Standardization of fractional flow reserve measurements

Citation for published version (APA):

DOI:
10.1016/j.jacc.2016.05.067

Document status and date:
Published: 01/08/2016

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
THE PRESENT AND FUTURE

TECHNOLOGY CORNER

Standardization of Fractional Flow Reserve Measurements

Gabor G. Toth, MD, a Nils P. Johnson, MD,b i, Allen Jeremias, MD, MSc,c Mariano Pellicano, MD,b d Pascal Vranckx, MD, Ph.D,e William F. Fearon, MD,f Emanuele Barbato, MD, Ph.D, g Morton J. Kern, MD,h Nico H.J. Pijls, MD, Ph.D, i, ii, jj Bernard De Bruyne, MD, Ph.Dd

This article has been selected as the month’s JACC CME activity, available online at http://www.acc.org/jacc-journals-cme by selecting the CME tab on the top navigation bar.

Accreditation and Designation Statement

The American College of Cardiology Foundation (ACCF) is accredited by the Accreditation Council for Continuing Medical Education (ACCME) to provide continuing medical education for physicians.

The ACCF designates this Journal-based CME activity for a maximum of 1 AMA PRA Category 1 Credit(s). Physicians should only claim credit commensurate with the extent of their participation in the activity.

Method of Participation and Receipt of CME Certificate

To obtain credit for JACC CME, you must:

1. Be an ACC member or JACC subscriber.
2. Carefully read the CME-designated article available online and in this issue of the journal.
3. Answer the post-test questions. At least 2 out of the 3 questions provided must be answered correctly to obtain CME credit.
4. Complete a brief evaluation.
5. Claim your CME credit and receive your certificate electronically by following the instructions given at the conclusion of the activity.

CME Objective for This Article: After reading this article, the reader should be able to: 1) perform fractional flow reserve measurement in an accurate, standardized manner; 2) recognize and avoid potential pitfalls of fractional flow reserve measurement; and 3) conduct clinical studies that involve fractional flow reserve in a standardized and thus reproducible/comparable manner.

CME Editor Disclosure: JACC CME Editor Ragavendra R. Baliga, MD, FACC, has reported that he has no financial relationships or interests to disclose.

Author Disclosures: Dr. Toth has a consultancy agreement with St. Jude Medical. Dr. Johnson has received internal funding from the Weatherhead PET Center for Preventing and Reversing Atherosclerosis; has received significant institutional research support from St. Jude Medical and Volcano/Philips outside of the submitted work; and has an institutional licensing and consulting agreement with Boston Scientific. Dr. Jeremias has reported speaker and consultant fees from Volcano Inc. and St. Jude Medical Inc. outside of the submitted work. Dr. Pellicano has been supported by a research grant provided by the Cardiopath PhD program. Dr. Vranckx has received speaking or consulting fees from AstraZeneca, Bayer, Boehringer Ingelheim, Daiichi-Sankyo, and The Medicines Co. outside of the submitted work. Dr. Fearon has received research support from Medtronic and St. Jude Medical outside of the submitted work; and has received consultant fees from Medtronic, HeartFlow, and Cathworks. Dr. Barbato has received institutional research grants and speakers, fees from St. Jude Medical outside of the submitted work. Dr. Kern has received consultant and speaker fees from St. Jude Medical, Volcano, Opsens, ACIST Medical, and HeartFlow outside of the submitted work. Dr. Pijls is a consultant for St. Jude Medical, Opsens, ACIST Medical, and HeartFlow outside of the submitted work; Dr. De Bruyne is a shareholder for Siemens, GE, Bayer, Philips, HeartFlow, Edwards Life Sciences, Sanoﬁ, and Omega Pharma; and his institution has received grant support from Abbott, Boston Scientiﬁc, Biotronik, and St. Jude Medical and receives consulting fees on his behalf from St. Jude Medical, Opsens, and Boston Scientiﬁc outside of the submitted work.

Medium of Participation: Print (article only); online (article and quiz).

CME Term of Approval

Issue Date: August 16, 2016
Expiration Date: August 15, 2017

From the aDepartment of Cardiology, University Heart Center Graz, Medical University Graz, Graz, Austria; bWeatherhead PET Center for Preventing and Reversing Atherosclerosis, Division of Cardiology, Department of Medicine, University of Texas Medical School and Memorial Hermann Hospital, Houston, Texas; cStony Brook University and Cardiovascular Research Foundation, New York, New York; dCardiovascular Center Aalst, Aalst, Belgium; eHartcentrum Hasselt, Division of Cardiology and Critical Care Medicine, Hasselt, Belgium; fDivision of Cardiovascular Medicine, Stanford University Medical Center, Stanford, California; gDepartment of Advanced Biomedical Sciences, University of Naples Federico II, Naples, Italy; hIrvine Medical Center, University of California, Irvine, California; iDepartment of Cardiology, Catharina Hospital, Eindhoven, the Netherlands; and the jDepartment of Biomedical Engineering, Eindhoven University of Technology, Eindhoven, the Netherlands. Dr. Toth has a consultancy agreement with St. Jude Medical. Dr. Johnson has received internal funding from the Weatherhead PET Center for Preventing and Reversing Atherosclerosis; has received significant institutional research support from St. Jude Medical and Volcano/Philips outside of the submitted work; and has an institutional licensing and consulting agreement with Boston Scientific. Dr. Jeremias has reported speaker and consultant fees from Volcano Inc. and St. Jude Medical Inc. outside of the submitted work. Dr. Pellicano has been...
Standardization of Fractional Flow Reserve Measurements

Gabor G. Toth, MD,⁎ Nils P. Johnson, MD,⁎ Allen Jeremias, MD, MSc,⁎ Mariano Pellicano, MD,⁎ Pascal Vranckx, MD, PhD,⁎ William F. Fearon, MD,⁎ Emanuele Barbato, MD, PhD,⁎ Morton J. Kern, MD,⁎ Nico H.J. Pijls, MD, PhD,⁎Bernard De Bruyne, MD, PhD⁎

ABSTRACT

Pressure wire-based fractional flow reserve is considered the standard of reference for evaluation of the ischemic potential of coronary stenoses and the expected benefit from revascularization. Accordingly, its application in daily practice or for research purposes has to be as standardized as possible to avoid technical or operator-related artifacts in pressure recordings. This document proposes a standardized way of acquiring, recording, interpreting, and archiving the pressure tracings for daily practice and for the purpose of clinical research involving a core laboratory. Proposed standardized steps enhance the uniformity of clinical practices and data interpretation. (J Am Coll Cardiol 2016;68:742-53) © 2016 by the American College of Cardiology Foundation.

To assess the contribution of a new diagnostic test, a hierarchical model of efficacy was proposed by Fryback and Thornbury (1). Although the model was developed for the evaluation of diagnostic imaging, its parameters also apply to “physiological imaging,” with its attributes of: 1) technical quality; 2) diagnostic accuracy; 3) diagnostic thinking efficacy; 4) effect on therapy; 5) patient’s outcome; and 6) economic aspects (Central Illustration). A key feature of this model is that for a test to be efficacious at a higher level in this hierarchy, it must be efficacious at lower levels.

Since the first description of pressure wire-based fractional flow reserve (FFR) (2-4), an abundance of data pertaining to each of these criteria have been reported. Accordingly, FFR is now considered to be the reference standard for the evaluation of the ischemic potential and the expected benefit from revascularization of coronary stenosis (5-8). Moreover, FFR is increasingly being used in clinical trials as an inclusion criterion or as an endpoint (9) and to derive from a lack of standardization (12). Although all major outcomes-randomized clinical trials have made decisions on the basis of operator-derived FFR values, a handful of recent diagnostic accuracy studies sent tracings to physiology core laboratories for post hoc analysis. However, no matter where analysis takes place, technical or operator-related artifacts in pressure recordings should be avoided, minimized, or at least identified if they occur.

FFR is calculated from distal coronary pressure (Pd) and aortic pressure (Pa) obtained during maximal coronary hyperemia. In principle, these measurements are straightforward and almost fully automated, as illustrated in Figure 1. Yet, minor differences among practices of different laboratories have led to some heterogeneity in acquiring and interpreting the data. Because FFR-based decisions are important for patients’ outcomes, and given the need for rigor and reproducibility in reading the tracings by core laboratories, the highest technical quality of FFR measurements is desirable. As FFR by itself is a highly reproducible diagnostic measure, deviations mainly derive from a lack of standardization (12). Accordingly, this document proposes a standardized way of acquiring, recording, interpreting, and...
storing the pressure tracings for daily practice and for the purpose of clinical research through a core laboratory. Comprehensive reviews of the principle of FFR and of the FFR-based clinical outcome data have been described previously (13,14).

**PATIENTS AND VESSEL SELECTION**

In clinical practice, 2 groups of patients undergo FFR assessment.

**STABLE CORONARY DISEASE.** In patients with signs suggesting stable coronary artery disease, the European Guidelines support FFR measurements with a Class IA recommendation for the evaluation of stenoses ranging between 50% to 90% diameter stenosis (by visual estimate of coronary angiogram) and when noninvasive ischemia testing is contraindicated, nondiagnostic, or not available (15). Recent data indicate that even lesions of <50% by quantitative coronary angiography can be hemodynamically significant (16). Their precise characterization by physiological measurements is desirable when located in proximal coronary segments that supply a large myocardial mass, because they may have prognostic significance (17,18). Therefore, it seems advisable to perform FFR measurements more on clinical grounds than on strict angiographic criteria, especially in the case of atypical symptoms or contradictory noninvasive and invasive findings.

**ACUTE CORONARY SYNDROMES.** In most patients referred to the catheterization laboratory for “unstable angina,” noninvasive stress testing is lacking, and the diagnosis often relies solely on the clinical history, electrocardiographic tracings, or markers of myonecrosis. In these patients, angiographically less-severe

**ABBREVIATIONS AND ACRONYMS**

FFR = fractional flow reserve

\( P_a \) = aortic pressure

PCI = percutaneous coronary intervention

\( P_d \) = distal coronary pressure

**CENTRAL ILLUSTRATION**

Fractional Flow Reserve: Example of Simultaneous DICOM Format Storage of Complete Physiological and Angiographic Information

Archiving this information (as well as intravascular ultrasound and optical coherence tomography, when available) side-by-side, in a format that is easily accessible (“same place, same time” principle) enables surgeons, interventional cardiologists, clinicians, and heart team meeting participants to be exposed to these different imaging modalities and to integrate “anatomy” and “physiology” into individual clinical decision making. CRA = cranial; DICOM = digital imaging and communications in medicine; ECG = electrocardiogram; FFR = fractional flow reserve; LAO = left anterior oblique; \( P_a \) = aortic pressure; \( P_d \) = distal coronary pressure.
stenoses are common, and FFR is helpful to guide treatment decisions. This also applies to patients with non-ST-segment elevation myocardial infarction (19). Moreover, in these patients, the presence of angiographic multi-vessel disease is frequent (20), and when present, FFR guidance of revascularization has been shown to improve the clinical outcome (21) similar to patients with stable angina, especially in nonculprit stenoses.

In patients with acute ST-segment elevation myocardial infarction, measuring FFR in the culprit stenosis makes little clinical sense. However, in remote myocardial infarctions, FFR enables the detection of residual reversible ischemic potential of an angiographically intermediate stenosis in the infarcted territory (22). FFR assessment of the nonculprit stenoses provides reliable information about the presence or absence of ischemia; therefore, it might be considered for treatment guidance, even when the measurements are performed in the setting of primary percutaneous coronary intervention (PCI). However, further data on clinical outcomes in this particular subset of patients are awaited (23). In patients with acute ST-segment elevation myocardial infarction, functionally complete revascularization guided by FFR improves outcomes, although the precise timing of treatment remains debatable (24).

**HEART FAILURE.** Calculation of FFR considers the central venous pressure as negligibly low compared with the arterial values; therefore, its value is not incorporated in the formula. Recent data verified the validity of this concept, even in patients with pathologically elevated filling pressures. Therefore, the measured FFR value can also be considered accurate in patients with heart failure, and the incorporation of right atrial pressure is not indicated in any circumstances (25).

**MATERIALS AND PRACTICALITIES**

Considering that intracoronary manipulations are needed for FFR measurements, proper anticoagulation (i.e., ≥50 U/kg unfractionated heparin) is mandatory. Also, full vasodilation of the epicardial artery by intracoronary administration of nitrates (200 µg isosorbide mononitrate) should be done routinely. These steps should not deviate from those routinely applied for any PCI or coronary imaging procedure.
To obtain FFR values, a catheter, a pressure-measuring guidewire, and a hyperemic agent are needed.

**Catheters.** **Guiding catheters.** Any size of guiding catheter can be used. However, it is important to realize that, depending on the relative size of the guiding catheter and the coronary ostium, the presence of the catheter can impede coronary flow (Figure 2). Impeded flow can be detected by ventricularization of the $P_a$ signal, which becomes apparent predominantly during hyperemia. This phenomenon will falsely increase the FFR value, and thus underestimate the degree of myocardial ischemia. Therefore, it is critical to pay close attention to the morphology of the aortic pressure tracing and to slightly disengage the guiding catheter immediately upon induction of hyperemia. Another potential pitfall is damping of the aortic waveform by residual contrast material in the guiding catheter. This occurs more frequently in smaller catheters (i.e., 5-F), and can be easily remedied by flushing the guiding catheter with saline prior to FFR measurements. Ideally, the dicrotic notch should be discernable on the aortic waveform to verify an adequate pressure tracing.

**Guiding catheters with side holes.** Their use is not recommended for FFR measurements. The pressure signal obtained through these catheters does not reflect the pressure proximal to the stenosis, but rather reflects a mix between the coronary pressure (through the distal end) and the $P_a$ (through the side holes). However, if the usage of a catheter with side holes is needed for clinical reasons, measurements should be performed with intravenous adenosine administration and with the guiding catheter disengaged from the coronary ostium.

**Diagnostic catheters.** Although technically feasible with most systems (see later discussion) and conceptually appealing, FFR measurements through diagnostic catheters should be discouraged, as a reliable aortic waveform cannot be routinely obtained. Furthermore, only a guiding catheter allows immediate intervention, when indicated.

**Pressure-measuring systems.** Currently, 5 coronary pressure-measuring systems are commercially available.

1. **PressureWire (St. Jude Medical, St. Paul, Minnesota).** This is a 0.014-inch pressure-measuring guidewire, equipped with an electric pressure sensor 3 cm from the tip, at the junction between radiopaque and nonradiopaque portions of the wire. It is available in 2 versions that are connected either by wire (Certus) or wirelessly (Aeris) to the console. It can be used as a regular guidewire when PCI becomes indicated.

2. **WaveWire (Philips, Eindhoven, the Netherlands).** This is a 0.014-inch pressure-measuring guidewire, equipped with an electric pressure sensor 3 cm from the tip, at the junction between radiopaque and nonradiopaque portions of the wire. It can be used as a regular guidewire when PCI becomes indicated. It is available in 2 versions that are connected with either a rotational (PrimeWire Prestige) or clip (Verrata) attachment to the console.

3. **OptoWire (Opsens Medical, Quebec, Quebec, Canada).** This is a 0.014-inch pressure-measuring guidewire, equipped with a fiber optic pressure

<table>
<thead>
<tr>
<th>TABLE 1 Hyperemic Stimuli</th>
<th>Dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adenosine</td>
<td>100 µg in RCA/200 µg in LCA as intracoronary bolus</td>
</tr>
<tr>
<td>Nitroprusside</td>
<td>140 µg/kg/min as intravenous infusion</td>
</tr>
<tr>
<td>0.6 µg/kg as intracoronary bolus</td>
<td></td>
</tr>
<tr>
<td>Nicorandil</td>
<td>2 mg as intracoronary bolus</td>
</tr>
<tr>
<td>Regadenoson</td>
<td>400 µg as intravenous slow bolus over 10 s</td>
</tr>
<tr>
<td>Papaverine</td>
<td>8 mg in RCA/12 mg in LCA as intracoronary bolus</td>
</tr>
</tbody>
</table>

LCA = left coronary artery; RCA = right coronary artery.
sensor 3.5 cm from the tip. It can be used as a regular guidewire when PCI becomes indicated.

4. Comet Pressure Guidewire (Boston Scientific, Marlborough, Massachusetts). This is a 0.014-inch pressure-measuring guidewire, equipped with a fiber optic pressure sensor 3 cm from the tip, at the junction between radiopaque and nonradiopaque portions of the wire. It can be used as a regular guidewire when PCI becomes indicated. The system allows both wired and wireless communication with the console.

5. Navvus (Acist Medical Systems, Eden Prairie, Minnesota). This is a 0.020-inch monorail pressure-measuring microcatheter, equipped with a fiber optic pressure sensor. It can be used over any regular guidewire. Note that the introduction of the catheter, albeit very small, will inevitably induce an additional resistance to flow, and therefore underestimate the true FFR value (i.e., overestimate lesion severity) (26). The extent of this underestimation depends on the flow and the dimensions of the stenosis under investigation, and can therefore vary between individual patients.

**HYPEREMIC AGENTS.** In addition to the vasodilation of the epicardial arteries by intracoronary administration of nitrates, FFR measurements require full vasodilation of the microvasculature to induce maximal hyperemia. Several pharmacological agents have been demonstrated to induce maximal vasodilation. Their characteristics are summarized in Table 1. The most commonly used hyperemic agent is adenosine, given by either intracoronary or intravenous administration.

**Intravenous adenosine.** Administration of intravenous adenosine provides reliably stable maximal hyperemia, maintainable for minutes, when indicated. Therefore, in daily practice, it is to be applied when PCI becomes indicated. The recommended dose is 140 μg/kg of body weight/min (27). Some investigators suggest increasing the dose to 180 μg/kg or adding a bolus of intracoronary adenosine when in doubt. As there is no general clinical benefit of further increasing the dosages, this might therefore be considered only in case of fluctuating hyperemic status. Although in practice, central venous administration of adenosine provides less fluctuation in hyperemic status and allows maximal hyperemia to be achieved somewhat faster, there is no clinically relevant difference in terms of accuracy between central venous versus peripheral cubital venous administration (28).

The latter is of increasing importance with the growing use of the radial approach.

**Intracoronary adenosine.** Maximal hyperemia is inducible by intracoronary administration of adenosine. The degree of vasodilation is very similar and the FFR values are comparable to those obtained with intravenous administration. The test/retest repeatability tends to be better with intracoronary than with intravenous administration of adenosine. As dose-response analysis data have shown, 100 μg in the right coronary artery and 200 μg in the left coronary artery reliably and reproducibly achieve >95% of maximum hyperemia without any significant side effects. The hyperemic effect of these doses is clinically indistinguishable from higher dosages, but with a lower rate of atrioventricular block; thus, there is no reason to use higher dosages (29).

**Alternative agents.** Other agents, such as regadenoson, nicorandil, nitroprusside, and dobutamine, can be used for inducing maximal microvascular dilation; however, they are not widely used in clinical practice (30–32). The use of papaverine is not recommended due to the occasional occurrence of ventricular arrhythmia (33).

In daily practice, it is recommended to always use the same means of producing hyperemia. This routine simplifies the process, increases familiarity among staff and operators, and thereby minimizes errors.

**PRACTICALITIES OF FFR MEASUREMENTS**

For the sake of standardization, a systematic step-by-step procedure can be proposed (34). As there are minor differences between the different commercially available systems, the manufacturer’s instructions should be followed. To create a routine and to minimize the risk of errors, it is advisable to become familiar with 1 commercially available system in a catheter laboratory.

**CALIBRATION OF PRESSURE SYSTEMS.** Before pressure-wire insertion, setting atmospheric pressure as the zero reference should be done carefully for the fluid-filled pressure transducer and for the coronary pressure-measuring systems. Both pressure transducers have to be “taught” what the atmospheric pressure is so that the latter can be taken out of the equation. All fluid-filled pressure lines should be carefully flushed with saline. If there is an electric sensor, the wire should also be flushed before calibration. For the coronary pressure-measuring systems, the “zero reference” is taken either automatically or manually when it is electronically connected to the console. There are only minor differences between the different coronary pressure-monitoring system wires.
EQUALIZING THE 2 PRESSURES. The pressure sensor should then be advanced and positioned 1 or 2 mm distal to the tip of the guiding catheter. The latter should be flushed with saline to remove any residual contrast used when positioning the guide. At that location, the 2 pressures should be identical. If this is not the case, the measured pressures have to be equalized electronically, using that function of the console. If ostial coronary disease exists, this can be performed with the guiding catheter disengaged and the pressure sensor positioned in the aorta. After these “zeroing” and “equalization” procedures, the 2 pressure systems “speak the same language.”

An introductory needle can be used only if it is very thin and does not leak. If the needle leaks, thus losing adenosine and also lowering the Pa reading, the needle should be removed from the Y connector for equalization, for the measurements, and for the final check for the absence of drift.

POSITIONING THE PRESSURE SENSOR FOR THE MEASUREMENT. The sensor should be manipulated in the distal part of the artery. In any case, the sensor should be placed at least 2 to 3 cm distal to the stenosis to be assessed, a distance where post-stenotic laminar flow is restored, avoiding flow eddies and pressure recovery phenomena. In general, to evaluate whether a given coronary artery is responsible for myocardial ischemia in the myocardial territory it supplies, the pressure sensor should be positioned at the very distal part of the coronary artery. From the clinical point of view, it makes sense to perform measurements with the sensor positioned just distal to where surgeons would anastomose a bypass graft. Note that in some tortuous vessels, it is important to recognize that positioning the sensor in the very distal part of the artery may induce an accordion phenomenon, which might lead to falsely low FFR values. The exact position of the sensor should be documented by angiography.

INDUCING HYPEREMIA AND RECORDING. Electronic recording of the pressure tracings should start at least 30 s after the last contrast medium injection to ensure stable baseline conditions. These stable baseline conditions should be captured for at least 10 heart cycles before the induction of hyperemia. The pressure scale should be set to take as much advantage as possible of the whole height of the screen.

When intravenous adenosine is given (140 µg/kg/min), the intravenous line should be filled with adenosine up to the place where the line enters the patient to avoid a long delay between the start of the pump.
and the effect of adenosine. For this purpose, it is convenient to place a 3-way stopcock at the skin and to prime the intravenous lines, leaving the flush with adenosine. The total length of the recording will vary between 1 and 4 min to encompass the baseline, the beginning of the maximal hyperemic phase, and the recovery phase. Once recording is started, the manifold should be put down on the table to avoid any movement artifacts (Figure 3).

With intracoronary adenosine, it is convenient to use a 10-ml syringe filled with 200 µg of adenosine. For the right coronary artery, 5 ml (100 µg in total) and for the left coronary artery 10 ml (200 µg in total) are briskly injected (29). After the adenosine is injected, the $P_a$ signal should be immediately switched back and the manifold should be gently placed on the table to avoid any movement artifacts (Figure 3).

The yellow arrow indicates the period of approximately 12 s during which the FFR values are stable between 0.64 and 0.65. ADO = adenosine; IC = intracoronary; RCA PROX = proximal right coronary artery; other abbreviations as in Figure 1.

The short-lasting effect of intracoronary adenosine allows these measurements to be made in duplicate without losing more than 1 min. A second hyperemic stimulus can then be given and the exact same tracing recorded. Because the test/retest repeatability of FFR is very high (12), the variation between the 2 consecutive values should be minimal. These duplicate measurements are therefore the first quality check for the FFR measurements.

The advantage of always recording for the same length of time is that the tracings become immediately recognizable, even for noninterventional cardiologists, as well as for core laboratory purposes.
FIGURE 5  FFR Pressure Tracings Recorded and a Commercially Available Physiological Monitoring System

(Top) Example of a page of the electronic patient data file (Centricity Cardio Workflow, GE Healthcare, Little Chalfont, United Kingdom) in which the main raw hemodynamic data, obtained from a commercially available physiological monitoring system (MacLab, GE Healthcare) can be stored and accessed for offline review. By double-clicking on each vignette, the tracing is magnified and can be scrolled through for detailed analysis. (Bottom) Example of a pressure recording embedded within the Impax system, along with the corresponding angiograms. AO = aortic; LAD = left anterior descending artery; LV = left ventricle; RCA = right coronary artery; other abbreviations as in Figure 1.
DETERMINATION OF THE FFR VALUE. FFR is to be measured at the level of the nadir of the Pd/Pa tracing. Most systems indicate it automatically, but manual control and fine-tuning is always recommended to avoid false calculations derived from artifacts in the coronary or the arterial pressure tracings. Data from large series have shown that the minimum Pd/Pa during intravenous infusion of adenosine and the minimum Pd/Pa after an intracoronary bolus of adenosine show good agreement and are both highly reproducible (12).

PULLBACK MANEUVER. A slow pullback of the pressure sensor under steady state hyperemia (induced by intravenous infusion of adenosine) is the best means to assess the distribution of the abnormal epicardial resistance, which is of extreme importance in case of multiple sequential stenoses, diffuse atherosclerotic disease, or ostial lesions. For this purpose, the exact position of the wire has to be documented, and it is advisable to interrogate the whole length of the artery over a period of approximately 15 to 20 s. Well-recognized angiographic landmarks could be indicated with markers on the pressure tracing, linking the angiographic finding to the FFR assessment.

CHECK FOR SIGNAL DRIFT. All pressure sensors are susceptible to a tendency to drift that will offset readings from the original calibrated state; however, this can be minimized with adequate device preparation, such as the calibration and equalization procedures described previously. For optimal FFR measurement, the drift should be absent or minimal. This is the case for both the coronary pressure-measuring systems and (albeit to a lesser extent) the fluid-filled pressure transducer. Checking for the absence of significant drift of both transducers immediately upon making the measurement should be part of the measuring procedure and should be documented. After finishing a measurement, the pressure sensor should be pulled back until positioned 1 or 2 mm distal to the tip of the guiding catheter. At that location, the 2 measured pressures should once again be identical. Please note that when checking for drift, the setting has to be consistent with the setting during equalization and during the measurement itself. If this is not the case, the measured pressures have to be equalized again electronically, and the measurement has to be repeated.

ELECTRONIC ARCHIVING OF THE PRESSURE TRACINGS

Like any other measurements upon which important medical decisions are made (e.g., left ventricular ejection fraction, left ventricular volumes and pressures, angiographic measurements, among others), the raw data of the pressure tracings from which FFR was calculated should be saved (Central Illustration). Ideally, these tracings should be automatically stored and incorporated into the electronic medical database in conjunction with the angiography. When a multidisciplinary heart team discusses clinical cases, these tracings should be at hand for review, akin to any other imaging technique.

The appropriateness of the clinical decision will largely depend on the quality of the recordings and of their actual display: the time scale should not be too long, so as to remain readable, and the pressure scale should be adjusted to the actual Pa to take advantage of the full height of the screen. Confirm the accuracy of FFR by viewing the pressure tracings. Decisions should not be taken blindly on the basis of a number automatically produced by the console, nor made by figures manually filed in the database or the medical report.

Figure 5 shows an example of FFR pressure tracings recorded and saved on a commercially available physiological monitoring system and automatically stored in the patients’ electronic medical database. This allows the FFR measurements to be available for later checks and for discussion at heart team meetings. Another possibility for storage with easy access is to save the pressure tracings in DICOM (digital imaging and communications in medicine) format with the corresponding angiogram. Seeing the raw FFR tracing data is more convincing than trusting a plain figure manually introduced in the database. The proper storage of FFR tracings might also have non-negligible medico-legal implications.

QUALITY ASSURANCE FOR FFR MEASUREMENTS

FFR is increasingly being used in scientific trials as an inclusion criterion or as a study endpoint (9), as well as to validate new diagnostic modalities (10,11). In many of these trials, akin to most other metrics, FFR tracings are also analyzed in core laboratories because modern clinical research relies on processes being highly specific, accurate, and consistent with pre-specified definitions. Just as for clinical decision-making, the accuracy of events adjudication depends on the accuracy and reproducibility of the FFR measurement and analysis. Therefore, each participating center should be trained in the step-by-step approach of FFR measurements and uniform recording of the FFR tracings. Also, core laboratory personnel should be trained in tracing interpretation and recognition of the potential pitfalls and errors. It
is suggested that to maximize transparency and accountability of future trials, the anonymized raw pressure tracings should be made publically available through dedicated websites.

TRANSFER OF THE TRACINGS TO CORE LABORATORIES

In contrast to most other diagnostic methods in interventional cardiology, FFR tracings, even as fully-detailed raw data, can be stored in extremely small files of fewer than 300 kilobytes per tracing. This allows for easy and quick data transfer to central core laboratories without placing a massive load on the network. In the future, even automated data transfers may be possible. The current limitations of data transfer and core laboratory analysis stem from the use of different formats of the various FFR consoles. A uniform output would enable easy data transfer and allow for more standardized data analysis. Additionally, “single-click” online data transfer via the FFR console would be desirable, and would allow for the possibility of rapid central data analysis or data validation, when requested.

TRIAL DESIGN ISSUES

As trial designs more frequently incorporate the use of FFR to establish the indication for revascularization or defining of endpoints, protocols must explicitly and uniformly outline which lesions to include for physiological evaluation. On the basis of recent data (16,35) and consensus statements (36), a more liberal use of FFR might be indicated, and interrogation of a wider range of stenoses (30% to 90% diameter stenosis) should be recommended, especially in cases of ambiguous pre-test probability and angiographic findings. Performance of the measurement must follow a rigorous and uniform protocol, and centrally trained investigators or, eventually, core laboratories should perform data analysis when indicated.

CONCLUSIONS

FFR has been established in multiple clinical trials to improve patient outcomes when used routinely for guidance of coronary revascularization. Accordingly, FFR-guided revascularization strategies have the strongest recommendation in the latest PCI guidelines. This benefit can be optimized when FFR measurement and analysis are performed in a rigorous and standardized manner. The same rigor in acquisition, recording, storage, and transfer is mandated for FFR measurements used in the setting of clinical studies.

REPRINT REQUESTS AND CORRESPONDENCE: Dr. Bernard De Bruyne, Cardiovascular Center Aalst, OLV-Clinic, Moorselbaan, 164, B-9300 Aalst, Belgium. E-mail: bernard.de.bruyne@olvz-aalst.be.

REFERENCES

17. Hamilos M, Muller O, Cuisset T, et al. Long-term clinical outcome after fractional flow reserve-guided treatment in patients with...

KEY WORDS coronary artery disease, functional assessment, percutaneous coronary intervention

Go to http://www.acc.org/jacc-journals-cme to take the CME quiz for this article.