Correction of Doppler Gradients for Pressure Recovery Improves Agreement with Subsequent Catheterization Gradients in Congenital Aortic Stenosis

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Background: In congenital aortic stenosis (AS), suboptimal agreement between Doppler-derived gradients and catheterization gradients may lead to inappropriate referrals for catheterization. To address this problem, the authors investigated whether adjusting Doppler gradients for pressure recovery (PR) improved their agreement with subsequent catheterization gradients.

Methods: One hundred encounters in which patients with congenital AS underwent echocardiography and subsequent catheterization were retrospectively identified. Peak instantaneous and mean transaortic Doppler gradients were recorded from an apical view. PR (mm Hg) was calculated as $4V_{CW}^2 \times (2 \times \text{EOA/AOA}) \times (1 - \text{EOA/AOA})$, where V_{CW} is continuous-wave peak velocity, EOA is effective orifice area (stroke volume/velocity-time integral), and AOA is aortic cross-sectional area ($\pi \times \text{radius}^2$). The PR-corrected peak Doppler gradient was calculated as peak Doppler gradient − PR. Doppler gradients were tested for correlation and agreement with the peak-to-peak systolic gradient at catheterization (cath gradient).

Results: The median age was 12.9 years (range, 0.7–24.6 years). Median AS gradients were as follows: cath, 39 mm Hg (range, 0—103 mm Hg); peak Doppler, 48 mm Hg (range, 10–94 mm Hg); mean Doppler, 25 mm Hg (range, 4–58 mm Hg); and PR-corrected peak Doppler, 35 mm Hg (range, 5–78 mm Hg). Correlation coefficients between the various Doppler and cath gradients were not significantly different. The mean difference between Doppler and cath gradients was smallest for the PR-corrected peak Doppler gradient (−4.1 ± 14.1 mm Hg), followed by the uncorrected peak Doppler gradient (9.7 ± 15.9 mm Hg) and the mean Doppler gradient (−14.6 ± 15.6 mm Hg) ($P < .001$). Receiver operating characteristic curve analysis for a cath gradient ≥ 35 mm Hg revealed a significantly larger area under the curve for the PR-corrected peak Doppler gradient (0.85) compared with the uncorrected peak Doppler gradient (0.80) ($P = .004$) and the mean Doppler gradient (0.78) ($P = .001$). A PR-corrected peak Doppler gradient ≥ 27 mm Hg was associated with a cath gradient ≥ 35 mm Hg with 90% sensitivity and 61% specificity.

Conclusions: In congenital AS, correcting the peak Doppler gradient for PR significantly improved agreement with the subsequently measured cath gradient. This approach may improve decisions regarding referral for catheterization. (J Am Soc Echocardiogr 2015;■:■-■.)

Keywords: Aortic stenosis, Catheterization, Echocardiography, Pressure recovery

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Aortic stenosis (AS) accounts for 3% to 8% of all cases of congenital heart disease[1,2] and often requires surgical or catheter-based treatment.[3-6] In pediatric patients with AS, the peak-to-peak gradient at catheterization (cath gradient) is a key parameter in deciding whether to perform these valve interventions.[7-9] However, catheterization carries some risk and significant expense. Accordingly, echocardiography often serves as a "gatekeeper" for referring patients with AS to catheterization. Given the reliance on the cath gradient for decisions regarding valve intervention, the performance of echocardiography in this gatekeeper role depends on its ability to accurately predict the cath gradient. Overestimations may lead to otherwise unnecessary catheterizations; underestimations potentially lead to undertreated disease. Nevertheless, despite their widespread use, Doppler AS gradients have suboptimal agreement with cath gradients.[10-18] The peak instantaneous gradient is frequently larger than the cath gradient, particularly at higher values, while the mean Doppler gradient tends to be smaller than the cath gradient.

Pressure recovery (PR) in the ascending aorta has been shown to be a significant cause of this discrepancy.[19-27] As blood flows across the stenotic aortic valve, potential energy in the form of pressure is converted into kinetic energy in the form of velocity. The flow converges in the vena contracta, where it reaches maximum velocity and minimum pressure. This maximum velocity at the

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Abbreviations

AOA = Ascending aortic area

AS = Aortic stenosis

AUC = Area under the curve

BSA = Body surface area

EOA = Effective orifice area

PR = Pressure recovery

SV = Stroke volume

VTI = Velocity-time integral

vena contracta is measured by continuous-wave Doppler and used to estimate the transvalvar pressure gradient on the basis of the modified Bernoulli equation. Distal to the vena contracta, the flow stream disperses. Some energy is lost as heat due to turbulence, and the remainder transforms back into potential energy (pressure). This PR increases the pressure downstream in the ascending aorta and thus reduces the net transvalvar pressure gradient. The magnitude of PR increases as the ratio of the ascending aortic area (AOA) compared with the effective orifice area (EOA) decreases, up to a maximum of approximately 50% recovered pressure when the AOA is twice the EOA.[19,20] Doppler-derived peak instantaneous gradients do not account for PR downstream of the vena contracta and are usually higher than cath gradients.[10,14,15,22,23,28-30] Echocardiographic measurements of the EOA are similarly affected. Using the continuity equation, the EOA is calculated as stroke volume divided by the velocity-time integral (VTI) measured with continuous-wave Doppler. Because this approach does not take the recovered pressure into account, it tends to yield a smaller EOA than that calculated by the Gorlin equation, which is based on the invasively measured mean gradient.[10,15,31]

Adjusting Doppler-derived measurements for PR may improve the ability of echocardiography to predict catheter measurements in congenital AS and, in turn, its gatekeeper performance. Baumgartner *et al.*[32] developed an equation to calculate PR on the basis of noninvasive measurements. Subtraction of the recovered pressure from the peak Doppler gradient yields a "PR-corrected" peak Doppler gradient, which has been shown to have better agreement with invasive measurements in adults with AS.[32,33] However, only two studies have evaluated this approach in children and young adults with congenital AS.[34,35] Although both of these studies showed improved agreement, they were rather small, with only 14 patients each. In addition, echocardiographic and invasive measurements were obtained simultaneously in both studies, and thus the findings may not be applicable to the gatekeeper scenario in which echocardiography is performed first, often in unsedated patients. Therefore, in an effort to improve the gatekeeper performance of echocardiography, we sought to determine whether adjusting the peak Doppler gradient for PR on outpatient echocardiograms improves the correlation and agreement with the subsequently obtained cath gradient in a large cohort of patients with congenital AS.

METHODS

Subjects

A retrospective database search at our institution identified all patients aged 6 months to 25 years who underwent cardiac catheterization for the evaluation of isolated congenital AS between 2007 and 2013 and underwent echocardiography at our institution in the 3 months preceding catheterization. Subjects were excluded if (1) their echocardiograms did not contain the data required for PR calculation, (2) they had additional levels of left ventricular outflow tract obstruction, (3) they had other significant cardiovascular anomalies (e.g., shunting lesions, residual coarctation, cardiomyopathy, or connective tissue disorder), or (4) they had previously undergone an arterial switch operation, Ross procedure, or aortic valve replacement. Patients who had undergone prior balloon aortic valvuloplasty, surgical aortic valvuloplasty, or coarctation repair were included. Subjects were added in chronologic order until a total of 100 comparisons of Doppler to cath gradient were attained. This number of comparisons was chosen to achieve >90% power to detect 5 mm Hg differences on the basis of previously published standard deviations.[34,35] The Committee on Clinical Investigation at Boston Children's Hospital approved this study.

Echocardiographic Measurements

All echocardiograms were obtained using a Philips iE33 xMATRIX echocardiography system (Philips Medical Systems, Andover, MA) and viewed on Merge Cardio workstations (Merge Healthcare, Chicago, IL). Echocardiographic images and reports were reviewed. Missing parameters were measured offline when possible.

From continuous-wave Doppler interrogations across the aortic valve, peak and mean velocities, VTI, mean Doppler gradient, and peak Doppler gradient were recorded. Velocities were converted to pressure gradients on the basis of the modified Bernoulli equation ($4V^2$). Continuous-wave Doppler interrogations from an apical window were used because these previously had been shown to correlate with invasive measurements better than those from a high parasternal view.[18]

PR (mm Hg) was calculated as previously described by Baumgartner *et al.*[32]:

$$\mathrm{PR} = 4V_{\mathrm{CW}}^2 \times (2 \times \mathrm{EOA}/\mathrm{AOA}) \times (1 - \mathrm{EOA}/\mathrm{AOA}),$$

where V_{CW} is the continuous-wave peak velocity at the vena contracta in m/sec, EOA is the effective orifice area in cm^2, and AOA is ascending aortic cross-sectional area in cm^2. The EOA in cm^2 was calculated as follows:

$$\mathrm{EOA} = \mathrm{SV}/\mathrm{VTI},$$

where SV is left ventricular stroke volume in ml, and VTI is velocity-time integral in cm. SV was calculated as the difference between left ventricular end-diastolic and end-systolic volumes. Volumes in ml were calculated as follows:

$$\mathrm{Volume} = 5/6 \times \mathrm{Area} \times \mathrm{Length},$$

where area was measured from a parasternal short-axis view at the level of the mitral valve leaflet tips in cm^2, and length was measured from an apical 4-chamber view from the mitral annulus to the apex in cm. This approach to volume calculation was chosen because studies in children have shown high accuracy and good reproducibility.[36-38] The AOA in cm^2 was calculated as follows:

$$\mathrm{AOA} = \pi \times (\text{Ascending aortic diameter}/2)^2,$$

where the diameter in cm was taken from a parasternal long-axis view as the largest internal edge dimension over the cardiac cycle. Because the optimal location for this measurement was unknown, it was performed at each of four locations for later comparison (Figure 1): (1) one aortic valve diameter distal to the valve annulus, (2) sinotubular