Pressure-Derived Fractional Flow Reserve to Assess Serial Epicardial Stenoses
Theoretical Basis and Animal Validation

Bernard De Bruyne, MD, PhD; Nico H.J. Pijls, MD, PhD; Guy R. Heyndrickx, MD, PhD; Dominique Hodeige, MD; Richard Kirkeeide, PhD; K. Lance Gould, MD

Background—Fractional flow reserve (FFR) is an index of stenosis severity validated for isolated stenoses. This study develops the theoretical basis and experimentally validates equations for predicting FFR of sequential stenoses separately.

Methods and Results—For 2 stenoses in series, equations were derived to predict FFR (FFR_{pred}) of each stenosis separately (ie, as if the other one were removed) from arterial pressure (P_a), pressure between the 2 stenoses (P_m), distal coronary pressure (P_d), and coronary occlusive pressure (P_w). In 5 dogs with 2 stenoses of varying severity in the left circumflex coronary artery, FFR_{pred} was compared with FFR_{app} (ratio of the pressure just distal to that just proximal to each stenoses) and to FFR_{true} (ratio of the pressures distal to proximal to each stenosis but after removal of the other one) in case of fixed distal and varying proximal stenoses (n=15) and in case of fixed proximal and varying distal stenoses (n=20). The overestimation of FFR_{true} by FFR_{app} was larger than that of FFR_{true} by FFR_{pred} (0.070±0.007 versus 0.029±0.004, P<0.01 for fixed distal stenoses, and 0.114±0.01 versus 0.036±0.004, P<0.01 for fixed proximal stenoses). This overestimation of FFR_{true} by FFR_{app} was larger for fixed proximal than for fixed distal stenoses.

Conclusions—The interaction between 2 stenoses is such that FFR of each lesion separately cannot be calculated by the equation for isolated stenoses (P_d/P_a during hyperemia) applied to each separately but can be predicted by more complete equations taking into account P_a, P_m, P_d, and P_w. (Circulation. 2000;101:1840-1847.)

Key Words: flow reserve • stenosis

Coronary pressure–derived fractional flow reserve (FFR) is a measure of coronary stenosis severity. FFR is the ratio of hyperemic myocardial blood flow in the presence of a stenosis to hyperemic flow in the absence of stenosis. Stated another way, FFR is the fraction of hyperemic flow that is preserved despite the presence of a stenosis in the epicardial coronary artery. This ratio of hyperemic flows with and without a single stenosis can be derived from the ratio of mean distal coronary pressure (P_d) to mean aortic pressure (P_a) recorded simultaneously under conditions of maximum hyperemia.1,2 FFR has been shown to be valid in patients with stable angina pectoris under widely varying hemodynamic conditions3,4 and to be clinically useful for diagnostic and interventional purposes.5–14

In humans, however, coronary atherosclerosis is diffuse, and coronary arteriograms frequently demonstrate several consecutive stenoses along the same epicardial artery, the severities of which need to be determined separately. In case of 2 consecutive stenoses, the fluid dynamic interaction between the stenoses alters their relative severity and complicates determination of FFR for each stenosis separately from the simple ratio of P_d/P_a for a single stenosis. Consequently, for stenoses in series, FFR determined by this simple ratio for a single stenosis may not predict to what extent a proximal lesion will influence myocardial flow after complete relief of the distal stenosis, and vice versa.

Therefore, in the present study, theoretical equations were developed for 2 serial stenoses to predict the FFR of each stenosis separately as if the other stenosis were absent. In addition, an animal model of sequential stenoses was used to validate these theoretical equations for determining FFR of each of 2 serial stenoses with direct clinical applicability.
Methods

Mathematical Model

As illustrated in Figure 1, \( P_a \) is the pressure proximal to the first stenosis, \( P_p \) is the pressure between the two stenoses, and \( P_d \) is the pressure distal to the second stenosis. For simplicity, it is assumed that the resistances of the microvasculature are minimal and that the central venous pressure (\( P_v \)) is close to zero.

Superficially, the apparent FFR of A and B (\( \text{FFR}_{\text{app}} \)) can be calculated by dividing the pressure distal to stenosis A or B by the pressure proximal to stenosis A or B, respectively, as follows:

\[
\text{FFR(A)}_{\text{app}} = \frac{P_a}{P_p} \\
\text{FFR(B)}_{\text{app}} = \frac{P_p}{P_d}
\]

However, fluid dynamics theory suggests that the FFR of proximal stenosis A is influenced by the presence of stenosis B and vice versa. In that case, the FFR of stenosis B is influenced by the presence of stenosis A, because hyperemic flow through 1 stenosis is limited by the presence of the other stenosis. As described in the Appendix, the predicted FFR of the proximal stenosis (A) and of the distal lesion (B) as if the other stenosis were hypothetically absent can be calculated by the following equations:

\[
\text{FFR(A)}_{\text{pred}} = \frac{P_p - (P_m/P_a) P_m}{P_p - P_m + P_w - P_m}
\]

and

\[
\text{FFR(B)}_{\text{pred}} = 1 - \frac{(P_d - P_m)(P_m - P_a)}{P_d P_m - P_w P_m}
\]

These predicted values of FFR (\( \text{FFR}_{\text{pred}} \)) as if the other stenosis were hypothetically absent can then be compared with the true FFR (\( \text{FFR}_{\text{true}} \)) determined for each stenosis when the other one was actually physically removed in the animal model.

When stenosis B is actually physically absent, the actual FFR of stenosis A [\( \text{FFR(A)}_{\text{true}} \)], and when stenosis A is actually physically absent, the actual FFR of stenosis B [\( \text{FFR(B)}_{\text{true}} \)] can be calculated as follows:

\[
\text{FFR(A)}_{\text{true}} = \frac{P_p}{P_p - P_m + P_w - P_m}
\]

and

\[
\text{FFR(B)}_{\text{true}} = \frac{P_d - P_m}{P_d - P_m + P_m - P_w}
\]

Animal Instrumentation

After premedication with 0.1 mg fentanyl, 5.0 mg droperidol, and 0.5 mg atropine IM, 5 mongrel dogs (weight 38 to 43 kg) were anesthetized with 7 mg/kg IV sodium thiopenthal, intubated, and ventilated with oxygen-enriched air with a respirator (Drager Spiron 200). General anesthesia was sustained with isoflurane gas ventilated with oxygen-enriched air with a respirator (Drager Spiro-14). Experimental Protocol

At first, maximum hyperemia was induced by continuous intravenous infusion of adenosine, from 130 to 300 \( \mu \text{g} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \). After a steady-state hyperemia had been achieved, a 20-second occlusion of the coronary artery was performed by inflation of the proximal occluder to determine coronary wedge pressure (\( P_w \)) and to verify that no additional, postocclusional hyperemia could be elicited. In 1 dog, no maximum hyperemia could be achieved by adenosine, and an additional infusion of dobutamine \( 20 \mu \text{g} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \) was started to further increase blood flow until the presence of a steady-state maximum hyperemia was confirmed as described above. Next, phasic and mean pressures were recorded by the guiding catheter (\( P_p \)) and by both pressure guidewires (\( P_m \), coronary pressure between both occluders, and \( P_p \), coronary pressure distal to the distal occluder). Thereafter, different degrees of proximal and distal stenoses were induced, as follows: at first, a mild stenosis was induced by the proximal occluder (stenosis A in Figure 1), guided by the pressure signal. Whereas this proximal stenosis remained constant, the distal occluder was inflated to create mild, moderate, severe, and very severe stenoses, respectively, guided by the pressure signals. It was aimed at inducing the stenosis in such a way that the classifications mild, moderate, severe, and very severe corresponded to transstenotic hyperemic gradients of \( \approx 25 \%, 50 \%, 75 \%, \) and 90% of the pressure gradient as observed at total coronary occlusion. Stenoses with a pressure gradient of \( < 5 \text{ mm Hg} \) were avoided. Next, all stenoses were relieved, and after all signals had stabilized again, a moderate stenosis was induced in the proximal occluder, followed by the same sequence of distal stenoses as described above. This sequence of induction of different distal stenoses was repeated for a severe and finally for a very severe proximal stenosis. After this first series, \( P_p \) as well as the presence of ongoing maximum hyperemia was checked again, and the second series of the sequences was started. This time, at first a mild stenosis was induced by the distal occluder (stenosis B in Figure 1), after which the proximal lesion was varied stepwise from mild to moderate to severe and to very severe. After release of all stenoses, this was repeated for a fixed moderate, severe, and very severe proximal lesion, respectively. Figure 2 illustrates these pressure tracings.

Data Processing and Statistical Analysis

To investigate the influence of a stenosis B on a given stenosis A, 71 combinations of a fixed stenosis A and a variable stenosis B were obtained. For each of these combinations, \( \text{FFR(A)}_{\text{app}} \) and \( \text{FFR(A)}_{\text{pred}} \) were compared with \( \text{FFR(A)}_{\text{true}} \) by linear regression analysis. To investigate the influence of a stenosis A on a given stenosis B, 84 combinations of a fixed stenosis B and a variable stenosis A were created. For each of these combinations, \( \text{FFR(B)}_{\text{app}} \) and \( \text{FFR(B)}_{\text{true}} \) were compared with \( \text{FFR(B)}_{\text{pred}} \) by linear regression analysis. For each comparison, a Bland-Altman plot was given. Paired t tests and \( \chi^2 \) tests were used when appropriate. Values of \( P > 0.05 \) were considered nonsignificant.

Results

Baseline Hemodynamics

Mean aortic pressure was \( 88 \pm 21 \text{ mm Hg} \) (range 71 to 125 mm Hg), and heart rate was \( 71 \pm 14 \text{ bpm} \) (range 64 to 129 bpm) at rest. Mean blood pressure decreased significantly to \( 78 \pm 19 \text{ mm Hg} \) (range 63 to 118 mm Hg) and heart rate increased significantly to \( 125 \pm 26 \text{ bpm} \) (range 76 to 158 bpm) during postocclusion hyperemia. Yet, during pharmacologi-
estimates FFR(A) true and that there is an inverse correlation
between FFR(B) true and FFR(B) app. As expected from the
theory, the scatter is observed in the plot of the relationship
between increasing level of stenosis A is created upstream. A large
between FFR(B) true and FFR(B) pred (given, fixed, stenosis B, a
close correlation was found when a progressively increasing level of
stenosis B is created downstream. The corresponding Bland-Altman
plot (Figure 3B) shows that FFR(A)app significantly over-
estimated FFR(B) true and that corresponding overestimation or
underestimation of FFR true by FFR pred is significantly smaller than
the corresponding overestimation or underestimation of FFR true
by FFR app. For a fixed stenosis B, the absolute error in FFR
was >0.1 in 22% of measurements for FFR(B)app and in 5%
of measurements for FFR(B) pred (P<0.01). For a fixed steno-
sis A, the absolute error in FFR was >0.1 in 45% of the
measurements of FFR(A)app and 9% of measurements for
FFR(A) pred (P<0.01). The error in calculating FFR for a
stenosis by use of the simple Pd/Pa ratio (FFR app) was
significantly larger in the presence of a second more proximal
stenosis than for a second more distal stenosis. The greatest
errors in FFR app were found for milder downstream stenoses
when the upstream stenosis was more severe.

**Relation Between** FFR true** and FFR app

A total of 15 distal stenoses (stenoses B) were created. For each
of them, a mean of 4.7 proximal stenoses (stenoses A) were
superimposed to test their influence on the calculation of
FFR on stenosis B. Figure 3A shows, in the 71 combinations
of stenoses (variable stenosis A and fixed stenosis B) analyzed
in all animals, the plots of the relation between the
FFR of lesion B alone [FFR(B)true] versus the apparent value
of FFR [FFR(B)app] of the same lesion B when a progressively
increasing level of stenosis A is created upstream. A large
scatter is observed in the plot of the relationship between
FFR(B)true and FFR(B)app. As expected from the theory, the
corresponding Bland-Altman plot (Figure 3B) shows that
FFR(B)app systematically overestimates FFR(B)true and that
there is an inverse correlation between this overestimation and
FFR(B)true (r=-0.39, P<0.01).

Similarly, a total of 20 proximal stenoses (stenoses A) were
created. For each of those, a mean of 4.2 distal stenoses
(stenoses B) were created to test their influence on the
calculation of FFR on stenosis A. Figure 3C shows, in the 84
combinations of stenoses (fixed stenosis A and variable
stenosis B) analyzed in all animals, the plots of the relation
between the FFR of lesion A alone [FFR(A)true] versus the
apparent value of FFR [FFR(A)app] of the same lesion A when a progressively
increasing level of stenosis B is created downstream. The corre-
sponding Bland-Altman plot (Figure 3D) shows that FFR(A)app significantly over-
estimates FFR(A)true and that there is an inverse correlation between this overestimation and FFR(A)true (r=-0.62,
P<0.01).

**Relation Between** FFR true** and FFR pred

In investigating the influence of a varying stenosis A on a
given, fixed, stenosis B, a close correlation was found between
FFR(B)true and FFR(B)pred (r=0.95, Figure 4A). The
Bland-Altman plot (Figure 4B) shows a small mean differ-
ence (+0.03±0.04) without systematic overestimation or
underestimation of FFR(B)true by FFR(B)pred. In investigation
of the influence of a varying stenosis B on a given fixed
stenosis A, a close correlation (r²=0.95) was found between
FFR(A)true and FFR(A)pred (Figure 4C). The Bland-Altman
plot (Figure 4D) indicates a small overestimation
(+0.040±0.066).

**Relation Between** Pw and FFR app Versus FFR pred

No relationship was found between the level of coronary
occlusive pressure (wedge pressure, Pw) and the accuracy
of FFR app versus FFR pred in determining FFR true.

**Accuracy of** FFR app and FFR pred in
**Determining** FFR true

Figure 5 depicts the absolute difference between FFR app
and FFR true and between FFR pred and FFR true in the 2 experimental
settings as described above, ie, fixed stenosis B and varying
stenosis A (left) and fixed stenosis A and varying stenosis B
(right). In both settings, the overestimation or underestima-
tion of FFR true by FFR pred is significantly smaller than the
corresponding overestimation or underestimation of FFR true
by FFR app. For a fixed stenosis B, the absolute error in FFR
was >0.1 in 22% of measurements for FFR(B)app and in 5%
of measurements for FFR(B) pred (P<0.01). For a fixed steno-
sis A, the absolute error in FFR was >0.1 in 45% of the
measurements of FFR(A)app and 9% of measurements for
FFR(A) pred (P<0.01). The error in calculating FFR for a
stenosis by use of the simple Pd/Pa ratio (FFR app) was
significantly larger in the presence of a second more proximal
stenosis than for a second more distal stenosis. The greatest
errors in FFR app were found for milder downstream stenoses
when the upstream stenosis was more severe.

**Discussion**

For serial epicardial stenoses without intervening arterial
branches, the equation of FFR (Pd/Pa, when central venous
pressure is neglected) remains valid for determining the
hemodynamic consequences of both stenoses together. How-
ever, the present study confirms that this simple ratio cannot
be applied to predict the FFR of each stenosis separately as if
the other were removed. In contrast, the individual FFR of
each stenosis separately can be predicted by different equa-
tions from Pw pressure between the 2 stenoses (Pd), Pa, and Pw
recorded during maximum hyperemia. The data also suggest
that FFR calculated as the Pd/Pa ratio for the stenosis has a
greater error in the presence of a second more proximal stenosis
than in the presence of a second proximal lesion.

**Importance of Maximum Transstenotic Flow**

Pressure-derived FFR is defined as the ratio of hyperemic
flow in a stenotic territory expressed as a fraction of what it
would be in the hypothetical case that the epicardial stenosis
were absent. This ratio of 2 flows can be derived, during
maximum hyperemia, from the ratio of their respective
driving pressures. An essential prerequisite for the calculation
of pressure-derived FFR is the achievement of maximum
transstenotic flow. When only 1 discrete stenosis is present,
physiologically induced microvascular vasodilatation will
lead to maximum transstenotic flow for a given lesion in a
given patient. For that reason, FFR tells us exactly to what
extent hyperemic flow is limited by the presence of an
epicardial stenosis and, conversely, to what extent hyperemic flow will increase after the conductance of the epicardial vessel is restored.

In contrast, when a second stenosis is present along the same epicardial vessel, flow through 1 stenosis will be submaximal because of the second stenosis, even during vasodilation of the microvasculature. The extent to which both stenoses influence each other is unpredictable from the simple ratio of the pressures distal and proximal to each individual stenosis.

Importance of Collateral Flow
In patients with severe coronary artery disease, myocardial perfusion depends both on antegrade flow through the stenotic epicardial artery and on collateral flow. A >2-fold increase of myocardial perfusion can be provided solely by collaterals. Myocardial FFR takes into account the contribution of collateral circulation to hyperemic myocardial flow, because the distal coronary pressure is determined by aortic pressure and by the extent of collateral circulation in case of isolated epicardial stenosis. Measurements of $P_w$ obtained during coronary occlusion determine the separate contributions of antegrade flow and of collateral flow to total hyperemic myocardial perfusion. In case of multiple stenoses along the same coronary artery, collateral flow will influence both $P_a$ and $P_w$. The extent to which collateral flow will influence $P_w$ depends on the severity of the second stenosis. Therefore, the value of $P_w$ cannot be neglected and was incorporated into the equations derived in the Appendix.

**Figure 2.** Example of hyperemic pressure tracings obtained in dog 4. Top, Influence of a varying distal stenosis B on a fixed proximal stenosis A. Bottom, Influence of a varying proximal stenosis A on a fixed distal stenosis B. In both examples, $\text{FFR}_{\text{pred}}$ remains very close to $\text{FFR}_{\text{true}}$ whereas $\text{FFR}_{\text{app}}$ progressively diverges from $\text{FFR}_{\text{true}}$ as other stenosis tightens.
be applied to each stenosis rather than the simple ratio $P_d / P_a$

Pw is probably more pronounced than in the present study and than in a canine model. Therefore, in humans, the influence of chronic coronary artery disease is most likely more developed with caution. First, the collateral circulation in humans with these experimental data should be extrapolated to humans.

**Limitations**

These experimental data should be extrapolated to humans with caution. First, the collateral circulation in humans with chronic coronary artery disease is most likely more developed than in a canine model. Therefore, in humans, the influence of $P_w$ is probably more pronounced than in the present study and must be included in the equations for FFR in case of serial stenoses.

Second, $P_w$ can be obtained only during balloon coronary occlusion, which constitutes a practical limitation.

Third, when 1 stenosis is very tight, so that the pressure distal to that stenosis is very close to $P_w$, very small inaccuracies in measuring $P_w$ might induce large errors in $\text{FFR}_{\text{pred}}$. However, this limitation is somewhat academic, because a very tight stenosis will be dilated anyway, and the second stenosis will be evaluated after treatment of the first stenosis.

Finally, for the 2 stenosis equations to be applicable, there should be no major arterial branch between the 2 stenoses being investigated. If there is an arterial branch between the 2 stenoses, the nonstenotic low-resistance branch increases flow through the first stenosis, thereby causing a greater pressure drop across the first stenosis than would occur without the intervening arterial branch. With a lower pressure between the stenoses, flow through the distal stenosis would be reduced in the presence of an arterial branch compared with that without the side branch. Thus, the side branch between the stenoses would divert a “steal” flow away from the second stenosis, so that the flow through the second stenosis would not be maximal. The pressure gradient across the second stenosis would therefore be less than it would have been in the absence of the side branch. Because the flow through the second stenosis would be reduced in the presence of a side branch, removal of the distal stenosis would result in only limited increased flow capacity through the first stenosis.

With several serial stenoses and intervening branches, this phenomenon of “branch steal” cumulatively along the length of a branching coronary artery may cause a fall in flow at the apex to below normal resting flow after dipyridamole, with resulting ischemia. In diffuse coronary artery disease, this phenomenon is seen as a longitudinal base-to-apex perfusion gradient on dipyridamole PET perfusion imaging. For multiple stenoses or diffuse disease with intervening arterial branches, calculation of flow reserve (or FFR) at each branch point becomes complex and requires fully developed fluid dynamics equations accounting for the myocardial mass supplied by each branch as described previously. For these complex branch-stenosis interactions, both pressure and flow velocity measurements may be necessary for assessing the functional severity of multiple stenoses and/or diffuse disease.

**Conclusions**

The present study demonstrates for interventionalists that for multiple stenoses in the same vessel, the hemodynamic assessment of a stenosis and the potential benefit of angioplasty is significantly influenced by the presence of the second stenosis. The practical clinical application of these new concepts for interventional decisions in patients with multiple stenoses and diffuse disease are now being studied.

**Appendix**

In this Appendix, the equations for predicting myocardial FFR of each of 2 sequential stenoses as if the other stenosis were removed will be derived mathematically from the initially measured pressures.
P_a, P_m, P_d, and P_w. These predicted values of myocardial FFR are called FFR(A)_pred and FFR(B)_pred for the proximal (A) and distal (B) stenoses, respectively. The terminology is consistent with the original article on the concept of FFR\(^1\) and is further clarified in Figure 1: P_a, P_m, P_d, and P_w indicate mean aortic pressure, coronary pressure between the 2 stenoses, coronary pressure distal to the second stenosis, and coronary wedge pressure (distal coronary pressure during total coronary occlusion) at that particular P_a, all measured at maximum coronary hyperemia before any intervention. P_a, P_m, P_d, and P_w indicate the corresponding pressures after 1 of the 2 lesions has been completely removed.

After the proximal stenosis A has been removed, P_w equals P_d, and after the distal stenosis B has been removed, P_d equals P_w. True measured FFR of 1 stenosis after physical removal of the other stenosis in the animal model is indicated by FFR(A)_true and FFR(B)_true, respectively. The terminology is consistent with the original article on the concept of FFR\(^1\) and is further clarified in Figure 1: P_a, P_m, P_d, and P_w indicate mean aortic pressure, coronary pressure between the 2 stenoses, coronary pressure distal to the second stenosis, and coronary wedge pressure (distal coronary pressure during total coronary occlusion) at that particular P_a, all measured at maximum coronary hyperemia before any intervention. P_a, P_m, P_d, and P_w indicate the corresponding pressures after 1 of the 2 lesions has been completely removed.

How to predict FFR(A)_true from P_a, P_m, P_d, and P_w?

Because all measurements are performed at maximum vasodilation of the coronary circulation, the resistances are constant, and therefore

\[
\frac{Q'_c}{Q_c} = \frac{Q'_w}{Q_w} = \frac{Q'_d}{Q_d} = \frac{Q'_m}{Q_m} = \frac{1}{\text{FFR}_{\text{cor}}}
\]

In that case, FFR(A)_pred equals P_m/P_a and FFR(B)_pred equals P_w/P_d.

\[
\Delta P(A) = \frac{Q'_m}{Q_m} \frac{P'_m - P_m}{P'_w - P_w}
\]

or

\[
(P'_d - P'_w) \cdot (P_d - P_w) = (P'_m - P_m) \cdot (P'_w - P_w)
\]

or

\[
P'_m (P'_d - P'_w) = P'_d (P'_m - P'_w)
\]

It has been proved theoretically and validated experimentally\(^1\) that P'_m/P'_d = P'_w/P'_w. Therefore, P'_m = P'_w/P'_d and those terms can be cancelled in the expression above.

By rearrangement of the remaining terms, the following equation is obtained:

\[
P'_m (P'_d - P'_w + P_d - P_w) = P'_d (P'_m - P'_w + P_m - P_w)
\]

Division of both the right and left terms by P'_d gives

\[
\frac{P'_m}{P'_d} \cdot (P_d - P_w + P_m - P_w) = P_d - \left( \frac{P'_m}{P'_d} \right) P'_w = P_d - \left( \frac{P_m}{P'_d} \right) P_w,
\]

and therefore,

\[
\text{FFR}(A)_{\text{pred}} = \frac{P_d - (P_m/P'_d) P_w}{P_d - P_m + P_d - P_w}
\]

The correctness of this expression can be verified by substitution of the boundary values of the respective pressures and verification if FFR(A) is obtained:

(a) No proximal stenosis: P_m = P_w.

In that case, FFR(A)_{pred} = 1 = FFR(A).

(b) No distal stenosis: P_d = P_w.

In that case, FFR(A)_{pred} = \frac{P_m - P_w}{P_d - P_w}
distal lesion influences the hemodynamics of the proximal lesion.

FFR(A), but it holds true only in the simplified case that collateral flow is neglected.

Suppose again that stenosis A will be completely eliminated. In that case, FFR(A) pred 5 0. 

In case of coronary stenosis, arterial pressure 5 proportional to blood flow and because  and as a consequence,

Or

Substitution of this latter expression by (*) gives

Equation (*) has erroneously been claimed to represent the functional severity of coronary artery stenoses.

Note: This emphasizes that only in the theoretical case that  does the proximal stenosis not influence the hemodynamics of the distal lesion.

In that case, FFR(A) pred 5 FFR(A) for a total occlusion.¹

Influence of Removal of Proximal Stenosis A on Hemodynamics of Distal Stenosis B

How to predict FFR(B) true from  ,  ,  , and  ?

As above, it is proved that

and because the hyperemic gradient across B is assumed to be proportional to blood flow and because  , this means that

or

In case of coronary stenosis, arterial pressure  is proportional to distal coronary pressure  and to coronary wedge pressure  (so-called pressure independence of FFR) during maximal hyperemia,¹,³ and therefore, in case of 2 stenoses,  . Therefore,  , and as a consequence,

Substitution of this latter expression by (**) gives

Or

Because

it is obtained by substitution of expression (**) that

References


Pressure-Derived Fractional Flow Reserve to Assess Serial Epicardial Stenoses: 
Theoretical Basis and Animal Validation
Bernard De Bruyne, Nico H. J. Pijls, Guy R. Heyndrickx, Dominique Hodeige, Richard 
Kirkeeide and K. Lance Gould

Circulation. 2000;101:1840-1847
doi: 10.1161/01.CIR.101.15.1840

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2000 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
http://circ.ahajournals.org/content/101/15/1840

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published
in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial
Office. Once the online version of the published article for which permission is being requested is located,
click Request Permissions in the middle column of the Web page under Services. Further information about
this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/