The Effect of the Sensor Position of the Pressure Wire Distal to a Coronary Stenosis on the Calculated Fractional Flow Reserve

B Tar[1], S Bakk[1], Z Béres[1], J Sánta[1], P Polgár[1], Shengxian Tu[2], Z Kőszegi[1,3]

[1]Invasive Cardiology Laboratory, Jósa András Teaching Hospital, Nyíregyháza, Hungary
[2]Division of Image Processing, Department of Radiology, Leiden University Medical Center, Leiden, The Netherlands
[3]Institute of Cardiology, University Medical School of Debrecen, Hungary

Abstract

The determination of the fractional flow reserve can be influenced by the position of the sensor of the pressure wire distal to a coronary lesion.

We aimed to calculate the pressure gradients restricted to the stenosis and with the inclusion of the distal reference segment up to the position of the pressure wire.

The coronary artery volumetric flow was calculated based on the velocity of the contrast material in the 3D reconstructed coronary segment. Pressure gradients were determined by fluid dynamic equations using the morphological data derived from 3D coronary angiography and contrast material velocities.

The Bland-Altman analysis showed smaller differences between the calculated and the measured FFR when the distal laminar resistances were also incorporated in the model, compared to the calculations restricted to the lesions (mean difference: -0.05 vs. -0.09, limits: -0.11–0.02 vs. -0.16–-0.01; range: 0.112 vs. 0.159).

The FFR reflects not only the pressure gradient of the stenosis, but also the laminar resistance of the poststenotic segment. Knowing the components of the detected gradients could be important for the clinical considerations of the cases near the cut-off value of the FFR.

1. Introduction

As the blood traverses through stenotic arterial segment, turbulence, friction and separation of laminar flow cause pressure gradient across the stenosis. There are physical components to the flow changes. The equation that characterizes the severity of the stenosis is as follows:

$$\Delta p = fQ + sQ^2$$

where **Δp** is the pressure gradient, **f** is the viscous friction factor of the laminar flow, **s** is the flow separation pressure loss coefficient at the site of the turbulent flow (or flow separation) and **Q** is the flow (Figure 1.). The pressure drop according to the Poisseuille's law is a linear function of **Q,** while **f** is quadratic function of the **Q** at the at the turbulent flow described by the Bordan-Carnot equation. The **f** is determined by the stenosis length (**L**) and inversely by the minimal cross-sectional lumen area (**MLA**): $f \sim L / MLA^2$. The **s** is influenced by the geometry of the stenosis (affected by the difference between the **MLA** and the non-stenotic part of the vessel) and fluid properties of blood (Figure 1.) [1-2]:

$$s \sim 1/ MLA^2 - AS^2/MLA^2 x104$$

The pressure drop can be calculated along the lesion as the sum of the resistance from the laminar and the turbulent flow. In case of diffuse disease the distal laminar flow from the end of the lesion to the position of the sensor of the pressure wire can also be taken into consideration for the calculation (Figure 2.). Our assumption was that the position of the pressure wire can modify significantly the calculated and the measured FFR values. Our aim was to determine the effect of the sensor position of the pressure wire distal to a coronary stenosis on the calculated fractional flow reserve and to validate the values to the measured ones (Figure 2).

2. Methods

2.1. Angiography and 3D reconstruction

X-ray angiographic images were recorded by flat panel systems (AXIOM-Artis, Siemens). The lumen of the interrogated vessel segments was reconstructed in 3D using a dedicated 3D QCA software package (QAngio XA Research Edition 1.0, Medis Specials bv, Leiden) [3]. During conventional cardiac catheterization coronary angiographic cine images were acquired at 15 or 30 frames per second. 2 ECG-gated end-diastolic frames separated from each other by at least 25° were used to reconstruct the segment of interest at the coronary lesion. First the guiding catheter was used to calibrate pixel size. The location of the stenosis, as well as the proximal and distal coronary artery segments were manually identified on the images then the software automatically generated the arterial lumen in 3D (Figure 3.). Minimum luminal area (**MLA**), length of the stenosis (**L**), distance to the sensor of the pressure wire from the end of stenosis (**L_{sensor}**), area of the non-stenotic part of vessel (**A**)were calculated by the program from 3D parameters.

2.2. Calculating of the volumetric flow

The flow velocity (mm/s) was assessed by the frame count on the coronary angiography following administration of 6 ml contrast material with a 3ml/s rate by ACIST™ Injection System (BBraun).

Volumetric blood flow was calculated on the basis of the contrast material transport time from the TIMI frame count (**t**), and contrast transport distance (during one heart cycle) (**d**) from the 3D reconstruction using the following equation (Figure 3):

$$\mathbf{Q = A_{norm} \times d / t}$$

where $\mathbf{A_{norm}}$ is the reference area

2.3. Calculating of the pressure gradients

The pressure gradients, which are measured by pressure wire depend on the pressure loss in the lesion (**ΔP_{lesion}**) and in the vessel segment from the end of lesion to the sensor of wire(**ΔP_{sensor}**). The whole pressure gradient (**ΔP_{total}**) is calculated on the basis of the fluid dynamic equations:

$$\Delta P_{F\ lesion} = 8\pi\eta L / A^2_{sten} \times Q$$

$$\Delta P_{S\ lesion} = \rho / 2 \times (1/A^2_{sten} - 1/A^2_{norm}) \times Q^2$$

$$\Sigma\Delta P_{lesion} = \Delta P_F + \Delta P_S$$

$$\Delta P_{F\ sensor} = 8\pi\eta L_{sensor} / A^2_{sensor} \times Q$$

$$\Delta P_{total} = \Sigma\Delta P_{lesion} + \Delta P_{sensor}$$

Where:

ρ – blood density: 1055 g/l

η – blood viscosity: 3.5 cP

L – stenosis length (mm)

L_{sensor} – length from the end of the stenosis to the sensor of the wire

A – normal and stenotic cross-sectional area (mm²)

Q – blood flow (ml/s)

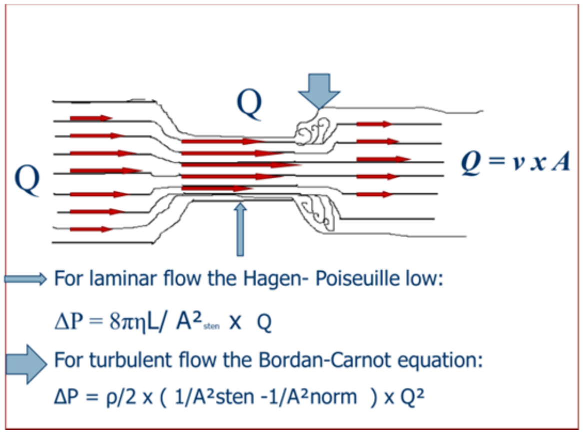

Figure 1. Pressure loss across the stenosis: as blood transverses an arterial lesion, the laminar and the turbulent flow cause energy loss, resulting in a pressure gradient across the stenosis.

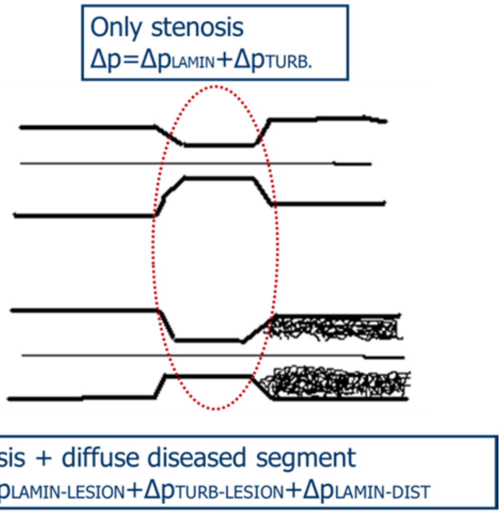

Figure 2. The pressure drop can be calculated along the lesion as the sum of the resistance from the laminar and the turbulent flow (above). In case of diffuse disease the distal laminar flow also may be taken into consideration into the calculation (under)

2.4. Calculation of the FFR

We calculated the FFR from the calculated pressure gradients and the measured aortic pressure values:

$$\mathbf{FFR}_{\text{calc.lesion}} = \mathbf{P}_{\text{meas.prox.}} - \boldsymbol{\Sigma\Delta}\mathbf{P}_{\text{lesion}} \,/\, \mathbf{P}_{\text{meas.prox.}}$$

$$\mathbf{FFR}_{\text{calc.total}} = \mathbf{P}_{\text{meas.prox.}} - \boldsymbol{\Delta}\mathbf{P}_{\text{total}} \,/\, \mathbf{P}_{\text{meas.prox.}}$$

2.5. Measuring of the FFR

During cardiac catheterization through either femoral or radial artery, 6 F guiding catheter without side-holes was carefully positioned at the orifice of the left or right coronary artery to detect the proximal (aortic) pressure without damping. The distal pressure was recorded by pressure-sensor guide wire (PressureWire Certus, Radi Medical). First, the pressure trace from the semiconductor sensor at the catheter tip was equalized to the fluid fill pressure trace of the guiding catheter. Then the pressure wire sensor was advanced through the lesion to a distal position. 100-200 µg nitroglycerine was administered to the guiding catheter to prevent arterial spasm. Maximal hyperemia was induced by intracoronary injection of 100-200 µg adenosine, while Pa (aortic pressure at the guide tip) and distal coronary pressure (Pd, at the sensor) were simultaneously measured. FFR was determined as the ratio of these pressures: Pa/Pd. At the end of FFR measurement the possibility of the drift of the trace was ruled out by pulling back the sensor to the tip of the guiding catheter.

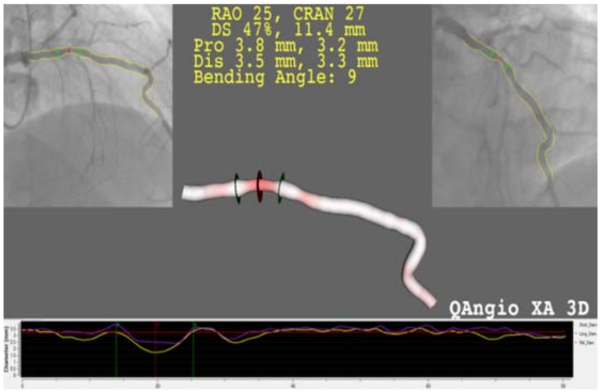

Figure 3. The lumen of the target segment of the vessel was reconstructed in 3D from 2 end-diastolic frames. The parameters of the stenosis were used to calculate the pressure gradient through the stenosis while the velocity determination was derived from the contrast travel time (on the basis of the frame count method) and the whole length of the vessel to the sensor position.

3. Results

The Bland-Altman analysis showed smaller differences between the calculated and the measured FFR when the distal laminar resistances were also incorporated in the model compared to the calculations restricted to the lesions (mean difference: -0.05 vs. -0.09, limits: -0.11–0.02 vs. -0.16–-0.01; range: 0.112 vs. 0.159) (Figure 4.). The Mann-Whitney test proved significant difference between the measured and calculated values only in those cases when the FFR was calculated for purely the lesions (p=0.084 vs. p=0.0006) (Figure 5.)

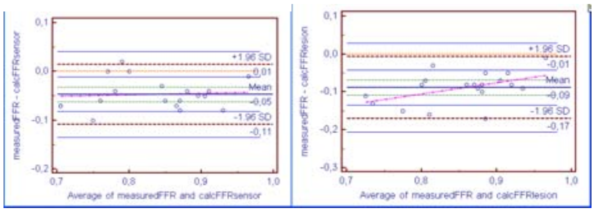

Figure 4. The Bland-Altman analysis of the calculated and the measured FFR: the distal laminar resistances incorporated in the model (left); the calculations restricted to the lesions (right)

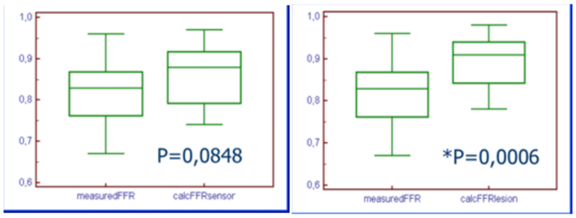

Figure 5. The Mann-Whitney test for the comparison of the measured and calculated FFR: non-significant difference between the measured and calculated values when the FFR was calculated for the whole measured vessel segments (left); significant difference when the FFR was calculated for purely to the lesions (right).

4. Discussion

The determination of the fractional flow reserve (FFR) by pressure sensor guide wire has become the gold standard for evaluating intermediate coronary lesions. FFR value<0.75 implies significance, with values between 0.75 and 0.80 being considered a gray zone. The DEFER and the FAME studies proved that interventions on intermediate lesions with FFR of ≥0.75-0.80 can be safely deferred, while bellow that values it is recommended. [4-5].

It was demonstrated that 2D coronary angiography is not suitable to predict the FFR in case of 50-70% diameter stenosis. Recently some studies have been published about the advantage of 3D angiography for the assessment of the functional consequence of these lesions [6-7]. Furthermore, FFR calculation non-invasively from CT images also challenged the need for the intracoronary pressure measurement [8]. However, these reports are based on calculations with assumed volumetric flow and anatomical parameters. In our study we used the flow velocity determination during vasodilatation by the TIMI frame count data and the measured length of the target vessel on the 3D reconstructions. This approach can improve the precision of the calculations. Even though we applied relatively simple formulas in compared to the more detailed finite volume computations fluid dynamic models used for the non-invasive FFR, in our opinion the direct intracoronary measurements validated that these calculations have clinically relevant results if we incorporate the whole target segment into the model. Our results showed that in the majority of the cases the distal resistance of the laminar flow significantly reduces the calculated and the measured FFR. These findings are in line with previously published papers [9-10].

In our opinion, the most important clinical relevance of these findings is that the position of the pressure wire can modify the result of the FFR determination. Taking into consideration the resistance of the segment distal to a lesion can change the clinical decision based on the FFR, especially in cases where the values are near the cut-off.

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Address for correspondence:

Zsolt Kőszegi M.D., Ph.D., F.E.S.C.

Jósa Andás Teaching Hospital,
Invasive Cardiology Laboratory
4400 Nyíregyháza, Szent István út 68
Hungary
koszegi@med.unideb.hu