

# How Important is the Impact of Pressure Recovery on Routine Evaluation of Aortic Stenosis? A Clinical Study in 91 Patients

Karl Isaaaz, Olivier Gaillard, Alexis Cerisier, Antoine Da Costa, Emmanuel Faure, Michel Lamaud, Claude Gerenton

*Division of Cardiology, University of Saint Etienne, Saint Etienne, France*

**Background and aim of the study:** Experimental investigations and invasive studies conducted in small series of patients using specially designed high-fidelity micromanometer tip catheters have suggested that downstream pressure recovery (PR) within the aorta may significantly affect transvalvular pressure gradient (PG) measurement. The study aims were to evaluate in a large cohort of patients the extent of PR when transvalvular PGs are routinely measured by fluid-filled pigtail side-hole catheters (FPC) using pullback from the left ventricle to the ascending aorta (AO), and to analyze factors influencing PR. The influence of PR on the correlation between catheter and Doppler PG measurements was also assessed in a subset of patients.

**Methods:** Transvalvular PG were measured in 91 patients with aortic stenosis using FPC pullback with the catheter positioned at different sites within the ascending aorta. In 71 patients, Doppler echocardiography was obtained within 24 h of catheterization.

**Results:** Mean PR ranged from 0 to 20 mmHg, corresponding to a PR index (percent of maximal PG)

ranging from 0 to 31%. PG was <50 mmHg in nine of 61 patients (15%) with a PG >50 mmHg at the origin of the aorta when further measurements were conducted with the catheter positioned more distally in the ascending aorta. PR index better correlated with the ratio of valve area to ascending AO cross-sectional area ( $r = 0.61$ ,  $p = 0.001$ ) than with valve area ( $r = 0.37$ ,  $p = 0.001$ ) and ascending AO cross-sectional area ( $0.27$ ,  $p = 0.02$ ) alone. Differences between Doppler and catheter-predicted PG were minimized when correcting Doppler by non-invasively calculated PR ( $p < 0.0001$ ).

**Conclusion:** The magnitude of PR recorded in aortic stenosis by FPC, as used in most clinical catheterization laboratories, is low in the vast majority of patients. As predicted from fluid mechanics theory, the ratio of valve area to ascending AO cross-sectional area is the central determinant of PR. PR may affect the Doppler-catheter correlation in some patients.

The Journal of Heart Valve Disease 2004;13:347-356

The pressure gradient (PG) across the aortic valve represents a central parameter for the hemodynamic evaluation of patients with aortic valve stenosis, as it is used, per se, as a basic index of valve obstruction severity. It is also required for calculating the stenotic valve area using the Gorlin equation (1). Severe obstruction of the aortic valve is usually characterized by a catheterization systolic PG exceeding 50 mmHg in the presence of normal cardiac pump function (2-4). Twenty years ago, based on fluid mechanics theory and the results of experimental investigations, Clark (5-7) introduced the concept of pressure recovery (PR)

in aortic stenosis - the increase of static pressure downstream of the stenosis due to reconversion of kinetic energy into potential energy - and the analysis of its determinants. More recent experimental investigations (8-15) and three clinical studies conducted in small series of patients using specially designed high-fidelity micromanometer tip catheters measurements (16-18) have suggested that PR may significantly affect PG invasive measurements and, consequently, the clinical decision in some patients with aortic stenosis. In many clinical catheterization laboratories, transvalvular PGs in patients with aortic stenosis are routinely measured using fluid-filled pigtail side-hole catheters (FPC) and a ventriculoaortic pullback method in order to avoid discomfort and potential risk to the patient in terms of dual catheter insertion into the arterial system. As a consequence, it remains unknown whether the findings from experimental studies or data obtained by

---

Address for correspondence:

Prof. Karl Isaaaz, Service de Cardiologie, Hôpital Nord, Centre Hospitalo-Universitaire de Saint Etienne, 42055 Saint Etienne Cedex 2, France

e-mail: isaaaz@univ-st-etienne.fr

specially designed high-fidelity micromanometer tip catheters in selected patients can be extrapolated in the practical world of routine catheterization.

In agreement with fluid mechanics theory (5-7), the results of experimental in-vitro studies (9,12) have suggested that the ratio of valve area to ascending aorta cross-sectional area (AVA/AOA) is a major determinant of PR, though in-vivo confirmation of this in a wide population of patients is lacking. In addition, although all parameters of PR can be calculated non-invasively using Doppler echocardiography, no clinical study has yet systematically reported the correlation between Doppler echocardiography-predicted PR and that measured by catheterization. In addition, as continuous-wave Doppler measures the highest velocities through the vena contracta before the occurrence of PR, some discrepancies between ultrasound and catheter PG measurements may be explained by more or fewer PR catheter recordings (8-15,17-21).

The main aim of the present prospective study was to evaluate, in a large population, the extent of PR in aortic valve stenosis when PGs were measured by current clinical catheterization techniques, and the physiological determinants of PR - with special attention being paid to the AVA/AOA ratio. Any influence of PR on the correlation between catheter- and Doppler-derived PG measurements was also analyzed in a subset of patients.

## Clinical material and methods

### Patient population

Between January 2000 and September 2001, a total of 91 patients (46 males, 45 females; mean age  $70 \pm 11$  years; range: 33 to 90 years) was referred to the authors' cardiac catheterization laboratory for evaluation of aortic valve stenosis. All patients were in sinus rhythm. Fifty-seven patients had no or trace aortic regurgitation, 31 had mild to moderate regurgitation, and three had severe regurgitation. The mean left ventricular ejection fraction was  $64 \pm 13\%$ . Sixty patients had no coronary artery disease, 22 had single-vessel disease, six had two-vessel disease, and three had triple-vessel disease.

### Left cardiac catheterization

A standard procedure of left heart catheterization using the percutaneous femoral approach was performed in all patients, including coronary angiography, left ventriculography, aortography and left heart pressure measurements. The left ventricle could be reached by retrograde advancement of a 5 or 6 Fr FPC in all patients. When direct crossing of the aortic valve was not possible with the FPC, a right Judkins or left

Amplatz catheter was used to cross the valve first, and this was then replaced by the FPC using an exchange guidewire. Left ventricular body pressures were measured with the FPC positioned under fluoroscopy and hand injections of radiographic contrast; in particular, care was taken to position the catheter deep enough within the ventricle but free of entrapment and to ensure that all side holes were at distance from the outflow tract. After recording the left ventricular pressure, the catheter was pulled back into the ascending aorta and, using contrast medium hand injections under fluoroscopy, positioned within the aorta successively at the level of the coronary arteries, mid-ascending aorta, and the rise of the brachiocephalic trunk. Corresponding peak systolic aortic pressures and peak-to-peak left ventricular-aortic PG were then measured: Pao1 = aortic pressure at the level of the coronary arteries; Pao2 = aortic pressure at the level of the mid-ascending aorta; Pao3 = aortic pressure at the level of the brachiocephalic trunk; PG1 = peak-to-peak PG between left ventricle and ascending aorta at the level of the coronary artery, PG2 = peak-to-peak PG between left ventricle and mid-ascending aorta, and PG3 = peak-to-peak PG between left ventricle and ascending aorta at the level of the brachiocephalic trunk. Measurements were averaged over 10 to 12 successive beats.

### Doppler echocardiographic examination

In 71 patients, ultrasound examination including M-mode, two-dimensional (2D) and Doppler echocardiography was performed in the authors' institution within 24 h of cardiac catheterization by two physicians highly experienced in ultrasound techniques, using a Vingmed CFM 800 equipment (Vingmed Sound A/S, Norway). Both physicians were blinded to the catheterization data. None of the 71 patients had severe aortic regurgitation. Peak and mean Doppler PGs were calculated from trans-stenotic velocities using the simplified Bernoulli equation ( $PG = 4V^2$ ). Aortic valve area (AVA) was derived from the standard continuity equation using trans-stenotic and left ventricular outflow tract velocity time integrals and outflow tract cross-sectional area measured by 2D echocardiography. The ascending aorta diameter was measured in the left parasternal long-axis view 2 cm distal to the sinotubular junction, and the cross-sectional area of the ascending aorta (AOA) was calculated from the diameter, assuming a circular shape.

### Pressure recovery: theoretical background, catheterization measurement and Doppler echocardiographic calculation

Based on fluid mechanics theory (5,6), the difference between the static pressure within the aorta distal to

the valve orifice at a point where the jet has fully expanded (Pao) and the lowest pressure across the stenosis, at the site of vena contracta (Pvc), may be written as:

$$P_{ao-Pvc} = \frac{1}{2} \rho V_{vc}^2 \cdot 2 \cdot \left[ \frac{AVA}{AOA} \right] \cdot \left[ 1 - \frac{AVA}{AOA} \right] \quad (1)$$

where  $V_{vc}$  is the maximal trans-stenotic velocity at the vena contracta and  $\rho$  the blood density. With pressures expressed in mmHg and velocities in m/s, Eqn. (1) can be rewritten:

$$P_{ao-Pvc} = 4V_{vc}^2 \cdot 2 \cdot \left[ \frac{AVA}{AOA} \right] \cdot \left[ 1 - \frac{AVA}{AOA} \right] \quad (2)$$

For comparison between various flow conditions, pressure recovery is presented as a dimensionless index (5-7,9,13,17,19) obtained by dividing both terms of Eqn. (2) by  $4V_{vc}^2$  as follows:

$$\frac{P_{ao-Pvc}}{4V_{vc}^2} = 2 \cdot \left[ \frac{AVA}{AOA} \right] \cdot \left[ 1 - \frac{AVA}{AOA} \right] \quad (3)$$

Multiplying both terms of Eqn. (3) by 100 gives the PR index - that is, the percentage of maximal transvalvular pressure gradient (dynamic pressure) recovered into static pressure:

$$PR \text{ index} = \frac{P_{ao-Pvc}}{4V_{vc}^2} \cdot 100 = 200 \cdot \left[ \frac{AVA}{AOA} \right] \cdot \left[ 1 - \frac{AVA}{AOA} \right] \quad (4)$$

PR and PR index can be measured by catheterization by recording aortic pressure at various positions distal to the valve. Predicted PR and PR index can be calculated from Doppler echocardiography using Eqns. (2) and (4), where  $4V_{vc}^2$  is the maximal transvalvular PG calculated by continuous-wave Doppler (Bernoulli equation), with AVA obtained using the continuity equation and AOA by 2D echocardiography.

### Statistical analysis

Data were expressed as mean  $\pm$  SD. The relation of catheter to Doppler PR and the relation of PR to Doppler echocardiographic parameters were analyzed using regression analysis. The differences between catheterization pressure recordings at the three sites, and between catheterization and Doppler PR index were analyzed using a paired *t*-test. A *p*-value  $<0.05$  was accepted as statistically significant.

### Results

#### Catheterization PR magnitude and its influence on correlation between catheter and Doppler PG measurements

In the whole population, a paired-*t*-test comparison showed that Pao1 ( $133 \pm 26$  mmHg,  $p < 0.0001$ ) was smaller than Pao2 ( $138 \pm 26$  mmHg) and Pao3 ( $139 \pm 26$  mmHg,  $p = 0.036$  versus Pao2). The difference between Pao2 and Pao3 confirmed the existence of further recovered pressure between these two sites (Pao3 -

Table I: Doppler echocardiography and catheterization pressure data.

Variable	Value*	p-value
PG1 (mmHg)	67.2 $\pm$ 29.4	<0.0001 vs. PG1 and PG2
PG2 (mmHg)	62.3 $\pm$ 28.6	0.039 vs. PG3
PG3 (mmHg)	61.5 $\pm$ 28.6	
Doppler max PG (mmHg)	79 $\pm$ 29	<0.0001 vs. PG1, PG2 and PG3
Doppler-predicted PR (mmHg)	9.8 $\pm$ 3.4	
Catheter-measured PR (mmHg)	5.7 $\pm$ 3.8	<0.0001 vs. Doppler-predicted PR
Doppler-predicted PR index (%)	13.5 $\pm$ 4.8	
Catheter-measured PR index (%)	9.4 $\pm$ 6.5	<0.0001 vs. Doppler-predicted PR index
[Doppler max PG - PG1] (mmHg)	11.4 $\pm$ 17	
[Doppler max PG - PG2] (mmHg)	16.4 $\pm$ 17	<0.0001 vs. [Doppler max PG - PG1]
[Doppler max PG - PG3] (mmHg)	17.1 $\pm$ 17	<0.0001 vs. [Doppler max PG - PG1]
[Corrected Doppler max PG - PG1] (mmHg)	1.6 $\pm$ 16	<0.0001 vs. [Doppler max PG - PG1]
[Corrected Doppler max PG - PG2] (mmHg)	6.5 $\pm$ 16	<0.0001 vs. [Doppler max PG - PG2]
[Corrected Doppler max PG - PG3] (mmHg)	7.2 $\pm$ 16	<0.0001 vs. [Doppler max PG - PG3]

\*Values are mean  $\pm$  SD.

PG: Pressure gradient; PG1: Peak-to-peak catheterization pressure gradient between left ventricle and ascending aorta at the level of the coronary artery; PG2: Peak-to-peak catheterization pressure gradient between left ventricle and mid ascending aorta; PG3: Peak-to-peak catheterization pressure gradient between left ventricle and brachiocephalic trunk; Predicted PR: Pressure recovery predicted from Doppler echocardiography measurement (see text).

Corrected Doppler max PG = Doppler max PG - predicted PR

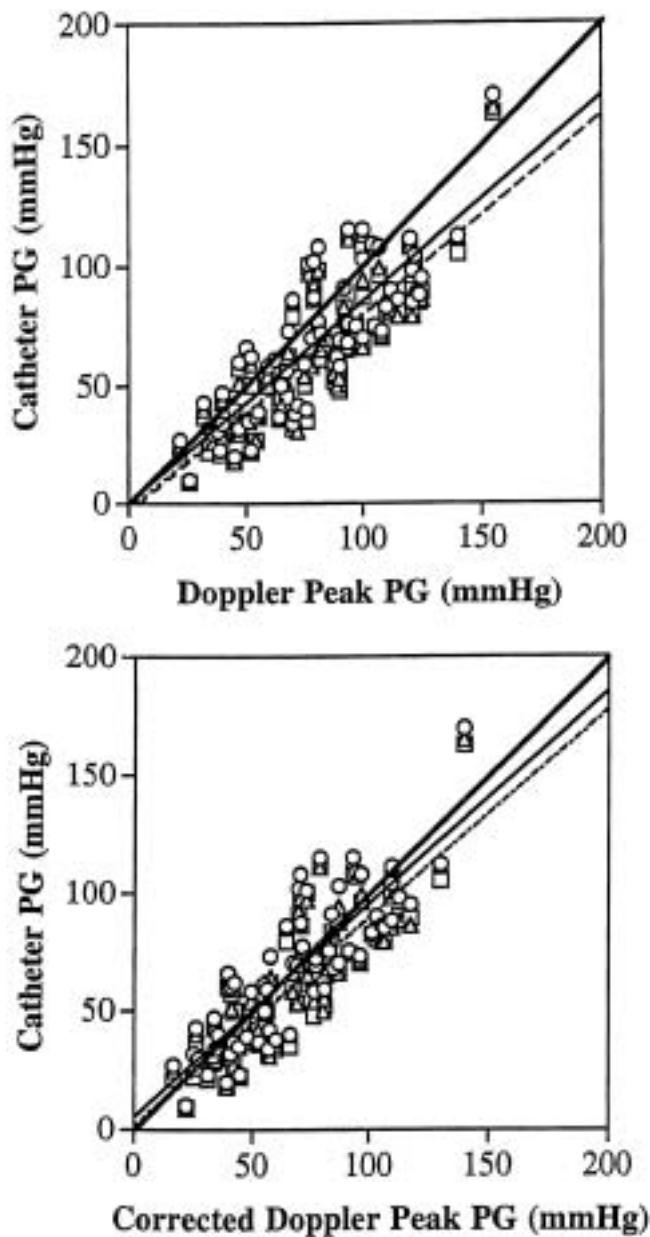


Figure 1: Correlations between Doppler and catheterization pressure gradients (PG). The thin line represents the relationship of Doppler pressure gradient to PG1, and the dotted lines represent the relationship of Doppler to PG2 and PG3. The thick line represents the line of identity.

$P_{a01} = 5.7 \pm 4.1$  mmHg versus  $P_{a02} - P_{a01} = 4.9 \pm 4.3$  mmHg,  $p = 0.036$ ). Therefore, all subsequent analyses were conducted with PR measured as  $(P_{a03} - P_{a01})$ . As shown in Table I, PG was maximal at position 1. Mean PR ranged from 0 to 20 mmHg (mean value 6 mmHg), and mean PR index was 9% (range: 0-32 %). Nine of the 61 patients with  $PG_1 > 50$  mmHg had a  $PG_2$  or  $PG_3 \geq 50$  mmHg. In 50 of the 52 patients with  $PG_1 \geq 60$  mmHg, both  $PG_2$  and  $PG_3$  remained  $> 50$  mmHg. The

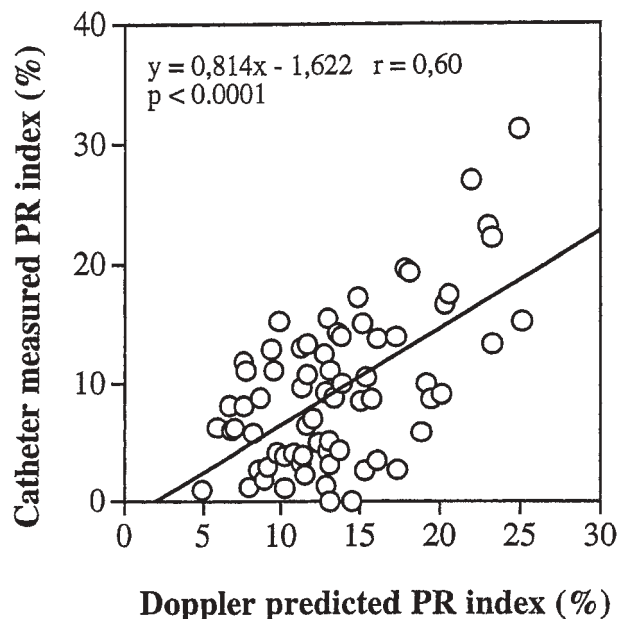


Figure 2: Correlation between pressure recovery (PR) index predicted by Doppler echocardiography and that measured by catheterization.

Doppler-catheter correlations regarding PG in the 71 patients with both Doppler echocardiography and catheter measurements are depicted in Figure 1, with linear regression equations shown in Table II.

#### Doppler echocardiographic prediction of PR

In 71 patients who underwent both catheterization and ultrasound measurements, PR predicted by Doppler echocardiography using Eqn. (2) was 10 mmHg (range: 4 to 21 mmHg) versus 6 mmHg (range: 0 to 16 mmHg) ( $p < 0.0001$ ) for catheterization, while the Doppler echocardiography-derived PR index using Eqn. (4) was 14% (range: 5 to 25%) compared with 9% (range: 0 to 31%) ( $p < 0.0001$ ) for catheterization (Table I). Subtracting Doppler echocardiography-predicted PR from Doppler maximal PG reduced the overestimations by Doppler of catheter-measured PG (Tables I and II; Fig. 1). A significant correlation was found between catheterization-measured PR index and PR index predicted from Doppler echocardiographic measurements using Eqn. (4) (Fig. 2). The ratio  $AVA/AOA$  predicted from catheterization PR using Eqn. (3) correlated with that ratio measured by Doppler echocardiography ( $r = 0.62$ ,  $p < 0.0001$ ).

#### Determinants of PR

PR index was linearly related to  $AVA$  ( $r = 0.37$ ,  $p = 0.001$ ) and to the ratio  $AVA/AOA$  ( $r = 0.61$ ,  $p = 0.001$ ), and inversely related to  $AOA$  ( $r = -0.27$ ,  $p = 0.02$ ) (Fig. 3), to the maximal transvalvular velocity ( $r = -0.38$ ,  $p =$

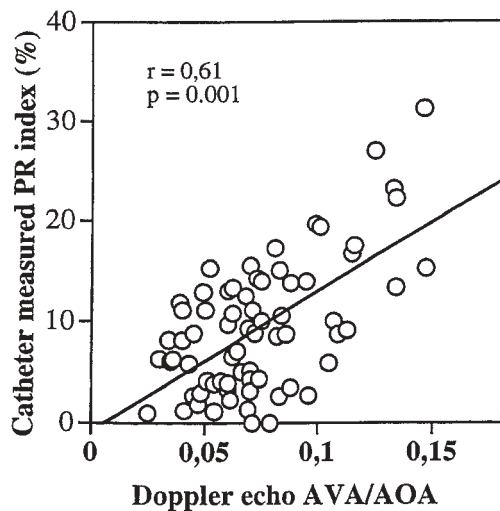
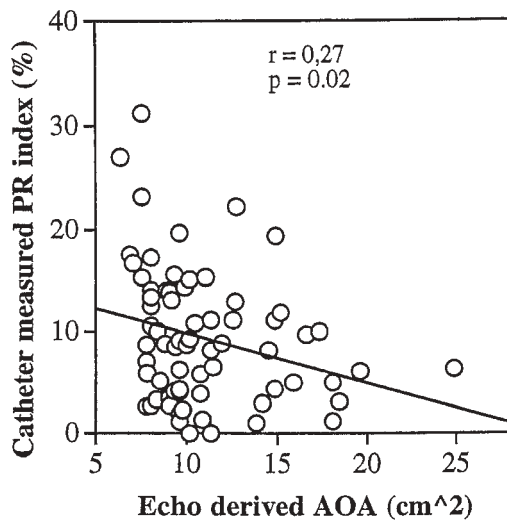
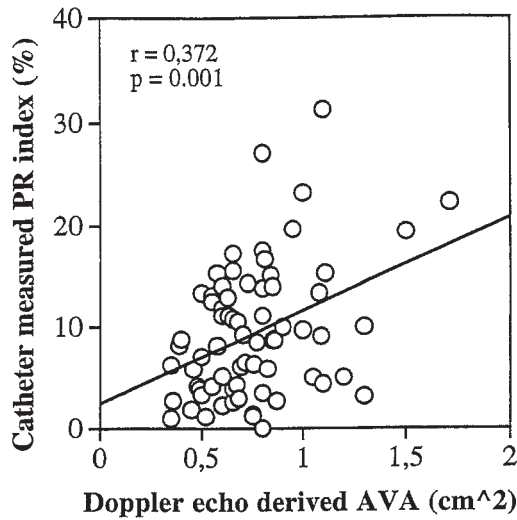


Figure 3: Determinants of pressure recovery (PR). AOA: Ascending aorta cross-sectional area; AVA: Aortic valve area.

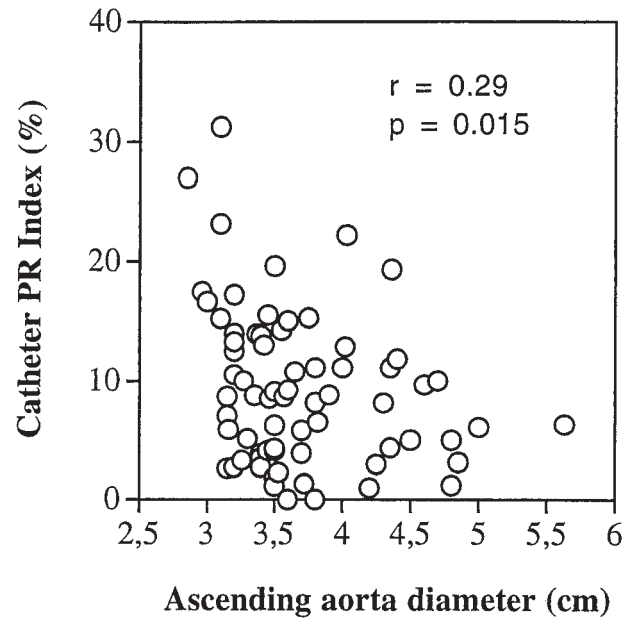


Figure 4: Relationship of pressure recovery (PR) index to diameter of the ascending aorta as measured by echocardiography.

0.001), to the maximal Doppler transvalvular PG ( $r = -0.37$ ;  $p = 0.001$ ), and to the mean Doppler transvalvular PG ( $r = -0.39$ ,  $p = 0.0007$ ).

## Discussion

Herein, the clinical relevance of the theoretical concept of PR on the hemodynamic evaluation of aortic stenosis as performed with current, most-often used techniques of clinical catheterization, was analyzed in a large population of 91 patients. This was also the first clinical prospective study to compare directly the PR predicted non-invasively from Doppler echocardiography using fluid mechanics principles with that measured invasively by catheterization and to confirm, in vivo, the role of the ratio AVA/AOA measured by Doppler echocardiography as a major determinant of PR.

### Extent of PR measured by fluid-filled catheters, and clinical relevance in aortic stenosis

Previously, only one clinical study has reported, in 15 patients with aortic stenosis, the effects of fluid-filled catheter positioning in the aorta on transaortic pressure gradient (22). In this latter study, as only one aortic position distal to the valve was evaluated, some additional recording of PR may have been omitted (22). In the present study, it was shown in a large population of 91 patients that pullback of a fluid-filled pigtail catheter - a method currently used in many clinical laboratories - allows the recording of PR in patients

Table II. Correlations between Doppler and catheterization pressure gradients.

x y	r	Slope	Intercept	SEE (mmHg)	p-value
Max Doppler PG					
PG1	0.83	0.85	0.63	5.7	<0.0001
PG2	0.83	0.82	-2.37	5.6	<0.0001
PG3	0.84	0.83	-3.73	5.5	<0.0001
[Max Doppler PG] - [predicted PR]					
PG1	0.84	0.90	5.35	5.2	<0.0001
PG2	0.84	0.88	1.98	5.1	<0.0001
PG3	0.85	0.89	0.596	4.9	<0.0001

Abbreviations as for Table I.

with aortic stenosis. In this study, PR ranged from 0 to 20 mmHg (mean 6 mmHg), while the mean PR index was 9% (range: 0 to 32%). This extent of PR, which was in agreement with that reported previously using micromanometer methodology (16-18), appears to be relatively small in the majority of patients. However, 15% of the patients with a maximal peak-to-peak PG >50 mmHg had a PG ≤50 mmHg at the site of pressure recovery, whilst only two of the 52 patients (4%) with a maximal peak-to-peak PG ≥60 mmHg had a PG ≤50 mmHg at the site of PR. Thus, PR might cause misclassification in some patients of the subgroup with peak-to-peak PGs of 50-60 mmHg, whereas its impact appears to be negligible in patients with peak-to-peak PGs >60 mmHg.

#### Central role of AVA/AOA ratio as a determinant of PR

Fluid mechanics theory (5,7) predicts that the PR index is a function of the ratio AVA/AOA (Eqn. (4)). Whilst several in-vitro studies (9,12,23,24) have con-

firmed the role of AVA/AOA ratio as an important determinant of PR, very few clinical data are available demonstrating, in vivo, the relationship between AVA/AOA and PR. In one clinical study with 34 patients in whom AVA was calculated invasively using the Gorlin formula and the ascending aorta systolic diameter measured by contrast aortography, Schöbel et al. (17) showed that the PR index, when measured by using specially designed high-fidelity micromanometer tip catheters, correlated with AVA/AOA ( $r = 0.44$ ). Surprisingly, in their study, Schöbel et al. (17) found that AVA/AOA, despite being the main variable of PR as predicted by fluid mechanics theory (Eqn. (4)), correlated less with PR than did AVA alone ( $r = 0.68$ ). Gjertsson et al. (25) estimated non-invasively the PR by Doppler echocardiography based on fluid mechanics (Eqns. (2-4)), but no invasive pressure measurement was obtained by these authors (25). In the present study, the AVA/AOA ratio was found to correlate better with PR index than did valve areas and ascending aorta cross-sectional areas alone (see Fig. 2). Thus, in

Table III: Correlations between Doppler using the long form of the simplified Bernoulli equation (incorporating subvalvular velocities) and catheterization pressure gradients.

x y	r	Slope	Intercept	SEE (mmHg)	p-value
[4V <sub>vc</sub> <sup>2</sup> - 4V <sub>sub</sub> <sup>2</sup> ]					
PG1	0.83	0.86	0.86	5.5	<0.0001
PG2	0.83	0.83	0.06	5.6	<0.0001
PG3	0.84	0.84	-1.4	5.5	<0.0001
[4V <sub>vc</sub> <sup>2</sup> - 4V <sub>sub</sub> <sup>2</sup> ] - [predicted PR]					
PG1	0.84	0.91	8.2	5.0	<0.0001
PG2	0.84	0.88	4.8	4.9	<0.0001
PG3	0.85	0.90	3.4	4.8	<0.0001

V<sub>sub</sub>: Subvalvular velocity measured by pulsed Doppler; V<sub>vc</sub>: Maximal trans-stenotic velocity at the vena contracta measured by continuous-wave Doppler. Other abbreviations as for Table I.

agreement with hydrodynamic principles and previous experimental findings, the post-valvular to orifice cross-sectional areas ratio does represent an important hemodynamic index of aortic stenosis due to its crucial role on downstream flow and pressure perturbation (26). An independent role of this ratio in the clinical course of patients with aortic stenosis has been recently suggested (23).

#### **Does relevant PR occur only in patients with small ascending aortas?**

Although fluid mechanics theory states that PR depends essentially on the AVA/AOA ratio, some investigators (12,20) have suggested that AOA size should be the most important variable, and must be <3 cm diameter before clinically relevant PR can be expected. By contrast, Schöbel et al. (17) documented a PR index as high as 29% even in patients with an aorta >3.5 cm at aortography. In the present study, a modest (but significant) inverse relationship was found between PR index and AOA diameter, though many patients with an aorta of >3 cm diameter and some with a diameter >3.5 cm still had a significant PR index of >15% (Fig. 4).

#### **Impact of PR on catheterization-Doppler echocardiography correlation**

As continuous-wave Doppler measures the highest velocities through the vena contracta before the occurrence of PR, ultrasound techniques using the Bernoulli equation may, in theory, provide a higher PG than those measured by catheterization due to more or fewer PR catheter recordings (8,9,11,12,14,19,21,24). In-vitro studies (11, 12) have confirmed that, under certain conditions, PR may lead to significant Doppler-catheter differences, but the relevance of this phenomenon in a clinical setting remains the subject of debate. Simultaneous Doppler-catheter correlative studies on large series of patients with aortic stenosis have shown excellent correlations, despite neglecting PR (27,28). More recent studies using high-fidelity micromanometer catheter measurements have reported significant differences between Doppler and catheterization that were reduced after correction by the PR (18,20). Multiple methodological factors, including small versus large population sample size, simultaneous versus non-simultaneous measurements, use of fluid-filled versus high-fidelity micromanometer catheters, and the recording in some cases of dynamic pressure rather than purely static pressure, might explain discrepancies at the level of clinical studies with regard to the influence of PR on the Doppler-catheter PG relationship. In addition, many physiological factors (other than AVA/AOA ratio) such as viscosity, inertial/turbulent effects, geometry

of the stenosis, eccentricity of the jet, aorta and peripheral arterial mechanical properties, are difficult to assess in a clinical situation and may modify the extent of PR (9-15).

In the present prospective clinical study, it was shown in a large population that PR does not significantly influence the values of correlation coefficients, but the findings do in part explain the overestimation in absolute value of catheterization PG by Doppler PG using the Bernoulli equation. By applying a linear regression equation (see Table II), it can be shown that a non-corrected Doppler PG of 100 mmHg may overestimate the catheterization PG by between 15 and 21%, whereas the overestimation ranged from only 5 to 11% with Doppler corrected by the non-invasively calculated PR. The remaining differences between Doppler and catheterization PGs after correction by calculated PR can be explained by the non-simultaneous measurement with fluid-filled catheters, the comparison of peak Doppler PG with catheterization peak-to-peak PG (27,28), and use of the short form of the simplified Bernoulli equation ( $PG = 4V^2$ ) rather than the fully developed formula. A simplified form of the Bernoulli equation that incorporates only the convective flow acceleration can be used for trans-stenotic PG calculations because the inertial term can be neglected in stenotic valves (29,35-37). Due to the low magnitude of subvalvular flow velocities compared with jet velocities, it has been proposed that the pressure drop related to these latter velocities be neglected in the simplified Bernoulli equation (29), and the short form of the simplified Bernoulli equation has been used in previously published studies validating transvalvular PG measurements by Doppler in large series of patients (27,28). Moreover, in previously published experimental investigations analyzing the role of PR on catheterization-Doppler correlations, Doppler PGs were measured using the short-form Bernoulli equation (9,11,12,20,24). The PGs calculated automatically with commercially available ultrasound equipment are also based on using the short-form Bernoulli equation. However, it remains possible that neglecting subvalvular velocities in the Bernoulli equation may contribute to an overestimation of PG by Doppler in some situations, especially in cases of high left ventricular outflow rate or in moderate stenosis. In the present patients, a non-corrected Doppler PG of 100 mmHg (calculated with the long form of the simplified Bernoulli equation:  $4 \text{ jet velocity}^2 - 4 \text{ subvalvular velocity}^2$ ) overestimates the catheterization PGs from 11 to 17% (versus 15 to 21% with  $PG = 4 \text{ jet velocity}^2$ ), and the overestimation varies from only 1 to 7% (versus 5 to 11% with  $PG = 4 \text{ jet velocity}^2$ ) when the long form of the Bernoulli equation is corrected by the non-invasively calculated PR (Table III). Thus, although the

short form, simplified Bernoulli may contribute to an overestimation of catheter PGs, pressure recovery may still represent an additional factor that causes catheter PG overestimation by Doppler measurements.

### **Comparison of Doppler-predicted PR with invasive measurements**

A significant correlation was found between PR calculated by Doppler echocardiography based on fluid mechanics theory and that measured by catheterization (see Fig. 2), though the extent of PR predicted by Doppler was greater than that measured by catheterization. The mean PR predicted by Doppler was 1.7-fold greater than that measured by catheter, whereas the differences were smaller for the PR index (14 versus 9%), which is more relatively flow-independent. The use of non-simultaneous measurements with fluid-filled catheters, as well as several physiological factors including viscosity, inertial/turbulent effects, geometry of the stenosis, eccentricity of the jet, aorta and peripheral arterial mechanical properties (9-15) not considered in Eqns. (2-4), may explain the discrepancies found between Doppler and catheter with regard to PR measurements.

### **Study limitations**

As the present study was designed to reproduce the conditions of invasive and non-invasive evaluation in clinical practice, Doppler and catheterization measurements were not performed simultaneously; hence, hemodynamic changes may have occurred between the times when the catheterization and ultrasound examinations were conducted. The coefficients of correlation between Doppler and catheterization PGs were therefore lower than those reported when Doppler and catheterization measurements are conducted simultaneously (27,28), but similar to those reported by Currie et al. (27,28) in their subgroups of patients with non-simultaneous Doppler and catheter measurements. Likewise, the use of fluid-filled catheters (which have a poor frequency response) instead of high-fidelity manometer catheters may have minimized the actual extent of PR measured during catheterization. However, as one of the study aims was to quantify the level of PR that may be recorded by fluid-filled catheters, these findings suggest that although catheterization data obtained by typical practices may distort the actual physical phenomenon, PR may still be observed and lead to misclassification in patients with peak-to-peak PGs of 50-60 mmHg.

The left ventricle to ascending aorta pullback method used in the present study is widely used in clinical laboratories, and results obtained with this method are similar to those obtained with simultaneous recording of left ventricular-ascending aortic pres-

ures, provided that the patients are in sinus rhythm (38). In addition, in clinical practice, the severity of aortic stenosis is often hemodynamically quantitated by monitoring peak-to-peak PGs in the absence of severe left ventricular dysfunction (2-4). A comparison of peak instantaneous PG with peak-to-peak values may influence the correlations for PGs between catheterization and Doppler echocardiography, independently of the PR phenomenon. Although peak instantaneous PGs are higher than peak-to-peak values (27,28), in-vitro studies have shown the extent of PGs to be similar when measured in either manner (9). Consequently, the findings of the present study in terms of PR should not be significantly affected by the use of peak instantaneous versus peak-to-peak PG measurements.

The present study was mainly designed to evaluate the impact of PR on PG measurement in a clinical setting. The influence of PR on valve area calculations using the Gorlin formula was not directly assessed. However, the variations of valve area in a given patient due to PR can be easily deduced as they are directly related to the square root of the PG variations. In the present series, PR measured by catheterization may have led to an average change in valve area of 5% (range: 0 to 21%) when using the Gorlin formula. The impact of PR on valve area measurements has been previously reported (17,24,39).

*In conclusion*, some PR in aortic stenosis - even in patients with a large aorta - can be recorded using fluid-filled pigtail side-hole catheters, and this may affect Doppler-catheterization PG correlation. The extent of PR is, however, small in the vast majority of patients, and might cause misclassification of severity of the disease in a subset of patients with PGs of 50-60 mmHg. As predicted from fluid mechanics theory, the ratio of aortic valve area to ascending aorta cross-sectional area appears to be the main determinant of PR.

### **Acknowledgements**

The authors thank Laure Richard, Brigitte Fréré and Bernard Samuel for their very important technical assistance.

### **References**

1. Gorlin R, Gorlin SG. Hydraulic formula for calculation of the area of the stenotic mitral valve, other cardiac valves and central circulatory shunts. *Am Heart J* 1951;41:1-29
2. Kirklin JW, Baratt-Boyes BG. In: Kirklin JW, Baratt-Boyes BG, eds., *Cardiac Surgery: Aortic valve disease*, 2nd edition. Churchill Livingstone, New York, 1993:491-571
3. Oakley CM. Management of valvular stenosis. *Curr Opin Cardiol* 1995;10:117-123

4. Braunwald E. Valvular heart disease. In: Braunwald E, Zipes DP, Libby P, eds., Heart Disease: A textbook of cardiovascular disease medicine, 6th edition. WB Saunders, Philadelphia, 2001:1643-1714
5. Clark C. The fluid mechanics of aortic stenosis. I. Theory and steady flow experiments. *J Biomech* 1976;9:521-528
6. Clark C. The fluid mechanics of aortic stenosis. II. Unsteady flow experiments. *J Biomech* 1976;9:567-573
7. Clark C. Energy losses in flow through stenosed valves. *J Biomech* 1979;12:737-746
8. Levine RA, Jimoh A, Cape EG, McMillan S, Yoganathan AP, Weyman A. Pressure recovery distal to a stenosis: Potential cause of gradient 'overestimation' by Doppler echocardiography. *J Am Coll Cardiol* 1989;13:706-715
9. Voelker W, Reul H, Stelzer T, Schmidt A, Karsch K. Pressure recovery in aortic stenosis: An in vitro study in a pulsatile flow model. *J Am Coll Cardiol* 1992;20:1585-1593
10. György W, Strauss AL, Rieger H, Scheffler A, Eisenhoffer JS. Miért nagyobb a Doppler-modszerrel meghatározott nyomaásgradiens a katéterrel mérhető értéknél? *Orv Hetil* 1992;133:1953-1958
11. Baumgartner H, Schima H, Tulzer G, Kuhn P. Effect of stenosis geometry on the Doppler-catheter gradient in vitro: A manifestation of pressure recovery. *J Am Coll Cardiol* 1993;21:1018-1025
12. Niederberger J, Schima H, Maurer G, Baumgartner H. Importance of pressure recovery for the assessment of aortic stenosis by Doppler ultrasound: Role of aortic size, aortic valve area, and direction of the stenotic jet in vitro. *Circulation* 1996;94:1934-1940
13. Cape E, Jones M, Yamada I, Van Auker M, Valdes-Cruz L. Turbulent/viscous interactions control Doppler/catheter pressure discrepancies in aortic stenosis. *Circulation* 1996;94:2975-2981
14. Heinrich RS, Fontaine AA, Grimes RY, et al. Experimental analysis of fluid mechanical energy losses in aortic valve stenosis: Importance of pressure recovery. *Ann Biomed Eng* 1996;24:685-694
15. Sung HW, Yu PS, Hsu CH, Hsu JC. Can cardiac catheterization accurately assess the severity of aortic stenosis? An in vitro pulsatile flow study. *Ann Biomed Eng* 1997;25:896-905
16. Laskey WK, Kussmaul WG. Pressure recovery in aortic valve stenosis. *Circulation* 1994;94:567-573
17. Schöbel WA, Voelker W, Haase KK, Karsch K-R. Extent, determinants and clinical importance of pressure recovery in patients with aortic valve stenosis. *Eur Heart J* 1999;20:1355-1363
18. Van Auker MD, Hla A, Meisner JS, Strom JA. Simultaneous Doppler/catheter measurements of pressure recovery in aortic valve disease: A correction to the Bernoulli equation based on velocity decay in the stenotic jet. *J Heart Valve Dis* 2000;9:291-298
19. Levine RA, Cape EG, Yoganathan AP. Pressure recovery distal to stenoses: Expanding clinical applications of engineering principles. *J Am Coll Cardiol* 1993;21:1026-1028
20. Baumgartner H, Stefenelli T, Niederberger J, Schima H, Maurer G. 'Overestimation' of catheter gradients by Doppler ultrasound in patients with aortic stenosis: A predictable manifestation of pressure recovery. *J Am Coll Cardiol* 1999;35:1655-1661
21. Yoganathan AP, Cape EG, Sung HW, Williams FP, Jimoh A. Review of hydrodynamic principles for the cardiologist: Applications to the study of blood flow and jets by imaging techniques. *J Am Coll Cardiol* 1988;12:1344-1353
22. Assey ME, Zile MR, Usher BW, Karavan MP, Carabello BA. Effect of catheter positioning on the variability of measured gradient in aortic stenosis. *Cathet Cardiovasc Diagn* 1993;30:287-292
23. Garcia D, Pibarot P, Dumesnil JG, Sakr F, Durand LG. Assessment of aortic valve stenosis severity. A new index based on the energy loss concept. *Circulation* 2000;101:765-771
24. Garcia D, Dumesnil J, Durand LG, Kadem L, Pibarot P. Discrepancies between catheter and Doppler estimates of valve effective orifice area can be predicted from the pressure recovery phenomenon. *J Am Coll Cardiol* 2003;41:435-442
25. Gjertsson P, Caidhal K, Svensson G, Wallentin I, Bech-Hanssen O. Important pressure recovery in patients with aortic stenosis and high Doppler gradients. *Am J Cardiol* 2001;88:139-144
26. Isaz K. The ratio of post-valvular aorta to valvular orifice cross-sectional areas: A new haemodynamic index of clinical importance in patients with aortic stenosis? *Eur Heart J* 1999;20:1294-1296
27. Currie PJ, Seward JB, Reeder GS, et al. Continuous-wave Doppler echocardiographic assessment of severity of calcific aortic stenosis: A simultaneous Doppler-catheter correlative study in 100 adult patients. *Circulation* 1985;71:1162-1169
28. Currie PJ, Hagler DJ, Seward JB, et al. Instantaneous pressure gradient: A simultaneous Doppler and dual catheter correlative study. *J Am Coll Cardiol* 1986;7:800-806
29. Hatle L, Angelsen B. Pulsed and continuous wave Doppler in diagnosis and assessment of various heart lesions. In: Hatle L, Angelsen B, eds., *Doppler Ultrasound in Cardiology. Physical principles and clinical applications*. Lea & Febiger, 1982:97-292
30. Holen J, et al. Doppler ultrasound in orifice flow: In vitro studies of the relationship between pressure difference and fluid velocity. *Ultrasound Med Biol*

- 1985;11:261-267
31. Terstein P, Yock P, Popp RL. The accuracy of Doppler ultrasound measurement of pressure gradients across irregular and tunnellike obstruction to blood flow. *Circulation* 1985;72:577
  32. Stamm RB, Martin RP. Quantification of pressure gradients across stenotic valves by Doppler ultrasound. *J Am Coll Cardiol* 1983;2:707
  33. Callahan MJ, Tajik AJ, Su-Fan Q, Bove AA. Validation of instantaneous pressure gradients measured by continuous wave Doppler in experimentally induced aortic stenosis. *Am J Cardiol* 1985;56:989-993
  34. Sholler GF, Colan SD, Sanders SP, Keane JF. Noninvasive estimation of left ventricular pressure waveform throughout ejection in young patients with aortic stenosis. *J Am Coll Cardiol* 1988;12:492-497
  35. Pasipoularides A. Clinical assessment of ventricular ejection dynamics with and without outflow obstruction. *J Am Coll Cardiol* 1990;15:859-882
  36. Isaz K. A theoretical model for the noninvasive assessment of transmitral pressure-flow relation using ultrasound technique. *J Biomech* 1992;25:581-589
  37. Isaz K. Expanding the frontiers of Doppler Echocardiography for the non invasive assessment of diastolic hemodynamics. *J Am Coll Cardiol* 2000;36:1950-1952
  38. Brogan WC, Lange RA, Hillis LD. Accuracy of various methods of measuring the transvalvular pressure gradient in aortic stenosis. *Am Heart J* 1992;123:948-953
  39. Levine RA, Schwammenthal E. Stenosis is the eye of the observer: Impact of pressure recovery on assessing aortic valve area. *J Am Coll Cardiol* 2003;41:443-445