Assessment of mechanical aortic valve prosthesis by means of Doppler echocardiography: What to measure and why?

Mani A. Vannan, MBBS
Kunal Sarkar, MD

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Comprehensive 2-dimensional Doppler echocardiography is the modality of choice for anatomic and hemodynamic evaluation of prosthetic heart valves. However, Doppler hemodynamic assessment of mechanical aortic valve prostheses, especially bileaflet valves, requires consideration of the physical principles governing transvalvular flows. In this issue De Carlo and colleagues¹ have evaluated the hemodynamic performance of the small-sized, bileaflet, Sorin Bicarbon aortic valve prosthesis (SBP) using Doppler peak and mean gradients and calculated effective orifice area (EoA) and effective orifice area index (EoAi). They have shown that these parameters are comparable with those of other small bileaflet mechanical valves in the aortic position and that there is significant regression in left ventricular hypertrophy (LVH). Because these data provide references for small SBP valves in the aortic position, it is relevant to ask the question of how best to evaluate aortic mechanical valves by means of Doppler echocardiography. To answer this question, it is important to understand the many physical principles that govern transvalvular flow dynamics and the problems and pitfalls associated with any single parameter. Routine echocardiographic evaluations of transvalvular gradients are done by using a simplification of the modified Bernoulli equation as follows: $PG = 1/2 \rho V^2$, where PG is the pressure gradient, ρ is the density of blood, and V is the Doppler transvalvular velocity. Because 1/2 is approximately 4 for blood, the formula is simplified as follows: $PG = 4V^2$.

This simplified equation neglects convective acceleration, flow acceleration, and viscous forces. Neglecting flow acceleration will overestimate transvalvular pressure decrease when the proximal (left ventricular outflow tract [LVOT]) velocities exceed 1 m/sec; normal velocity is between 0.7 and 1 m/sec. Patients who have undergone aortic valve replacement frequently have left ventricular hypertrophy and hyperdynamic left ventricular systolic function when the proximal velocity can exceed 1 m/sec, especially with small prosthetic valves. Under these circumstances, the expanded Bernoulli equation should be applied as follows: $PG = 4(V_1^2 - V_2^2)$, where V1 and V2 are proximal and transvalvular velocities, respectively. This principle is relevant independent of valve design and geometry.

Another issue pertains to discrepancies in transvalvular gradients measured across prosthetic valves by using invasive catheter techniques and Doppler echocardiography.²⁻⁴ There have been many studies to elucidate the physics of flow across prosthetic valves by using both pulsatile and steady state fluid systems.⁴⁻⁶ Particle image velocimetry and particle tracking velocimetry show that the fluid velocity field downstream of an artificial heart valve is highly inhomogeneous and unsteady, with large-scale vortex formation around valve leaflets. Furthermore, substantial shear stresses occur at the jet-wake interface downstream of valve leaflets and close to large-scale vortices. Given the different geometric configurations of aortic valve prostheses, the amount of spatial variation in pressure fields is extremely high and can contribute to the discrepancies in measurement of gradients (Figures 1 and 2). An additional factor has to do with the phenomenon of pressure

From the Drexel University College of Medicine, Hahnemann University Hospital, Philadelphia, Pa.

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Address for reprints: Mani A. Vannan, MBBS, Drexel University College of Medicine, Hahnemann University Hospital, 215 N 15th St, Philadelphia, PA 19102 (E-mail: mav25@drexel.edu).

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Figure 1. Flow visualizations using multiple frame overlapping at the systolic peak (a) and long exposure time acquisitions in the sinus of Valsalva (b and c). The *vertical arrows* indicate the position of the 2 leaflets when opened. Images *B* and *C* correspond to 150 and 180 ms after the beginning of the cycle, respectively. The frame rate was 250 Hz. Reproduced with permission from a presentation at the 11th International Symposium on Application of Laser Anemometry to Fluid Mechanics (Lisbon, Portugal; July 2002) by A. Balducci and colleagues.

recovery. For any stenotic orifice, the pressure would be lowest and the velocity highest at the narrowest point, as enunciated by the Bernoulli equation. If the geometry of the bileaflet valve is one in which the flow flares gradually from its narrowest point, then a smooth deceleration is possible. This in turn implies that some of the potential energy converted into kinetic energy at the level of the valve (or stenosis) is reconverted to pressure and potential energy downstream. This is called pressure recovery (Figure 3). In a bileaflet prosthesis the pressure decrease and recovery across the side orifices occurs further downstream and is much less pronounced than in the central orifice.⁷ The maximum pressure decrease with an invasive catheter is also seen at the central orifice at the valve level, but in a clinical setting it is not feasible to position the catheter across the valve leaflets. This leads to a situation in which 2 modalities intended to measure the same physical phenomenon are doing so at different locations. The catheter

technique measures the gradient a few millimeters downstream, and the continuous-wave Doppler echocardiography provides the maximum velocity along the line of interrogation and reflects the highest gradient along the path of the beam.

The concept of EOA and EOAI provides a complimentary technique to assess the performance of prosthetic valves. However, the formula used to calculate this includes Doppler data, which require meticulous attention to technical details, such as alignment of Doppler beam to flow. The continuity equation is then used to calculate the EoA as follows: $EOA = (ALVOT \times VTI_{LVOT}) / VTI_{valve}$, where A is area of LVOT and VTI is the velocity time integral of LVOT (pulsed-wave Doppler echocardiogram) and valvular flows. Additionally, subvalvular geometry, orientation of the prosthesis, and nonuniformity of the subvalvular velocity profile might all lead to underestimation or overestimation of EOA. Normalizing EOA to body surface area yields

Figure 2. Example of image acquisition (a) and image analysis with particle image velocimetry (b; right, sinus of Valsalva). The frame rate was 1 kHz. Reproduced with permission from a presentation at the 11th International Symposium on Application of Laser Anemometry to Fluid Mechanics (Lisbon, Portugal; July 2002) by A. Balducci and colleagues.

EOAi. An EOA of less than $0.9 \text{ cm}^2/\text{m}^2$ is suboptimal and is associated with significant residual hemodynamic burden on the left ventricle. Clinical symptoms are often unresolved in these patients and illustrate the problem of patient-prosthesis mismatch. Bortolotti and colleagues¹ have provided reassuring data on the EOAi of small SBP aortic valves, except for in 3 of the 182 patients. Resting EOAi is usually sufficient to assess aortic prosthesis, although stress flow dynamics might be necessary on occasion. If LVH was caused by valve stenosis, aortic valve replacement should result in significant regression of LVH by 6 months if the EOAi is optimal. Hence the data on regression of LVH by De Carlo and associates¹ for small SBP valves over 1 years' follow-up support their conclusion that these valves have a favorable in vivo hemodynamic profile.

How does one interpret a Doppler peak systolic velocity of 4 m/sec across an aortic mechanical prosthesis? First, attention to mean Doppler gradient is recommended over peak gradient. If the proximal LVOT velocity does not

Figure 3. Pressure profiles through central (solid line) and side (dashed line) orifices obtained from numeric simulations, showing the marked pressure decrease in the central orifice located slightly more proximal than the side orifices. Reprinted with permission from Vandervoort PM, Greenberg NL, 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.

exceed 1 m/sec, then the simplified Bernoulli equation is valid; otherwise, the expanded Bernoulli equation should be used to determine the transvalvular gradient. An early peaking Doppler velocity profile would suggest either a pressure-recovery phenomenon or increased flow across an unobstructed valve, despite a peak velocity of 4 m/sec. If the peak systole is delayed in the Doppler profile, it reflects an obstructed flow either as a result of a patient-prosthesis mismatch or pathologic causes, such as thrombus or pannus. Calculation of EOA and EOAi is helpful in this situation because a pathologically obstructed valve would have an extremely small EOA and EOAi compared with the reference values for any given valve size. Obviously, clinical history is valuable in distinguishing these 2 conditions. Thus Doppler echocardiography can be used effectively for both elucidation of baseline hemodynamics and for long-term follow-up of aortic mechanical valves. An understanding of the physics of flow dynamics and factors relevant to Doppler echocardiography should preclude errors and inaccuracies in the assessment of the performance of aortic mechanical prostheses.

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