Cardiac Ultrasound

Discrepancies Between Catheter and Doppler Estimates of Valve Effective Orifice Area Can Be Predicted From the Pressure Recovery Phenomenon

Practical Implications With Regard to Quantification of Aortic Stenosis Severity

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OBJECTIVES	We sought to obtain more coherent evaluations of aortic stenosis severity.
BACKGROUND	The valve effective orifice area (EOA) is routinely used to assess aortic stenosis severity. However, there are often discrepancies between measurements of EOA by Doppler echocardiography (EOA_{Dop}) and those by a catheter (EOA_{cath}). We hypothesized that these discrepancies might be due to the influence of pressure recovery.
METHODS	The relationship between EOA_{cath} and EOA_{Dop} was studied as follows: 1) in an in vitro model measuring the effects of different flow rates and aortic diameters on two fixed stenoses and seven bioprostheses; 2) in an animal model of supravalvular aortic stenosis (14 pigs); and 3) based on catheterization data from 37 patients studied by Schöbel et al.
RESULTS	Pooling of in vitro, animal, and patient data showed a good correlation (r = 0.97) between EOA_{cath} (range 0.3 to 2.3 cm^2) and EOA_{Dop} (range 0.2 to 1.7 cm^2), but EOA_{cath} systematically overestimated EOA_{Dop} (24 ± 17% [mean ± SD]). However, when the energy loss coefficient (ELCo) was calculated from EOA_{Dop} and aortic cross-sectional area (A_A) to account for pressure recovery, a similar correlation (r = 0.97) with EOA_{cath} was observed, but the previously noted overestimation was no longer present.
CONCLUSIONS	Discrepancies between EOA_{cath} and EOA_{Dop} are largely due to the pressure recovery phenomenon and can be reconciled by calculating ELCo from the echocardiogram. Thus, ELCo and EOA_{cath} are equivalent indexes representing the net energy loss due to stenosis and probably are the most appropriate for quantifying aortic stenosis severity. (J Am Coll Cardiol 2003;41:435–42) © 2003 by the American College of Cardiology Foundation

According to the American College of Cardiology/American Heart Association (ACC/AHA) recommendations (1), the aortic valve effective orifice area (EOA) can be used to grade aortic stenosis severity as follows: mild at >1.5 cm^2; moderate at >1.0 to ≤1.5 cm^2; and severe at ≤1.0 cm^2. In the clinical situation, the valve EOA is routinely determined by using either the Gorlin formula during cardiac

catheterization or the continuity equation during Doppler echocardiography (2–6). However, there are often discrepancies between catheter- and Doppler-derived valve EOAs, resulting in potentially divergent estimations of aortic stenosis severity. Because catheter pressure measurements are

generally performed a few centimeters downstream from the aortic valve, we hypothesized that these discrepancies might be due to the pressure recovery phenomenon, which mainly depends on the size of the ascending aorta (7–16). Thus, the objective of this study was to more closely examine the relationship between catheter (EOA_{cath}) and Doppler (EOA_{Dop}) measurements of EOA to reconcile such measurements and present more coherent evaluations of aortic stenosis severity.

Theoretical background. The transvalvular pressure gradient through a stenotic valve is maximal (TPG_{max}) at the level of the vena contracta. However, it is generally difficult to obtain an adequate measurement of TPG_{max} by a catheter because of the difficulty in adjusting and maintaining the position of the pressure sensor or pressure lumen orifice at the level of the vena contracta, as well as the position instability caused by flow-jet turbulences. Nonetheless, when TPG_{max} (mm Hg) is successfully measured by a catheter, the EOA at the vena contracta (cm^2; $EOA_{cath/max}$) can be calculated as follows using the Gorlin formula:

$$EOA_{cath/max} = \frac{Q}{50\sqrt{TPG_{max}}} \quad [1]$$

Abbreviations and Acronyms

A_A	= cross-sectional area of the aorta
EL	= energy loss
ELCo	= energy loss coefficient
EOA	= effective orifice area
EOA_{cath}	= effective orifice area measured by catheter
$EOA_{cath/max}$	= effective orifice area measured by catheter with use of maximal transvalvular pressure gradient
EOA_{Dop}	= effective orifice area measured by Doppler echocardiography
TPG_{net}	= net transvalvular pressure gradient
TPG_{max}	= maximal transvalvular pressure gradient

where Q is the flow rate in ml/s. Previous studies have demonstrated that the original Gorlin formula contains several errors that can be corrected by using a constant of 50 instead of 44.3 (17). To ensure the coherence of the results from both a theoretical and physiologic standpoint, we thus elected to use a constant of 50 in Equation 1. Because the EOA measured by Doppler using the continuity equation (EOA_{Dop}) is also meant to represent the EOA at the vena contracta, there should theoretically be a close agreement between $EOA_{cath/max}$ and EOA_{Dop}.

After the vena contracta, part of the jet kinetic energy is recovered in pressure, resulting in a net pressure gradient (TPG_{net}) lower than TPG_{max}, and the magnitude of $TPG_{max} - TPG_{net}$ (i.e., pressure recovery) is dependent on the valve EOA and the size of the ascending aorta (7–16).

It should be noted that the measurement generally recorded during cardiac catheterization is TPG_{net}, and consequently, the EOA reported corresponds to:

$$EOA_{cath} = \frac{Q}{50\sqrt{TPG_{net}}} \quad [2]$$

Recently, we proposed a new index based on EOA_{Dop} and aortic cross-sectional area (A_A) that takes into account the pressure recovery phenomenon. Hence, the energy loss coefficient (ELCo) provides an accurate estimation of the energy loss (EL) due to aortic stenosis (16), as demonstrated by this equation:

$$ELCo = \frac{EOA_{Dop} \times A_A}{A_A - EOA_{Dop}} = \frac{Q}{50\sqrt{EL}} \quad [3]$$

where A_A is in cm² and EL is in mm Hg. It should be noted that ELCo can be calculated from the echocardiogram using measurements of EOA_{Dop} and A_A. Because the transvalvular flow rate at rest is mainly dependent on body size, ELCo can also be indexed for body surface area to take into account the cardiac output requirements of the patient. In a previous study (16), we found that the indexed ELCo (i.e., EL index) was superior to either EOA_{Dop} or indexed EOA_{Dop} in predicting adverse outcomes in patients with aortic stenosis.

It is interesting to note that Equation 3 is very similar to the traditional Gorlin equation. However, instead of the

valve EOA, the left-hand side of the equation represents ELCo, and the right-hand side represents EL in terms of pressure instead of TPG_{net}.

The EL is the sum of TPG_{net} and the dynamic pressure gradient:

$$EL = TPG_{net} + 4(V_V^2 - V_A^2) \quad [4]$$

where V_V and V_A are the blood velocities (expressed in m/s) in the left ventricular outflow tract and ascending aorta, respectively. In patients with aortic stenosis, the dynamic pressure gradient $4(V_V^2 - V_A^2)$ is negligible compared with TPG_{net}, so that $EL \sim TPG_{net}$ and thus $ELCo \sim EOA_{cath}$, according to Equations 2 and 3. Hence, it should theoretically be possible to estimate EOA_{cath} from Doppler echocardiographic data by calculating ELCo using the left-hand side of Equation 3.

METHODS

In vitro study. The pulse duplicator used for the in vitro study has been previously described in detail (16,18). Two fixed stenoses (2 plates with circular orifices of 1.0 and 1.5 cm²) and seven aortic bioprosthetic heart valves (Medtronic Intact 19, 21, 23, and 25 mm, and Medtronic Mosaic 21, 23, and 25 mm) were tested in this model under 10 levels of flow rate ranging from 90 to 430 ml/s and using two aortic sizes: 2.54 cm (cross-sectional area: 5.07 cm²) and 3.8 cm (11.34 cm²).

Flow rate was measured with an electromagnetic flowmeter, and pressure measurements were performed using fluid-filled, side-hole catheters. Ventricular pressure was measured 20 mm upstream from the valve, and aortic pressures at 5 and 100 mm downstream of the valve to calculate TPG_{max} and TPG_{net}, respectively. EOA_{cath} was calculated from TPG_{net} and mean flow rate using Equation 2, and $EOA_{cath/max}$ was calculated from TPG_{max} and mean flow rate using Equation 1.

An Ultramark 9 HDI (Philips Medical Systems/ATL, Bothell, Washington) was used for Doppler velocity measurements. EOA_{Dop} was determined by the standard continuity equation using stroke volume measured by the electromagnetic flowmeter and the velocity–time integral of the continuous-wave Doppler aortic jet signal. The ELCo was calculated using the left-hand term of Equation 3.

Animal study. Animal care and experiments were conducted in accordance with the Guidelines of the Canadian Council for Animal Care. The protocol was approved by the institutional Animal Care Committee of Laval University, Sainte-Foy, Quebec, Canada. Fourteen pigs weighing between 27 and 35 kg were anesthetized, and a lateral thoracotomy was performed in the fourth left intercostal space. A supravalvular aortic stenosis was created using umbilical tape tightened around the aorta ~2 cm downstream from the aortic valve annulus (19).

The pressure measurements were performed using a Millar catheter (customized model, Millar Instruments, Houston, Texas) with a distal (P1), intermediary (P2), and

proximal (P3) sensor. The P2 was positioned at the level of the vena contracta (minimal pressure downstream from the stenosis). The P1, which is at 1.5 cm of the intermediary sensor, was therefore located ~1 cm upstream from the stenosis. The P3, located at 4 cm of the intermediary sensor, was used to measure the aortic pressure after recovery. Cardiac output was measured using an ultrasonic flowmeter (T206, Transonic Systems, Ithaca, New York), with the probe positioned around the main pulmonary artery. The electrocardiogram, the three pressure signals, and the flow signal were simultaneously recorded and digitized (Digidata 1322, Axon Instruments, Foster City, California). The systolic trans-stenotic pressure gradients were calculated as follows: $TPG_{max} = P1 - P2$; and $TPG_{net} = P1 - P3$. EOA_{cath} and $EOA_{cath/max}$ were calculated as described in the in vitro study.

The Doppler echocardiographic measurements were performed with a Sonos 5500 (Philips Medical Systems/Agilent Technologies, Andover, Massachusetts). An upper laparotomy was performed, and the ultrasound probe was introduced in the abdominal cavity and positioned on the diaphragm at the level of the cardiac apex. This window allowed the visualization of high-quality apical five-chamber images and optimal recording of the left ventricular outflow tract pulsed-wave velocity and aortic jet continuous-wave velocity. EOA_{Dop} was calculated using the standard continuity equation. The diameter of the ascending aorta was measured at 2 to 3 cm downstream of the stenosis by epicardial bi-dimensional echocardiography, using a 12-MHz probe. The A_A was calculated assuming a circular shape. The ELCo was calculated using Equation 3.

These measurements were obtained under the following experimental conditions: 1) moderate stenosis; 2) severe stenosis; 3) severe stenosis plus a mild increase in systemic resistance; 4) severe stenosis plus a moderate increase in systemic resistance; and 5) severe stenosis plus a marked increase in systemic resistance. The increase in resistance was obtained by constriction of the descending thoracic aorta. The objective of this intervention was to increase the aortic pressure downstream of the stenosis to produce dilation of the ascending aorta and thus an increase in A_A.

Patient data. To further validate the results obtained in the pulsed duplicator and in the animals, we used the raw data published by Schöbel et al. (14). Their study was performed in 37 patients with aortic stenosis and no significant regurgitation. They simultaneously recorded the pressures within the left ventricle, at the vena contracta, and in the aorta at the site after pressure recovery. Cardiac output was determined by thermodilution, and the mean transvalvular flow rate was calculated. EOA_{cath} (noted as A_{V-A} in their report) and $EOA_{cath/max}$ (noted as A_{V-X}) were determined from the Gorlin formula using TPG_{net} and TPG_{max}, respectively. However, Schöbel and colleagues used the original Gorlin formula with a constant of 44.3. Schöbel's raw EOA data were therefore corrected by multiplying by 0.89 (44.3/50). In their study, the A_A was derived from

Table 1. Catheter and Doppler Echocardiographic Data Obtained In Vitro, in Animals, and in Patients*

	EOA_{Dop}	$EOA_{cath/max}$	EOA_{cath}
In vitro data (n = 172)	1.06 ± 0.33	1.10 ± 0.36	1.29 ± 0.45†‡
	(0.40–1.66)	(0.41–1.83)	(0.45–2.32)
Animal data (n = 65)	0.52 ± 0.19	0.58 ± 0.21	0.72 ± 0.31†‡
	(0.25–1.03)	(0.27–1.36)	(0.29–1.83)
Patient data (n = 37)	N/A	0.59 ± 0.15	0.68 ± 0.21‡
	N/A	(0.39–1.03)	(0.41–1.35)

*Data of Schöbel et al. (14). †Significant ($p < 0.05$) difference versus EOA_{Dop}; ‡Significant ($p < 0.05$) difference versus $EOA_{cath/max}$. Data are presented as the mean value ± SD (range) in cm².
EOA_{Dop} = EOA estimated by Doppler echocardiography; $EOA_{cath/max}$ = EOA estimated by catheter using the maximal pressure gradient; EOA_{cath} = EOA estimated by catheter using the net pressure gradient; N/A = nonavailable.

angiographic images in the middle part of the ascending aorta.

Data analysis. Data are expressed as the mean value ± SD. The EOA values obtained from different methods (EOA_{Dop}, $EOA_{cath/max}$, and EOA_{cath}) were compared within each data subset (in vitro, animals, and patients) using one-way analysis of variance for repeated measures. Statistical analysis of the association between variables was performed with the Pearson correlation coefficient, and graphs were constructed with the corresponding regression equation. Values of $p < 0.05$ were considered significant.

RESULTS

Table 1 presents the Doppler echocardiographic and catheter data obtained in vitro and in the animals, as well as the catheter data from the patients studied by Schöbel et al. (14). It should be noted that EOA_{Dop} was not available in the latter study. In the in vitro model and the animals, EOA_{Dop} was, on average, $24 \pm 17\%$ lower than the EOA_{cath} values ($p < 0.001$), whereas EOA_{Dop} and $EOA_{cath/max}$ were in close agreement and correlated strongly (in vitro data: $y = 1.12x - 0.09$, $r = 0.97$; animal data: $y = 1.06x + 0.03$, $r = 0.92$; all data: $y = 1.02x + 0.03$, $r = 0.98$) (Fig. 1). These experimental results confirm that $EOA_{cath/max}$ (EOA determined by a catheter using TPG_{max}) and EOA_{Dop} are equivalent parameters reflecting EOA at the vena contracta.

Figure 2 shows the relationship ($r = 0.97$) found between EOA_{cath} and EOA_{Dop}. For the patient data, $EOA_{cath/max}$ was substituted for EOA_{Dop}, as the latter was not available in the study of Schöbel (14). This substitution is nonetheless valid because, as shown in Figure 1, there is a strong agreement between $EOA_{cath/max}$ and EOA_{Dop}. Figure 2 confirms that EOA_{Dop} is systematically lower than EOA_{cath} (in vitro data: $y = 1.36x - 0.16$, $r = 0.96$; animal data: $y = 1.47x - 0.04$, $r = 0.81$; patient data: $y = 1.38x - 0.13$, $r = 0.95$; all data: $y = 1.26x - 0.02$, $r = 0.97$) (Fig. 2). The discrepancy between EOA_{Dop} and EOA_{cath} tended to be more important in animals than in patients; this may be due to the fact that pigs have relatively smaller aortas compared with humans.

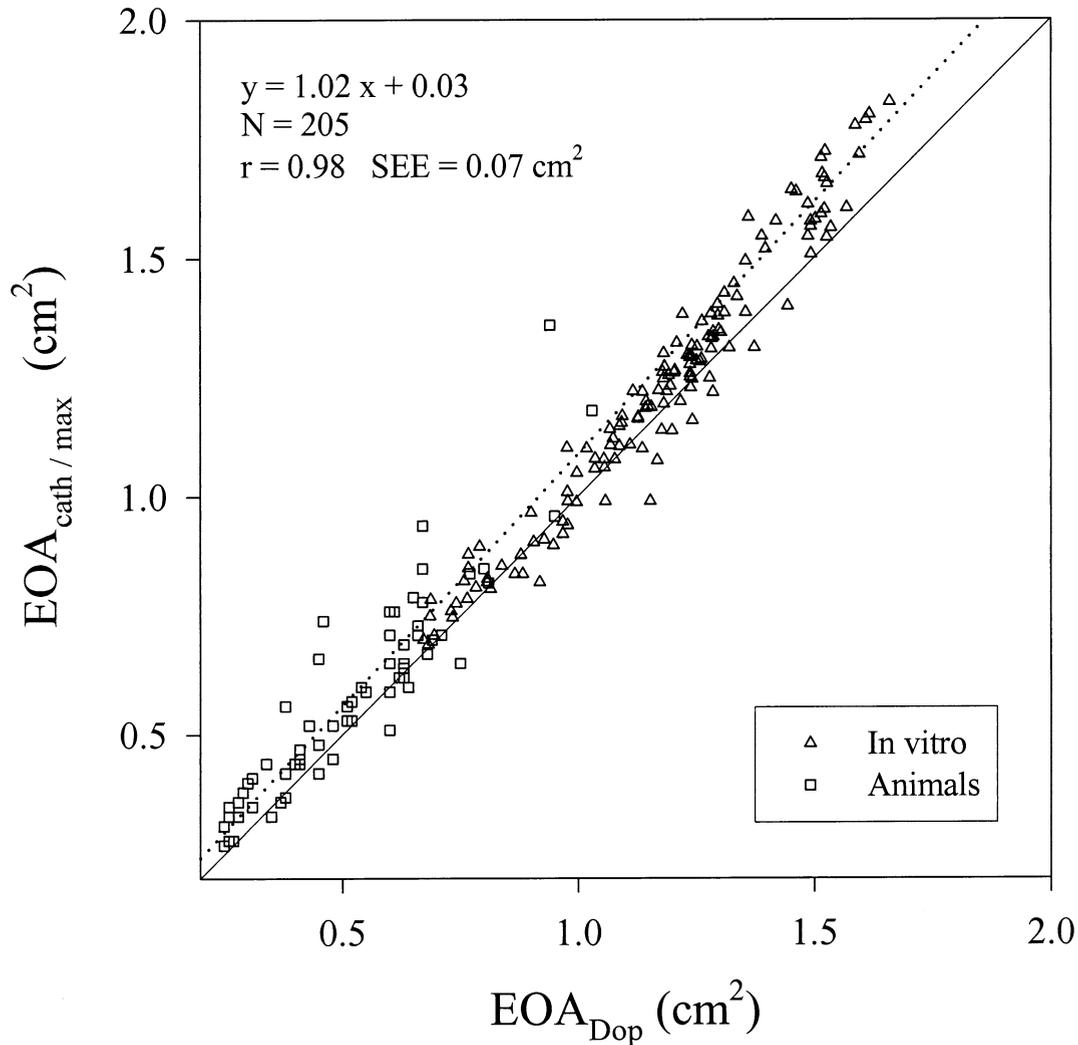Finally, Figure 3 shows that there is an excellent corre-

Figure 1. Relationship between valve effective orifice area (EOA) measured by a catheter using the maximal transvalvular pressure gradient ($EOA_{cath/max}$) and EOA measured by Doppler echocardiography (EOA_{Dop}). **Open triangles** and **open squares** represent in vitro (n = 172) and animal (n = 65) data, respectively. The **solid and dotted lines** represent the identity and regression lines, respectively. The regression line was constructed including the whole data set (in vitro and animal data). Several data points are superimposed.

lation and concordance (in vitro data: y = 0.93 + 0.10, r = 0.94; animal data: y = 0.87x + 0.12, r = 0.81; patient data: y = 1.15 − 0.04, r = 0.94; all data: y = 0.93x + 0.09, r = 0.97) between EOA_{cath} and ELCo and that, in contrast to EOA_{Dop}, ELCo does not systematically underestimate EOA_{cath}. This result thus confirms that EOA_{cath} can be accurately predicted from Doppler echocardiographic data by calculating ELCo using Equation 3.

DISCUSSION

Because it is less flow-dependent than pressure gradients, the valve EOA is one of the main parameters on which clinicians have relied to assess aortic stenosis severity (1). However, although some investigators have found a relatively good agreement between Doppler and catheter EOA measurements (4,5,20,21), others have reported important discrepancies, and in the latter studies, the catheter EOAs

were usually higher than the Doppler EOAs (9,22–27). Consistent with the latter studies, the present study also found catheter EOAs to be consistently higher than Doppler EOAs in the same individuals.

Moreover, the theoretical background shows that the systematic underestimation of EOA_{cath} by EOA_{Dop} is largely justified by the important following concepts: 1) EOA_{Dop} is derived from the maximal velocity of the jet and reflects the cross-sectional area of the vena contracta. As confirmed by the present study, $EOA_{cath/max}$ is a parameter equivalent to EOA_{Dop} that can also be used to estimate the area of the vena contracta. 2) The calculation of $EOA_{cath/max}$ requires the measurement of TPG_{max}, which is rarely performed during routine catheterization because of the difficulty in obtaining adequate pressure measurements within the vena contracta. The fact that EOA_{Dop} underestimates EOA_{cath} is therefore not surprising, because
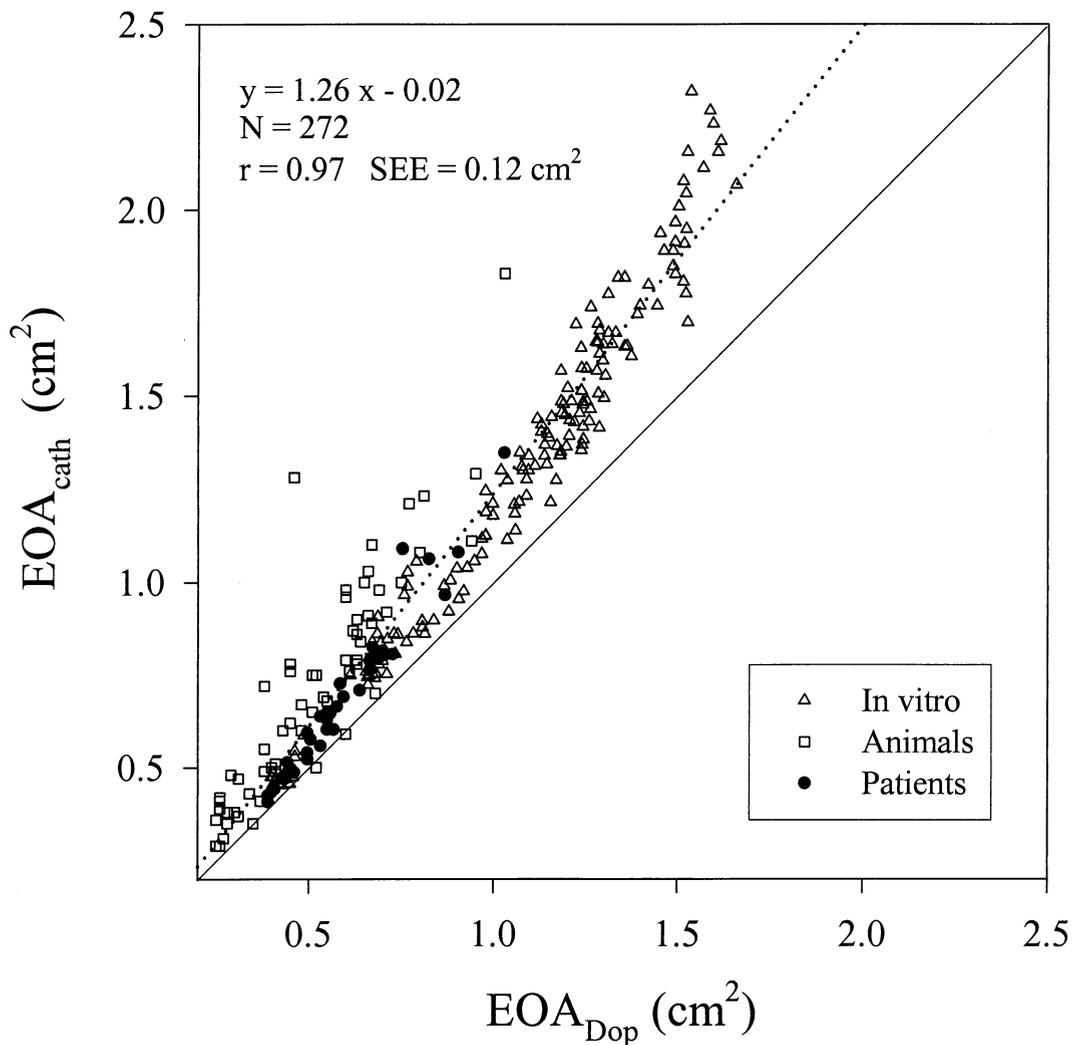
Figure 2. Relationship between valve effective orifice area (EOA) measured by a catheter using the net transvalvular pressure gradient (EOA_{cath}) and EOA measured by Doppler echocardiography (EOA_{Dop}) or, in the case of the data from Schöbel et al. (14), the EOA measured by a catheter using the maximal transvalvular pressure gradient ($EOA_{cath/max}$). **Open triangles, open squares, and closed circles** represent in vitro data (n = 172), animal data (n = 65), and data from Schöbel (n = 37), respectively. The **solid and dotted lines** represent the identity and regression lines, respectively. The regression line was constructed including the whole data set (in vitro, animal, and patient data).

EOA_{Dop} reflects the area at the vena contracta, whereas EOA_{cath} is derived from TPG_{net} recorded after pressure recovery and thus downstream of the vena contracta. 3) Given 1) and 2), EOA_{cath} will thus necessarily be higher than EOA_{Dop}, but in varying proportions depending on the size of the ascending aorta and the severity of the stenosis (12–16,28). 4) The discrepancies between EOA_{Dop} and EOA_{cath} can be reconciled by calculating ELCo from the echocardiogram. This parameter takes into account pressure recovery and, as shown by Equations 2 and 3, its formulation is very close to that of EOA_{cath}. 5) Neither EOA_{cath} nor ELCo represents the true EOA, but are rather dimensionless and relatively flow-independent indexes representing the relative loss of energy due to stenosis.

Our experimental results largely confirm these theoretical considerations. As shown in Figure 1, there is indeed a very good correlation and concordance between EOA_{Dop} and $EOA_{cath/max}$, as both parameters are a reflection of the cross-sectional area of the vena contracta. In contrast, EOA_{cath} overestimated both EOA_{Dop} and $EOA_{cath/max}$, but in varying proportions depending on the diameter of the aorta (Table 1). Finally, when ELCo was calculated from the echocardiogram to account for pressure recovery, there was an excellent agreement between EOA_{cath} and ELCo, and the aforementioned discrepancy between echocardiographic and catheter measurements was no longer present (Fig. 3). It should be noted that according to fluid mechanics considerations and previous in vivo studies (13,16,29), the diameter of the aorta used to calculate ELCo should be measured at the sino-tubular junction (i.e., at the site where pressure recovery is ongoing). Schöbel et al. (14) also proposed an equation that incorporates $EOA_{cath/max}$ and A_A to predict EOA_{cath}. Nonetheless, this equation is not readily applicable to reconcile the discrepancies between EOA_{cath} and EOA_{Dop}, as the latter was not measured in their study.

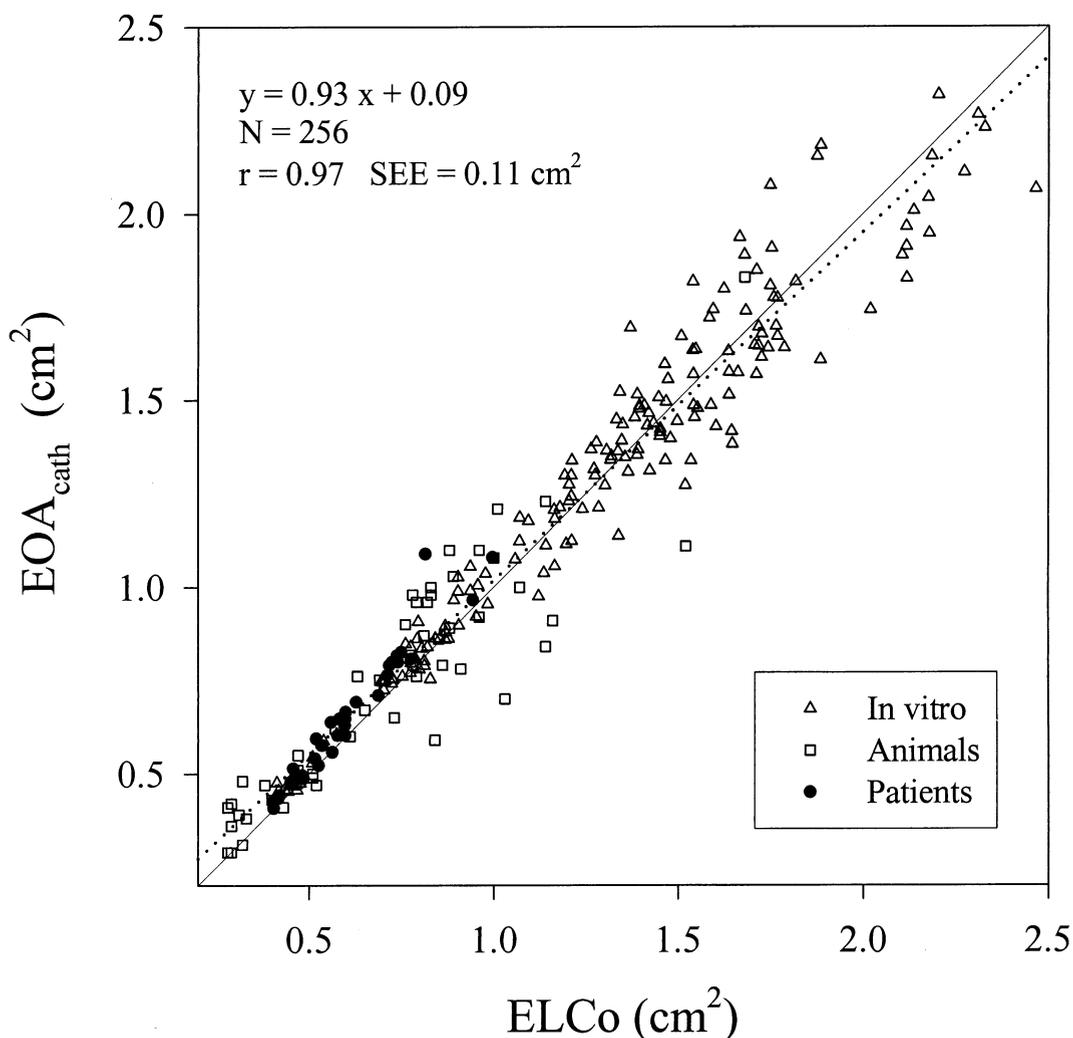The clinical implications of these findings are important

Figure 3. Relationship between valve effective orifice area (EOA) measured by a catheter using the net transvalvular pressure gradient (EOA$_{cath}$) and ELCo. A format similar to that of Figure 2 is used.

because they may have a direct implication with regard to the criteria used to quantify aortic stenosis severity. As mentioned, measurements of TPG$_{max}$ and EOA$_{cath/max}$ are rarely performed in the clinical setting because of the difficulty in obtaining adequate pressure measurements in the vena contracta, and the parameters routinely reported from catheter measurements are TPG$_{net}$ and EOA$_{cath}$. In this context, it should be emphasized that the ACC/AHA guidelines for defining aortic stenosis severity were established mainly based on data obtained from catheter measurements, as well as clinical outcomes in relation to these measurements (1,30–32). The same values for aortic stenosis severity (e.g., <1.0 cm^2) were then extended to the echocardiographic data on the assumption that EOA$_{Dop}$ and EOA$_{cath}$ were equivalent parameters, and indeed, the aforementioned guidelines do not distinguish between catheter and Doppler measurements.

A most important finding of this study is that the pressure recovery phenomenon may cause important dis-

crepancies between EOA$_{cath}$ and EOA$_{Dop}$, and that EOA$_{Dop}$ systematically tends to overestimate aortic stenosis severity, compared with EOA$_{cath}$. The practical implications of this finding are best evidenced by considering Table 2, where Equations 2 and 3 are used to calculate the theoretical values of EOA$_{Dop}$ for different values of EOA$_{cath}$ and aortic size. The range of aortic sizes used in this table is based on the study of Gjertsson et al. (29), performed in a large group of patients with aortic stenosis (range of aortic diameters at the sino-tubular junction 2.1 to 4.1 cm, mean 3.0 cm). As expected, the greatest discrepancies between EOA$_{cath}$ and EOA$_{Dop}$ are observed in patients with smaller aortas (diameter ≤3.0 cm), and when comparing Doppler and catheter EOAs in a given patient, it is therefore important to remember that these parameters are not equivalent and that discrepancies up to 50% may be observed depending on the size of the aorta and the severity of the stenosis. Overall, 10% (27/274) of the stenoses examined in the present study would have been classified as

Table 2. Theoretical Values of Doppler-Derived Effective Orifice Areas for Given Catheter-Derived Effective Orifice Areas and Aortic Diameters*

Catheter-Derived EOA (cm²)†	Doppler-Derived EOA (cm²)		
	Aortic Diameter = 2.0 cm (A_A = 3.14 cm²)	Aortic Diameter = 3.0 cm (A_A = 7.07 cm²)	Aortic Diameter = 4.0 cm (A_A = 12.6 cm²)
1.50 (1.69)	1.02	1.24	1.34
1.00 (1.13)	0.76	0.88	0.93
0.75 (0.85)	0.61	0.68	0.71
0.50 (0.56)	0.43	0.47	0.48

*These values were derived from Equations 2 and 3. †The EOA value in parentheses was calculated from the Gorlin equation with the use of a constant of 44.3.

EOA = effective orifice area; A_A = cross-sectional area of the aorta.

severe on the basis of EOA_{Dop} and moderate on the basis of EOA_{cath}. Of the 37 patients included in this study, three (8%) would have been misclassified. Furthermore, these discrepancies become even more important if one uses the Gorlin formula with a constant of 44.3, as routinely done in catheterization laboratories (Table 2). The present guidelines, based mostly on EOAs measured during catheterization, may therefore not be directly applicable to measurements made from EOA_{Dop} and may result in overestimations of severity, thus affecting clinical management.

From a practical standpoint, there would appear to be two options. One would be to use a different threshold of severity (e.g., EOA ≤0.75 cm²) when EOA is measured by Doppler echocardiography. However, the underestimation of EOA_{cath} by EOA_{Dop} will vary depending on the size of the aorta, and the large standard deviation (±17%) observed in this study suggests that it would not be appropriate to apply a single correction factor. The second alternative would be to use ELCo as the Doppler echocardiographic measurement of aortic stenosis severity. As shown in Figure 3, this would have the advantage of consistency with catheter measurements, and the present guidelines for severe aortic stenosis (EOA ≤1.0 cm²) could then be directly applicable to this parameter. From a conceptual standpoint, it should also be emphasized that ELCo and EOA_{cath} both reflect the net EL due to stenosis and, as such, are more representative of the increased burden imposed on the left ventricle, compared with EOA_{Dop} and $EOA_{cath/max}$. In contrast, uncorrected EOA_{Dop} has major disadvantages for clinical use because it does not account for differences in actual left ventricular burden, as the latter varies markedly depending on the magnitude of pressure recovery (10–16).

For these reasons, it would appear logical to use ELCo rather than EOA_{Dop} as the preferred echocardiographic parameter for quantifying aortic stenosis severity, in which case the severity criteria proposed in the ACC/AHA guidelines would become directly applicable (1). Also, as previously shown, ELCo can be indexed for the patient's body surface area to better account for differences in cardiac output requirements due to differences in body size (16). Previous studies are consistent in suggesting that an indexed

EOA_{cath} or EL index ≤0.55 to 0.60 cm²/m² is indicative of severe aortic stenosis (16,32).

Study limitations. An obvious limitation of this study is the absence of a gold standard method for the direct measurement of EOA at the vena contracta. Nonetheless, the strong agreement between the experimental results and the theoretical equations derived from fluid dynamics confirms the conceptual validity of our results and conclusions.

Ideally, it would also have been interesting to obtain simultaneous measurements of EOA_{Dop} and EOA_{cath} not only in vitro and in animals, but also in patients. However, the measurement of EOA_{cath} requires complete left- and right-heart catheterization, a procedure that is not without risk for the patient. Indeed, the most recent ACC/AHA guidelines recommend that this procedure should be performed only if there is a discrepancy between the clinical and echocardiographic evaluations of aortic stenosis severity (1). Hence, systematic performance of such a procedure in patients would have been difficult to justify from an ethical standpoint, and for this reason, we elected to use the data previously published by Schöbel et al. (14). The fact that these data were collected independently and agree well with our own results further validates the conclusions of the present study.

Conclusions. Discrepancies between catheter and Doppler measurements of EOA are largely due to the pressure recovery phenomenon and can be reconciled by calculating ELCo from the Doppler echocardiogram. Although EOA_{Dop} better represents the actual cross-sectional area of the vena contracta, ELCo and EOA measured from the catheter net gradient are equivalent indexes that primarily reflect the net EL due to stenosis rather than the EOA, per se. As such, the latter indexes better reflect the increased burden imposed by the stenosis upon the left ventricle and are probably the most appropriate for quantifying aortic stenosis severity.

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REFERENCES

1. Bonow RO, Carabello BA, de Leon AC Jr., et al. The ACC/AHA guidelines for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Committee on Management of Patients With Valvular Heart Disease). J Am Coll Cardiol 1998;32:1486–588.
2. 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.
3. Cannon SR, Richards KL, Crawford M. Hydraulic estimation of stenotic orifice area: a correction of the Gorlin formula. Circulation 1985;71:1170–8.
4. Skjaerpe T, Hegrenaes L, Hatle L. Noninvasive estimation of valve area in patients with aortic stenosis by Doppler ultrasound and two-dimensional echocardiography. Circulation 1985;72:810–8.
5. Otto CM, Pearlman AS, Comess KA, Reamer RP, Janko CL, Huntsman LL. Determination of the stenotic aortic valve area in adults using Doppler echocardiography. J Am Coll Cardiol 1986;7:509–17.
6. Otto CM. Echocardiographic evaluation of valvular heart disease. In: Otto C, editor. Valvular Heart Disease. Philadelphia, PA: W.B. Saunders, 1999:43–79.
7. Clark C. The fluid mechanics of aortic stenosis. I. Theory and steady flow experiments. J Biomechanics 1976;9:521–8.
8. Clark C. The fluid mechanics of aortic stenosis. II. Unsteady flow experiments. J Biomechanics 1976;9:567–73.
9. Levine RA, Jimoh A, Cape EG, McMillan S, Yoganathan AP, Weyman AE. Pressure recovery distal to a stenosis: potential cause of gradient 'overestimation' by Doppler echocardiography. J Am Coll Cardiol 1989;13:706–15.
10. Laskey WK, Kussmaul WG. Pressure recovery in aortic valve stenosis. Circulation 1994;89:116–21.
11. Voelker W, Reul H, Stelzer T, Schmidt A, Karsch KR. Pressure recovery in aortic stenosis: an in vitro study in a pulsatile flow model. J Am Coll Cardiol 1992;20:1585–93.
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;94:1934–40.
13. Baumgartner H, Steffenelli 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;33:1655–61.
14. Schöbel WA, Voelker W, Haase KK, Karsch KR. Extent, determinants and clinical importance of pressure recovery in patients with aortic valve stenosis. Eur Heart J 1999;20:1355–63.
15. Heinrich RS, Marcus RH, Ensley AE, Gibson DE, Yoganathan AP. Valve orifice area alone is an insufficient index of aortic stenosis severity: effects of the proximal and distal geometry on transaortic energy loss. J Heart Valve Dis 1999;8:509–15.
16. 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;101:765–71.
17. Dumesnil JG, Yoganathan AP. Theoretical and practical differences between the Gorlin formula and the continuity equation for calculating aortic and mitral valve areas. Am J Cardiol 1991;67:1268–72.
18. Durand LG, Garcia D, Sakr F, et al. A new flow model for Doppler ultrasound study of prosthetic heart valves. J Heart Valve Dis 1999;8:85–95.
19. Smith MD, Dawson PL, Elion JL, et al. Correlation of continuous wave Doppler velocities with cardiac catheterization gradients: an experimental model of aortic stenosis. J Am Coll Cardiol 1985;6:1306–14.
20. Foster GP, Weissman NJ, Picard MH, Fitzpatrick PJ, Shubrooks SM Jr., Zarich SW. Determination of aortic valve area in valvular aortic stenosis by direct measurement using intracardiac echocardiography: a comparison with the Gorlin and continuity equations. J Am Coll Cardiol 1996;27:392–8.
21. Come PC, Riley MF, McKay RG, Safian R. Echocardiographic assessment of aortic valve area in elderly patients with aortic stenosis and of changes in valve area after percutaneous balloon valvuloplasty. J Am Coll Cardiol 1987;10:115–24.
22. Danielsen R, Nordrehaug JE, Vik-Mo H. Factors affecting Doppler echocardiographic valve area assessment in aortic stenosis. Am J Cardiol 1989;63:1107–11.
23. Oh JK, Taliercio CP, Holmes DRJ, et al. Prediction of the severity of aortic stenosis by Doppler aortic valve area determination: prospective Doppler-catheterization correlation in 100 patients. J Am Coll Cardiol 1988;11:1227–34.
24. Kitabatake A, Fuji K, Tanouchi J, et al. Doppler echocardiographic quantitation of cross-sectional area under various hemodynamic conditions: an experimental validation in a canine model of supravalvular aortic stenosis. J Am Coll Cardiol 1990;15:1654–61.
25. Chambers JB, Sprigings DC, Cochrane T, et al. Continuity equation and Gorlin formula compared with directly observed orifice area in native and prosthetic aortic valves. Br Heart J 1992;67:193–9.
26. Wippermann CF, Schranz D, Stopfkuchen H, Huth R, Freund M, Jungst BK. Evaluation of the valve area underestimation by the continuity equation. Cardiology 1992;80:276–82.
27. Burwash IG, Thomas DD, Sadahiro M, et al. Dependence of Gorlin formula and continuity equation valve areas on transvalvular volume flow rate in valvular aortic stenosis. Circulation 1994;89:827–35.
28. Vandervoort PM, Greenberg NL, Pu M, Powell KA, Cosgrove DM, Thomas JD. Pressure recovery in bileaflet heart valve prostheses: localized high velocities and gradients in central and side orifices with implications for Doppler-catheter gradient relation in aortic and mitral position. Circulation 1995;92:3464–72.
29. Gjertsson P, Caidahl K, Svensson G, Wallentin I, Bech-Hanssen O. Important pressure recovery in patients with aortic stenosis and high Doppler gradients. Am J Cardiol 2001;88:139–44.
30. Turina J, Hess O, Sepulcri F, Krayenbuehl HP. Spontaneous course of aortic valve disease. Eur Heart J 1987;8:471–83.
31. Horstkotte D, Loogen F. The natural history of aortic valve stenosis. Eur Heart J 1988;9:57–64.
32. Rahimtoola SH. Perspective on valvular heart disease: an update. J Am Coll Cardiol 1989;14:1–23.