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Pressure Wire Compared to Microcatheter Sensing for Coronary Fractional Flow Reserve: The PERFORM Study

Brief title: Wire versus catheter-based FFR

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Abstract

***Aims*—**Among technologies used to assess FFR, a monorail, sensor-tipped micro pressure catheter (PC) may be advantageous for delivery and re-assessment. We sought to determine whether the larger cross-sectional area of the PC influences FFR measurements compared to the pressure wire.

***Methods and Results*—**PERFORM was a single-center, prospective study designed to determine the precision and accuracy of the PC compared with the pressure wire (PW) for measurement of FFR. Eligible patients had native coronary artery target lesions with visually estimated diameter stenosis of 40-90%. The independently adjudicated primary endpoint was the difference in hyperemic PW-determined minimal FFR with and without the PC distal to the stenosis. Seventy-four patients (95 lesions) were prospectively analyzed between December 2015 and December 2016. Median hyperemic FFR was 0.84 [IQR 0.78, 0.89] with the PW and 0.79 [IQR 0.73, 0.85] with the PC distal to the stenosis ($p<0.001$). Such differences led to clinical discordance, whereby the PC decreased the hyperemic PW-determined FFR from >0.80 to ≤0.80 in 17 of 95 measurements (19%). Median resting Pd/Pa was lower following introduction of the PC compared with the PW alone (0.93 [IQR 0.90, 0.97] versus 0.90 [IQR 0.86, 0.95], $p<0.001$). Median pressure drift was not different between the PW and the PC (0.01 [IQR -0.01, 0.05] versus 0.01 [IQR 0.00, 0.02], $p=0.38$).

***Conclusions*—**Introduction of the PC reduced device success and both hyperemic FFR and resting Pd/Pa compared with the PW alone, leading to re-classifying physiological significance to below ischemic threshold in one out of five assessments.

***Clinical Trial Registration*—**URL: http://www.clinicaltrials.gov. Unique identifier: NCT02648230

Key Words: stable angina, no specific risk, fractional flow reserve

Condensed Abstract

Among technologies used to assess FFR, a monorail, sensor-tipped micro pressure catheter (PC) may be advantageous for delivery and re-assessment. We sought to determine whether the larger cross-sectional area of the PC influences FFR measurements compared to the pressure wire. Median hyperemic FFR was 0.84 [IQR 0.78, 0.89] with the PW and 0.79 [IQR 0.73, 0.85] with the PC distal to the stenosis (p<0.001). Median resting Pd/Pa was lower following introduction of the PC compared with the PW alone (0.93 [IQR 0.90, 0.97] versus 0.90 [IQR 0.86, 0.95], p<0.001). Introduction of the PC reduced both hyperemic FFR and resting Pd/Pa compared with the PW alone.

Abbreviations

FFR = fractional flow reserve

IQR = interquartile range

MLD = minimum lumen diameter

Pa = aortic pressure

PC = pressure catheter

Pd = distal pressure

PW = pressure wire

QCA = quantitative coronary angiography

RVD = reference vessel diameter

Introduction

Fractional flow reserve (FFR) measurements in randomized clinical outcomes trials were made using a 0.014" coronary hypotube with a piezo-resistive sensor near its tip. [1-3] However, the presence of electrical connections, and more recently optical fiber, within the shaft of these "wires" limit their torqueability in comparison to workhorse wires. A new FFR technology with an optical pressure sensor mounted at the tip of a monorail microcatheter (Navvus; ACIST Medical Systems, Eden Prairie, MN) has been developed to counter some of the limitations of the wire-based FFR measurement. While a microcatheter system facilitates multiple advancement and withdrawal over the operator's guidewire of choice, the larger diameter of the catheter may also influence coronary hemodynamics across the target lesion. The degree to which this may occur in practice is unknown.

The PrEssure wiRe Compared to Microcatheter-based Sensing Technology For the Evaluation of FFR Measurements (PERFORM) study was designed to determine the precision and accuracy of the Navvus pressure catheter (PC) compared with the pressure wire (PW) among an unselected group of patients undergoing FFR assessment for routine clinical indications.

Methods

Study Design

PERFORM was a prospective, single-center study conducted at Columbia University Medical Center (New York, NY) comparing the the PW (Aeris, St. Jude Medical, St. Paul, MN) and the PC (Navvus, Acist, Eden Prarie, MN). The institutional review board approved the study protocol. The trial was registered at ClinicalTrials.gov (NCT02648230).

Participants

Patients undergoing coronary angiography based on clinical indication were considered for enrollment. Eligible patients had one or more target lesions located in a native coronary artery with visually estimated diameter stenosis of 40%-90% and planned use of FFR for clinical decision making.[4] Left main or ostial right coronary artery stenosis, bypass graft stenoses, and chronic total occlusions were excluded.

Procedures

Coronary angiography was performed via femoral or radial access, and anticoagulation, dual antiplatelet therapy and other medications were administered per local standard of care. A minimum 6Fr guiding catheter was used.

Following angiography, performed in a view that would allow optimal quantitative coronary angiography (QCA), physiological assessments were performed (Figure 1). Briefly, the PC was loaded onto the PW, and the aortic pressure transducer, PC, and PW all equilibrated to zero pressure outside of the body. With the PC used as an introducer, the PW alone was advanced to the aorto-ostial junction where PW equalization was performed after ensuring presence of an appropriate aortic waveform, with guide disengagement performed if necessary. The PW was then advanced across the lesion with the sensor located at least 3 cm distal to the lesion and preferably in the distal third of the artery. Following administration of intracoronary nitroglycerin and saline flush, the guide catheter was disengaged, the position of the PW was recorded on cine angiography, and the lowest basal distal pressure/aortic pressure (Pd/Pa) was recorded. The preloaded PC was then advanced from outside the body to the aorto-ostial junction where PC equalization was performed, again ensuring the presence of the appropriate aortic waveform. The PC was then advanced just proximal to the PW sensor, and the lowest

basal Pd/Pa of both the PC and PW were recorded simultaneously. To induce hyperemia, intravenous adenosine was infused at 140 μg/kg/min. At maximal hyperemia, the FFR was recorded on both the PW and the PC. The PC was then slowly pulled back, making note of pressure step-ups across the lesion, and the PC drift was recorded at the aorto-ostial junction. Subsequently, the PC was completely removed, and the FFR was recorded again with the PW alone. The PW was then slowly pulled back, making note of pressure step-ups across the lesion, and the pressure again recorded at the aorto-ostial junction. Pd/Pa, FFR, and pressure drift of each device were also recorded in real time using time-stamped still photography. Revascularization was guided by hyperemic FFR measured by the PW alone.

Outcomes

The primary endpoint of the study was the difference in hyperemic PW-determined minimal FFR with and without the presence of the PC distal to the stenoses. Secondary endpoints included device success (the ability to cross the lesion and record a hyperemic FFR), the difference in PW-determined resting Pd/Pa with and without the PC distal to the stenosis, PW and PC pressure drift, and discordance in physiological significance (hyperemic FFR ≤0.80 by one modality versus >0.80 with the other modality and hyperemic FFR ≤0.75 by one modality versus >0.80 with the other modality). Other outcomes assessed were the proportion of lesions with a mean hyperemic FFR difference ≥0.05 and ≥0.10, and a sensitivity analysis for resting Pd/Pa and hyperemic FFR comparing measurements made using the PW versus the PC when both devices were in the distal coronary artery.

Data Analysis

Primary and secondary imaging and physiology endpoints were independently performed in the angiography and physiology core laboratories at the Cardiovascular Research Foundation (New

York, NY). Offline QCA analyses to determine percentage diameter stenosis, reference artery diameter, and lesion level characteristics were performed by an independent core lab (Cardiovascular Research Foundation) using automated software (Medis QA Angio, Leiden, The Netherlands). Hemodynamic data were analyzed by an independent physiology core lab (Cardiovascular Research Foundation). Tracing from the PW and the PC were scrambled in the core laboratory such that measurements did not undergo paired analysis, avoiding bias.

Statistical Analysis

Sample size was calculated assuming a difference of 0.02 between PC and PW determined FFR with a standard deviation of 0.065.[5, 6] At α 0.025 (one-sided), 85 lesions would be required to reject the null hypothesis that there was no difference between PC and PW measured FFR with 80% power. Normal distribution of parameters was assessed using the Kolmogorov–Smirnov test, and homogeneity of variances was assessed using Levene's test. Continuous values were summarized using median and interquartile range (IQR), and differences were compared using the Mann-Whitney U test. Systematic errors of measurement induced by the PC were assessed using Pearson correlation and Bland–Altman analysis. The univariate association between the PW and PC difference in measurements (ΔFFR) and patient or lesion characteristics was assessed using the Student *t* test (binary parameters) or Pearson correlation (continuous parameters). The adjusted association between the ΔFFR and patient and lesion characteristics was determined using multivariable linear regression. P values <0.05 were considered statistically significant. All analyses were performed with SAS version 9.4 (SAS Institute, Cary, North Carolina).

Results

Patients and Procedures

Between December 17, 2015, and December 8, 2016, 74 patients with 95 lesions had successful PW measurements and were enrolled in the study. Patient data and angiographic lesion characteristics are presented in Table 1.

Study Endpoints

Device success in crossing the lesion was 100% with the PW and 95% with the PC (p=0.02). FFR was available with both the PW and the PC for 89 lesions (94%) and resting Pd/Pa was available with both the PW and PC for 88 lesions (93%). Resting Pd/Pa measured on the PW significantly decreased from 0.93 [IQR 0.90, 0.97] to 0.90 [IQR 0.86, 0.95], following advancement of the PC distal to the stenosis (p<0.001) (Table 2). While the PW and PC assessment of resting Pd/Pa were closely correlated (Figure 2A), the PC led to overestimation of the pressure gradient. Bland-Altman analysis did not identify systematic differences between PW and PC measurements of the resting Pd/Pa. (Figure 2B). The distribution of the differences in Pd/Pa is shown in Figure 2C.

Following the introduction of the PC distal to the target lesion, hyperemic FFR measured on the PW significantly decreased from 0.84 [IQR 0.78, 0.89] to 0.79 [IQR 0.73, 0.85], (p<0.001) (Table 2). While the PW and PC assessment of hyperemic FFR were well correlated (R^2=0.82, p<0.0001, Figure 2D), introduction of the PC distal to the stenosis led to overestimation of the severity of the pressure gradient. Moreover, the difference between PW and PC measurements increased with decreasing FFR values (Figure 2E), indicating that FFR overestimation by the PC occurs more frequently in more severe lesions. The introduction of the PC resulted in a decrease in FFR compared with the PW alone by ≥0.10 in 13 (15%) lesions and by ≥0.05 in 35 (39%) lesions. These differences led to discordance in ascribing physiologic significance in a

number of lesions, with the PC measuring FFR ≤0.80 in 17 lesions (19%) for which the FFR measured by the PW was >0.80 (Table 2); and with the PC measuring FFR ≤0.75 in 8 lesions (9%) for which the PW was >0.80. There were no instances of the PW measuring FFR ≤0.80 and the PC >0.80. The distribution of the differences in FFR is shown in Figure 2F.

Sensitivity analyses identified no difference in resting Pd/Pa (0.90 [IQR 0.86, 0.95] versus 0.91 [IQR 0.87, 0.96], p=0.054) or hyperemic FFR (0.79 [IQR 0.73, 0.85] versus 0.80 [IQR 0.73, 0.86], p=0.44) measured by the PW or PC when both devices were simultaneously in the distal coronary circulation. Pressure drift was not different between the PC and the PW (0.01 [IQR -0.01, 0.05] versus 0.01 [IQR 0.00, 0.02], p=0.38).

Among patients with ΔFFR (difference between FFR measured by PC and PW), lesion location in the right coronary artery, interpolated RVD, distal RVD, in-segment MLD, and lesion length were significantly associated with the ΔFFR in univariate analyses (Table 3). Discordance between PW and PC measurements were observed more often in vessels with small distal RVD and longer lesion length with differences pronounced in different ranges of FFR values (Figure 3). In multivariable analyses only distal RVD and lesion length were identified as independent predictors of ΔFFR (Table 4).

Discussion

PERFORM is a direct comparison of the PW and the PC for physiologic assessment of moderate coronary artery stenosis, aimed to determine whether the larger cross-sectional area of the PC influences translesional pressure measurement compared with PW alone. We report a number of clinically relevant findings. First, while the PW was successful in crossing the target lesion and providing physiological measurements in all cases, device success for the PC was lower. Second, introduction of the PC distal to the target lesion significantly reduced both the resting Pd/Pa and the hyperemic FFR compared with the PW. Third, pressure drift was not

different between the PC and the PW. Forth, the magnitude of change in FFR following introduction of the PC was large, reducing FFR by ≥0.05 in 39% and by ≥0.10 in 15% of lesions. Fifth, these differences would reclassify 19% of "negative" FFR measurements by PW (FFR >0.80) to "positive" measurements (FFR ≤0.80) with the PC, thus representing a false positive frequency of approximately 1 in 5, which may adversely impact clinical decision-making. Finally, multivariable regression identified smaller distal RVD as an independent predictor of the mean difference in FFR.

The PC may be delivered over a conventional flexible guidewire, aiding delivery through significant tortuosity and into angulated side branches and distal vessels. The rapid exchange design offers the advantage of performing repeated assessment of the FFR to determine the physiological significance of tandem lesions after treatment of a single stenosis,[7] where one lesion may be the culprit lesion. As data accumulates suggesting the prognostic significance of post-PCI FFR,[8, 9] the PC also holds a significant advantage in this respect, negating the need for re-wiring the vessel with the FFR wire or pulling back the FFR wire for re-equalization following stenting. Nevertheless, in its current design the PC has a larger cross-sectional profile (0.022" circular diameter and maximum diameter of 0.036' at the site of the pressure sensor) compared with the PW (0.014" circular diameter). In keeping with the central premise of FFR measurement, the larger catheter cross-sectional area artificially increases the stenosis severity and could impact coronary hemodynamics. Indeed, previous *in vitro* studies have suggested this possibility for not only a monorail catheter[10] but also the simultaneous presence of two-guidewires.[11] The present study confirms that the PC impacts FFR measurements in the clinical setting. Furthermore, despite the theoretical benefits of improved deliverability, the larger catheter cross-sectional area may in fact impede delivery. We found that lesion crossability was significantly lower for the PC compared to the PW as have other recent studies that confirm lower device success for the PC.[12-14] Of the 5 lesions that could not be crossed in our study, 1

was due to excessive tortuosity, 1 due to moderate calcification, 2 due to a combination of the latter, and 1 due to acute angle at the origin of a large culprit vessel diagonal branch. Taken together, deliverability is not improved for the PC compared to the PW.

The ACCESS-NZ study examined 50 intermediate coronary lesions, excluding vessels with visually estimated diameter <2.5 mm.[15] This analysis demonstrated a reduction in FFR from 0.81±0.11 with the PW alone to 0.79±0.12 with the Navvus PC across the stenosis. Limitations of this study were the small sample size, lack of QCA, and skewed drift values reported as means rather than medians. The IMPACT study included assessment of 28 stenoses, also showing a reduction in FFR after introduction of the Navvus PC (0.82±0.07) compared with PW-only assessment (0.86±0.06).[16] Although the results of this trial support findings of the current study, the small sample size, intracoronary-only administration of adenosine (limiting assessment of drift), and small number of FFR values below the ischemic threshold were limitations of this study.

Recently two other studies evaluated the effect of the PC on hyperemic FFR measurement. The ACIST-FFR study evaluated 210 patients in which 169 paired-measurements were performed. The authors reported a mean bias introduced by the PC of -0.03 (95% CI -0.037, -0.013) and a diagnostic agreement of 81% (95% CI 75%, 87%). Importantly, using their definition of clinical discordance where the difference between PC and PW crossed the grey zone from 0.75 to 0.80, only 2.9% of patients could have been potentially over-treated. In multivariate analysis only FFR measured by the PC was independently associated with a bias. The authors concluded the clinical impact of these findings are likely minimal. While ACIST-FFR is the largest study comparing the PC to the PW, the exclusion of 20% of tracings due to suboptimal FFR measurement (compared to none in our study, measured at the same Core Laboratory), the repeated dose of adenosine to measure FFR with and without the PC (which itself has a mean measurement difference of 0.022±0.020)[6], and the

exclusion of clinical discordance across the established cut-point of 0.80 are limitations. Another study by Pouillot et al[12] examined 88 stenoses in 99 consecutive patients and found that introduction of the PC led to a mean decrease in FFR of of -0.03 ± 0.05. Moreover, using a threshold of 0.80 for FFR, they identified clinical discordance in 23% of lesions and 23% of patients. The marked similarity between the results reported by Pouillot et al[12] and our findings substantiate that introduction of the PC impacts both the measurement of FFR and also potentially clinical decision making.

In the current study, the finding of a clinically relevant effect of the PC on measured FFR raises a number of clinically relevant questions. Can a correction factor be applied to the pressure catheter such that the difference between modalities is negated? Our data suggest that this may not be possible, as significant variability between the PW and the PC, especially in values around the 0.8 ischemia threshold (Figure 2B), exists. We did, however, identify a systematic and proportional difference in the FFR, finding a greater difference between devices the lower the FFR values were (Figure 2B). Univariate analysis identified a number of factors associated with the ΔFFR between devices. Nonetheless, in multivariable analysis only distal RVD and lesion length were identified as an independent predictor of ΔFFR. These data suggest that operators need to pay close attention to placement of the PC during physiological assessment, perhaps placing the PC distal to the stenosis, but not in the very distal coronary artery, or interpreting the PC-based FFR measurements in smaller vessels with caution.

Study Limitations

Our study has a number of important limitations. First, our study was conducted in a single center with significant experience in physiological assessment using FFR, which may limit its generalizability. Nevertheless, no pressure tracing were rejected by the physiology core laboratory, highlighting a potential advantage of a single center where both physician training and trial monitoring are closely regulated and uniform. Second, our study was not randomized.

The IMPACT study randomized physiological assessment by PC or PW, changing the order of use of the devices by random allocation[16]; however, measurements in our study were performed during a single administration of intravenous adenosine as an infusion and thus may be less prone to the error introduced by intracoronary bolus adenosine administration in the IMPACT study.[16] Third, a larger sample size may have been able to provide greater power to detect specific patient or lesion characteristics associated with the ΔFFR. Fourth, we compared the PC to a specific PW from a single manufacturer. Although similar findings between the PC and other PWs may be inferred, our study can neither confirm nor refute this possibility. Finally, a new iteration of the PC is available with 33% less cross-sectional area, likely impacting our findings.

Conclusion

In conclusion, introduction of the larger cross-sectional area PC reduced device success and both resting Pd/Pa and hyperemic FFR compared with the PW, with no difference in drift. Compared with the PW, the PC led to re-classifying physiological significance to below ischemic threshold in 1 out of 5 assessments, particularly in vessels with small distal reference vessel diameter and long lesions, where PC measurements may be unreliable.

Impact on Daily Practice

The results of the current study are consistent with others evaluating the hemodynamic effect of the larger diameter PC across intermediate coronary stenoses. While varying marginally in the magnitude of the difference, the PC undoubtedly introduces a decrease in the hyperemic FFR.

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Conflicts of Interests

The authors have institutional research grant support from both St. Jude Medical and ACIST Medical Systems. Ziad Ali has served as a consultant to St Jude Medical and ACIST Medical Systems and holds grant support from St. Jude Medical and Cardiovascular Systems Inc. to Columbia University. Gary S. Mintz has received consulting fees from ACIST, Boston Scientific, InfraReDx, St Jude, and Volcano. Akiko Maehara has received consulting fees from Boston Scientific and OCT Imaging Inc. and research grants from Boston Scientific and St Jude Medical. Allen Jeremias: Consultant – Philips and Abbott Vascular. Ajay J Kirtane reports institutional grants to Columbia University and/or Cardiovascular Research Foundation from Medtronic, Boston Scientific, Abbott Vascular, Abiomed, Cardiovascular Systems Inc., CathWorks, Siemens, Philips, ReCor Medical, and Spectranetics. Other authors declare no conflicts of interest relevant to this report.

References

1. De Bruyne B, Pijls NH, Kalesan B, Barbato E, Tonino PA, Piroth Z, Jagic N, Mobius-Winkler S, Rioufol G, Witt N, Kala P, MacCarthy P, Engstrom T, Oldroyd KG, Mavromatis K, Manoharan G, Verlee P, Frobert O, Curzen N, Johnson JB, Juni P, Fearon WF. Fractional flow reserve-guided pci versus medical therapy in stable coronary disease. *The New England journal of medicine*. 2012;367:991-1001
2. Pijls NH, van Schaardenburgh P, Manoharan G, Boersma E, Bech JW, van't Veer M, Bar F, Hoorntje J, Koolen J, Wijns W, de Bruyne B. Percutaneous coronary intervention of functionally nonsignificant stenosis: 5-year follow-up of the defer study. *Journal of the American College of Cardiology*. 2007;49:2105-2111
3. Tonino PA, De Bruyne B, Pijls NH, Siebert U, Ikeno F, van' t Veer M, Klauss V, Manoharan G, Engstrom T, Oldroyd KG, Ver Lee PN, MacCarthy PA, Fearon WF. Fractional flow reserve versus angiography for guiding percutaneous coronary intervention. *The New England journal of medicine*. 2009;360:213-224
4. Tonino PA, Fearon WF, De Bruyne B, Oldroyd KG, Leesar MA, Ver Lee PN, Maccarthy PA, Van't Veer M, Pijls NH. Angiographic versus functional severity of coronary artery stenoses in the fame study fractional flow reserve versus angiography in multivessel evaluation. *Journal of the American College of Cardiology*. 2010;55:2816-2821
5. De Bruyne B, Pijls NH, Barbato E, Bartunek J, Bech JW, Wijns W, Heyndrickx GR. Intracoronary and intravenous adenosine 5'-triphosphate, adenosine, papaverine, and contrast medium to assess fractional flow reserve in humans. *Circulation*. 2003;107:1877-1883
6. Johnson NP, Johnson DT, Kirkeeide RL, Berry C, De Bruyne B, Fearon WF, Oldroyd KG, Pijls NHJ, Gould KL. Repeatability of fractional flow reserve despite variations in systemic and coronary hemodynamics. *JACC. Cardiovascular interventions*. 2015;8:1018-1027

7. Daniels DV, van't Veer M, Pijls NH, van der Horst A, Yong AS, De Bruyne B, Fearon WF. The impact of downstream coronary stenoses on fractional flow reserve assessment of intermediate left main disease. *JACC. Cardiovascular interventions*. 2012;5:1021-1025
8. Rimac G, Fearon WF, De Bruyne B, Ikeno F, Matsuo H, Piroth Z, Costerousse O, Bertrand OF. Clinical value of post-percutaneous coronary intervention fractional flow reserve value: A systematic review and meta-analysis. *American heart journal*. 2017;183:1-9
9. Agarwal SK, Kasula S, Hacioglu Y, Ahmed Z, Uretsky BF, Hakeem A. Utilizing post-intervention fractional flow reserve to optimize acute results and the relationship to long-term outcomes. *JACC. Cardiovascular interventions*. 2016;9:1022-1031
10. Banerjee RK, Peelukhana SV, Goswami I. Influence of newly designed monorail pressure sensor catheter on coronary diagnostic parameters: An in vitro study. *Journal of biomechanics*. 2014;47:617-624
11. Verberne HJ, Meuwissen M, Chamuleau SA, Verhoeff BJ, van Eck-Smit BL, Spaan JA, Piek JJ, Siebes M. Effect of simultaneous intracoronary guidewires on the predictive accuracy of functional parameters of coronary lesion severity. *American journal of physiology. Heart and circulatory physiology*. 2007;292:H2349-2355
12. Pouillot C, Fournier S, Glasenapp J, Rambaud G, Bougrini K, Vi Fane R, Geyer C, Adjedj J. Pressure wire versus microcatheter for ffr measurement: A head-to-head comparison. *EuroIntervention : journal of EuroPCR in collaboration with the Working Group on Interventional Cardiology of the European Society of Cardiology*. 2017
13. Masdjedi K, Van Mieghem NM, Diletti R, van Geuns RJ, de Jaegere P, Regar E, Zijlstra F, van Domburg RT, Daemen J. Navvus ffr to reduce contrast, cost and radiation (contract); insights from a single-centre clinical and economical evaluation with the rxi rapid-exchange ffr device. *International journal of cardiology*. 2017;233:80-84

14. Fearon WF, Chambers JW, Seto AH, Sarembock IJ, Raveendran G, Sakarovitch C, Yang L, Desai M, Jeremias A, Price MJ. Acist-ffr study (assessment of catheter-based interrogation and standard techniques for fractional flow reserve measurement). *Circulation. Cardiovascular interventions*. 2017;10

15. Menon M, Jaffe W, Watson T, Webster M. Assessment of coronary fractional flow reserve using a monorail pressure catheter: The first-in-human access-nz trial. *EuroIntervention : journal of EuroPCR in collaboration with the Working Group on Interventional Cardiology of the European Society of Cardiology*. 2015;11:257-263

16. Wijntjens GW, van de Hoef TP, Kraak RP, Beijk MA, Sjauw KD, Vis MM, Madera Cambero MI, Brinckman SL, Plomp J, Baan J, Jr., Koch KT, Wykrzykowska JJ, Henriques JP, de Winter RJ, Piek JJ. The impact study (influence of sensor-equipped microcatheters on coronary hemodynamics and the accuracy of physiological indices of functional stenosis severity). *Circulation. Cardiovascular interventions*. 2016;9

Table 1. Patient and Procedural Characteristics

Patient-level characteristics (N = 74)	
Age, years	64 ± 11
Male	54 (73)
Weight, kg	83 ± 18
Height, cm	171 ± 10
Diabetes	53 (72)
Hypertension	71 (96)
Hypercholesterolemia	73 (99)
Former smoker	38 (51)
Current smoker	12 (16)
History of heart failure	43 (58)
Ejection fraction, %	55 ± 13
Lesion-level characteristics (N=95)	
Target vessel	
Left anterior descending	47 (49)
Left circumflex	23 (24)
Right	25 (26)
Eccentric lesion	64 (67)
Thrombus	1 (1)
Tortuosity	32 (34)
Calcification	51 (54)
Aneurysmal lesion	5 (5)
Ectasia present	12 (13)
Bifurcation	21 (22)
Interpolated reference vessel diameter, mm	2.84 ± 0.58
Distal reference vessel diameter, mm	2.66 ± 0.58
In-segment minimum lumen diameter, mm	1.61 ± 0.48
Diameter stenosis (by quantitative coronary angiography), %	44±10
Diameter stenosis (visual), %	66±10
Lesion length, mm	12.2±7.3
Lesion angle, °	26.5 ± 10.3

Values are mean ± standard deviation or n (%).

Table 2. Physiological Parameters

Parameter	Pressure Wire	Pressure Catheter	p Value
FFR	0.84 [0.78, 0.89]	0.79 [0.73, 0.85]	<0.001
Clinically discordant (FFR from >0.80 to ≤0.80)	—	17 (19)	<0.001
FFR underestimated by ≥0.05, %*	2 (2)	35 (39)	<0.001
FFR underestimated by ≥0.10, %*	0 (0)	13 (15)	<0.001
Pd/Pa	0.93 [0.90, 0.97]	0.90 [0.86, 0.95]	<0.001
Pressure drift	0.01 [-0.01, 0.05]	0.01 [0.00, 0.02]	0.38

*Versus the other device. Values are median (Interquartile range)
FFR = fractional flow reserve; Pd = pressure diastolic; Pa = pressure aortic.

Table 3. Univariate Associations Between Patient/Lesion Characteristics and the Difference in Fractional Flow Reserve Measured With the Pressure Wire Versus Pressure Catheter

Observed Difference in Fractional Flow Reserve According to the Presence Versus Absence of a Characteristic

Patient/Lesion Characteristic	ΔFractional Flow Reserve		p Value
	Characteristic Present	Characteristic Absent	
Male (men vs. women)	-0.03 (-0.05, -0.02)	-0.03 (-0.08, -0.01)	0.63
Diabetes (yes vs. no)	-0.03 (-0.08, 0.00)	-0.03 (-0.07, -0.02)	0.46
Hypertension (yes vs. no)	-0.03 (-0.13, -0.02)	-0.03 (-0.06, -0.01)	0.16
History of heart failure (yes vs. no)	-0.04 (-0.09, -0.02)	-0.03 (-0.05, 0.00)	0.12
Previous cerebrovascular accident (yes vs. no)	-0.06 (-0.09, -0.02)	-0.03 (-0.05, 0.00)	0.053
Former smoker (yes vs. no)	-0.03 (-0.05, -0.01)	-0.04 (-0.08, -0.02)	0.40
Current smoker (yes vs. no)	-0.03 (-0.08, -0.02)	-0.03 (-0.04, -0.01)	0.43
Non-smoker (yes vs. no)	-0.03 (-0.06, -0.02)	-0.03 (-0.11, -0.01)	0.80
Target vessel			
LAD (yes vs. no)	-0.03 (-0.06, -0.02)	-0.04 (-0.08, -0.02)	0.35
LCx (yes vs. no)	-0.03 (-0.05, -0.02)	-0.04 (-0.09, -0.02)	0.30
RCA (yes vs. no)	-0.04 (-0.08, -0.02)	-0.03 (-0.04, 0.00)	0.033
Eccentric lesion (yes vs. no)	-0.03 (-0.06, -0.02)	-0.04 (-0.08, -0.02)	0.32
Tortuosity (yes vs. no)	-0.04 (-0.06, -0.02)	-0.04 (-0.09, -0.02)	0.23
Calcification (yes vs. no)	-0.04 (-0.07, -0.02)	-0.04 (-0.08, -0.02)	0.74
Ulcerated lesion (yes vs. no)	-0.04 (-0.08, -0.02)	-0.07 (-0.08, -0.03)	0.46
Aneurysmal lesion (yes vs. no)	-0.04 (-0.07, -0.02)	-0.04 (-0.04, -0.02)	0.93
Ectasia present (yes vs. no)	-0.04 (-0.07, -0.02)	-0.05 (-0.08, -0.02)	0.69
Bifurcation (yes vs. no)	-0.04 (-0.07, -0.02)	-0.04 (-0.09, -0.01)	0.88

Correlation Between Continuous Variables and the Observed Difference in Fractional Flow Reserve

Patient/Lesion Characteristic	ΔFractional Flow Reserve		p Value
	Mean ± Standard Deviation	Correlation coefficient	
Age, years	63.90±10.66 (89)	0.10 (-0.11, 0.30)	0.36

Weight, kg	81.73±18.07 (89)	0.11 (-0.11, 0.31)	0.33
Height, cm	170.18±9.55 (89)	0.10 (-0.11, 0.30)	0.35
Ejection fraction, %	55.10±13.23 (60)	0.14 (-0.12, 0.38)	0.30
Interpolated reference vessel diameter, mm	2.84±0.59 (89)	0.31 (0.11, 0.49)	0.003
Distal reference vessel diameter, mm	2.66±0.59 (89)	0.35 (0.16, 0.52)	<0.001
In segment minimum lumen diameter, mm	1.61±0.50 (89)	0.27 (0.06, 0.45)	0.01
Diameter stenosis (by QCA), %	43.92±10.45 (89)	-0.08 (-0.29, 0.13)	0.43
Diameter stenosis (visual), %	65.84±10.34 (89)	-0.16 (-0.36, 0.05)	0.13
Lesion length, mm	12.10±7.22 (89)	-0.23 (-0.42, -0.03)	0.027
Lesion angle, °	26.47±10.20 (89)	-0.09 (-0.29, 0.13)	0.43

Values are median (Interquartile range) or mean ± standard deviation (N) and correlation coefficient (95% confidence interval).
LAD = left anterior descending coronary artery; LCx = left circumflex coronary artery; QCA = quantitative coronary angiography; RCA = right coronary artery.

Table 4. Independent Predictors of ΔFFR Measured With the Pressure Catheter Versus Pressure Wire

Variable	Adjusted difference (per 0.01 point difference)	95% Confidence Interval	p Value
Distal RVD (per 0.1 mm)	0.42	0.009 to 0.83	0.045
In-segment MLD (per 0.1 mm)	-0.26	-0.94 to 0.42	0.45
Diameter stenosis (visual, %)	-0.07	-0.27 to 0.13	0.51
Lesion length (per 1mm)	-0.13	-0.26 to 0.00	0.048

MLD = minimum lumen diameter; RVD = reference vessel diameter

Figure Legends

Figure 1. Protocol for Physiologic Assessment Using a Pressure Wire and a Pressure Catheter.

FFR = fractional flow reserve; IV = intravenous; PC = pressure catheter; PW = pressure wire.

Figure 2. Correlation Between Resting Pd/Pa and Hyperemic Fractional Flow Reserve between Pressure Catheter and Pressure Wire

Correlation between the pressure catheter (PC) and pressure wire (PW) (2A) and Bland-Altman analysis of agreement (2B) for resting Pd/Pa. Distribution of the difference in Pd/Pa between PC and PW (2C). Correlation between the PC and PW (2D) and Bland-Altman analysis of agreement (2E) for hyperemic fractional flow reserve (FFR). Distribution of the difference in FFR between PC and PW (2F).

Figure 3. Relationship Between ΔFFR and Distal Reference Vessel Diameter, lesion length and agreement by FFR range.

FFR = fractional flow reserve; PC = pressure catheter; PW = pressure wire.