Intracoronary Blood Flow Velocity and Transstenotic Pressure Drop in an Awake Human Being During Coronary Vasodilation

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The pressure drop over a coronary stenosis and the intracoronary Doppler blood flow velocity were measured at rest and during coronary vasodilation. We report the first observation that confirms the validity of fluid dynamic equations to describe the hemodynamics of a coronary stenosis based on quantitative arteriography in a human being. (J Interven Cardiol 1988:1:1)

coronary stenosis, coronary vasodilation

Introduction

Recently, quantitative coronary arteriographic methods of calculating pressure-flow characteristics have been proposed to describe the hemodynamic consequences of a coronary stenosis.[1–5] The fluid dynamic equations that are used in these methods have been validated in experimental animal preparations.[1–3,6–8] This report describes the first observation that confirms the validity of these equations to describe the hemodynamic consequences of a coronary stenosis in an awake human being.

Methods

A 43-year-old man underwent cardiac catheterization for severe disabling angina despite intensive medical therapy. Coronary angiography showed single-vessel coronary artery disease with a lesion in the proximal left anterior descending artery. Left ventriculography showed an ejection fraction of 65% with normal systolic and diastolic wall motion. Subsequently, the patient underwent percutaneous balloon angioplasty. A guiding catheter was placed in the left main coronary artery and a long guidewire (length: 315 cm, diameter: 0.14 in) was passed through the coronary stenosis. Isosorbide dinitrate was given intracoronary several times during the procedure to ensure constant and maximal epicardial vasodilation.

Intracoronary Blood Flow Velocity and Pressure Measurements

A 20 MHz pulsed Doppler probe mounted on the tip of the angioplasty catheter[9] with a balloon diameter size of 3.4 mm was introduced over the guidewire. Recently, Sibley et al. validated clinically and experimentally the ability of a similar catheter with an end-mounted piezoelectric crystal to provide accurate continuous on-line measurement of coronary blood flow velocity and vasodilator reserve.[10] The Doppler crystal has a 1.0-mm diameter annulus with a 0.5-mm central hole. Leads are soldered to each face and pushed through the catheter between the original 0.5-mm lumen and a thin-walled tube that serves as a new 0.4-mm lumen. The leads exit near the proximal Luer hub and are wired to a two-pin plug for connection to the pulsed Doppler instrument (Fig. 1). The mean and phasic spatially averaged blood flow velocities are measured continuously from the catheter tip transducer using a range-gated Doppler unit designed specially for this purpose. The sampling window was adjusted to obtain the

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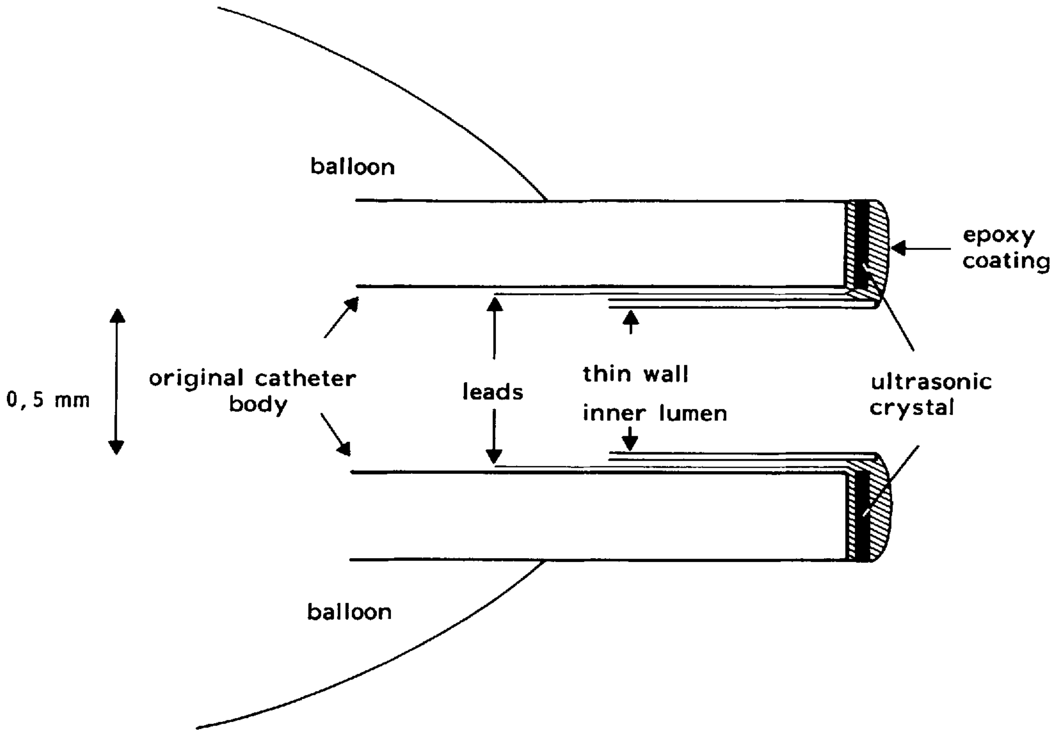

Figure 1. Schematic cross-sectional drawing of the Doppler-balloon catheter.

optimal signal that resulted in a sampling window of 1.8 mm. The output of the pulsed Doppler is a frequency shift (Δf) that can be related to blood velocity by the Doppler equation:

$$\Delta f = 2F(V/c)\cos a,$$

where F is the ultrasonic frequency, V is the velocity within the sampling volume, and a is the angle between the velocity vector and the sound beam. Using an end-mounted crystal with the catheter parallel (±20°) to the vessel axis, $\cos a = 1 \pm 6\%$, and the relation between the Doppler shift and velocity is approximately 3.75 cm/s per KHz.[9]

Previous calibration experiments in canine femoral arteries have shown that the measured Doppler frequency shift is proportional to volume flow.[10-13] After three balloon inflations with pressures up to 12 atmospheres and a total inflation time of 180 seconds the long guidewire was removed and the central lumen of the balloon catheter was vigorously flushed to record simultaneously the proximal intracoronary pressure through the guiding catheter, as well as the intracoronary pressure distal of the dilated lesion as previously described.[14,15] In 13 selected heartbeats, blood flow velocity and proximal and distal intracoronary pressures were measured. For each heartbeat, velocity and pressures were measured in

Table 1. Pressure-flow Characteristics of Coronary Stenosis

Flow Veloc (cm/sec)	Vol Flow (ml/sec)	Pressure-drop (mmHg)	
		x-Ray Predicted	Measured
12	1.0	14	11
13	1.1	16	13
14	1.2	17	17
15	1.3	19	17
16	1.3	21	17
18	1.5	25	22
19	1.6	28	28
20	1.7	29	28
21	1.8	31	28
23	1.9	36	33
24	2.0	38	32
25	2.1	40	36
26	2.2	43	36

Flow veloc = flow velocity measured with the intracoronary doppler catheter; vol flow = calculated volume flow.

early, mid, and late diastole, and these values were averaged to obtain a mean diastolic blood flow velocity and a mean diastolic pressure drop (Table 1). Resting intracoronary blood flow velocity and pressure drop over the residual stenosis were recorded. Thereafter, coronary vasodilation was induced by injecting 5 mg papaverine subselectively through the distal lumen of the balloon catheter.[16] The measured pressure drop increased from 11 to 37 mmHg and the intracoronary blood flow velocity increased from 12 to 26 cm/s. During the subsidence of the hyperemic response following the papaverine injection, intracoronary pressures and blood velocity were recorded continuously. Two examples are shown in Figure 2.

Quantitative Analysis of the Residual Coronary Artery Lesion

After removal of the angioplasty catheter, coronary angiography of the dilated artery was performed in two orthogonal projections on 35-mm cinefilm. There was no intimal dissection or haziness of the dilatation site. The determination of the coronary arterial dimensions have been implemented on the computer-based Cardiovascular Angiography Analysis System and have been described.[5,17,18] The boundaries of the selected coronary artery segment were detected automatically from optically magnified and videodigitized regions of interest of a cineframe. Calibration of the

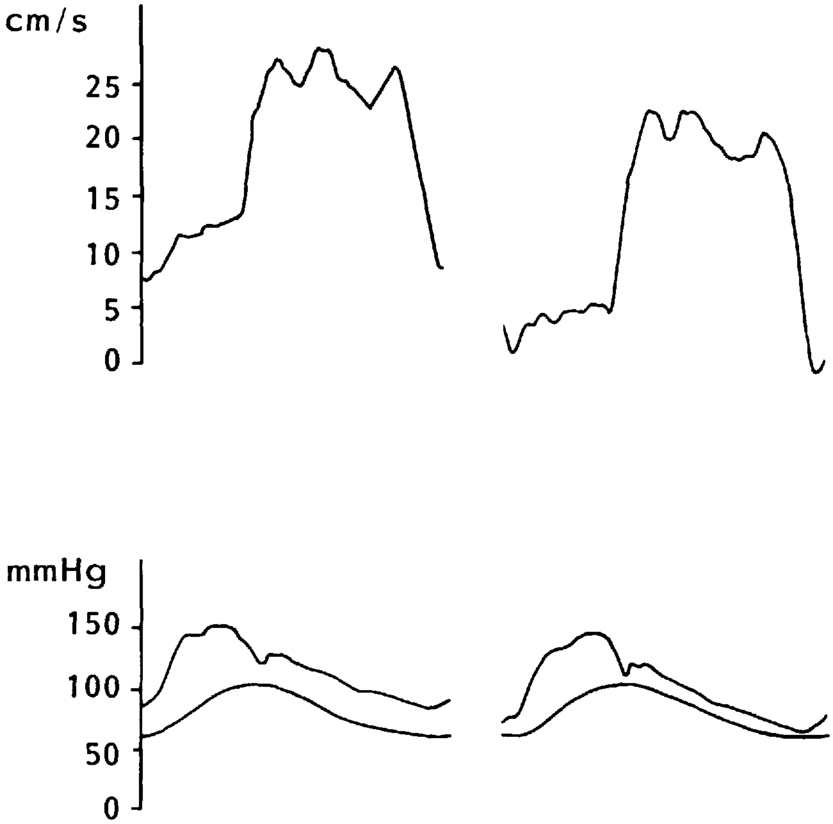

Figure 2. Two examples of the relationship between intracoronary blood flow velocity and intracoronary pressure proximal and distal to the stenosis. From top to bottom: intracoronary blood flow velocity (cm/s), proximal intracoronary blood pressure and distal intracoronary blood pressure (mmHg). During papaverine induced hyperemia the increased intracoronary blood flow velocity is accompanied by an increased pressure drop across the stenosis (left heart beat), whereas after subsidence of the hyperemia (right heart beat) intracoronary blood flow velocity and pressure drop across the stenosis are considerably lower.

diameter data in absolute values (mm) was achieved by detecting the boundaries of a section of the contrast catheter and comparing the mean diameter in pixels with the known size in mm. Each catheter is measured individually.[19] The contour positions of the arterial and catheter segments were corrected for pincushion distortion.[18] Since the functional significance of a stenosis is related to the expected normal area of the vessel at the point of obstruction, we used a computer estimation of the original arterial dimensions at the site of obstruction to define the reference region.[18] The length of the obstructive lesion was determined from the diameter function on the basis of a curvature analysis.[18] The percentage area stenosis and the minimal obstruction area (mm^2) were then calculated from the two orthogonal projections.

Calculation of the Pressure Drop Flow Relation on the Basis of the Stenosis Geometry

The theoretical pressure drop was calculated according to the fluid dynamic equations validated in experimental animal preparations:

$$\Delta P = \left[\frac{8\pi\mu L A_n}{A_s^2}\right]V + \frac{\rho}{0.266}\left[\frac{A_n}{A_s} - 1\right]^2 V^2$$

where ΔP is pressure drop across the stenosis, μ is absolute blood viscosity, L is stenosis length, A_s is the minimal cross-sectional area of the stenosis, A_n is cross-sectional area of the normal artery, p is blood density, V is flow velocity through the normal portion of the artery.

For volume flow (Q) this equation can be rewritten as:

$$\Delta P = \left[\frac{8\pi\mu L}{A_s^2}\right]Q + \frac{\rho}{0.266}\left[\frac{1}{A_s} - \frac{1}{A_n}\right]^2 Q^2$$

In a simplified form this equation can be described as:

$$\Delta P = fV + sV^2$$

where f is the coefficient of pressure loss due to viscous friction (Poiseuille resistance) and s is the coefficient of pressure loss due to exit separation.

Results

The quantitative measurements of the coronary artery showed a percentage area stenosis of 72% and a percentage diameter stenosis of 51%. For the calculation of the theoretical or x-ray predicted pressure drop, the stenosis area was corrected for the cross-sectional area of the balloon catheter with the balloon deflated. The diameter of the angioplasty catheter was measured with a microcaliper. We calculated a stenosis area of 0.8 mm^2. The measured flow velocity and pressure drop, as well as the calculated volume flow and pressure drop are shown in Table 1. Linear regression analysis of x-ray predicted versus measured pressure drop showed: x-ray predicted pressure drop = 1.1 × measured pressure drop + 1 mmHg, and an r value of 0.98 (95% confidence interval 0.94 to 0.99), with a SEE of 2 mmHg. The mean difference of the individual measurements between calculated and measured pressure drop was 11%. Angiographic measurement of the luminal cross-sectional area in the postangioplasty state may be difficult due to microdissections.[20,21] Measurement of the cross-sectional area of the deflated angioplasty catheter with a microcaliper could be erroneous to some extent. Therefore, we show the relationship between the measured intracoronary blood flow velocity, the theoretical or x-ray predicted pressure drop, and the measured pressure drop in Figure 3 for stenosis areas ranging from 0.6 to 0.9 mm^2.

Discussion

The visual assessment of coronary angiograms inadequately predicts the physiological significance of a coronary stenosis.[22] Recently, two approaches have been developed to overcome this problem. First, regional vasodilatory reserve can now reliably be assessed with intracoronary blood flow velocity measurements or by radiographic measurements of myocardial perfusion using contrast media.[5,13,23] Second, computer-based quantitative analysis of the coronary angiogram makes possible the calculation of hemodynamic parameters of the coronary artery lesion.[3-5] Gould et al. validated the fluid dynamic equations that can be

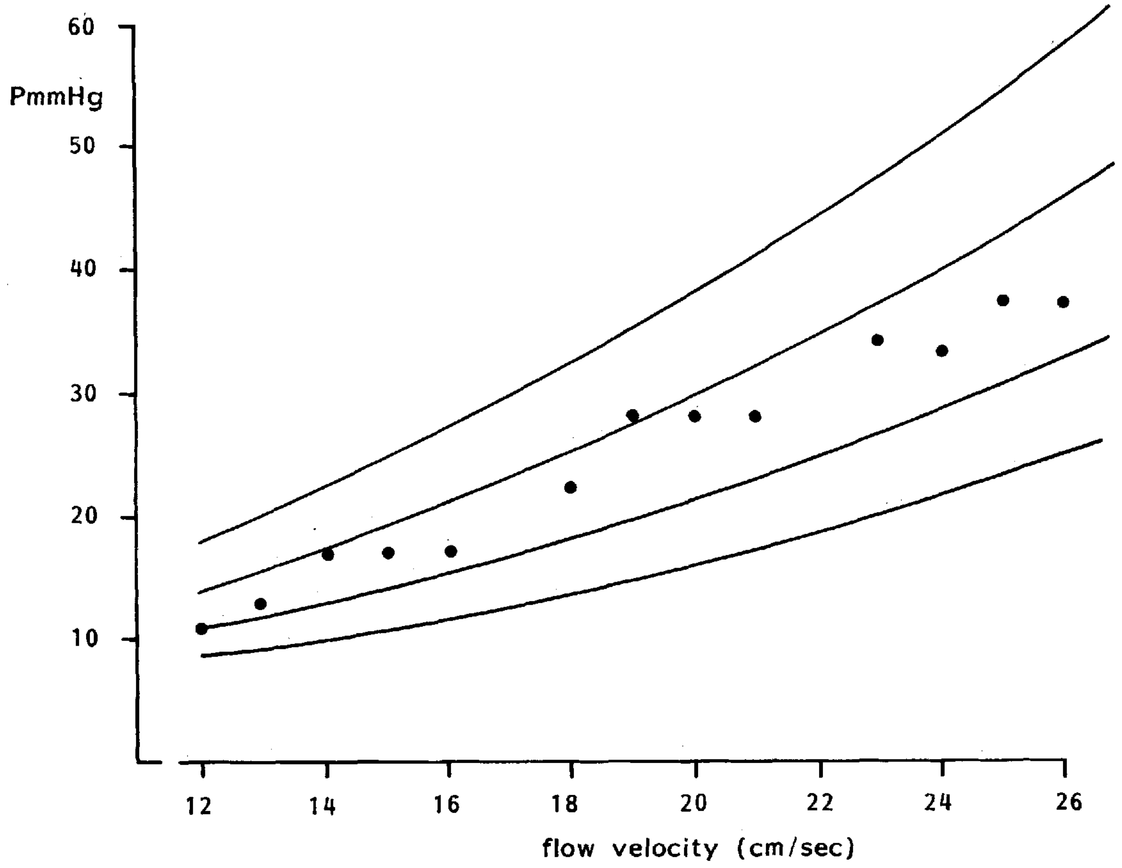

Figure 3. Relationship between the measured intracoronary blood flow velocity and the pressure drop (P) across the stenosis. The measured pressure drop is represented by the dots. The calculated pressure flow characteristics are represented by the lines; from top to bottom, stenosis areas 0.6, 0.7, 0.8, and 0.9 mm^2.

used to determine pressure flow characteristics of a coronary stenosis on the basis of x-ray determined geometry.[3] In their study a considerable scatter of measured versus x-ray predicted pressure drop was found despite an excellent overall correlation. The authors stated that this was mainly due to difficulties in visually tracing arterial borders on angiograms. We have used an extensively validated and highly accurate computer-assisted technique that includes automated contour detection.[17,18] Nevertheless, small errors in measured cross-sectional area of the stenosis and/or the deflated angioplasty catheter could result in a downward or upward shift of the calculated pressure flow relationship. Therefore, we show the pressure flow characteristics of the stenosis for stenotic areas ranging from 0.6 to 0.9 in Figure 3. Regardless of the potential error in quantification of the stenotic area, the calculated and measured relationship between pressure and flow remains characterized by a similar curvilinear pattern. Previous work from our laboratory showed that hemodynamic parameters calculated from x-ray geometry are correlated with measured coronary flow reserve,[5] measured translesional pressure gradient,[14] and exercise thallium perfusion scintigraphy.[15] Therefore, the concept that quantitative analysis of coronary artery dimensions can be used to predict the physiological significance of a coronary stenosis is attractive.

This report is the first observation in an awake human being suggesting that this quantitative angiographic approach to determine the pressure flow characteristics of a coronary stenosis is applicable in the clinical setting. A new generation of

Doppler tip angioplasty catheters has made this observation possible, but it needs to be further investigated and confirmed in a large series of patients.

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