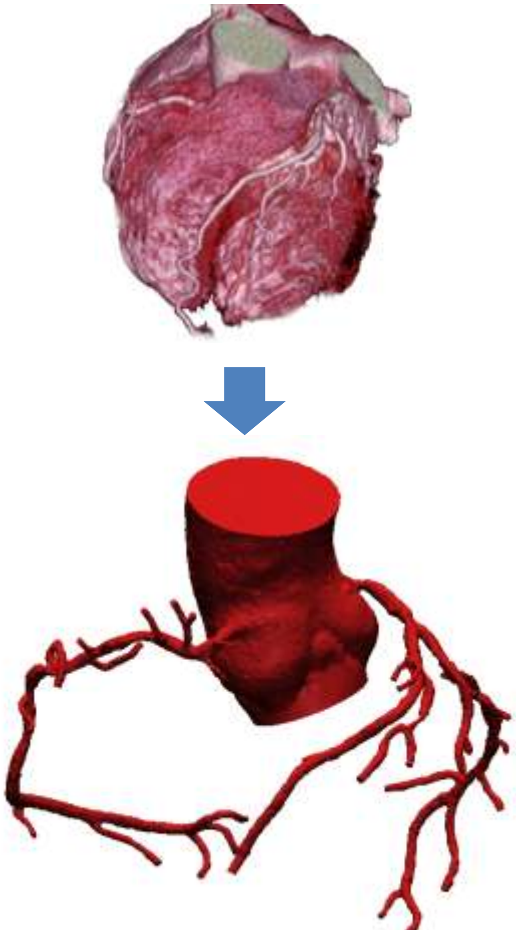


Hemodynamics

- 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

3-D geometry from CCTA



Hemodynamics

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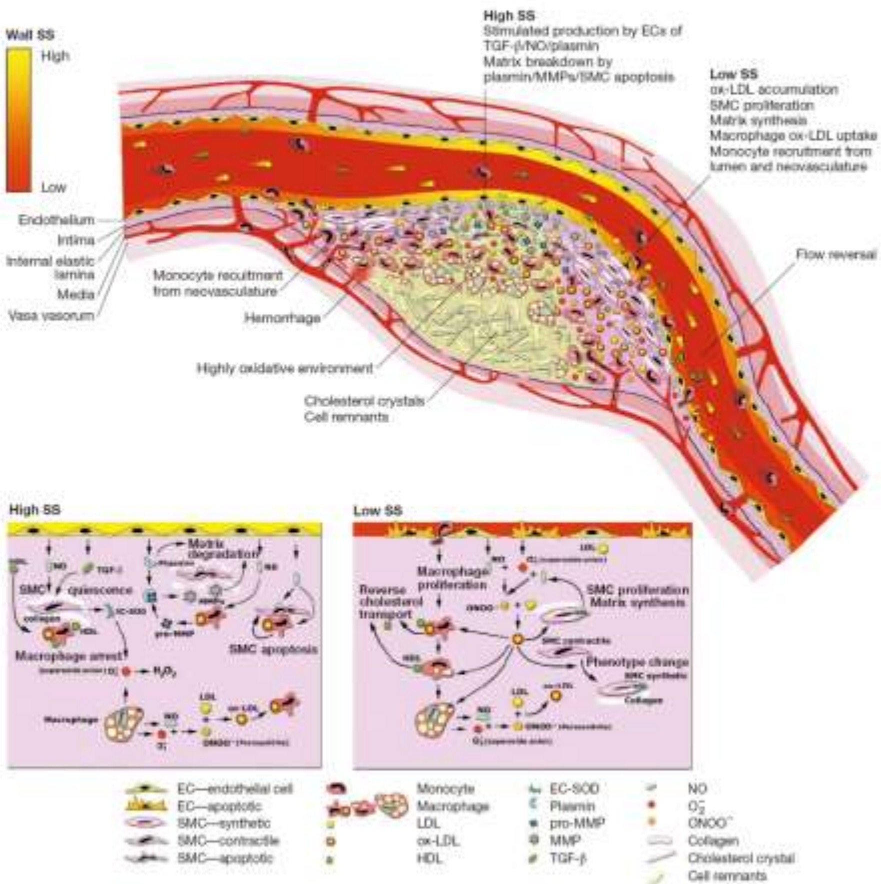
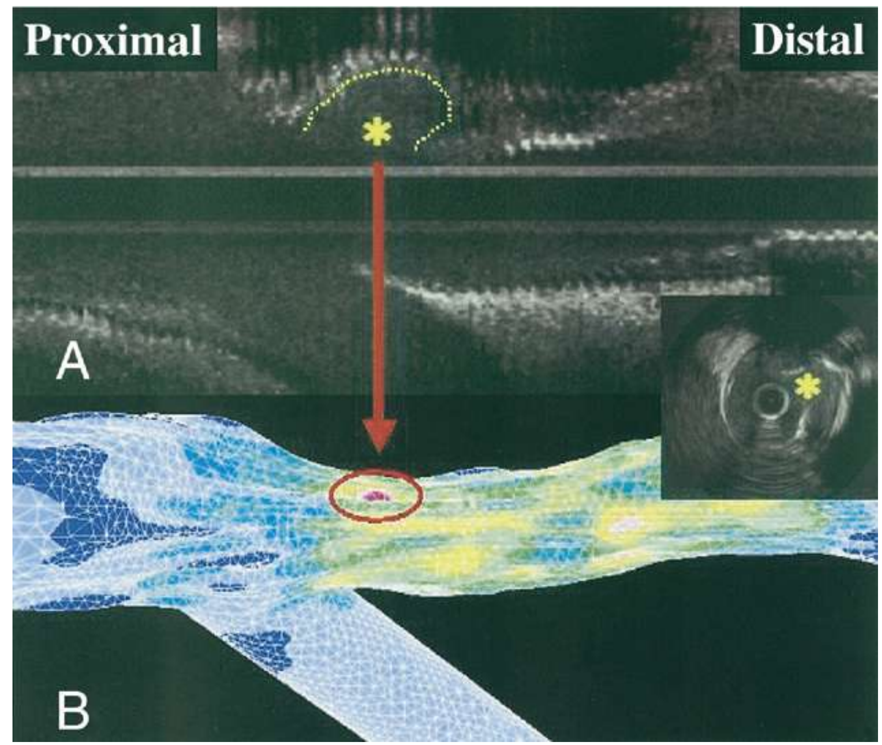
- Hyperemic
- Exercise – mild, moderate, peak

Coronary hemodynamics: WSS, WSSG, traction, pressure, axial stress.......

: Key determinanats of plaque development, growth, vulnerability and rupture

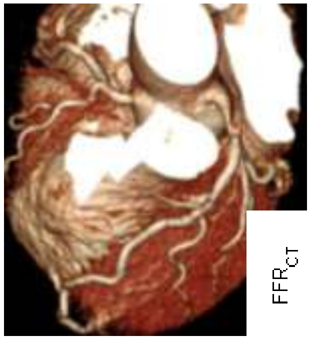


Slager, et al. Nature Clin Pract 2005

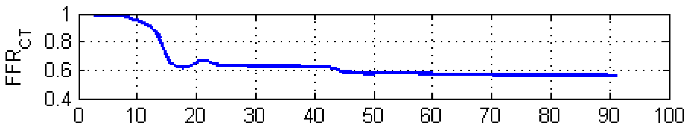


Fukumoto, et al. JACC 2008

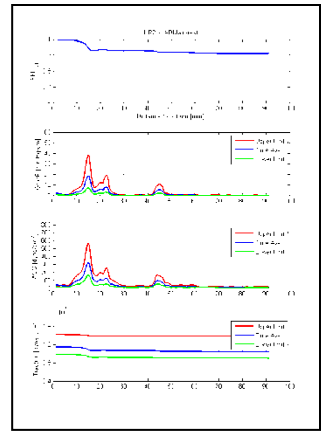
Image-based computerised modelling of coronary circulation: ***Potentials***



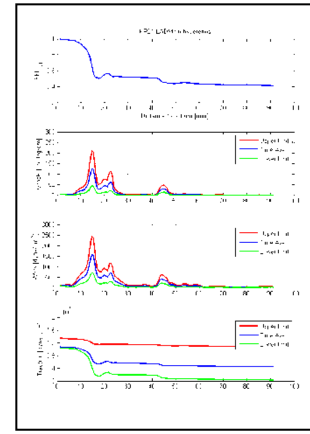
Static flow - hyperemic



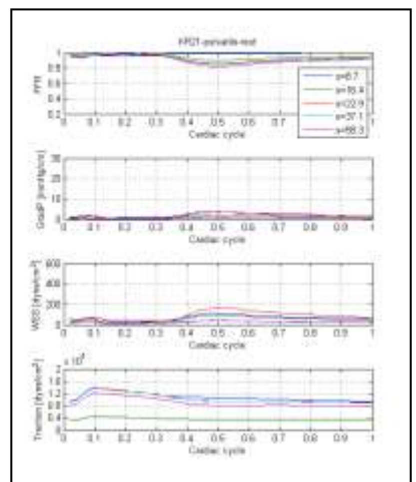
Pulsatile flow - rest



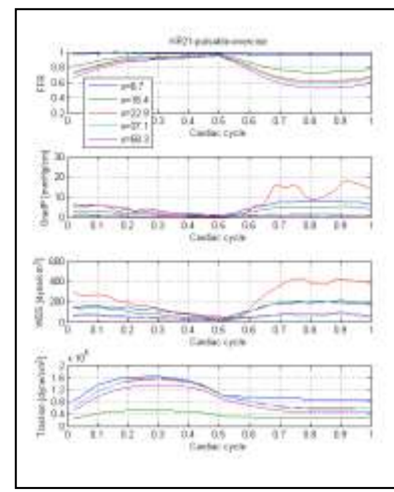
Pulsatile flow - Hyper



Pulsatile flow - rest



Pulsatile flow - Exercise

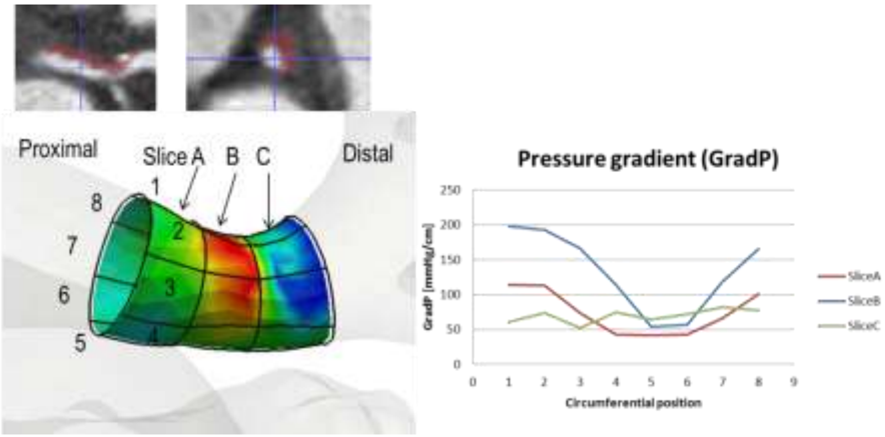


Preliminary data, unpublished

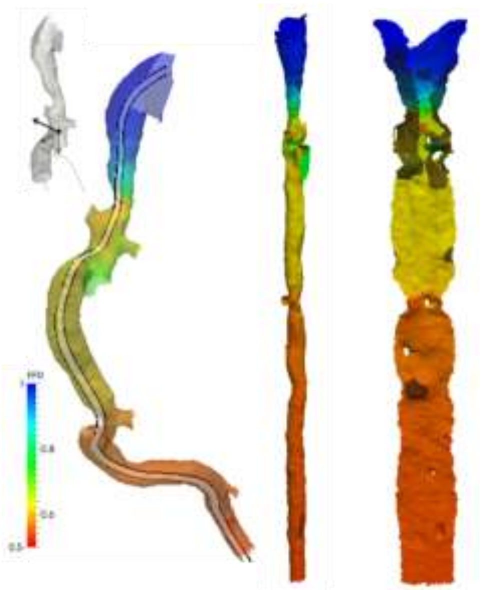
Image-based computerised modelling of coronary circulation: ***Potentials***

Regional analysis
: Epicardial vs. Myocardial

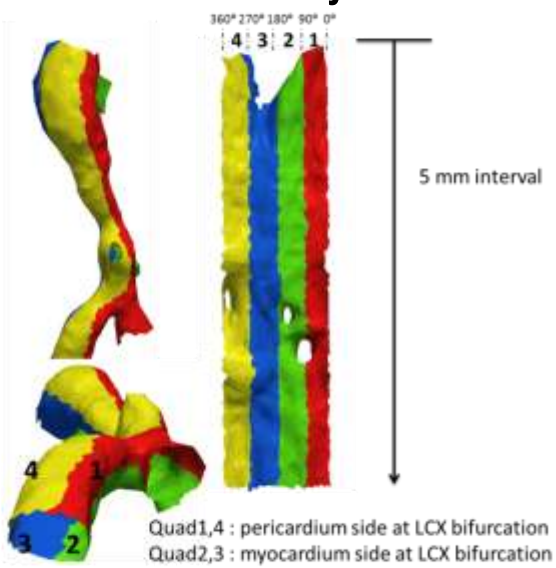
Circumferential/Longitudinal analysis

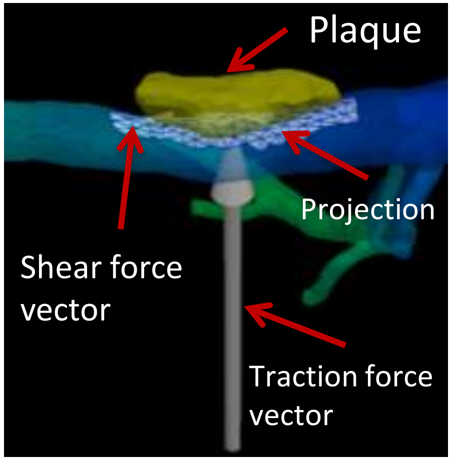


Vessel straightening/unfolding



Patch analysis





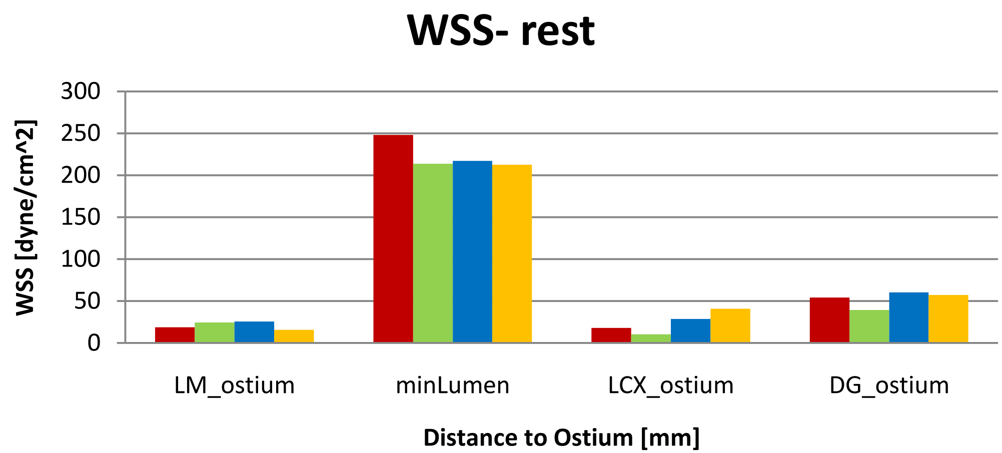
Plaque stress analysis

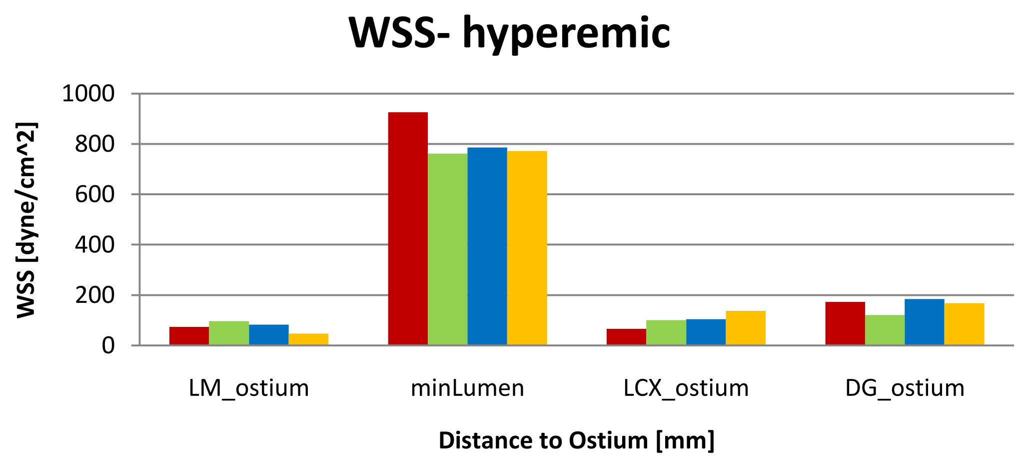
Image-based computerised modelling of coronary circulation: ***Potentials***

Q1: Why the plaque distribution is different at each segment?

Preliminary data, unpublished

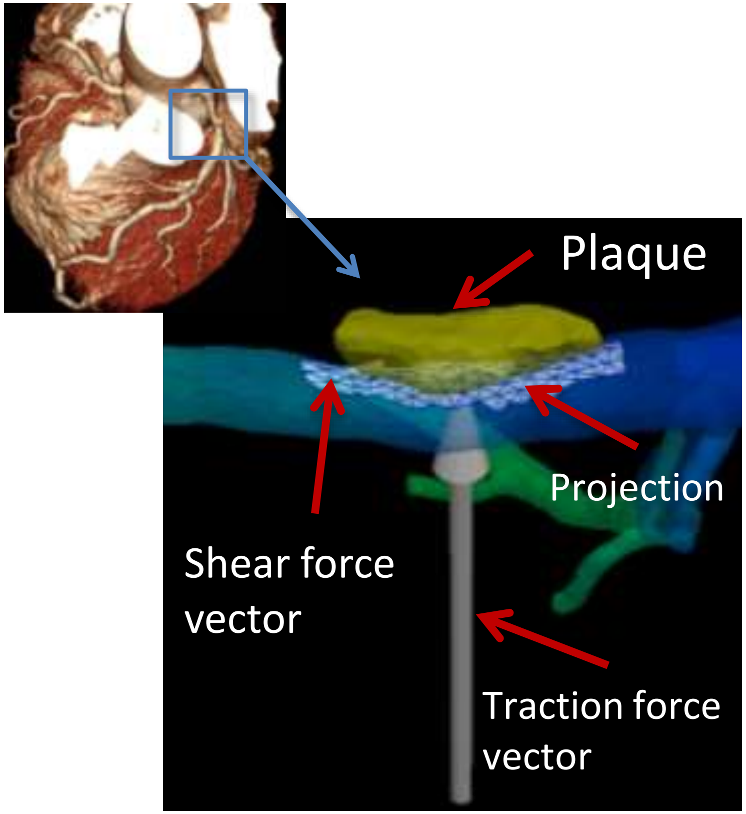
Image-based computerised modelling of coronary circulation: ***Potentials***





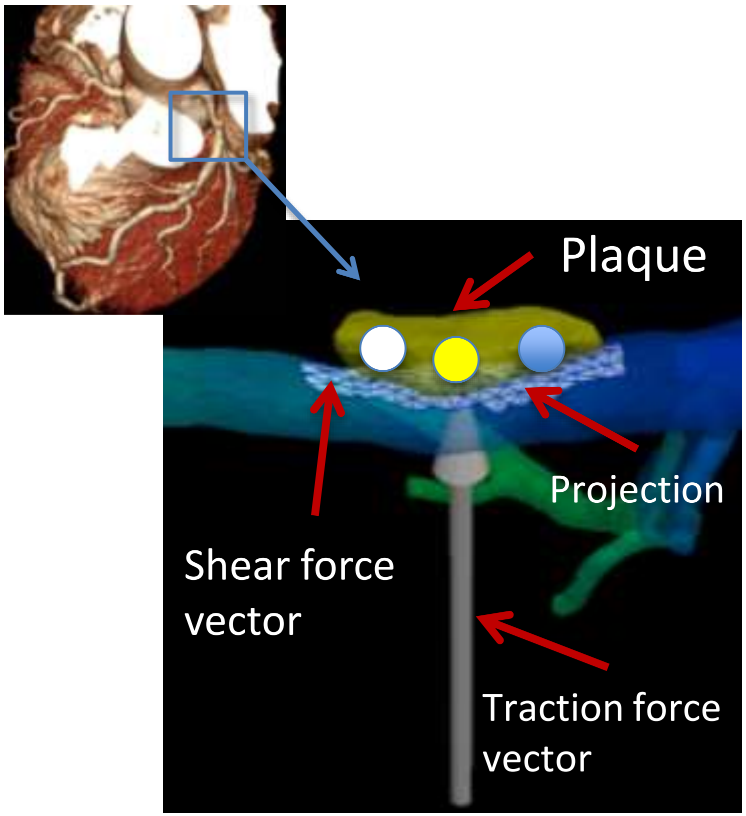
Preliminary data, unpublished

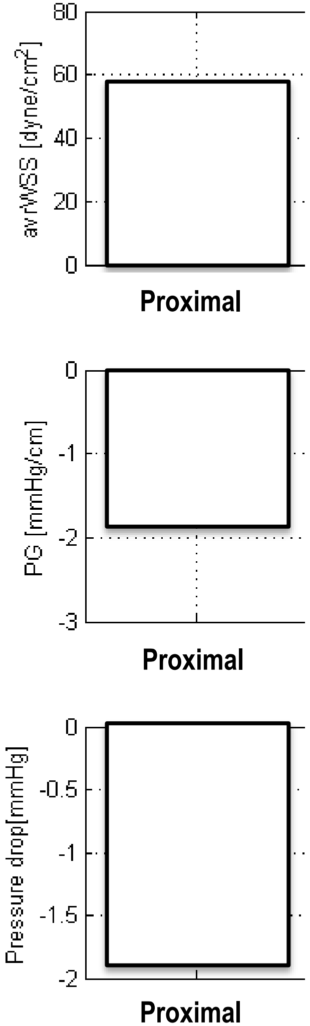
Image-based computerised modelling of coronary circulation: ***Potentials***



Q2: Why the plaque rupture frequently occurs at the upstream or MLA segment of a plaque?

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





Preliminary data,unpublished

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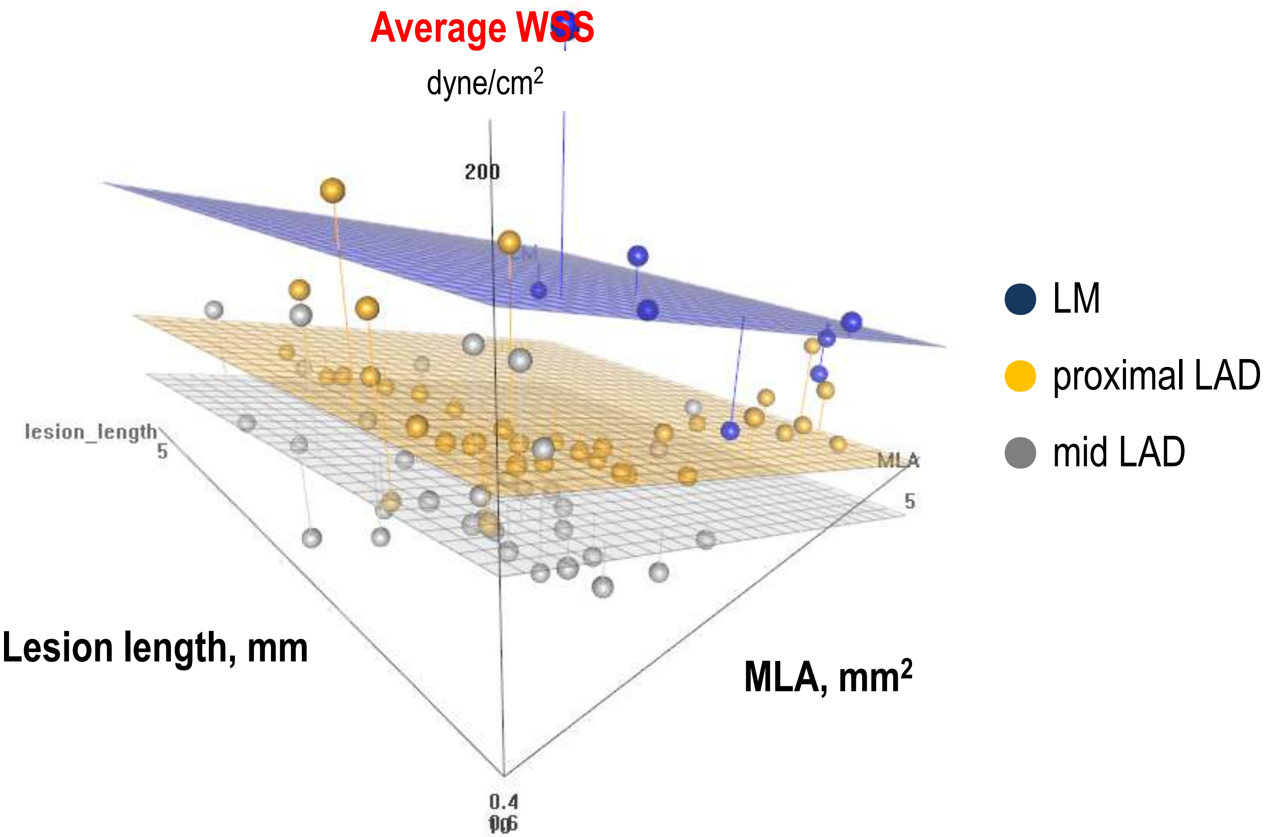
Image-based computerised modelling of coronary circulation: ***Potentials***

Q3: How lesion severity can predict the acute coronary event?
Q4? Why plaque rupture clusters at the proximal part of LAD?

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

Relation between lesion characteristics and WSS



Preliminary data, unpublished

From CTA to CT-FFR and its beyond….

- Integration of coronary CT angiography and hemodynamic assessment is feasible using CFD technologies.
- FFR_{CT} can be helpful to predict the functional significance of coronary lesions and to plan the treatment strategy before the invasive procedures.
- Important hemodynamic factors such as WSS, plaque stress and traction can also be measured and be helpful to answer questions related to atherosclerosis.
- Further technical development will improve its accuracy and expand its applicability.