MedTech Innovation
7 May 2023

From CFD to Artificial Intelligence based OCT FFR

Jung-Joon Cha MD PhD FESC

**Division of Cardiology, Cardiovascular Center,
Korea University Anam Hospital,
Korea University College of Medicine**

FFR-guided PCI

FFR-guided
vs.
Angio-guided

PCI + MT
vs.
MT

European Heart Journal (2010) 31, 2501–2555
doi:10.1093/eurheartj/ehq277

ESC/EACTS GUIDELINES

Guidelines on myocardial revascularization

The Task Force on Myocardial Revascularization of the European Society of Cardiology (ESC) and the European Association for Cardio-Thoracic Surgery (EACTS)

	Class[a]	Level[b]
FFR-guided PCI is recommended for detection of ischaemia-related lesion(s) when objective evidence of vessel-related ischaemia is not available.	I	A
DES[d] are recommended for reduction of restenosis/re-occlusion, if no contraindication to extended DAPT	I	A

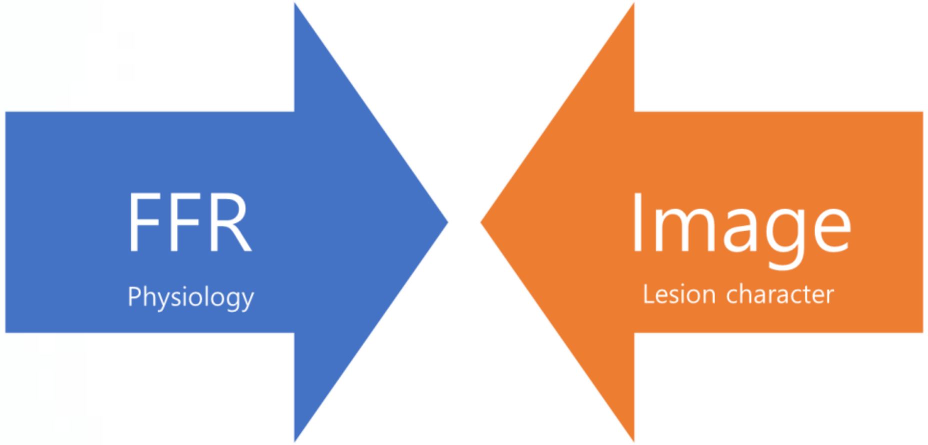
- Pressure ratio under hyperemia = Degree of flow reduction
- Degree of flow reduction = Degree of ischemia
- Relieving certain level of pressure gradient = Better clinical outcomes

Low FFR → ISCHEMIA → REVASCULARIZATION → Better prognosis

Modified from Dr Koo's presentation

Several pitfalls

- Lack of anatomical information on atherosclerotic plaques



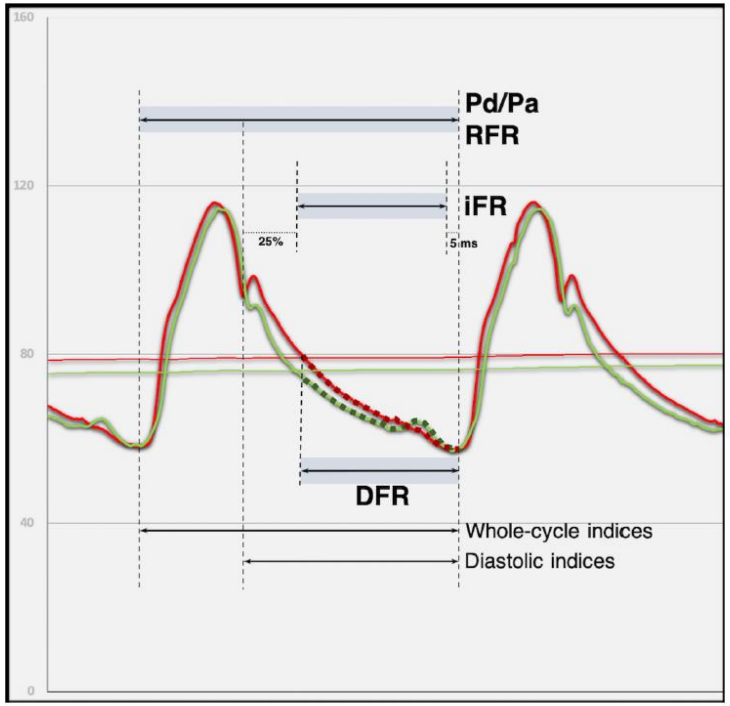
- Technical issue
  - Submaximal hyperemia
  - Guiding catheter
  - Pressure signal drift

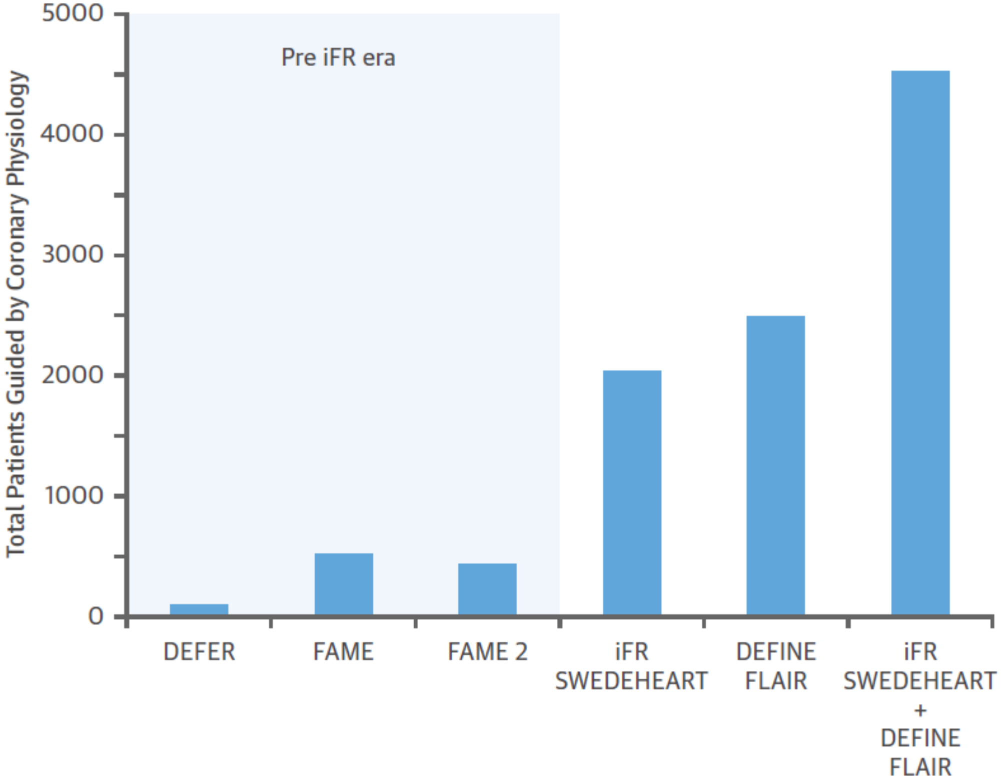
THE PRESENT AND FUTURE

STATE-OF-THE-ART REVIEW

The Evolving Future of Instantaneous Wave-Free Ratio and Fractional Flow Reserve

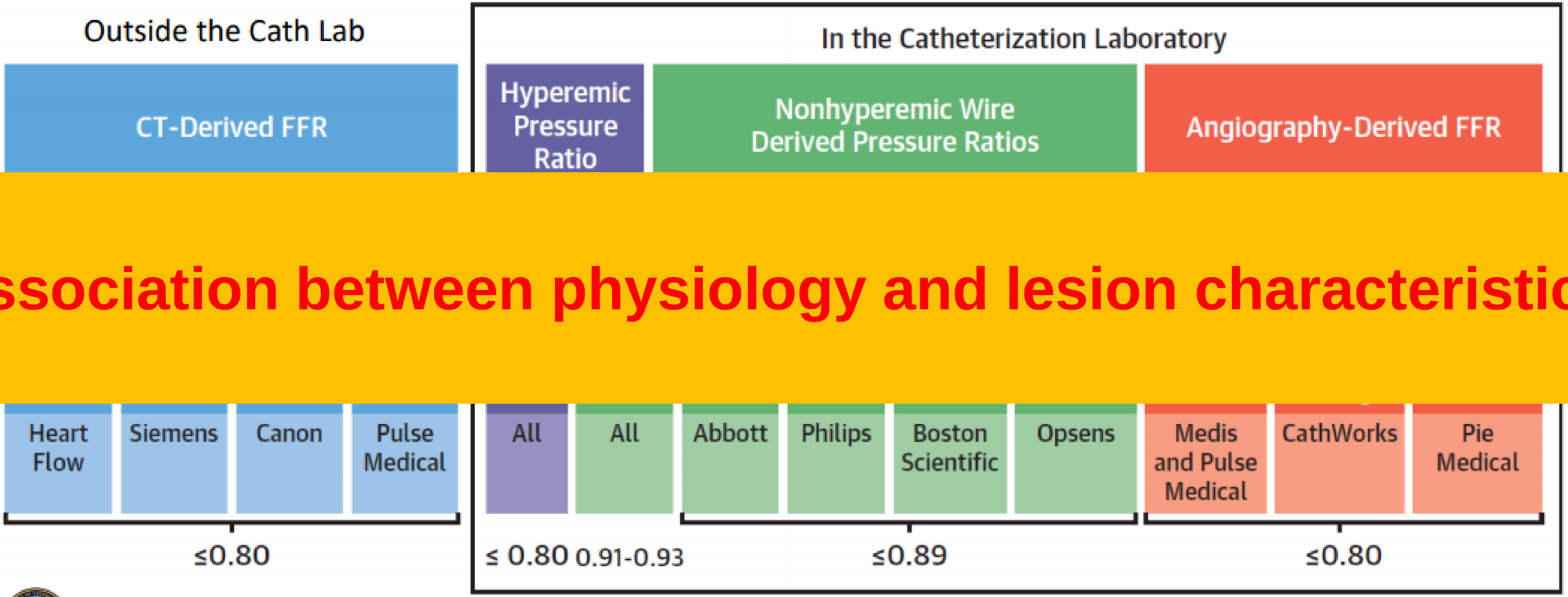
Non Hyperemic Method





J Am Coll Cardiol 2017;70:1379–402, J Am Coll Cardiol Cardiovasc Interv. 2020 Jul, 13 (14) 1617–1638, Open Heart 2020;7:e001308

Currently Available Physiological Assessment



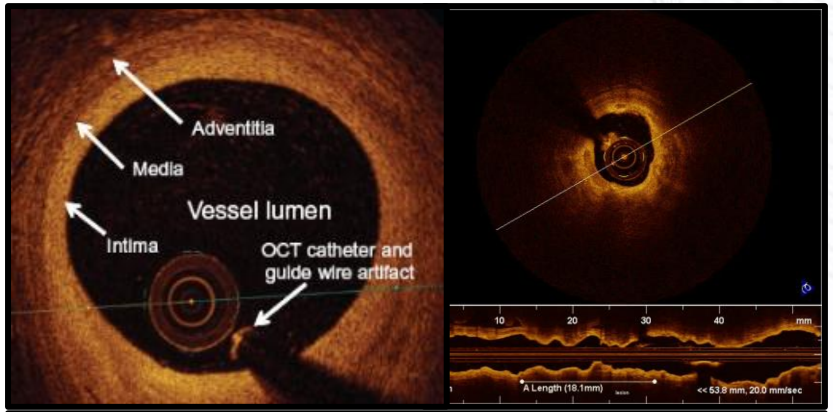
Current cutoff criteria for revascularization

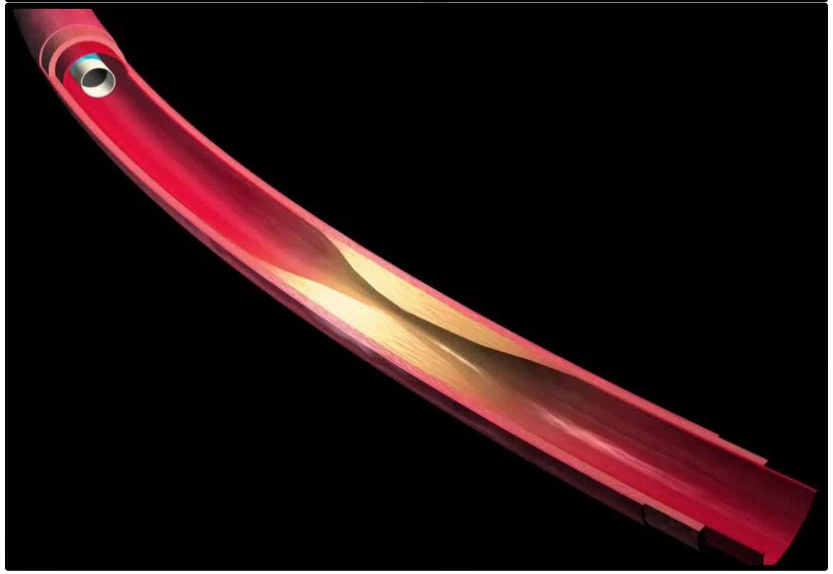
Association between physiology and lesion characteristics?

Kogame N et al. J Am Coll Cardiol Intv 2020;13:1617-1638

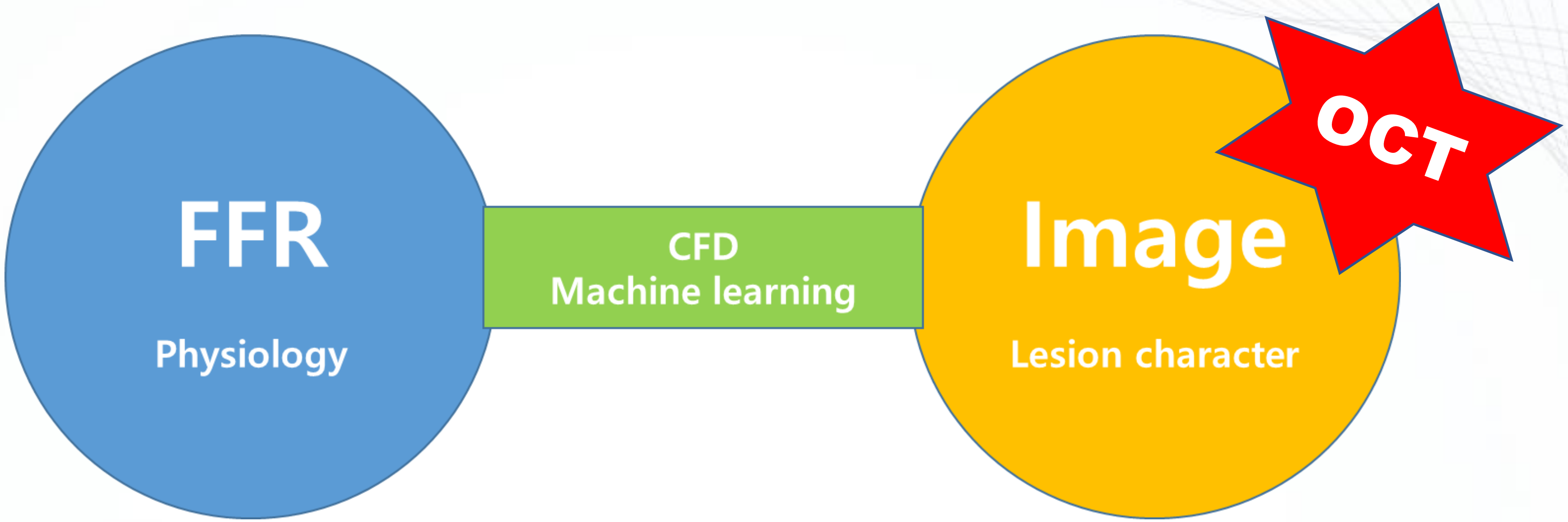
Classification and comparisons across the indices for functional assessment of coronary stenosis alternative to FFR

	INVASIVE										
	Pressure-Wire Based						*Coronary Angiography*			*Coronary Intravascular Imaging*	
	Phase-Specific			*Whole Cardiac-Cycle*							
	iFR	dPR	DFR	Rest P_d/P_a	cFFR	RFR	QFR	vFFR	FFR_{angio}	$IVUS_{FFR}$	OCT_{FFR}
Agreed Cut-off	0.89	0.89	0.89	0.92	0.84 0.88	0.89	0.80	0.80	0.80	0.80	0.80
Hyperaemia required	No	No	No	No	Yes	No	No	No	No	No	No
Procedural Time	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓	↑	↓↓
Patient's Discomfort	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
Procedural Costs	↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓↓	= or ↑	= or ↑
RCTs Available	Yes	No	No	No	No	No	No	No	No	No	No
Vendor-specific	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Pullback Analysis in Tandem Lesions	Yes	?	?	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Haemodynamic Dependence	?	?	?	Yes	No	?	?	?	?	No	No
Anatomic Detail	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Learning Curve	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes



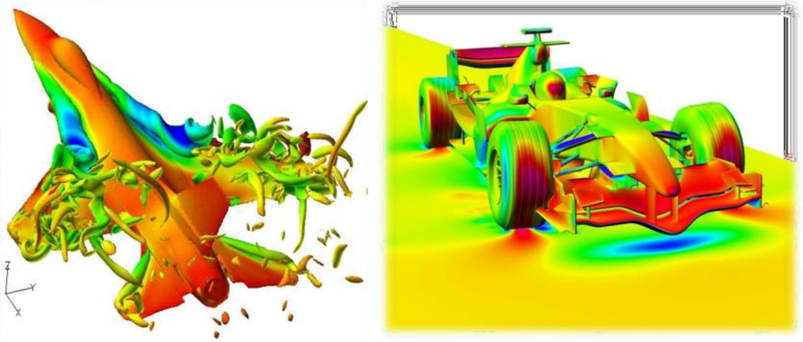


Circ Cardiovasc Interv. 2020;13:e008487



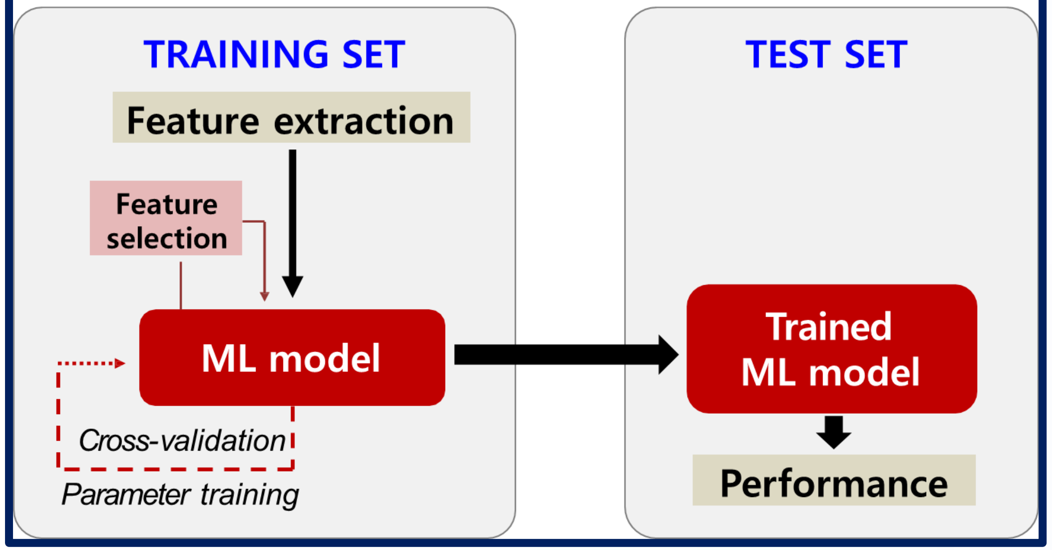
Computational Fluid Dynamics (CFD)

- Computational fluid dynamics (CFD) quantifies fluid pressure and velocity, based on physical laws of mass conservation and momentum balance.
- CFD is widely used in the aerospace and automotive industries for design and testing.



Courtesy of C. Taylor, HeartFlow

Supervised Machine Learning



FFR

Physiology

CFD
Machine learning

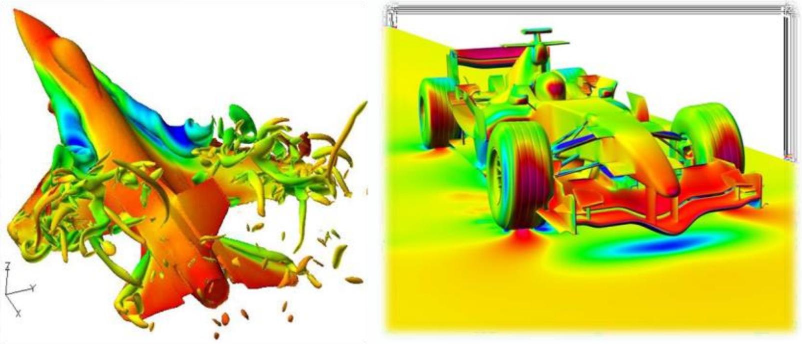
Image

Lesion character

OCT

Computational Fluid Dynamics (CFD)

- Computational fluid dynamics (CFD) quantifies fluid pressure and velocity, based on physical laws of mass conservation and momentum balance.
- CFD is widely used in the aerospace and automotive industries for design and testing.



Courtesy of C. Taylor, HeartFlow

Supervised Machine Learning

TRAINING SET

Feature extraction

Feature selection

ML model

Cross-validation

Parameter training

TEST SET

Trained ML model

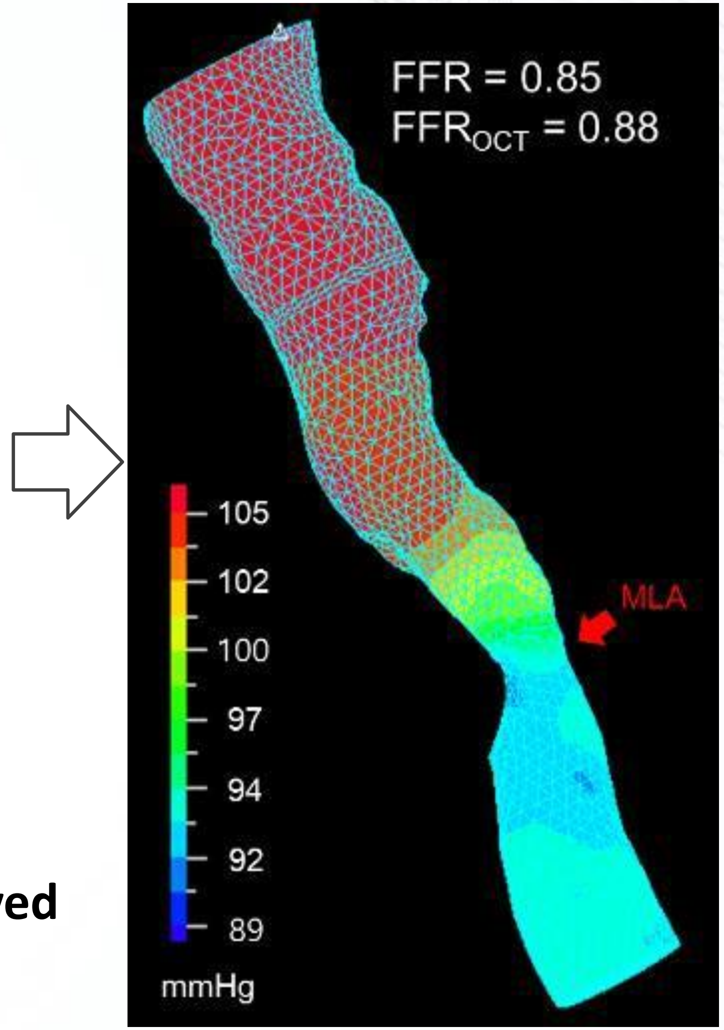
Performance

CFD based OCT-FFR

Assessing Computational Fractional Flow Reserve From Optical Coherence Tomography in Patients With Intermediate Coronary Stenosis in the Left Anterior Descending Artery

- Blood flow simulation was performed by solving the Navier- Stokes equations (ADINA)
- Mean flow velocity
  - obtain average velocity from TIMI frame count on coronary angiography (0.273 m/s)
- Mean blood pressure
  - calculated by averaging the mean pressure acquired at the guiding catheter tip in 37 lesions (retrospective group, 93.2 mmHg)

OCT lumen-derived 3D geometry



→ ***FFR$_{OCT}$ was calculated as the mean Pr at the outlet divided by the mean Pr at the inlet***

Ha J, Kim JS, Hong MK, et al. Cir Cardiovasc Interv 2016

CFD based OCT-FFR

Table 1. Baseline Clinical Characteristics

Variables	Total (n=92)
Age, y, mean±SD	62.7±9.6
Sex, male, n (%)	58 (63.0)
Unstable angina, n (%)	27 (29.3)
Diabetes mellitus, n (%)	20 (21.7)
Hypertension, n (%)	54 (58.7)
Dyslipidemia, n (%)	64 (69.6)
Current smoker, n (%)	12 (13.0)
Multivessel disease, n (%)	22 (26.8)

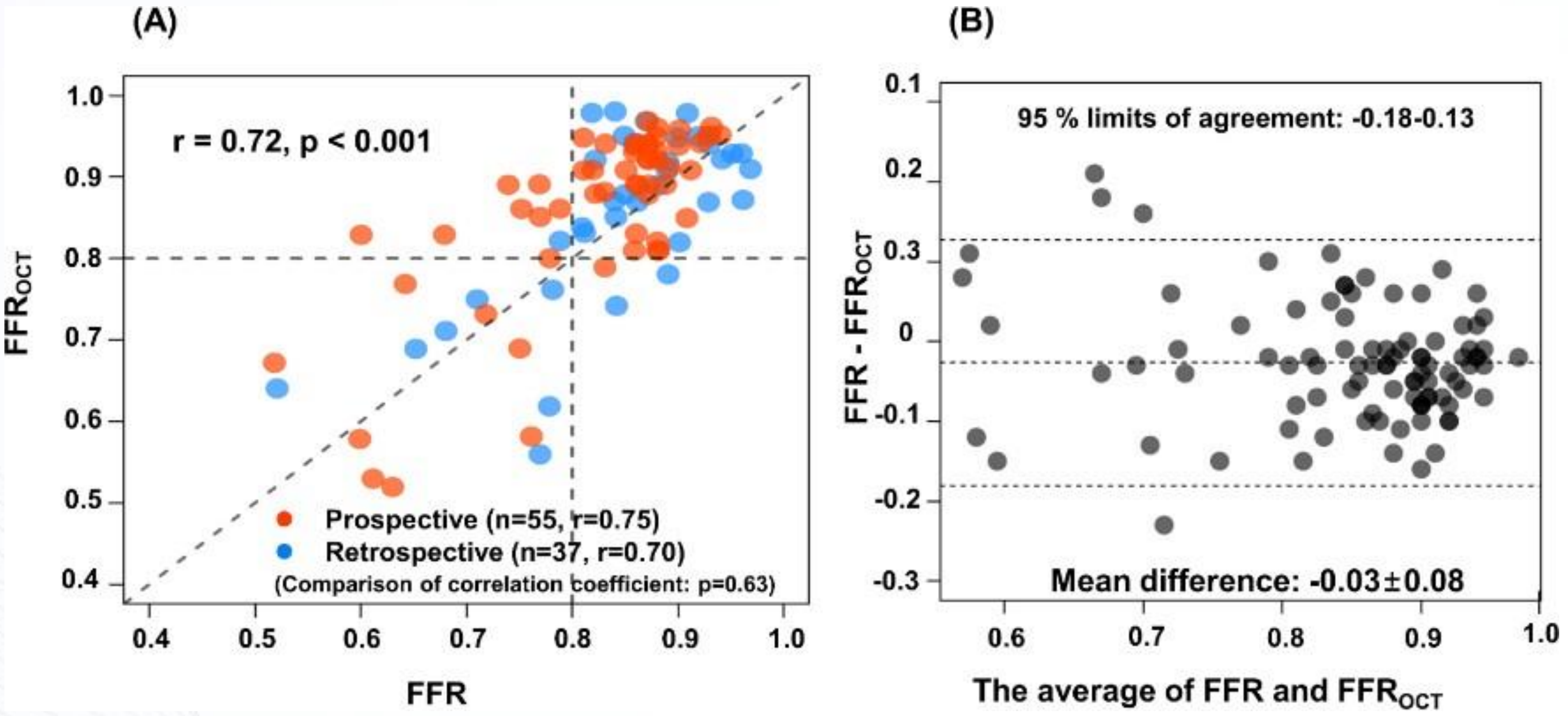
Table 2. Coronary Angiographic and Optical Coherence Tomographic Findings

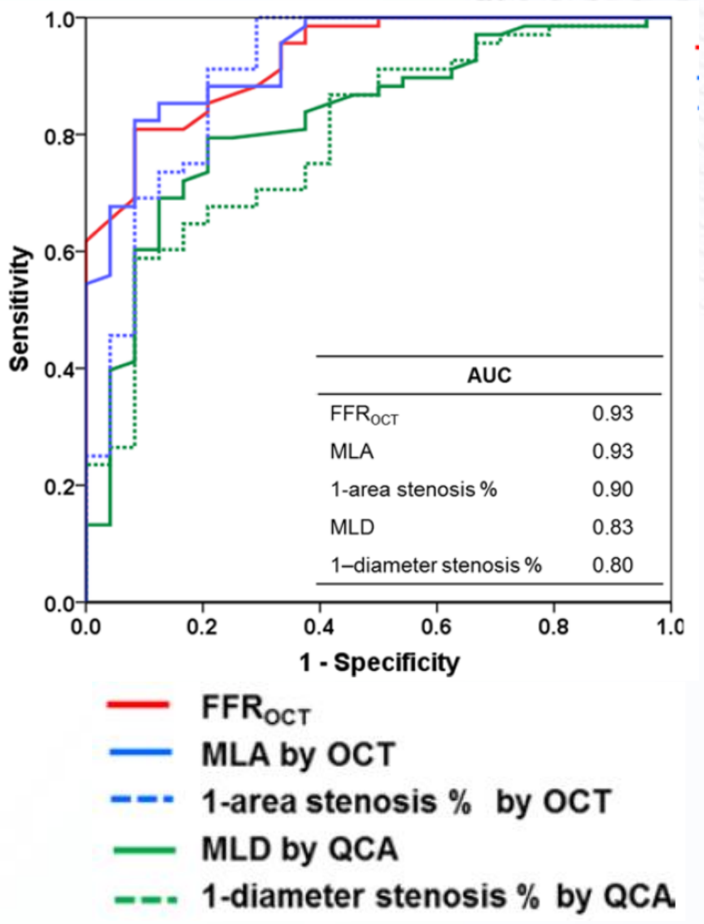
	Total (n=92)
Bifurcation, n (%)	19 (20.7)
Calcification, n (%)	2 (2.2)
Quantitative coronary angiography data, mean±SD	
Reference vessel diameter, mm	3.0±0.5
Minimal lumen diameter, mm	1.3±0.5
Diameter stenosis, %	58.1±13.4
Lesion length, mm	14.0±7.3
Optical coherence tomography data, mean±SD	
Proximal reference segment lumen area	8.7±3.0
Distal reference segment lumen area	6.4±2.3
Minimal lumen area of target lesion	2.5±1.3
Area stenosis, %	67.5±13.5

Ha J, Kim JS, Hong MK, et al. Cir Cardiovasc Interv 2016

CFD based OCT-FFR

Correlation between FFR_{OCT} and FFR





FFR_{OCT} was well-correlated with FFR (r=0.72, p<0.001)

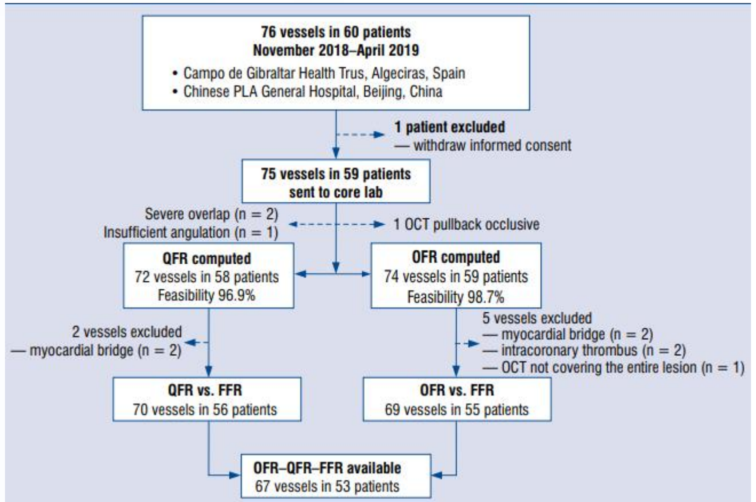
Patient No	Sensitivity	Specificity	PPV	NPV	Accuracy
92	69%	96%	84%	89%	88%

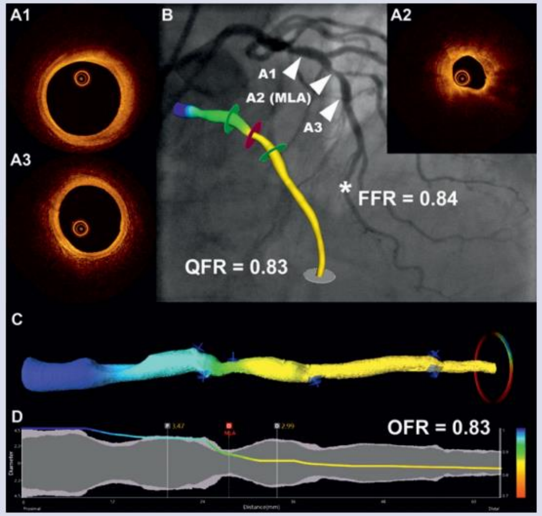
Ha J, Kim JS, Hong MK, et al. Cir Cardiovasc Interv 2016

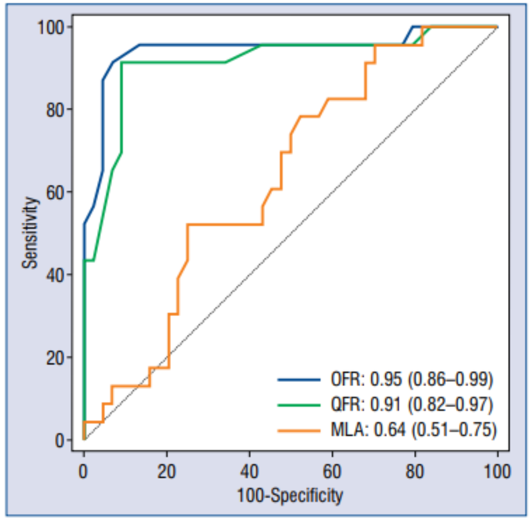
Diagnostic accuracy and reproducibility of optical flow ratio for functional evaluation of coronary stenosis in a prospective series

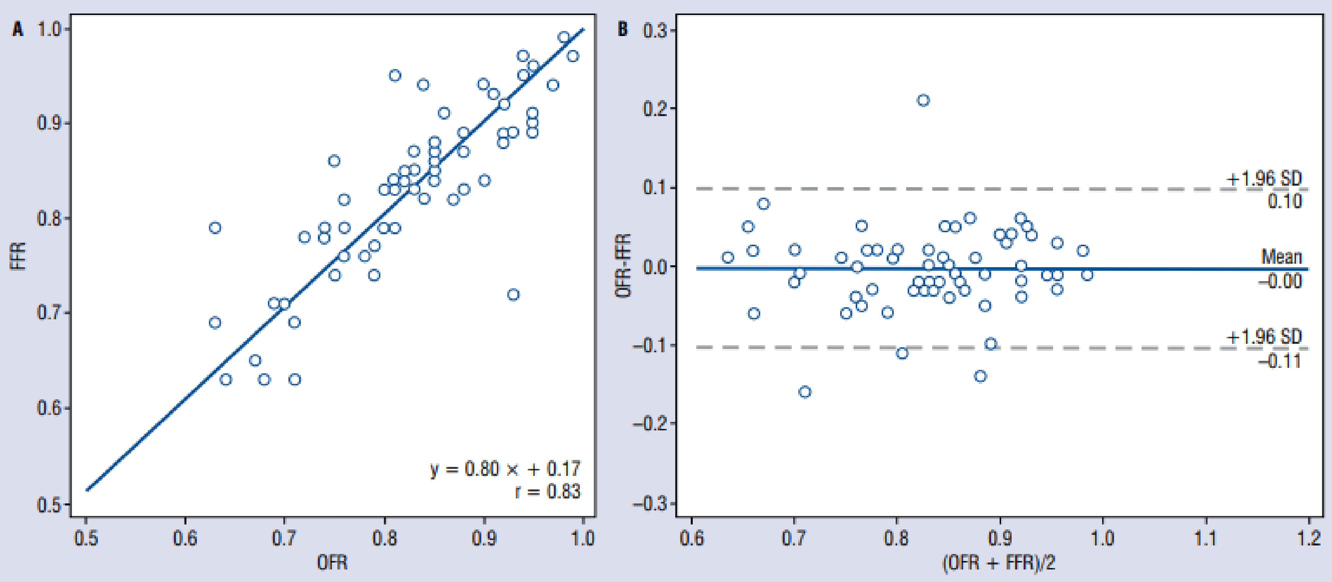
Juan Luis Gutiérrez-Chico[1]*, Yundai Chen[2]*, Wei Yu[3]*, Daixin Ding[3], Jiayue Huang[3], Peng Huang[3], Jing Jing[2], Miao Chu[1,3], Peng Wu[3], Feng Tian[2], Bo Xu[4], Shengxian Tu[3]

CFD based OCT-FFR









	OFR ≤ 0.80	QFR ≤ 0.80	MLA ≤ 1.63 mm²
Accuracy	93 (86–99)	90 (83–97)	68 (57–79)
Sensitivity	92 (73–99)	91 (72–99)	54 (33–74)
Specificity	93 (82–99)	89 (77–97)	76 (61–87)
PPV	88 (69–98)	81 (61–93)	54 (33–74)
NPV	96 (85–99)	96 (85–99)	76 (61–87)
+LR	13.8 (4.6–41.3)	8.6 (3.7–19.8)	2.2 (1.2–4.2)
–LR	0.1 (0.0–0.3)	0.1 (0.0–0.4)	0.6 (0.4–1.0)

Cardiol J 2020; 27,4: 350–361

jaa
Just accepted article

EuroIntervention

CFD based OCT-FFR

Title: Comparison of Diagnostic Performance of Intracoronary Optical Coherence Tomography-based and Angiography-based Fractional Flow Reserve for Evaluation of Coronary Stenosis.

All patients underwent both OCT imaging and FFR measurement from August 1st, 2011 to October 31st, 2018 were enrolled
339 vessels in 277 patients

41 patients excluded
- predilation prior to OCT imaging

Sent to core laboratory
298 vessels in 236 patients

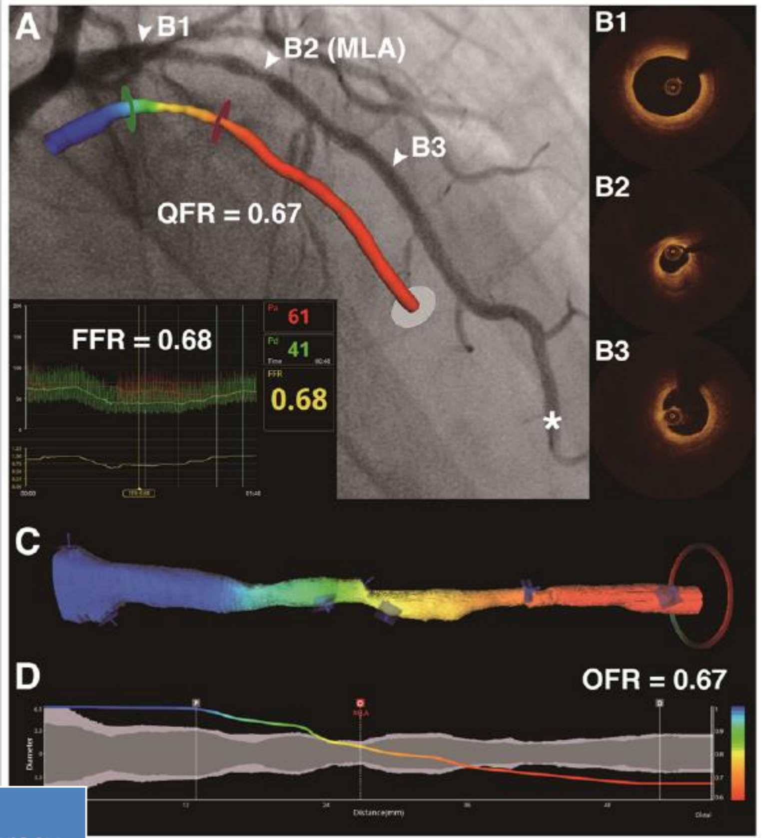
OFR analysis not possible (2 vessels)
- OCT image quality not acceptable (n=2)

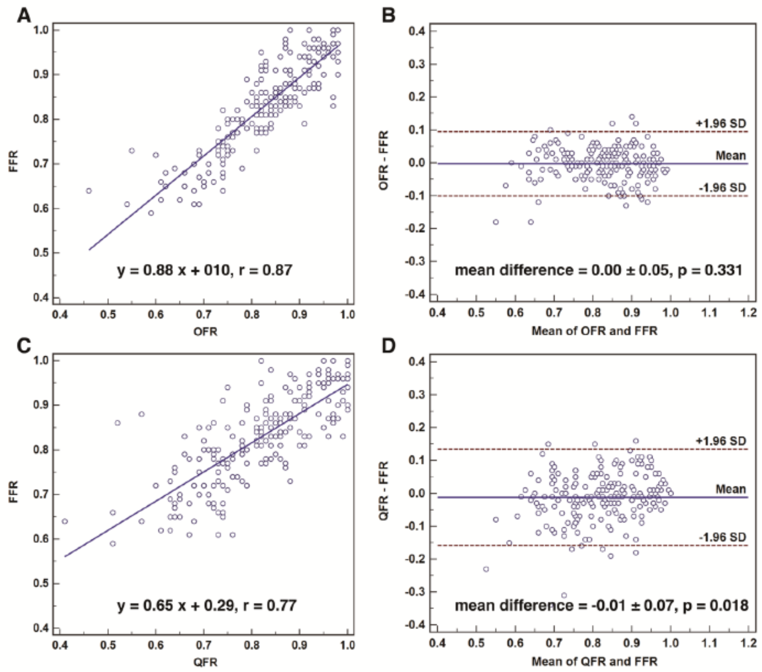
OFR excluded for comparison with FFR (66 vessels)
- Myocardial bridge (n=4)
- OCT not covering the entire lesion (n=59)
- Presence of bypass graft in the interrogated vessel (n=1)
- Substantial thrombosis identified by OCT (n=1)
- No sign of hyperemic respond in FFR tracing after administration of vasodilators (n=1)

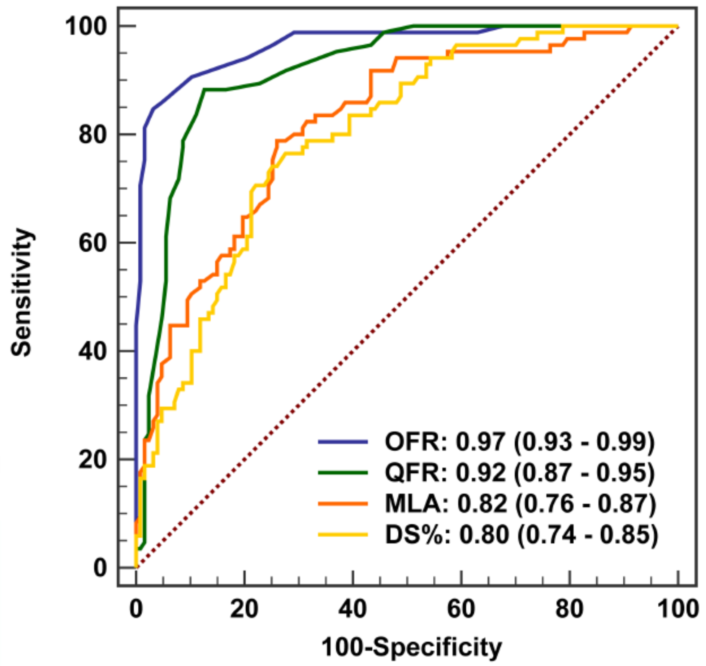
Both OFR and FFR avaliable
230 vessels in193 patients

QFR analysis not possible (18 vessels)
- Severe overlap (n=7)
- Insufficient image quality for TIMI frame count (n=1)
- Angiographic view ≤ 25 degrees (n=3)
- Severely tortured vessels (n=5)
- Automatic calibration not possible due to missing DICOM parameters (n=2)

OFR, QFR and FFR all avaliable
212 vessels in 181 patients

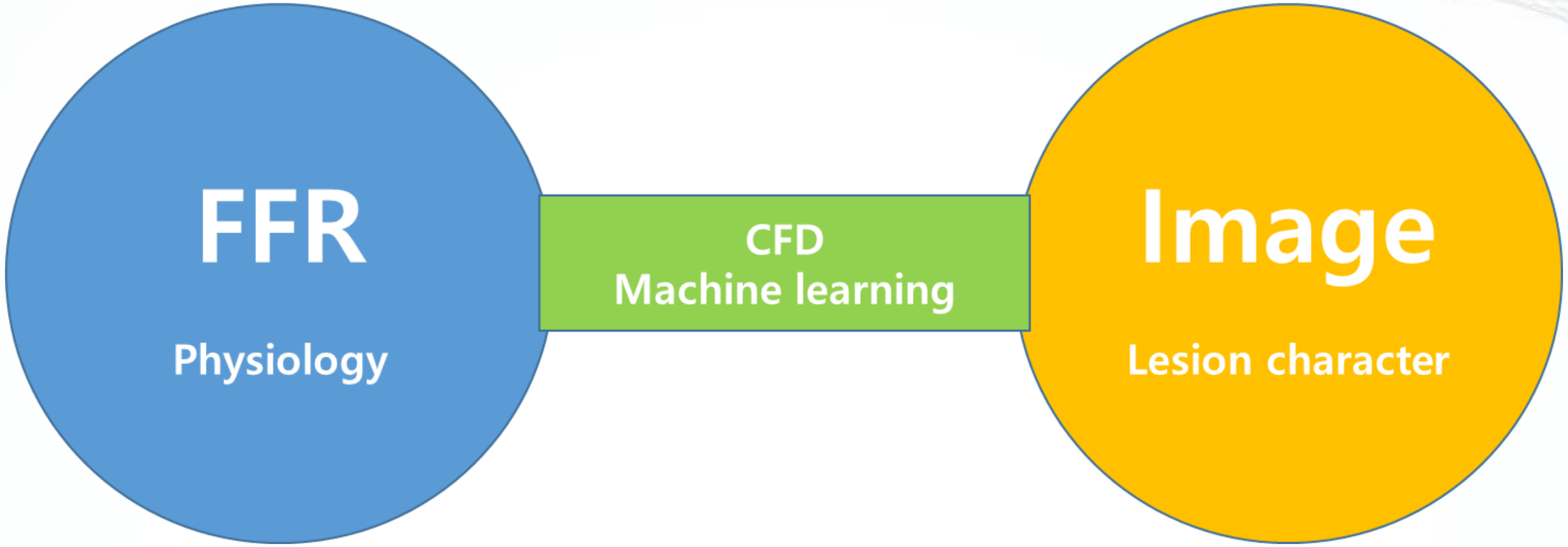


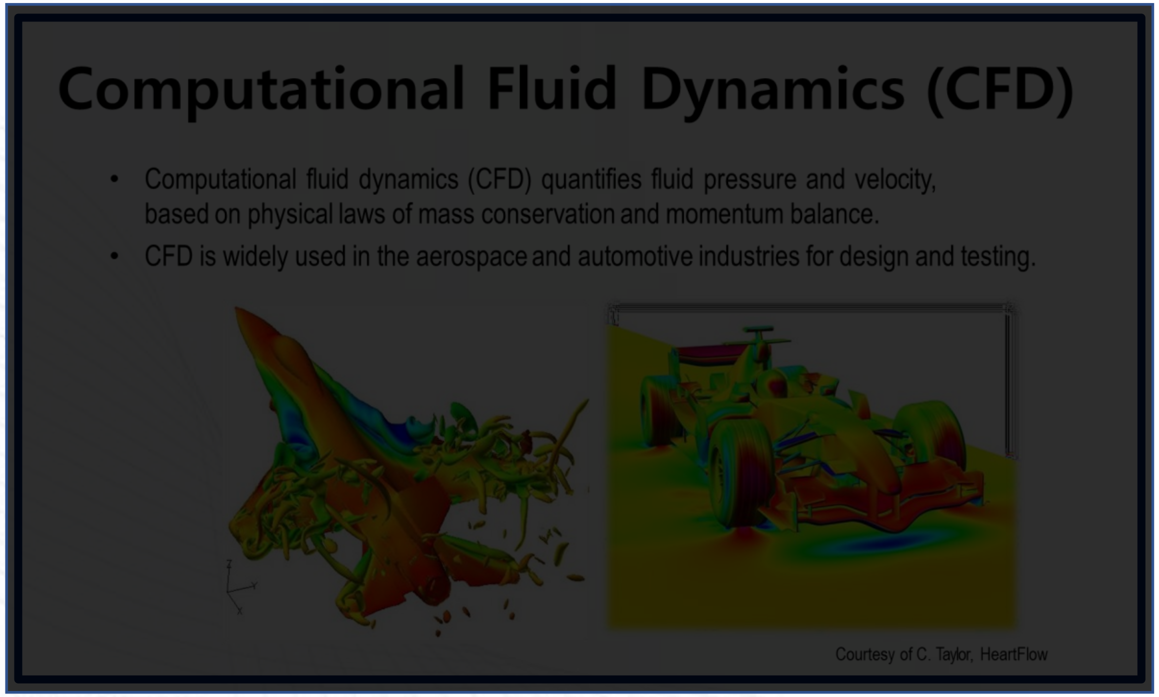


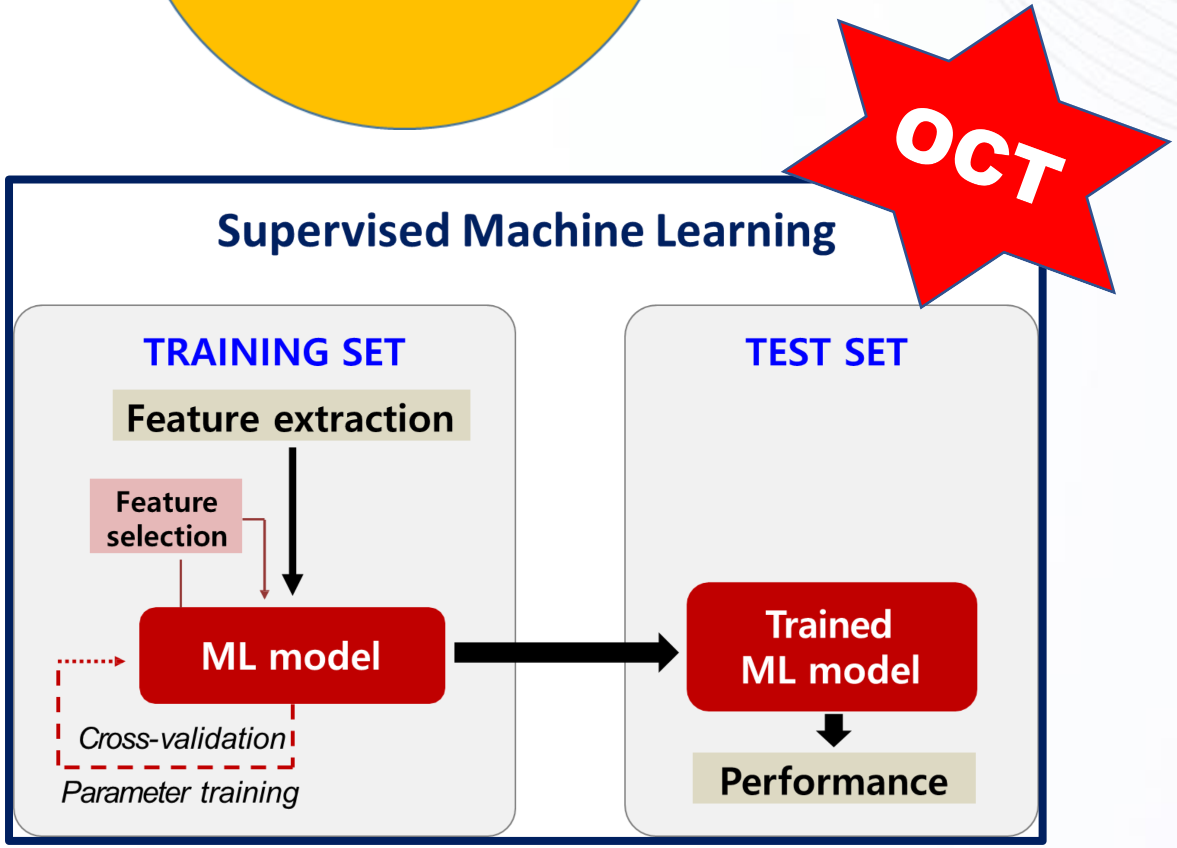


Patient No	Sensitivity	Specificity	PPV	NPV	Accuracy
181	86%	95%	92%	91%	92%

EuroIntervention 2020;16:568-576


FFR
Physiology
CFD
Machine learning
Image
Lesion character


Computational Fluid Dynamics (CFD)
• Computational fluid dynamics (CFD) quantifies fluid pressure and velocity, based on physical laws of mass conservation and momentum balance.
• CFD is widely used in the aerospace and automotive industries for design and testing.
Courtesy of C. Taylor, HeartFlow


OCT
Supervised Machine Learning
TRAINING SET
Feature extraction
Feature selection
ML model
Cross-validation
Parameter training
TEST SET
Trained ML model
Performance

scientific reports

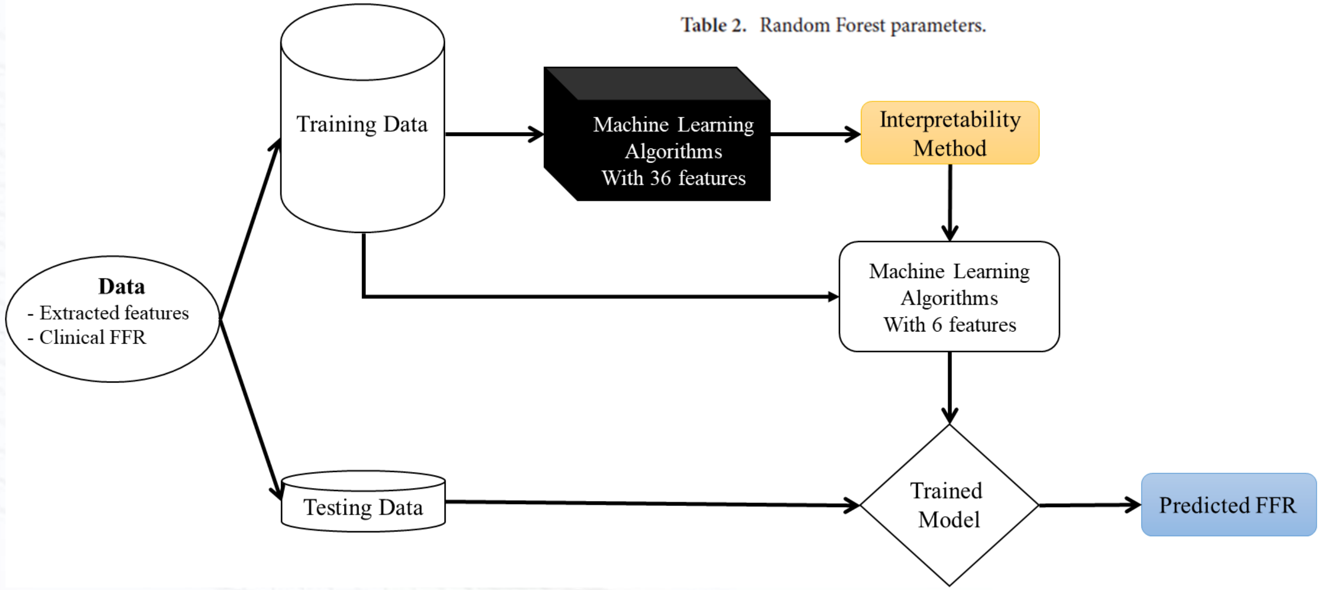
OPEN

Optical coherence tomography-based machine learning for predicting fractional flow reserve in intermediate coronary stenosis: a feasibility study

ML based OCT-FFR

Optimized hyperparameters	Description	Value
N_estimators	Number of trees in Random forest	1000
Max_depth	Maximum number of levels in tree	50
Min_samples_split	Minimum number of samples required to split a node	2
Min_samples_leaf	Minimum number of samples required at each leaf node	2

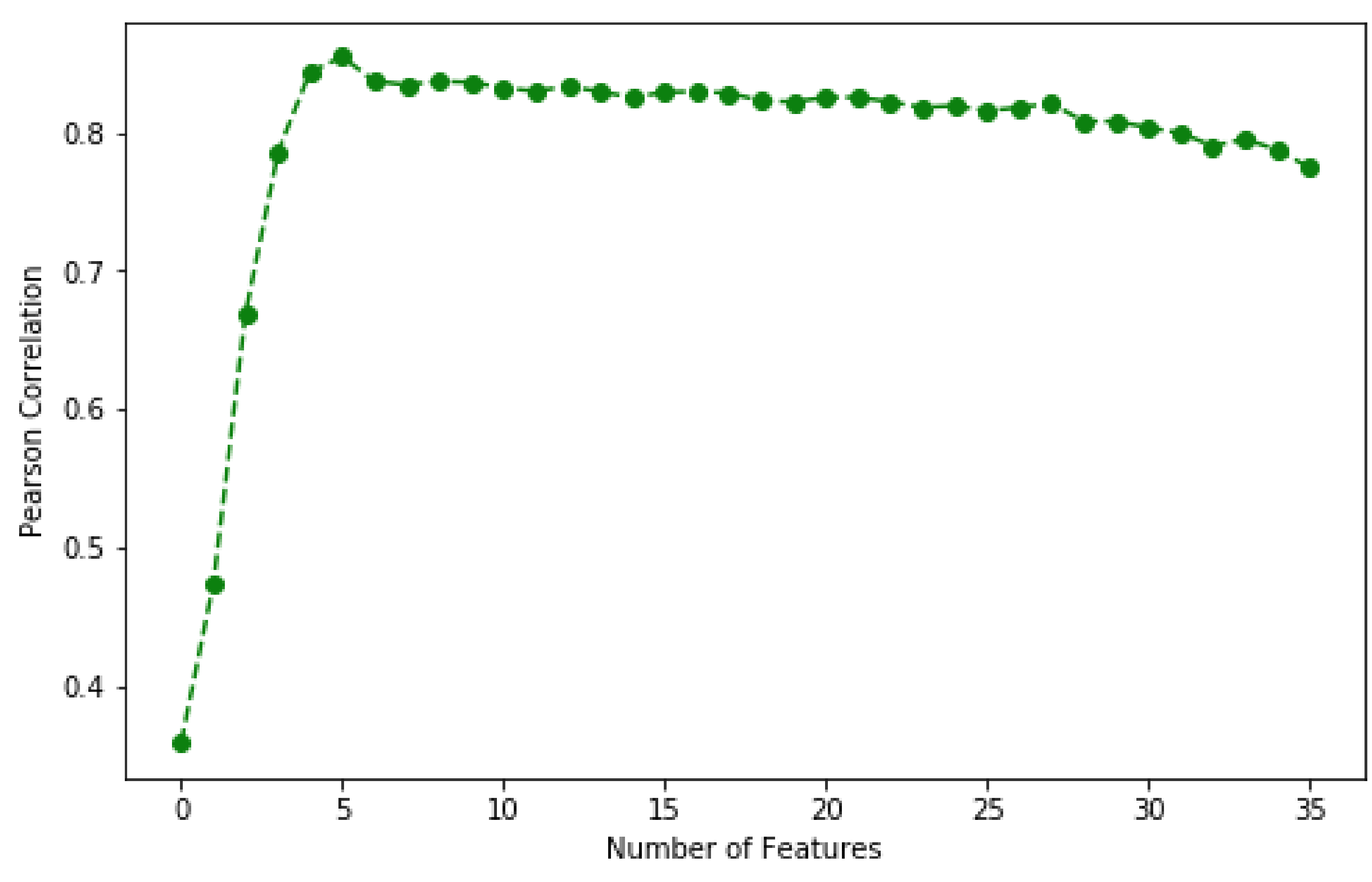
Table 2. Random Forest parameters.



	Feature	Weight	Standard deviation
1	Minimal lumen area	0.431489	0.201828
2	Area stenosis (%)	0.115880	0.038884
3	Lesion length	0.035337	0.011430
4	Pre-procedural platelet count	0.033187	0.021882
5	Proximal lumen area	0.026289	0.004752
6	Hypertension	0.016973	0.006676
7	Distal lumen area	0.009928	0.015942
8	Pre-procedural blood urea nitrogen level	0.007642	0.007495
9	Hypercholesterolemia	0.002688	0.002036
10	Calcified nodule	0.002309	0.000532
11	Pre-procedural hemoglobin level	0.001440	0.010278
12	Fibrocalcific nodule	0.000846	0.001332
13	Lipid rich plaque	0.000843	0.000886
14	Existence of thrombus	0.000077	0.001775
15	Dissection	0.000008	0.000292
16	lipid arc over 90° with thickness less than 65 μm	0.000000	0.000000
17	Existence of ruptured plaque	− 0.000032	0.002259
18	Diabetes mellitus	− 0.000096	0.001015
19	Age	− 0.000137	0.004589
20	Existence of erosion	− 0.000268	0.000213
21	Weight	− 0.000353	0.007105
22	lipid arc over 90°	− 0.000460	0.002299
23	Existence of macrophage	− 0.000802	0.004656
24	Unstable angina	− 0.000820	0.003374
25	Fibrous nodule	− 0.000922	0.001797
26	Existence of necrotic core	− 0.000950	0.000307
27	Gender	− 0.001616	0.000551
28	Existence of cholesterol crystal	− 0.002124	0.001706
29	Current smoking	− 0.003752	0.002504
30	Pre-procedural creatinine level	− 0.004177	0.012168
31	Existence of microvessels	− 0.004760	0.001435
32	Body mass index	− 0.006832	0.002180
33	Systolic blood pressure	− 0.008183	0.004773
34	diastolic blood pressure	− 0.008704	0.000831
35	Plaque area	− 0.011278	0.017001
36	Height	− 0.024011	0.013424

Cha et al. Scientific Reports (2020) 10:20421

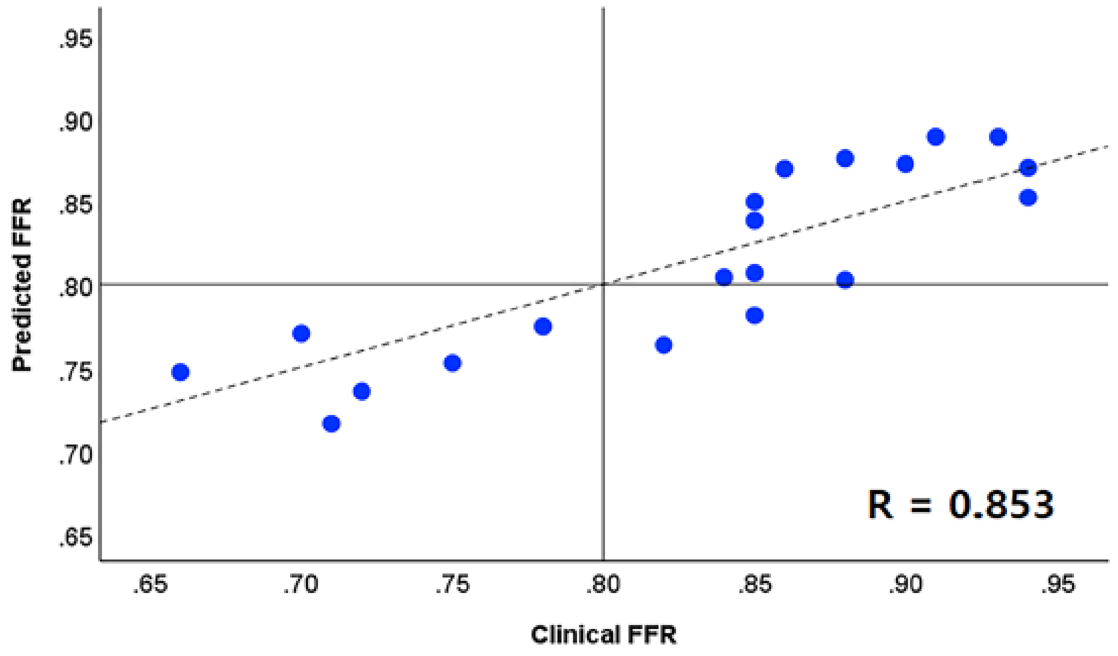
ML based OCT-FFR

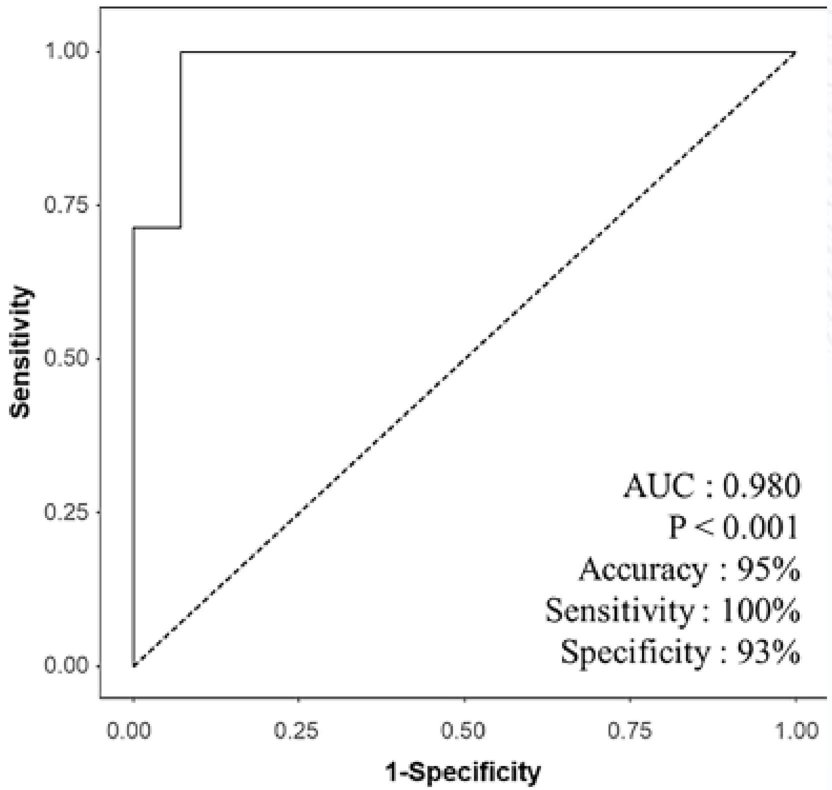


<6 Major Features>
Minimal lumen area
percentage of the stenotic area
Lesion length
Proximal lumen area
Pre-procedural platelet count
Hypertension

Cha et al. Scientific Reports (2020) 10:20421

ML based OCT-FFR





- **CFD-based OCT FFR computation : about 20 min**
  manual procedure of OCT lumen extraction and 3D rendering for CFD
- **Machine learning-based OCT FFR : 2–3 min**
  extract key OCT features and analyze FFR

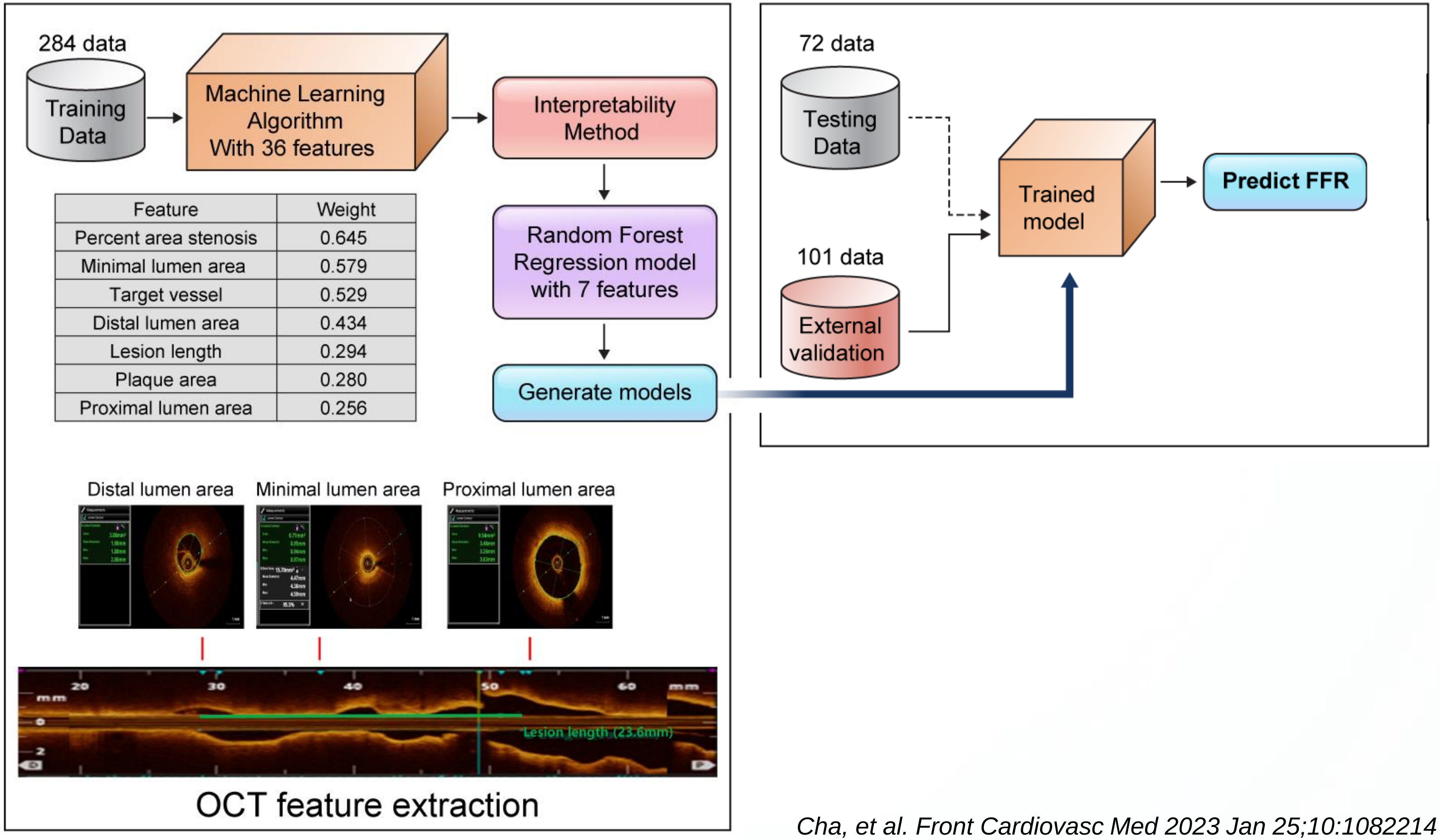
Cha et al. Scientific Reports (2020) 10:20421

ML based OCT-FFR on intermediate coronary stenosis

[Global model]

Machine Learning Model Development

OCT-based ML FFR prediction



Feature	Weight
Percent area stenosis	0.645
Minimal lumen area	0.579
Target vessel	0.529
Distal lumen area	0.434
Lesion length	0.294
Plaque area	0.280
Proximal lumen area	0.256

Cha, et al. Front Cardiovasc Med 2023 Jan 25;10:1082214

Baseline characteristics

ML based OCT-FFR

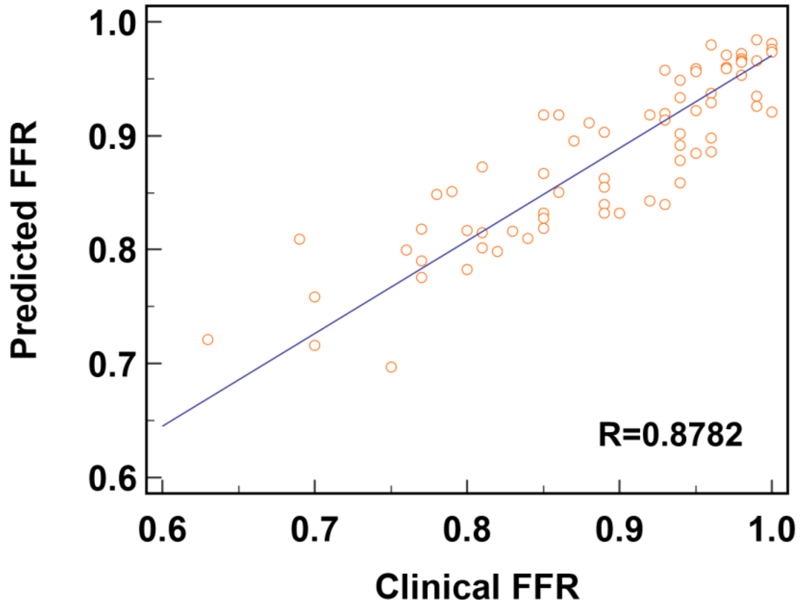
Clinical Data	
Age (years)	62.5 ± 8.8
Sex, male, n (%)	97 (74.6)
Coronary artery location, n (%)	
- Left anterior descending	130 (36.5)
- Left circumflex	110 (30.9)
- Right coronary artery	116 (32.6)
Systolic blood pressure (mmHg)	131.9 ± 19.3
Diastolic blood pressure (mmHg)	75.3 ± 11.0
Height (cm)	165.9 ± 8.0
Weight (kg)	69.8 ± 10.4
Body mass index (kg/m^2)	25.3 ± 3.0
Acute coronary syndrome, n (%)	38 (29.2%)
Hypertension, n (%)	79 (60.8%)
Diabetes mellitus, n (%)	41 (31.5%)
Hypercholesterolemia	58 (44.6%)
Current smoking, n (%)	29 (22.3)
Pre-procedural hemoglobin level (mg/dL)	14.3 ± 1.3
Pre-procedural platelet count (×10^3 µL)	234.7 ± 60.8
Pre-procedural BUN level (mg/dL)	15.8 ± 4.4

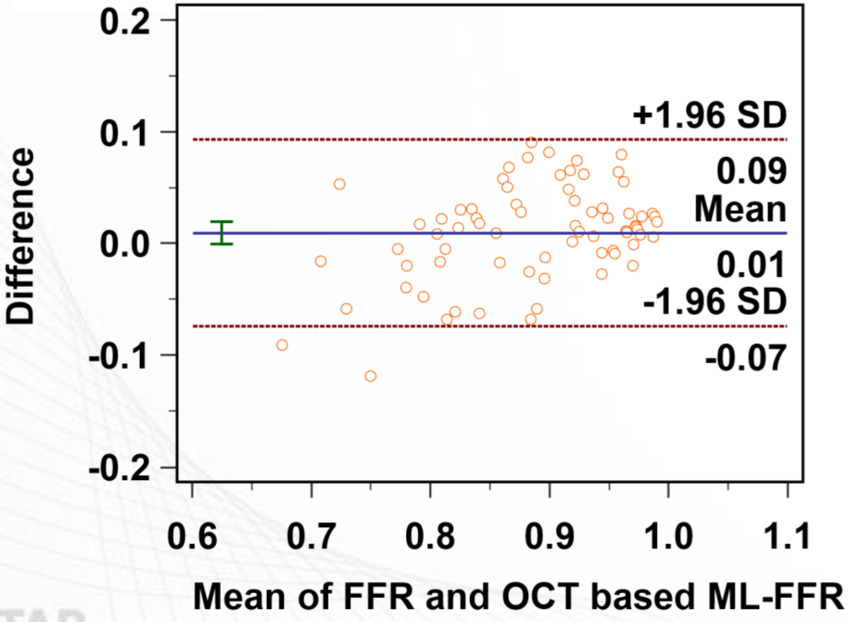
Clinical Data	
Pre-procedural creatinine level (mg/dL)	0.8 ± 0.1
Optical coherence tomography parameters	
Proximal lumen area (mm)	7.6 ± 3.4
Minimal lumen area (mm)	3.6 ± 2.5
Distal lumen area (mm)	8.2 ± 3.6
Lesion length (mm)	22.7 ± 12.0
Plaque area	14.6 ± 5.0
Area stenosis (%)	76.4 ± 11.0
Calcified nodule	34 (9.6)
Lipid-rich plaque, n (%)	87 (24.4)
Lipid arc over 90 degrees, n (%)	60 (16.9)
Lipid arc over 90 degrees with thickness < 65 µm, n (%)	24 (6.7)
Existence of dissection, n (%)	16 (4.5)
Existence of necrotic core, n (%)	162 (45.5)
Existence of microvessels, n (%)	94 (26.4)
Existence of cholesterol crystal, n (%)	137 (38.5)
Existence of rupture, n (%)	42 (11.8)
Existence of erosion, n (%)	24 (6.7)
Existence of macrophage, n (%)	34 (9.6)

Cha, et al. Front Cardiovasc Med 2023 Jan 25;10:1082214

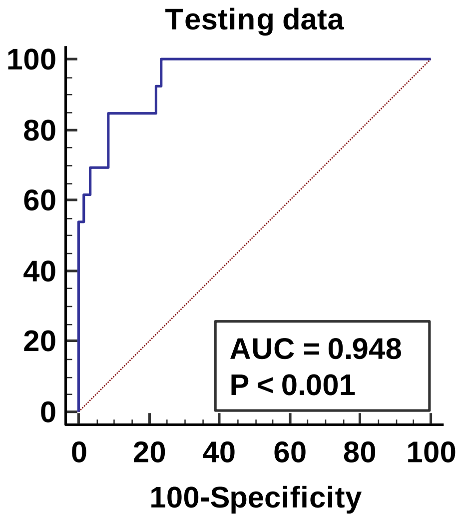
Results

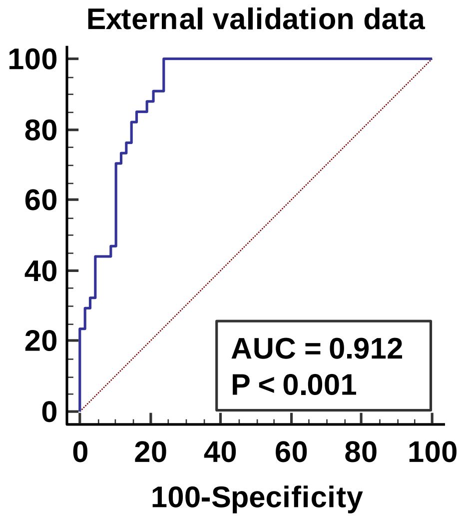
ML based OCT-FFR





	Testing (n=72)	External validation (n=101)
Pearson correlation	0.8782	0.7884
Sensitivity	98.3%	89.6%
Specificity	61.5%	70.6%
Positive prediction value	92.1%	85.7%
Negative prediction value	88.9%	77.4%
Accuracy	91.7%	83.2%





Cha, et al. Front Cardiovasc Med 2023 Jan 25;10:1082214

Conclusion

- Intravascular **OCT** has the highest resolution imaging modality compared with CT, angiography, IVUS.
- Thus, OCT can provide morphological information about lesion characteristics more **accurately** to CFD and Machine learning methods.
- **CFD** or **ML** based OCT-FFR derived techniques can be a useful method for the evaluation the functional and anatomic severity of coronary stenosis.
- Compared to the CFD-based OCT-FFR, ML-based OCT FFR has **cost effectiveness** with **time saving** (Real-time procedure)
- Although CFD or ML had still several limitations to apply real clinical practice, integration of functional and anatomical information may provide **better treatments for intermediate coronary artery stenosis.**