In vitro assessment of prosthesis type and pressure recovery characteristics: Doppler echocardiography overestimation of bileaflet mechanical and bioprosthetic aortic valve gradients

David S. Bach, MD,^a Christoph Schmitz, Dipl-Ing,^b Guido Dohmen, MD,^c Keith D. Aaronson, MD, MS,^a Ulrich Steinseifer, PhD,^b and Peter Kleine, MD, PhD^d

Objective: Pressure recovery results in Doppler gradients greater than catheter gradients and is well established in association with bileaflet mechanical aortic valves. Because pressure recovery is influenced by orifice geometry, it might manifest differently with various valve prostheses. If true, then the reliability of Doppler echocardiography for the estimation of aortic valve gradients might be different with different prostheses. The purpose of the present study was to test, in an in vitro setting, the degree to which pressure recovery results in Doppler overestimation of gradients for three commonly used aortic valve prostheses.

Methods: Carpentier Edwards Perimount, Medtronic Mosaic, and St. Jude Medical bileaflet prostheses were tested under various flow conditions in a pulsatile mock flow loop with a normal aorta size. Mean pressure gradient was assessed with transducers 1 cm and 10 cm distal to the valve and with Doppler echocardiography. Pressure recovery was defined as the difference between the Doppler gradient and a 10-cm gradient. The percentage of the maximum pressure gradient composed of pressure recovery and the percentage of pressure recovery complete 1 cm distal to the valve were calculated.

Results: There was substantial pressure recovery for all valves in all flow states. Pressure recovery was responsible for 50% or more of the Doppler gradients for almost all conditions and was more than 70% complete within 1 cm for almost all conditions. Multivariate analysis found that flow and valve area (but not valve type) were predictors of pressure recovery; that flow was the major predictor of the percentage of Doppler gradient composed of pressure recovery (with minor contributions from the aorta size and prosthesis type); and that valve type and aorta size were the major predictors of the percentage of pressure recovery complete at 1 cm.

Conclusions: In an in vitro model with a normal aorta size, substantial pressure recovery occurred with all three aortic valve prostheses. Although statistically significant differences were found between valve types in the percentage of pressure recovery and percentage of pressure recovery complete at 1 cm, the differences were small and clinically unimportant. Clinically, among patients with an ascending aorta diameter less than 3.0 cm, Doppler echocardiography likely substantially overestimates aortic valve mean gradient, regardless of prosthesis type. (J Thorac Cardiovasc Surg 2012;144:453-8)

Echocardiography/Doppler imaging is the current standard for the clinical assessment of aortic valve gradients, including gradients associated with prosthetic valves. Although

Doppler-derived gradients generally correlate well with invasive measures, the presence of pressure recovery can result in Doppler overestimation of invasively derived gradients. Pressure recovery occurs when pressure energy proximal to a valve, converted to kinetic energy as flow accelerates through the valve, is “recovered” as pressure energy distal to the valve, rather than being lost as heat.¹⁻³ The maximum pressure gradient (P_{MAX}) represents the pressure difference between the left ventricle and site of lowest pressure (the vena contracta). The net pressure gradient (P_{NET}) represents the pressure difference after pressure recovery is complete. Pressure recovery (P_{PR}) represents the difference between P_{MAX} and P_{NET} . Invasive testing measures P_{NET} , with placement of the aorta catheter several centimeters distal to the aortic valve. In contrast, Doppler echocardiography estimates the P_{MAX} , measuring the pressure difference using the maximum velocity of flow at the vena contracta.

The presence of P_{PR} is well established in association with bileaflet mechanical aortic valves.⁴⁻⁸ Although

From the Division of Cardiovascular Medicine,^a Department of Internal Medicine, University of Michigan, Ann Arbor, Mich; Department of Cardiovascular Engineering,^b Helmholtz Institute, RWTH Aachen University, Aachen, Germany; Department of Thoracic and Cardiovascular Surgery,^c University Hospital Aachen, Aachen, Germany; and Department of Thoracic and Cardiovascular Surgery,^d J. W. Goethe University, Frankfurt am Main, Germany.

This research was supported in part by a grant from Medtronic Cardiovascular, Minneapolis, Minn.

Disclosures: D. S. Bach has received more than \$10,000 in consulting fees or honoraria from Edwards LifeScience, Medtronic CardioVascular, and CVRx and less than \$10,000 from St. Jude Medical; and P. Kleine has received more than \$10,000 in consulting fees or honoraria from Medtronic CardioVascular; the other authors have nothing to disclose with regard to commercial support.

Received for publication Sept 21, 2011; revisions received Nov 18, 2011; accepted for publication Dec 14, 2011; available ahead of print Jan 20, 2012.

Address for reprints: David S. Bach, MD, Department of Internal Medicine, Division of Cardiovascular Medicine, University of Michigan, CVC Room 2147, SPC 5853, 1500 East Medical Center Drive, Ann Arbor, MI 48109 (E-mail: dbach@umich.edu). 0022-5223/\$36.00

Copyright © 2012 by The American Association for Thoracic Surgery
doi:10.1016/j.jtcvs.2011.12.036

Abbreviations and Acronyms

P_{MAX}	= maximum pressure gradient
P_{NET}	= net pressure gradient
P_{PR}	= pressure recovery
$P_{PR}\%$	= percentage of maximum gradient composed of pressure recovery
$P_{PR}[1cm]\%$	= percentage of pressure recovery complete 1 cm distal to valve

documented with bioprostheses⁵⁻⁹ and with a disc-type mechanical valve,^{5,6,10} P_{PR} is believed to be of the greatest magnitude with bileaflet valves.⁴⁻⁸ Factors known to affect P_{PR} include the severity of stenosis,^{2,5} stenosis geometry,^{1,2,4} flow rate,² and the size of the ascending aorta relative to the aortic valve orifice area.^{7,9,11,12} Because various heart valve prostheses have different orifice shapes, the influence of orifice geometry on P_{PR} suggests that it might manifest differently with different aortic valve prostheses. If true, then the reliability of Doppler echocardiography for the estimation of aortic valve gradients might be different with different prostheses. The purpose of the present study was to test, in an in vitro setting, the degree to which P_{PR} results in Doppler overestimation of gradient for three commonly used aortic valve prostheses.

METHODS**Prosthetic Heart Valves**

All testing was performed using 19-mm and 23-mm heart valve prostheses: Carpentier Edwards Perimount bioprosthesis (Edwards LifeSciences, Irvine, Calif), Mosaic porcine bioprosthesis (Medtronic CardioVascular, Minneapolis, Minn), and St. Jude Medical bileaflet mechanical prosthesis (St. Jude Medical, St. Paul, Minn). Three different prostheses were used for each tested valve and size (18 total valve prostheses).

Pulse Duplicator

A previously described pulsatile circulatory mock flow loop was used to provide consistent flow hemodynamics during all measurements.^{2,13} In brief, the flow loop is a hydraulic model of the human systemic circulatory system with adjustable compliance and resistance; the dimensions of the flexible silicon left ventricle and rigid aorta are based on physiologic geometry. The size of the ascending aorta varied, using two aorta sizes for each aortic valve prosthesis size. The 19-mm prostheses were tested using a 21-mm and 29-mm diameter aorta, and the 23-mm prostheses were tested using a 25-mm and 29-mm aorta. The smaller aorta sizes were the smallest size that would accommodate the valve prostheses.

Each combination of aortic valve and aorta was tested in three flow states: 3, 5, and 8 L/min. The heart rate was 70 beats/min for the 3- and 5-L/min flows and 110 beats/min for the 8-L/min flow. The systolic interval was 35% of the cardiac cycle. Normal saline at room temperature was used for all flow conditions.

Invasive Hemodynamics

Pressure in the mock flow loop was measured using calibrated pressure transducers located in the left ventricle and in the aorta 1 and 10 cm distal to

the aortic valve. The mean pressure gradient was taken as the average difference in instantaneous pressures throughout ejection. The aortic valve area was calculated as $V_{RMS}/(51.6 \times \sqrt{\Delta P})$, where V_{RMS} (L/min) is the root mean square of systolic flow and ΔP (mm Hg) is the mean gradient at 10 cm. All measurements were based on the average of 10 cardiac cycles.

Doppler Echocardiography Hemodynamics

Doppler analyses were performed using clinically available echocardiographic imaging equipment (Vivid 3 Cardiovascular Ultrasound System, GE Healthcare, Munich, Germany). A 5.5-MHz transesophageal echocardiography transducer was introduced in the flow loop 12 cm distal to the prosthetic valve and manually aligned to interrogate the transvalvular flow velocity using 2-dimensionally guided continuous-wave Doppler; the scale and sweep were optimized for measurement of antegrade flow. The greatest velocity spectral Doppler envelopes were measured on-line for the mean gradient using the integrated echocardiography machine software and the modified Bernoulli equation. When necessary, normal saline in the mock loop was agitated to provide cavitation targets for Doppler assessment. All measurements were based on the average of 3 cardiac cycles.

Pressure Recovery

P_{PR} was assumed to be complete 10 cm distal to the prosthesis, and the invasively derived gradient at this location was taken as P_{NET} . P_{PR} was defined as the difference between the Doppler mean gradient (P_{MAX}) and the invasively derived gradient at 10 cm (P_{NET}). The percentage of the Doppler gradient composed of P_{PR} was calculated as the $P_{PR}\% = 100 \times P_{PR}/P_{MAX}$. The percentage of P_{PR} that was complete 1 cm distal to the valve was calculated as $P_{PR}[1cm]\% = 100 \times (P_{MAX} - P_{1cm})/P_{PR}$, where P_{1cm} is the mean gradient 1 cm distal to the valve.

Statistical Analysis

For each structural and hemodynamic scenario (valve size, aorta size, flow rate), analyses were performed using three different heart valve prostheses. Data are shown as the mean $\pm$ standard deviation. Linear regression analysis was used to evaluate the association between Doppler and invasive gradients. Analysis of variance was performed to test for differences in the mean values between the three groups and significant differences were subsequently evaluated by independent sample *t* tests for pairwise comparisons without adjustment for multiple hypothesis testing group comparisons. Paired *t* tests were used to test for within-group mean differences. Associations between continuous variables (valve size, valve area, aorta size, flow) and P_{PR} (P_{PR} , $P_{PR}\%$, $P_{PR}[1cm]\%$) were assessed using the Pearson correlation coefficient; associations between valve type and P_{PR} were assessed using the Spearman correlation coefficient. Variables independently associated with P_{PR} , $P_{PR}\%$, and $P_{PR}[1cm]\%$ were determined using multivariate linear regression analysis. Variables with $P < .20$ on univariate analysis were entered into the multivariate model in a forward stepwise fashion and included in the model using the criteria of $F \leq 0.05$ to enter and $F \geq 0.10$ to remove. All statistical analyses were performed using PASW Statistics, version 18.0, for Macintosh (SPSS/IBM, Somers, NY).

RESULTS
Hemodynamics

Invasively derived valve areas at various flow rates are listed in Table 1. Valve areas progressively increased at progressively greater flow rates for all valves and valve sizes. Mean gradients 1 and 10 cm distal to the valve and Doppler-derived mean gradients are listed in Table 2. For all prosthesis types, a strong association was found between Doppler-derived and invasively derived gradients (Figure 1).

TABLE 1. Invasively derived aortic valve area

Prosthesis (size, mm)	3 L/min	5 L/min	8 L/min	Δ3L–5L	Δ3L–8L	Δ5L–8L
CEP (19)	1.4 ± 0.2	1.7 ± 0.2	2.1 ± 0.4	0.24 ± 0.09 (.001)	0.71 ± 0.25 (.001)	0.47 ± 0.21 (.003)
Mosaic (19)	1.0 ± 0.1	1.1 ± 0.2	1.3 ± 0.2	0.08 ± 0.6 (.02)	0.24 ± 0.11 (.003)	0.16 ± 0.06 (.002)
SJM (19)	1.2 ± 0.0	1.3 ± 0.0	1.4 ± 0.0	0.03 ± 0.02 (.03)	0.11 ± 0.03 (<.001)	0.08 ± 0.03 (.003)
CEP (23)	2.2 ± 0.1	2.5 ± 0.2	3.2 ± 0.1	0.28 ± 0.07 (<.001)	0.97 ± 0.16 (<.001)	0.69 ± 0.11 (<.001)
Mosaic (23)	1.5 ± 0.0	1.7 ± 0.1	2.0 ± 0.2	0.14 ± 0.05 (.001)	0.49 ± 0.20 (.002)	0.34 ± 0.16 (.003)
SJM (23)	2.0 ± 0.1	2.1 ± 0.1	2.2 ± 0.1	0.10 ± 0.02 (<.001)	0.18 ± 0.03 (<.001)	0.08 ± 0.02 (<.001)

Δ3L–5L, Δ3L–8L, and Δ5L–8L reflect change ± standard deviation between flow states; data in parentheses are *P* values. CEP, Carpentier Edwards Perimount valve; Mosaic, Mosaic porcine valve; SJM, St. Jude Medical valve.

Pressure Recovery

For all valve prostheses and in almost all flow states, the mean pressure gradient 10 cm distal to the valve was significantly lower than the mean gradient 1 cm distal to the valve, confirming the presence of P_{PR} . As anticipated in the setting of P_{PR} , the echocardiographic gradient (P_{MAX}) was greater than the invasively derived gradient at 10 cm (P_{NET}). However, for all valves and in all but one flow state, the Doppler gradient also was greater than the gradient 1 cm distal to the valve (Table 2), suggesting that P_{PR} had already taken place only 1 cm distal to the valve. P_{PR} , $P_{PR}\%$, and $P_{PR}[1cm]\%$ are listed in Table 3. The average $P_{PR}\%$ across all flow conditions for the Perimount, Mosaic, and St. Jude Medical valves was $61.6\% \pm 7.6\%$, $58.9\% \pm 7.4\%$, and $57.4\% \pm 6.4\%$, respectively. Both P_{PR} and $P_{PR}\%$ increased at higher flows. Different valve prostheses were associated with different amounts of P_{PR} . Differences between the valve types in $P_{PR}\%$ were evident at higher flow rates but not at low-flow conditions.

The factors predictive on multivariate regression analysis of P_{PR} , $P_{PR}\%$, and $P_{PR}[1cm]\%$ are listed in Table 4. P_{PR} , $P_{PR}\%$, and $P_{PR}[1cm]\%$ were influenced by flow rate and aorta size. $P_{PR}\%$ and $P_{PR}[1cm]\%$, but not P_{PR} , were influenced by the prosthesis type.

DISCUSSION

Existing Data

The classic model of P_{PR} is that localized high velocities occur close to the valve, with subsequent flow deceleration and recovery of pressure several centimeters distal to the valve orifice.^{2–5} Although P_{PR} has been documented with several aortic valve prostheses, it is thought to occur to a greater magnitude with bileaflet valves.^{4–8} In 1990, Baumgartner and colleagues⁴ demonstrated higher gradients closer to the orifice of a bileaflet mechanical valve using catheter pullback in a pulsatile in vitro model but found no evidence of P_{PR} with a bioprosthesis. Bech-Hanssen and colleagues^{5–7} used combined Doppler and catheter studies in a continuous-flow model to show that P_{PR} exists with multiple prosthesis types (including bileaflet, single disc, and tissue valves) but is of greatest magnitude with a bileaflet valve and can occur at variable locations.⁷ Niederberger and colleagues¹¹ reported in 1996 that the magnitude of P_{PR} in a model of aortic stenosis can be predicted using the Doppler effective orifice area and the cross-sectional area of the ascending aorta, which was confirmed both in vitro and in vivo for aortic valve prostheses by Garcia and colleagues⁹ in 2003.

TABLE 2. Doppler and invasive mean pressure gradients at 3, 5, and 8 L/min

Prosthesis (size, mm)	Aorta (mm)	3 L/min		5 L/min		5 L/min		8 L/min		8 L/min	
		Doppler (P_{MAX})	1 cm	Doppler (P_{MAX})	10 cm (P_{NET})	Doppler (P_{MAX})	1 cm	Doppler (P_{MAX})	10 cm (P_{NET})	Doppler (P_{MAX})	1 cm
CEP (19)	21	10.6 ± 2.8*	6.5 ± 1.9	23.8 ± 4.2†	4.8 ± 1.5*	14.0 ± 2.9	9.6 ± 2.0*	52.4 ± 6.6†	22.8 ± 2.7	12.7 ± 2.4†	
Mosaic (19)	21	18.8 ± 1.4†	10.8 ± 2.5	39.6 ± 7.5*	8.1 ± 2.0†	22.7 ± 4.1	16.8 ± 3.1*	96.6 ± 17.0*	43.3 ± 3.9	29.7 ± 2.9†	
SJM (19)	21	16.9 ± 2.9*	8.9 ± 0.9	50.8 ± 1.9†	7.2 ± 0.4†	23.1 ± 0.5	17.4 ± 0.2†	95.0 ± 1.8†	47.5 ± 2.0	33.9 ± 1.8†	
CEP (19)	29	12.5 ± 2.1†	6.8 ± 1.6	27.4 ± 5.6*	5.6 ± 1.1*	15.5 ± 3.9	12.1 ± 3.0*	63.0 ± 12.8*	29.0 ± 6.8	20.4 ± 4.8*	
Mosaic (19)	29	21.6 ± 0.6*	13.0 ± 2.1	55.0 ± 6.1†	11.3 ± 1.9†	33.1 ± 5.6	27.9 ± 5.6†	116.8 ± 20.8*	63.1 ± 13.7	50.3 ± 12.1†	
SJM (19)	29	15.3 ± 2.5*	7.7 ± 1.3	46.8 ± 6.2†	6.8 ± 0.9§	20.5 ± 3.1	16.7 ± 2.2†	91.6 ± 9.5*	42.9 ± 2.6	33.4 ± 2.1†	
CEP (23)	25	5.1 ± 0.4†	2.9 ± 0.3	12.0 ± 0.7†	2.3 ± 0.2†	6.4 ± 0.1	4.7 ± 0.0‡	22.8 ± 1.8†	10.4 ± 0.6	6.4 ± 0.6†	
Mosaic (23)	25	10.9 ± 0.4†	5.6 ± 0.2	28.2 ± 1.5†	4.7 ± 0.1†	13.9 ± 1.2	10.8 ± 0.9†	60.1 ± 7.1†	23.4 ± 3.6	16.1 ± 3.0†	
SJM (23)	25	5.4 ± 0.7*	2.9 ± 0.1	14.2 ± 1.5*	2.7 ± 0.1§	8.2 ± 0.4	6.9 ± 0.3†	35.6 ± 4.3*	19.6 ± 0.5	14.6 ± 0.1†	
CEP (23)	29	5.9 ± 0.3†	3.4 ± 0.1	11.9 ± 0.6†	2.6 ± 0.1†	6.8 ± 0.1	5.2 ± 0.1‡	26.8 ± 0.7†	11.7 ± 0.2	8.1 ± 0.0†	
Mosaic (23)	29	12.1 ± 1.2†	6.8 ± 0.9	27.3 ± 0.5†	5.6 ± 0.5*	15.0 ± 0.4	11.7 ± 0.2†	56.4 ± 3.5†	25.6 ± 1.4	19.6 ± 1.5†	
SJM (23)	29	6.1 ± 1.2¶	3.4 ± 0.1	15.6 ± 2.0*	3.2 ± 0.1†	7.9 ± 0.3	7.0 ± 0.3†	35.7 ± 4.1*	18.0 ± 0.8	14.4 ± 0.6†	

Invasive mean gradients shown 1 and 10 cm distal to valve; Doppler gradient represents maximum pressure gradient (P_{MAX}); 10-cm invasive gradient represents net pressure gradient (P_{NET} ; see text for details). P_{MAX} , Maximum pressure gradient; P_{NET} , net pressure gradient; other abbreviations as in Table 1. Compared with 1 cm: * $.01 \leq P < .05$; † $.001 \leq P < .01$; ‡ $P < .001$; § $P = .06$ compared with 1 cm; ¶ $P = .05$ compared with 1 cm.

FIGURE 1. Associations between Doppler and invasive gradients. P_{MAX} (Doppler mean gradient) plotted against P_{NET} (mean gradient 10 cm distal to valve). Associations between Doppler and invasively derived gradients excellent for all prostheses tested; $P_{MAX} > P_{NET}$ due to P_{PR} . A, Carpentier Edwards Perimount bioprosthesis ($P_{MAX} = 3.2 \times P_{NET} - 2.4$ [$R = 0.94$, $R^2 = 0.89$, $P < .001$]); B, Mosaic porcine bioprosthesis ($P_{MAX} = 2.4 \times P_{NET} + 3.1$ [$R = 0.93$, $R^2 = 0.87$, $P < .001$]); C, St. Jude Medical bileaflet prosthesis ($P_{MAX} = 2.9 \times P_{NET} - 3.8$ [$R = 0.99$, $R^2 = 0.98$, $P < .001$]); D, all valves ($P_{MAX} = 2.6 \times P_{NET} + 0.8$ [$R = 0.96$, $R^2 = 0.91$, $P < .001$]).

Present Study Findings

The present study found that P_{PR} occurred with all three prosthesis types and is responsible for a substantial amount of the observed Doppler gradient—ranging from 47% to 76% in various flow states. Although univariate analysis

suggested that P_{PR} differs between the prostheses (Mosaic more than St. Jude bileaflet more than Perimount), multivariate analysis found that flow and valve orifice area were the major determinants of P_{PR} . As such, the observed differences between the prosthesis types actually were a reflection

TABLE 3. Pressure recovery, percentage of Doppler gradient composed of pressure recovery, and percentage of pressure recovery complete at 1 cm

Prosthesis	Aorta (size, mm)	P_{PR} (mm Hg)			$P_{PR}\%$			$P_{PR}[1cm]\%$		
		3 L/min	5 L/min	8 L/min	3 L/min	5 L/min	8 L/min	3 L/min	5 L/min	8 L/min
CEP (19)	21	5.8 ± 1.3	14.1 ± 2.2**	39.7 ± 5.3**,††	55 ± 3	60 ± 2	76 ± 3*,††	71 ± 2†	69 ± 1	74 ± 2
Mosaic (19)	21	10.7 ± 10.8§§	22.7 ± 4.6§,§	66.9 ± 14.1*,†,§	57 ± 8†	57 ± 2###	69 ± 2†,§	74 ± 6†	74 ± 2††,§,§	79 ± 3
SJM (19)	21	9.7 ± 2.7	33.5 ± 1.8***,§§§	61.1 ± 3.4*,†,§§	57 ± 6	66 ± 1§§	64 ± 2§§	81 ± 4§	83 ± 1†,§§§	78 ± 2†
CEP (19)	29	6.9 ± 1.0	15.3 ± 3.9*	42.6 ± 8.0*,†	55 ± 3	56 ± 7	68 ± 1*	84 ± 5	77 ± 5	80 ± 1
Mosaic (19)	29	10.3 ± 1.6§	27.2 ± 3.1*,§	66.5 ± 12.9*,†	48 ± 8	50 ± 6#	57 ± 7††	83 ± 5	81 ± 2###	80 ± 3
SJM (19)	29	8.6 ± 1.9	30.1 ± 4.1**,*§	58.3 ± 9.0**,*†	56 ± 5	64 ± 1	63 ± 4*	89 ± 4	88 ± 1§	83 ± 2
CEP (23)	25	2.8 ± 0.4	7.3 ± 0.7*,††	16.4 ± 2.2*,†	55 ± 4	61 ± 2††	72 ± 4	78 ± 3	76 ± 2	75 ± 3
Mosaic (23)	25	6.2 ± 0.2§§§,##	17.4 ± 1.5**,*§§§,##	44.1 ± 6.3**,*†,§§,##	57 ± 0†	62 ± 3#	73 ± 4*,†,§	84 ± 1###	82 ± 2§	83 ± 2§,#
SJM (23)	25	2.7 ± 0.7	7.3 ± 1.3**	21.0 ± 4.2*,†	49 ± 7	51 ± 4§	59 ± 5§	96 ± 1§§	81 ± 1**,*†,§	76 ± 4**,*†
CEP (23)	29	3.3 ± 0.4	6.7 ± 0.6*	18.8 ± 0.7***,††	56 ± 4	56 ± 2	70 ± 1*,††	76 ± 2	76 ± 3	81 ± 1
Mosaic (23)	29	6.5 ± 0.7§§,##	15.6 ± 0.5**,*§§§,##	36.8 ± 2.5**,*†,§§§,##	54 ± 2	57 ± 1	65 ± 2*,††,§	81 ± 5#	79 ± 2###	84 ± 2
SJM (23)	29	2.9 ± 1.1	8.6 ± 1.7*	21.4 ± 4.7*	47 ± 10	55 ± 4	59 ± 6§	91 ± 4§§	89 ± 3§§	82 ± 4

P_{PR} , Pressure recovery; $P_{PR}\%$, percentage of maximum gradient composed of pressure recovery; $P_{PR}[1cm]\%$, percentage of pressure recovery complete 1 cm distal to valve; other abbreviations as in Table 1. Comparison vs 3L flow: * $.01 \leq P < .05$; ** $.001 \leq P < 0.01$; *** $P < 0.001$. Comparison vs 5L flow: † $.01 \leq P < .05$; †† $.001 \leq P < .01$. Comparison vs 29 mm aorta: ‡ $.01 \leq P < .05$; ‡‡ $.001 \leq P < .01$. Comparison vs CEP valve: § $.01 \leq P < .05$; §§ $.001 \leq P < 0.01$; §§§ $P < .001$. Comparison vs SJM valve: # $.01 \leq P < 0.05$; ## $.001 \leq P < .01$; ### $P < .001$.

TABLE 4. Independent determinants on multivariate regression analysis of variables of pressure recovery

Variable	Standardized coefficient	ΔR^2	P value
P_{PR}			
Flow (L/min)	0.93	0.58	<.001
Valve area (cm ²)	−0.53	0.26	<.001
Aorta size (mm)	−0.09	0.01	.03
P_{PR}%			
Flow (L/min)	0.65	0.43	<.001
Aorta size (mm)	−0.25	0.06	<.001
Valve type	−0.21	0.05	.002
P_{PR}[1cm]%			
Valve type	0.63	0.32	<.001
Aorta size (mm)	0.41	0.18	<.001
Flow (L/min)	−0.23	0.03	.002

ΔR^2 , Respective contribution of variable to full model predicting P_{PR}, P_{PR}%, and P_{PR}[1cm]%; other abbreviations as in Table 3.

of the different valve orifice areas for the various prostheses. Flow was found to be the major determinant of the amount that P_{PR} contributed to the Doppler gradient, with aorta size and valve type playing statistically significant, but quantitatively minor, roles. Finally, the present study found that a substantial amount of P_{PR} (≥70%) occurred within 1 cm of the valve. Although the prosthesis type played a role, the magnitude of the differences between the valve types was minor and of doubtful clinical importance.

Comparison With Previous Studies

The finding that flow rate and valve area were the major determinants of P_{PR} is consistent with previously published reports.^{2,5} The finding that a smaller aorta dimension was associated with greater P_{PR} also correlates with previously published reports.^{7,9,11,12} The relatively minor quantitative influence of aorta size on P_{PR} in this model likely resulted from the absence of any condition with a substantially enlarged aorta. Clinical recommendations are to consider P_{PR} if the ascending aorta diameter is 3.0 cm or less,^{3,9} and the present model included no conditions with an aorta diameter greater than 2.9 cm.

The present study found that P_{PR} was responsible for greater than 50% of the Doppler gradients for all three tested valve prostheses and that valve type played only a minor role. In contrast, previous reports have described P_{PR} in the range of 13% to 35% for bioprostheses and 41% to 71% for a bileaflet mechanical valve.^{4,5,7,8} Although 1 report suggested that P_{PR} does not occur with a bioprosthesis,⁴ that study used catheter pull-back through the valve orifice; because it is likely impossible to maintain a catheter within the high-velocity vena contracta, it is possible that the catheter-based maximal gradient (and therefore, the calculated P_{PR}) was underestimated relative to the use of well-aligned Doppler ultrasonography.⁵⁻¹² In addition, the present study used a sophisticated pulsatile

mock circulatory system with chamber geometry, compliance, and resistance intended to mimic the human circulatory system. It is possible that the differences in the amount of observed P_{PR} between our study and those of others could reflect the previous use of continuous-flow models^{1,5-7} and the use of catheter-based assessments of pressure gradients.^{1,2,4}

In contrast to the classic concept that P_{PR} occurs several centimeters distal to the valve,²⁻⁵ the present study found that a substantial amount of P_{PR} occurred within 1 cm. Although prosthesis type appeared to influence magnitude of proximal P_{PR}, it was substantial for all the tested prostheses, with differences that were not of clinical relevance. At least one previously published study found substantial P_{PR} within the valve housing and distinguished P_{PR} within the prosthesis from that within the aorta.⁵ In clinical scenarios, a catheter is not introduced to the level of the vena contracta and could not be maintained at that location for any appreciable interval. Because of the substantial magnitude of P_{PR} that was complete within 1 cm of the prostheses, Doppler measurements of gradient will exceed invasive estimates, regardless of catheter location, if P_{PR} is present.

Previously published reports have described varying degrees of localized low velocities and P_{PR} through central versus side orifices of a bileaflet mechanical valve.^{4,6} In the present study, the highest velocity Doppler envelopes were analyzed, presumably through the central valve orifice.

Clinical Implications

High Doppler gradients can be observed after aortic valve replacement despite a normally functioning prosthesis.³ Although P_{PR} might be recognized in some patients based on the clinical scenario, reports exist of patients referred for reoperation that was avoided only when invasive testing documented Doppler overestimation of gradients.¹⁴ In the present study, the Carpentier Edwards Perimount bioprosthesis, Mosaic porcine bioprosthesis, and St. Jude Medical bileaflet mechanical valves all were associated with substantial P_{PR}. When clinically derived Doppler gradients are obtained in patients with these prostheses and an ascending aorta diameter less than 3.0 cm, a substantial portion of the observed Doppler gradient—typically in excess of 50%—can be attributed to P_{PR}. As a clinical rule, in patients with one of these prostheses and a normal caliber aortic root, the Doppler gradients probably reflect at least double the gradient that would be derived using invasive testing.

Study Limitations

The present study had several limitations. First, it was an in vitro study. Thus, although the mock flow loop is designed to simulate the geometry and function of the human systemic circulatory system, observations might differ among patients

ET/BS

after valve replacement. Normal saline was used in the model; although a fluid viscosity different from blood could affect the Doppler gradients, conditions were the same for all prostheses. The mock loop used small valve sizes and normal caliber aorta sizes, both of which promote P_{PR} ; thus, P_{PR} would be expected to be less among patients with larger valves and an ascending aorta diameter greater than 3.0 cm. Additional testing is required to define the degree to which Doppler echocardiography overestimates the gradients in these conditions. Finally, it has been well established that labeled valve sizes are not comparable between manufacturers¹⁵⁻¹⁷; the present study used the same labeled valve sizes from various manufacturers and should not be interpreted as a comparison of the overall hemodynamics between these prostheses.

CONCLUSIONS

In an in vitro model with a normal aorta size, substantial P_{PR} occurred in association with all three valves tested. Flow and valve area (but not the prosthesis type) were the dominant determinants of P_{PR} . For all three prosthesis types, P_{PR} was responsible for 50% or more of the observed Doppler gradient. A preponderance of P_{PR} occurred very close to or within the prosthesis. Clinically, among patients with an ascending aorta diameter less than 3.0 cm, it should be assumed that Doppler echocardiography substantially overestimates prosthetic aortic valve mean gradient.

References

1. 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.
2. 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.
3. Bach DS. Echo/Doppler evaluation of hemodynamics after aortic valve replacement: principles of interrogation and evaluation of high gradients. *J Am Coll Cardiol Img*. 2010;3:296-304.
4. Baumgartner H, Khan S, DeRobertis M, Czer L, Mauer G. Discrepancies between Doppler and catheter gradients in aortic prosthetic valves in vitro: a manifestation of localized gradients and pressure recovery. *Circulation*. 1990;82:1467-75.
5. Bech-Hanssen O, Caidahl K, Wallentin I, Brandberg J, Wranne B, Ask P. Aortic prosthetic valve design and size: relation to Doppler echocardiographic findings and pressure recovery—and in vitro study. *J Am Soc Echocardiogr*. 2000;13:39-50.
6. Bech-Hanssen O, Caidahl K, Wallentin I, Ask P, Wranne B. Assessment of orifice area of prosthetic aortic valves with Doppler echocardiography: an in vivo and in vitro study. *J Thorac Cardiovasc Surg*. 2001;122:287-95.
7. Bech-Hanssen O, Gjerdtsson P, Houlitz E, et al. Net pressure gradients in aortic prosthetic valves can be estimated by Doppler. *J Am Soc Echocardiogr*. 2003;16:858-66.
8. Aljassim O, Svensson G, Houlitz E, Bech-Hanssen O. Doppler-catheter discrepancies in patients with bileaflet mechanical prostheses or bioprostheses in the aortic valve position. *Am J Cardiol*. 2008;102:1383-9.
9. Garcia D, Dumesnil JG, 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: Practical implications with regard to quantification of aortic stenosis severity. *J Am Coll Cardiol*. 2003;41:435-42.
10. Dohmen G, Schmitz C, Langebartels G, Steinseifer U, Schmitz-Rode T, Autschbach R. Impact of pressure recovery in the evaluation of the Omnicarbon tilting disc valve. *Thorac Cardiovasc Surg*. 2006;54:173-7.
11. Niederberger J, Schima H, Mauer 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.
12. Baumgartner H, Stefanelli T, Niederberger J, Schima H, Mauer 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.
13. Knott E, Reul H, Knoch M, Steinseifer U, Rau G. In vitro comparison of aortic heart valve prostheses. *J Thorac Cardiovasc Surg*. 1988;96:952-61.
14. Turgot T, Deeb M, Moscucci M. Left ventricular apical puncture: a procedure surviving well into the new millennium. *Cathet Cardiovasc Interv*. 2000;49:68-73.
15. Christakis GT, Buth KJ, Goldman BS, et al. Inaccurate and misleading valve sizing: a proposed standard for valve size nomenclature. *Ann Thorac Surg*. 1998;66:1198-203.
16. Youdelman BA, Hirose H, Jain H, Kresh JY, Entwistle JWC, Wechsler AS. Comparison of eight prosthetic aortic valves in a cadaver model. *J Thorac Cardiovasc Surg*. 2007;134:1526-32.
17. Doenst T, Amorim PA, Al-Alam N, Lehmann S, Mukherjee C, Faerber G. Where is the common sense in aortic valve replacement? A review of hemodynamics and sizing of stented tissue valves. *J Thorac Cardiovasc Surg*. 2011;142:1180-7.