CVN Interview

ORIGINAL RESEARCH

Validation and Characterization of Transcatheter Aortic Valve Effective Orifice Area Measured by Doppler Echocardiography

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OBJECTIVES The objectives were to compare different Doppler echocardiographic methods for the measurement of prosthetic valve effective orifice area (EOA) following transcatheter aortic valve implantation (TAVI) and to determine the factors influencing the EOA of transcatheter balloon expandable valves.

BACKGROUND Previous studies have used different methods for the measurement of the valve EOA following TAVI. Factors influencing the EOA of transcatheter valves are unknown.

METHODS A total of 122 patients underwent TAVI with the use of the Edwards-SAPIEN valve (Edwards Lifesciences, Irvine, California). The EOA was measured by transthoracic echocardiography at hospital discharge, 6 months and 1 year after TAVI with the use of 2 methods as described in previous studies. In Method #1 (EOA_1), LVOT diameter (LVOTd) entered in the continuity equation was measured at the base of prosthesis cusps whereas, in Method #2 (EOA_2), LVOTd was measured immediately proximal to the prosthesis stent.

RESULTS The average EOA_2 (1.57 ± 0.41 cm^2) was larger ($p < 0.01$) than the EOA_1 (1.21 ± 0.38 cm^2). Accordingly, incidence of severe PPM (indexed EOA ≤ 0.65 cm^2/m^2) was 3-fold lower with the use of EOA_2 than with EOA_1 (9% vs. 33%; $p < 0.001$). Mean transprosthetic gradient correlated better ($p = 0.03$) with indexed EOA_2 ($r = -0.70$, $p < 0.0001$) than with indexed EOA_1 ($r = -0.58$, $p < 0.0001$). Intraobserver and interobserver variability were lower for EOA_2 compared to EOA_1 (intra: 5% vs. 7%, $p = 0.06$; inter: 6% vs. 14%; $p < 0.001$). Aortic annulus size was the sole independent determinant ($p = 0.01$) of prosthetic valve EOA_2. The average EOA varied from 1.37 ± 0.23 cm^2 for aortic annulus size <19 mm up to 1.90 ± 0.17 cm^2 for size >23 mm.

CONCLUSIONS When estimating the EOA of Edwards-SAPIEN valves by Doppler-echocardiography, it is recommended to use the LVOT diameter and velocity measured immediately proximal to the stent. The main determinant of the EOA of transcatheter valves is the patient's annulus size and these valves provide excellent hemodynamics even in patients with a small aortic annulus. (J Am Coll Cardiol Img 2011;4:1053–62) © 2011 by the American College of Cardiology Foundation

Transcatheter aortic valve implantation (TAVI) has emerged as an alternative to standard aortic valve replacement (AVR) in high-risk patients with severe aortic stenosis. The aortic valve effective orifice (EOA) is one of the main Doppler echocardiographic index utilized to characterize the hemodynamic performance of prosthetic valves and to identify the presence of prosthesis–patient mismatch (1,2). Accurate esti-

mation of the EOA is also crucial for the post-procedural follow-up of valve function and for the detection of prosthesis stenosis. The design of TAVI prosthetic valves is markedly different from that of surgical prostheses. In particular, the stent of TAVI valves is longer, and its proximal portion extends deeper into the left ventricular outflow tract (LVOT), whereas with sur-gical prostheses, it is located at the level of the aortic annulus (intra-annular implan-tation) or at the level of the Valsalva sinuses (supra-annular implantation). It remains unknown whether these differ-ences in valve design alter the accuracy of the Doppler echocardiographic estimation of the prosthetic valve EOA following TAVI. Moreover, pre- or periprocedural factors influencing the EOA of transcath-eter valves remain unknown.

The calculation of the EOA with the use of the continuity equation requires the measurement of 3 variables: the LVOT diameter and the LVOT and transprosthetic flow velocities. In previ-ous studies, 2 methods have been used to estimate the EOA of TAVI prostheses: some investigators have used the LVOT diameter measured at the base of the prosthetic valve leaflets, whereas others used the diameter measured just proximal to the prosthesis stent (3–6).

The first objective of this study was to compare the accuracy and reliability of these 2 methods for the measurement of EOA following TAVI. The sec-ond objective was to identify the factors determin-ing the EOA of transcatheter balloon-expandable valves.

METHODS

A total of 122 patients diagnosed with symptomatic severe aortic stenosis who underwent TAVI with the Edwards-SAPIEN valve (Edwards Life-sciences, Irvine, California) at the Québec Heart & Lung Institute were included in this study. TAVI was approved under the compassionate clinical use program approved by the Canadian Department of Health and Welfare (Ottawa, Ontario, Canada) for patients with symptomatic severe AS considered either nonoperable or very high-risk surgical candi-dates. All patients provided signed informed con-sent for the procedures.

Based on transesophageal echocardiographic (TEE) measurements of the aortic valve annulus, the 23-mm valve was implanted if the annulus was between 17 and 21 mm, and the 26-mm valve was implanted if the aortic annulus measured between 22 and 25 mm. A total of 63 patients (52%) received the 23-mm valve, and 59 patients (48%) received the 26-mm valve. All clinical, echocardio-graphic, procedural, and post-procedural data were prospectively collected.

Doppler echocardiography. Patients underwent a complete transthoracic echocardiography before the procedure, and early (pre-discharge exam), 6 months, and 1 year after the procedure. The transvalvular gradients were measured with the use of the Bernoulli formula, and the post-procedural EOA was determined by the continu-ity equation using 2 methods. In Method #1 (EOA_1), the LVOT diameter entered in the continuity equation was measured at the base of the prosthetic valve leaflets ($LVOTd_1$); whereas in Method #2 (EOA_2), the LVOT diameter was mea-sured immediately proximal to the prosthesis stent ($LVOTd_2$) (Figs. 1A and 1B):

$$EOA_1 = \pi \times \left(\frac{LVOTd_1}{2} \right)^2 \times \frac{VTI_{LVOT}}{VTI_{A_o}}$$

$$EOA_2 = \pi \times \left(\frac{LVOTd_2}{2} \right)^2 \times \frac{VTI_{LVOT}}{VTI_{A_o}}$$

where VTI_{LVOT} and VTI_{AO} are the velocity time-integrals of the LVOT and transprosthetic flow, respectively. To avoid the region of subvalvular acceleration, the pulsed-wave Doppler sample volume was positioned at 0.5 to 1.0 cm below the insertion of the bioprosthetic valve leaflets, i.e., immediately proximal to the prosthesis stent.

We measured the energy loss coefficient (ELC) to take into account the pressure recovery phenom-
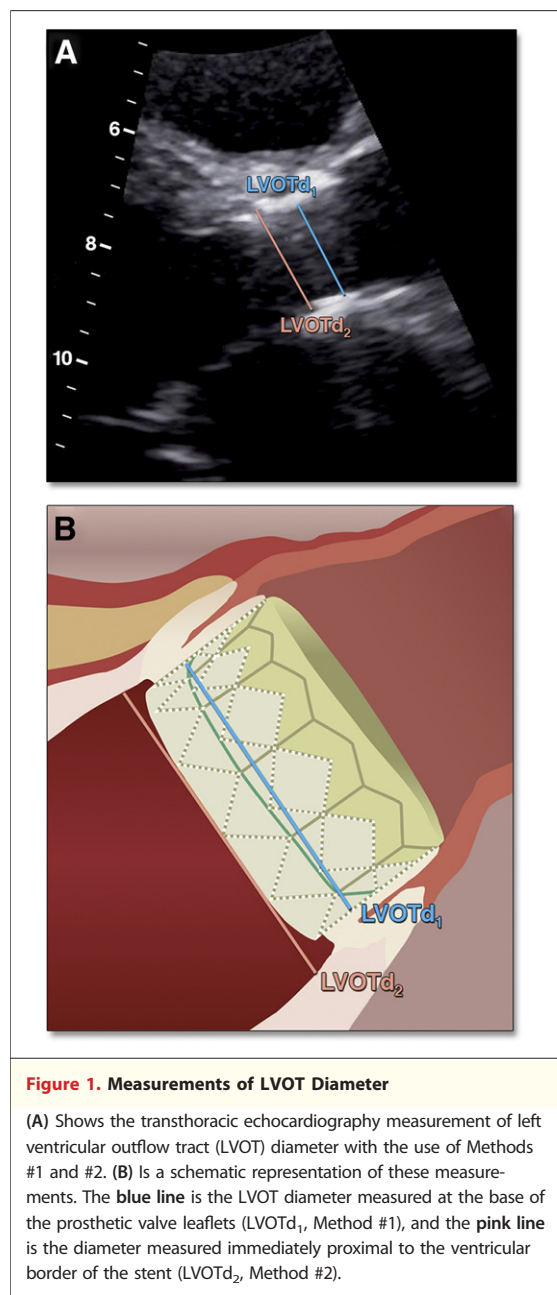
Figure 1. Measurements of LVOT Diameter

(A) Shows the transthoracic echocardiography measurement of left ventricular outflow tract (LVOT) diameter with the use of Methods #1 and #2. (B) Is a schematic representation of these measurements. The **blue line** is the LVOT diameter measured at the base of the prosthetic valve leaflets ($LVOTd_1$, Method #1), and the **pink line** is the diameter measured immediately proximal to the ventricular border of the stent ($LVOTd_2$, Method #2).

enon that may occur downstream of the valve in patients with small aortic diameters (7):

$$ELC_1 = \frac{EOA_1 \times AA}{AA - EOA_1}$$

$$ELC_2 = \frac{EOA_2 \times AA}{AA - EOA_2}$$

where AA is the aortic cross-sectional area (in square centimeters) measured approximately 1 cm downstream of the sinotubular junction.

We also calculated the Doppler velocity index:

$$DVI = \frac{VTI_{LVOT}}{VTI_{Ao}}$$

Twenty-six patients were randomly selected and measurements of EOA were repeated in these patients by 2 independent observers. The intraobserver and interobserver measurement variability was calculated. The prosthetic valve EOAs were indexed for body surface area. Moderate and severe prosthesis–patient mismatch (PPM) were defined as an indexed EOA ≤ 0.85 and ≤ 0.65 cm^2/m^2, respectively (1).

Subanalysis in patients with normal flow rate. To validate the measurements of EOA obtained by Methods #1 and #2, we examined the relationship between mean transprosthetic gradient and the EOA indexed for body surface area. However, it has been shown that an important proportion of patients with severe aortic stenosis have reduced stroke volume, and thus low transvalvular flow rate, and this situation may occur in patients with low left ventricular (LV) ejection fraction as well as in those with preserved LV ejection fraction (8–10). In low flow–state conditions, the gradient may be pseudo-normalized and the EOA may be pseudo-severized, which may alter the relationship between EOA and gradient (8–10). So, to validate the methods used for EOA measurement, we performed a subanalysis of the Doppler echocardiographic data in the subset of patients with stroke volume index >35 ml/m^2 (9).

Statistical analysis. Results are expressed as mean $\pm$ SD or percentages unless otherwise specified. Changes in Doppler echocardiographic variables during post-procedural follow-up were analyzed with the use of a 1-way analysis of variance for repeated measures followed by a Tukey post hoc test. Correlation and agreement between variables were determined with the use of the Pearson correlation and Bland-Altman (11) methods, respectively. Correlation coefficients were compared using the Wolfe test. Intraobserver and interobserver variability between methods of measurement were calculated by dividing the absolute value of the difference between the 2 measurements by the average value of the measurements, and analyzed with the use of the 2-sided paired Student t test. Relationship between indexed EOA and mean gradient was assessed with multiple nonlinear regression models, and the equation providing the best fit was retained. Individual and multivariable

Table 1. Baseline Clinical and Procedural Characteristics

Age, yrs	80 ± 8
Male	56 (46)
Body surface area, m^2	1.71 ± 0.22
Obesity	22 (18)
NYHA functional class III to V	114 (93)
Diabetes	35 (29)
Dyslipidemia	100 (82)
Hypertension	115 (94)
Chronic obstructive pulmonary disease	47 (39)
Coronary artery disease	90 (74)
Previous myocardial infarction	58 (48)
Society of Thoracic Surgeons score, %	9.0 ± 6.3
Logistic EuroSCORE, %	24.0 ± 15.6
Left ventricular ejection fraction, %	53 ± 15

Values are mean ± SD or n (%).
EuroSCORE = European System for Cardiac Operative Risk Evaluation;
NYHA = New York Heart Association.

linear regression analyses were used to identify the variables associated with prosthetic valve EOA. Given that multiple measurements per patient were included in the correlation, regression, and Bland-Altman analyses, the significance testes were adjusted with the use of Dunn/Sidak correction. A p value <0.05 was considered statistically significant. The statistical analyses were performed with the JPM version 8.01 (SAS Institute, Cary, North Carolina) and Table Curve version 5.01 (curve-fitting analyses, Systat Software, Chicago, Illinois) software programs.

RESULTS

Baseline characteristics of the 122 patients included in the study are presented in Table 1. Mean follow-up time was 11 ± 10 months. Thirty (25%) patients died during follow-up. After TAVI, mild and moderate prosthetic valve regurgitation was present in 14% and 5% of patients, respectively. The severity of regurgitation remained stable during follow-up.

Tables 2 and 3 show the Doppler echocardiographic data at baseline and at the post-TAVI follow-up time points for the whole cohort and for the subset of patients who had a complete (up to 1 year) Doppler echocardiographic follow-up, respectively.

Comparison of the 2 methods for the estimation of valve EOA. Figure 2 shows the Bland-Altman plot comparing values of EOAs obtained by Method #1 versus Method #2. The average EOA obtained by Method #2 was larger than the EOA obtained by Method #1 ($EOA_2 = 1.57 \pm 0.41$ cm^2 vs. $EOA_1 = 1.21 \pm 0.38$ cm^2; p < 0.01). This difference was due to the much smaller LVOT diameter measured by Method #1 versus Method #2 ($LVOTd_2 = 22.1 \pm 1.7$ mm vs. $LVOTd_1 = 19.3 \pm 1.6$ mm; p < 0.001). Accordingly, the incidence of severe PPM was 3-fold lower with the use of EOA_2 than EOA_1: 9% vs. 33%. The ELC was also significantly lower when calculated with EOA_1 versus EOA_2 ($ELC_1 = 1.50 \pm 0.64$ cm^2 vs. $ELC_2 = 2.03 \pm 0.77$; p < 0.001). There was a borderline significant decrease in EOA_1 during follow-up (p = 0.05), whereas EOA_2 remained stable (p = 0.46) (Table 3). The peak and mean gradients and the Doppler velocity index also remained unchanged during follow-up. Interobserver and intraobserver variability were lower for $LVOTd_2$ than $LVOTd_1$ (intra: 3 ± 3% vs. 7 ± 10%, p = 0.02; inter: 4 ± 3% vs. 8 ± 9%;

Table 2. Baseline and Follow-Up Doppler Echocardiographic Data in the Whole Cohort

	Pre-Procedural (n = 122)	Early Post-Procedural (n = 118)	6-Month Post-Procedural (n = 63)	1-Year Post-Procedural (n = 47)
Gradient, mm HG				
Peak gradient	64 ± 25	21 ± 9	18 ± 8	18 ± 8
Mean gradient	39 ± 16	11 ± 5	10 ± 4	10 ± 4
LVOTd, mm				
$LVOTd_1$	20.3 ± 1.9	19.4 ± 1.7	19.4 ± 1.7	19.0 ± 1.6
$LVOTd_2$	21.0 ± 2.4	22.2 ± 1.6	22.0 ± 1.8	21.7 ± 1.7
EOA, cm^2				
EOA_1	0.62 ± 0.20	1.21 ± 0.43	1.25 ± 0.34	1.15 ± 0.28
EOA_2	0.69 ± 0.22	1.57 ± 0.46	1.60 ± 0.37	1.52 ± 0.36
ELC, cm^2				
ELC_1	0.67 ± 0.23	1.61 ± 0.55	1.57 ± 0.58	1.42 ± 0.60
ELC_2	0.74 ± 0.27	2.09 ± 0.56	2.05 ± 0.65	1.93 ± 0.60
Doppler velocity index	0.19 ± 0.05	0.41 ± 0.12	0.42 ± 0.08	0.41 ± 0.08

ELC = energy loss coefficient; EOA = effective orifice area; LVOTd = left ventricular outflow tract diameter.

Table 3. Baseline and Follow-Up Echocardiographic Data for Patients (n = 47) With Complete Doppler Echocardiographic Follow-Up

	Pre-Procedural (n = 47)	Early Post-Procedural (n = 47)	6-Month Post-procedural (n = 47)	1-Year Post-Procedural (n = 47)	p Value
Gradient, mm Hg					
Peak gradient	67 ± 21	19 ± 7	18 ± 6	19 ± 8	0.78
Mean gradient	41 ± 14	10 ± 4	10 ± 3	10 ± 4	0.46
LVOTd, mm					
LVOTd$_1$	20.1 ± 1.6	19.5 ± 1.3	19.4 ± 1.7	19.0 ± 1.6	0.04
LVOTd$_2$	20.7 ± 2.3	21.8 ± 1.5	21.7 ± 1.7	21.7 ± 1.7	0.32
EOA, cm^2					
EOA$_1$	0.62 ± 0.14	1.28 ± 0.38	1.26 ± 0.37	1.14 ± 0.28	0.05
EOA$_2$	0.67 ± 0.17	1.60 ± 0.40	1.56 ± 0.39	1.53 ± 0.36	0.46
ELC, cm^2					
ELC$_1$	0.71 ± 0.16	1.55 ± 0.51	1.54 ± 0.55	1.40 ± 0.39	0.12
ELC$_2$	0.76 ± 0.21	2.06 ± 0.55	2.04 ± 0.61	1.95 ± 0.57	0.44
Doppler velocity index	0.20 ± 0.05	0.43 ± 0.12	0.42 ± 0.08	0.41 ± 0.08	0.57

The p value is for the analysis of variance for repeated measures that included only the post-procedural data. The data of the native valve Doppler echocardiographic data were excluded from this analysis.

Abbreviations as in Table 2.

$p < 0.001$) and for EOA$_2$ than for EOA$_1$ (intra: $5 \pm 5\%$ vs. $7 \pm 14\%$, $p = 0.06$; inter: $6 \pm 6\%$ vs. $14 \pm 15\%$; $p < 0.001$) (Fig. 3).

Relationship between EOA and gradients in patients with normal flow rate. In a subanalysis that included only the data from patients with a stroke volume index >35 ml/m^2, mean transprosthetic gradient correlated better ($p = 0.03$) with indexed EOA$_2$ ($r = -0.70$, $p < 0.0001$) than with indexed EOA$_1$ ($r = -0.58$, $p < 0.0001$) (Fig. 4).

Determinants of transcatheter valve EOA. WHOLE COHORT. The variables that correlated with prosthetic valve EOA$_2$ in the whole cohort were: male gender ($r = 0.42$; $p = 0.0001$), body surface area ($r = 0.31$; $p = 0.006$), baseline native valve EOA ($r = 0.29$; $p = 0.02$), stroke volume index ($r = 0.30$; $p = 0.02$), aortic annulus size measured by TEE ($r = 0.45$; $p < 0.0001$), and prosthesis size ($r = 0.43$; $p < 0.0001$). On multivariable annulus size ($r = 0.37$; $p = 0.004$) and baseline stroke volume index ($r = 0.25$; $p = 0.04$) remained independent predictors of EOA$_2$.

SUBSET OF PATIENTS WITH NORMAL FLOW RATE. In patients with a stroke volume index >35 ml/m^2, the variables that correlated with prosthetic valve EOA$_2$ were: body surface area ($r = 0.34$, $p = 0.006$), baseline native valve EOA ($r = 0.26$, $p = 0.03$), stroke volume index ($r = 0.23$, $p = 0.04$), aortic annulus size ($r = 0.46$, $p < 0.0001$), and prosthesis size ($r = 0.38$, $p < 0.0001$). In multivariable analysis, only aortic annulus size was associated with prosthetic

valve EOA$_2$ ($r = 0.43$, $p = 0.01$). Table 4 shows the values of EOA$_2$ for the different subclasses of annulus size in patients with normal flow rate.

Incidence of prosthesis–patient mismatch. The average aortic annulus size measured by TEE at the time of TAVI was 21 ± 2 mm, and 50% of patients had an annulus size ≤21 mm. The incidence of moderate and severe PPM estimated with the use of indexed EOA$_2$ was 20% and 9%, respectively, in the whole cohort and 18% and 6% in the subset of patients with normal stroke volume index. The incidence of severe PPM in the whole cohort was higher in patients with an
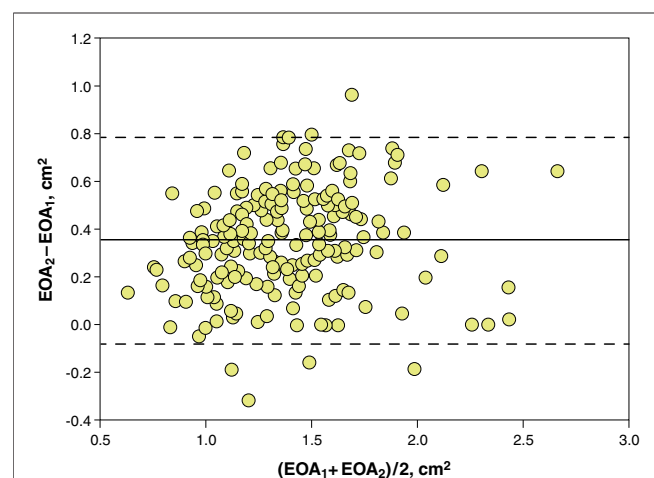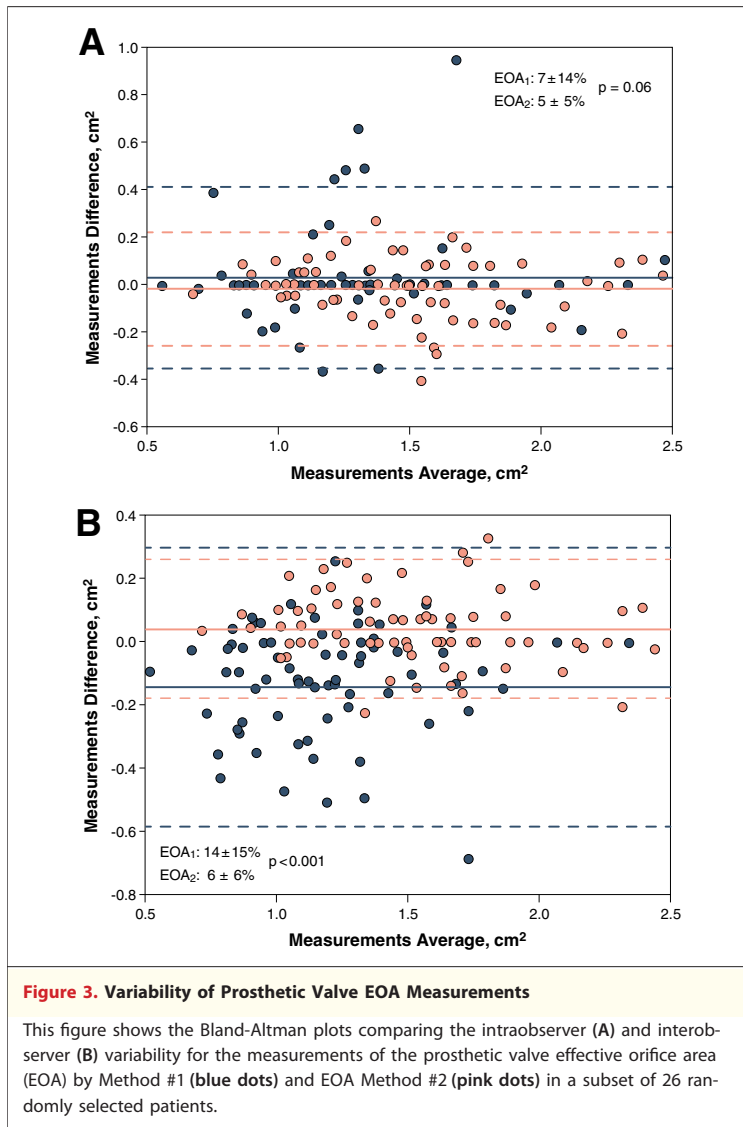

Figure 2. Agreement Between the 2 Methods for Estimation of Valve Area

This graph shows the Bland-Altman plot comparing Method #1 and #2 for the estimation of the prosthetic valve effective orifice area (EOA).

Figure 3. Variability of Prosthetic Valve EOA Measurements

This figure shows the Bland-Altman plots comparing the intraobserver **(A)** and interobserver **(B)** variability for the measurements of the prosthetic valve effective orifice area (EOA) by Method #1 **(blue dots)** and EOA Method #2 **(pink dots)** in a subset of 26 randomly selected patients.

annulus size ≤21 mm (14%) compared with those with larger annulus (4%) (Fig. 5).

DISCUSSION

The main findings of this study are:

1. When estimating the EOA of transcatheter balloon expandable valves by the continuity equation method, it is recommended to use the LVOT diameter and velocity measured immediately proximal to the stent.
2. The EOA obtained by this method correlates better with transprosthetic gradient and has lower intraobserver and interobserver measurement variability.

3. The main determinant of the EOA of transcatheter valves is the size of the patient's annulus.
4. In this high-risk population with a high proportion of patients with small aortic annulus, transcatheter bioprostheses provided an excellent hemodynamic performance, and the incidence of severe prosthesis–patient mismatch was low.

Method for the measurement of the EOA of transcatheter valves. There have been some discrepancies among previous studies with regard to the method used for the measurement of the EOA in native aortic valve stenosis. The method described originally (12,13) and used in numerous articles and textbooks (14,15) was Method #1, where the LVOT diameter is measured at the base of the aortic valve cusps and the pulsed-wave Doppler sample volume is positioned in the center of the LVOT 0.5 to 1.0 cm below the aortic annulus. However, in the most recent recommendations of the American Society of Echocardiography/ European Association of Echocardiography published in 2009 for the echocardiographic assessment of native valve stenosis (16), the authors recommended measuring both the LVOT diameter and the LVOT velocity at 0.5 to 1.0 cm below the aortic valve annulus. In the 2009 American Society of Echocardiography guidelines for the Doppler-echocardiographic assessment of prosthetic valve function, it is recommended to measure the LVOT diameter just beneath the prosthesis sewing ring (2).

For the measurement of the EOA of TAVI valves, some investigators (4) have applied Method #1 (i.e., LVOT measured within the stent at the base of bioprosthetic valve leaflets), whereas other investigators (5,6) have applied Method #2 (i.e., LVOT measured just proximal to the stent). In addition, most of the investigators have not described the method used to determine the EOA of transcatheter valves (17–20). The results of the present study suggest that Method #2 provides a more accurate and reliable estimate of valve EOA following TAVI. The higher intraobserver and interobserver variability of Method #1 compared with Method #2 is most likely related to the fact that precise identification of the base of the bioprosthetic cusps is often difficult because of the reverberations and acoustic shadowing created by the prosthesis stent and by the calcification of the native aortic valve and annulus. Conversely with Method #2, the proximal (i.e., ventricular) border of the stent provides more precise and reproducible anatomic landmarks to posi-

tion the measurements of LVOT diameter and velocity at serial Doppler echocardiographic exams during follow-up. As expected, the LVOT diameter measured with Method #2 was larger than the LVOT diameter measured with Method #1 because the former includes the stent, whereas the later excludes it (Fig. 1). Nonetheless, the LVOT diameter measured immediately proximal to the stent (Method #2) is likely more appropriate for the estimation of stroke volume and EOA because, in the case of transcatheter balloon-expandable valves, it is measured at about the same location of velocity sampling. In balloon-expandable valves, the apical ventricular border of the stent is indeed close ($\sim$5 mm) to the base of the bioprosthetic valve leaflets, and the flow is thus often accelerated within the proximal portion of the stent. The pulsed-wave Doppler sample should thus be positioned just proximal to the prosthesis stent to avoid this in-stent subvalvular flow acceleration.

The LVOT diameter and thus the EOA calculated by Method #1 decreased during follow-up, whereas those measured by Method #2 remained stable. This finding may be, at least in part, related to the higher variability of $LVOTd_1$ measurement. It is also possible that, following TAVI, there is some recoil phenomenon at the level of the native aortic annulus (approximate location of $LVOTd_1$ measurement), where the radial forces applied on the stent are likely more important. This phenomenon would not occur, or would occur to a lesser extent, beneath the native annulus (location of $LVOTd_2$ measurement). Fibrocalcific remodeling may also develop around the prosthesis stent after TAVI, thereby increasing the reverberations and acoustic shadowing over the region of bioprosthetic valve cusps at late follow-up. This phenomenon may have contributed to more pronounced under-estimation of LVOT diameter at 1-year follow-up. **Determinants of transcatheter valve EOA.** In patients with surgical prostheses, there is a relatively good correlation between the label valve size and the EOA for a given model of prosthesis (1). In the present study, there was only a weak correlation between TAVI prosthesis size and valve EOA, and the sole independent determinant of the EOA was the patient's annulus diameter. As opposed to surgical prostheses, the TAVI prostheses are deployed within the aortic annulus, and the same size of prosthesis is used for a relatively wide range of annulus size: e.g., the 23-mm Edwards-SAPIEN valve is used for annulus sizes ranging from 17 to 21 mm, and the 26-mm valve is used for annulus size
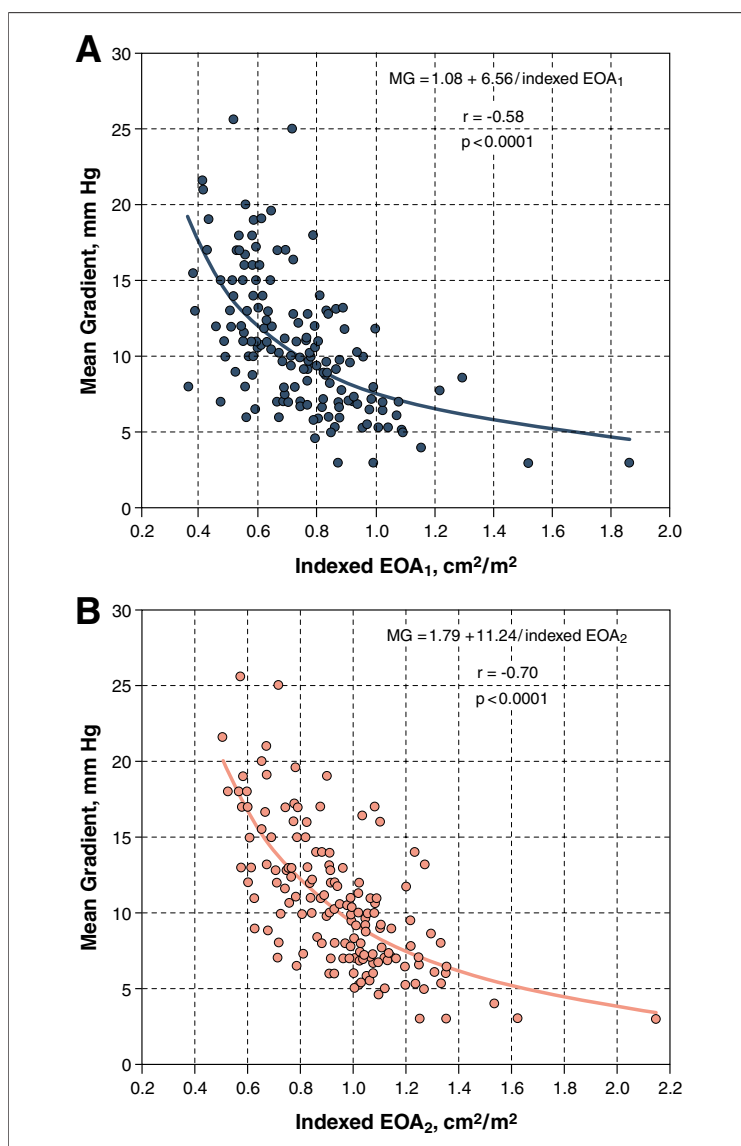

Figure 4. Correlations Between Mean Pressure Gradient and Indexed EOA

This figure shows the correlation between mean transprosthetic gradient and indexed effective orifice area (EOA) in the subset of patients (n = 84) with a stroke volume index >35 ml/m². In **A,** EOA was measured by Method #1, and in **B,** it was measured by Method #2.

of 22 to 25 mm. The main factor limiting the full expansion of the valve, and thus the EOA, is the size of the patient's aortic annulus. As a matter of fact, the average EOA of the 23-mm valve was 1.37 ± 0.23 cm² for annulus size <19 mm versus 1.57 ± 0.34 cm² for 21-mm annulus size, whereas the average EOA of the 26-mm valve was 1.61 ± 0.17 cm² for 22-mm annulus size versus 1.90 ± 0.17 cm² for annulus size >23 mm (Table 4).

Nonetheless, even after accounting for the prosthesis size, the patient's annulus diameter, and the flow

Table 4. Hemodynamic Parameters of the Edwards-SAPIEN Bioprosthesis in the Subset of Patients (n = 84) With Stoke Volume Index >35 ml/m²

	n	Valve EOA* (cm²)	Mean Gradient (mm Hg)	Doppler Velocity Index
Patient annulus size (measured by TEE)				
<19	9	1.37 ± 0.23	12 ± 4	0.41 ± 0.09
19	10	1.46 ± 0.33	11 ± 3	0.41 ± 0.08
20	14	1.48 ± 0.29	11 ± 3	0.41 ± 0.08
21	15	1.57 ± 0.34	12 ± 6	0.45 ± 0.14
22	12	1.61 ± 0.17	10 ± 3	0.38 ± 0.07
23	16	1.82 ± 0.27	10 ± 4	0.43 ± 0.06
>23	8	1.90 ± 0.17	10 ± 4	0.41 ± 0.05
Valve size				
23 mm	48	1.51 ± 0.30	11 ± 4	0.43 ± 0.10
26 mm	36	1.74 ± 0.26	11 ± 4	0.41 ± 0.07

Values are mean ± SD. *The EOA was measured by Method #2.
EOA = effective orifice area; TEE = transesophageal echocardiography.

rate, a large part of the EOA variance remains unexplained, thus suggesting that other factors may be involved. The amount and distribution of calcium within the valve and annulus as well as the position of the prosthesis relative to the aortic annulus are among the other factors that could contribute to the variance of the EOA of TAVI valves. In this regard, Jilaihawi (4) reported that the valve positioning may influence the valve EOA, and thus the occurrence of PPM, after TAVI with the CoreValve prosthesis (Medtronic, Minneapolis, Minnesota).

Hemodynamic performance of TAVI valves and incidence of prosthesis–patient mismatch. The results of this study suggest that the transcatheter prosthetic valves have an excellent hemodynamic performance in terms of EOA and gradients. Because TAVI is performed in a selected group of patients who are considered to be inoperable or at high risk for AVR, the proportion of patients with a small aortic annulus is very high in this series and a much larger proportion than what is generally reported in surgical series (21–23). Despite this unfavorable anatomic profile, the transcatheter valves provided an excellent hemodynamic performance and were thereby associated with a low incidence of severe PPM. There are currently no published data regarding the impact of PPM on clinical outcomes following TAVI. However, several studies suggest that PPM, and especially severe PPM, may have a detrimental impact on outcomes after surgical valve replacement, particularly in patients with depressed systolic function or severe LV hypertrophy (1).

In a previous case-match study including 50 patients with TAVI, we reported that the EOAs and gradients are better in transcatheter valves than in surgical stented or stentless bioprostheses and that, accordingly, the incidence of severe PPM is lower in transcatheter (6%) than in surgical prostheses (stented: 28%, stentless: 20%) (5). Potential mechanisms that could explain the superior hemodynamic performance of transcatheter valves include the lower profile of the
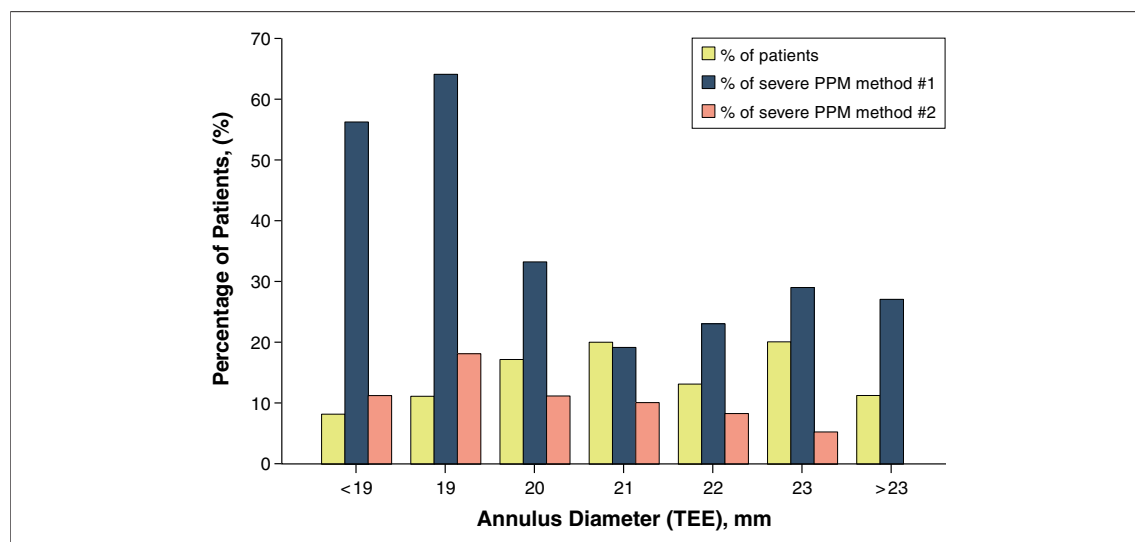
Figure 5. Incidence of Severe PPM According to Aortic Annulus Size

This figure shows the incidence of severe prosthesis–patient mismatch (PPM) as a function of aortic annulus diameter measured by transesophageal echocardiography (TEE) at the time of the procedure. The **yellow bars** represent the percentage of patients of the whole cohort for each annulus size category. The **blue bars** (Method #1) and **pink bars** (Method #2) represent the percentages of patients of each annulus size category who have severe PPM.

stent compared with that of surgical prostheses, the slight expansion of the aortic annulus during TAVI, and the funnel shape of the valve inflow that may contribute to minimize flow contraction.

The incidences of moderate (20%) and severe (9%) PPM reported in the present study with the Edwards-SAPIEN valve are similar to what has been reported by Jilaihawi et al. (4) (moderate 32%, severe 2%) (4) and Tzikas et al. (6) (moderate 23%, severe 16%) for the CoreValve prosthesis. However, the results of these studies are difficult to compare given that, as a result of the differences in sizing between these 2 valve models, the average patient's annulus diameter was smaller in the present series with Edwards-SAPIEN (21 ± 2 mm) than in the previous series with CoreValve (Jilaihawi et al. [4]: 23 ± 2 mm; Tzikas et al. [6]: 22 ± 2 mm). Further studies with case-match or randomized design are necessary to compare the hemodynamic and clinical performance of these 2 models of transcatheter prostheses. In the series of patients who underwent surgical AVR (1,21–23), the incidence of severe PPM in the subset of patients with a small aortic annulus (≤21 mm) was between 20% and 80%, whereas in the present series with TAVI, it was 14%. In light of these findings, TAVI appears an interesting alternative to surgical AVR for patients with a small aortic annulus.

Study limitations. An important proportion of patients undergoing TAVI have prosthetic valve regurgitation. Accordingly, in the present study, 19% of patients had mild or moderate valve regurgitation. However, the presence of valve regurgitation does not affect the measurement of EOA of aortic prosthetic valves.

In the present series, we used the aortic annulus size measured by TEE to select valve size, and this parameter was found to be the most important independent determinant of EOA. However, TEE may underestimate the size of aortic annulus because the latter is often oval, and TEE generally measures the smaller diameter. Some investigators have thus suggested that multislice computed tomography may be superior to TEE for accurate measurement of aortic annulus size (24).

In the present study, we present the 1-year Doppler echocardiographic follow-up. A recent study from Gurvitch et al. (17) that included 70 patients of whom 37 reached 3-year follow-up,

reported a slight deterioration in EOAs and gradients of Edwards-SAPIEN prostheses. Our study is monocentric and included a relatively small number of patients. Further studies with a larger number of patients, longer follow-up, and analysis of echocardiographic images in a core laboratory are thus needed to establish the normal reference values of the valve hemodynamic parameters of transcatheter valves and to determine whether their hemodynamic performance is maintained in the long term. However, in such studies, it is recommended to use Method #2 to measure EOA because the utilization of Method #1 could lead the investigators to falsely conclude that there is a deterioration of hemodynamic performance, as illustrated in Table 1. Furthermore, it is preferable to use a multiparametric approach integrating the measures of valve EOA, transvalvular gradients, and Doppler velocity index and their serial changes over time to adequately identify and quantify prosthetic valve dysfunction (1,2). Finally, the results of this study cannot be extended to other models of TAVI valves, such as the CoreValve, for example.

CONCLUSIONS

When estimating the EOA of transcatheter balloon-expandable valves by Doppler echocardiography, it is preferable to use the LVOT diameter and velocity measured immediately proximal to the prosthesis stent. The main determinant of the EOA of transcatheter valves is the patient's annulus size since this is the main factor determining the size of the bioprosthesis as well as the magnitude of its expansion during implantation. This study also shows that TAVI provides an excellent hemodynamic performance and that, accordingly, the incidence of severe PPM is low, even in patients with a small aortic annulus.

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