Noninvasive Estimation of the Severity of Aortic Stenosis
Going Beyond Bernoulli

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Ever since the original reports by Hatle et al., echocardiography has been the mainstay for diagnosing the severity of aortic stenosis noninvasively. They reported that the modified Bernoulli equation could be applied to estimate the pressure drop across a valve and that the continuity equation could be used to estimate its area. The behavior of fluids is described by the Navier–Stokes differential equations, derived from the conservation of momentum (Newton second law) and applying the conservation of energy. Using these equations and assuming negligible gravity, viscous forces, and flow acceleration, a relation can be derived between the pressure gradient between 2 points and the velocities of flow at those 2 points. This is the Bernoulli equation, the cornerstone of Doppler hemodynamics, and it is used to estimate the pressure drop that is the primary determinant of the consequences of aortic stenosis. The modified Bernoulli equation gave gradients that were 54% higher than those obtained by MR using the Navier–Stokes equations with velocities measured and averaged across the whole of the vena contracta. The mean gradient by MR in the aortic stenosis group was only 16 mm Hg, and in individual patients, differences between the 2 techniques ranged from 5% to 136%. These observations make the possibility of percutaneous valve implantation as well as open heart surgery, tomographic imaging is used increasingly, and new 3-dimensional (3D) imaging techniques are being exploited to generate 4D flow fields. In light of these developments, the accuracy of the existing methods is being re-examined.

The Bernoulli equation describes the relationship between pressure and velocity. When applied to the measurements obtained by echocardiography, it is usually simplified by assuming that the velocity proximal to a stenosis is normal (and thus low), so that only peak velocity needs to be considered. By applying the complete Navier–Stokes equations together with a 3D acquisition of the complete flow field, obtained by magnetic resonance imaging (MRI), Donati et al report in this issue of *Circulation: Cardiovascular Imaging* that some assumptions implicit in the simplified Bernoulli equation that might reduce this error, using angle-independent 2D blood velocity estimates obtained by high-frame-rate speckle tracking with dual-angle plane wave imaging, but even when there seems to be good alignment within the 2D imaging plane, there may still be poor alignment in the azimuthal plane. This application also assumes that all blood flowing through a stenotic orifice has the same velocity, so that a single measurement of peak velocity will accurately represent its flow pattern.

See Article by Donati et al

The component of the Bernoulli equation that describes convective (or advective) acceleration accounts for the other 99% of the pressure drop. This requires accurate measurement of the peak velocity across the stenosis, which is the main potential source of error using echocardiography: it is difficult to align the ultrasound beam precisely along the flow path that has the maximal velocity. New methods are being evaluated that might reduce this error, using angle-independent 2D blood velocity estimates obtained by high-frame-rate speckle tracking with dual-angle plane wave imaging, but even when there seems to be good alignment within the 2D imaging plane, there may still be poor alignment in the azimuthal plane. This application also assumes that all blood flowing through a stenotic orifice has the same velocity, so that a single measurement of peak velocity will accurately represent its flow pattern.

It can be argued that it does not matter whether an established diagnostic technique is inaccurate as long as it is reproducible and that any cut-points used for making clinical decisions have been well validated and developed from observing clinical outcomes in sufficient numbers of patients. Then, using a reproducible test will lead to predictable and appropriate clinical conclusions. Importantly, however, Donati et al suggest that in the case of aortic stenosis the echocardiographic errors are unpredictable; on average, the modified Bernoulli equation gave gradients that were 54% higher than those obtained by MR using the Navier–Stokes equations with velocities measured and averaged across the whole of the vena contracta. The mean gradient by MR in the subjects with aortic stenosis was only 16 mm Hg, and in individual patients, differences between the 2 techniques ranged from 5% to 136%. These observations make the possibility of a more accurate and reliable method than Doppler echocardiography an intriguing prospect.

It should be noted that the investigators simulated echocardiographic measurements from the 3D flow fields that were obtained with MR imaging, and they assumed that echocardiography would have detected the maximal velocity across each valve. Previous investigators who also used 4D flow MR, in a study of children and adolescents with bicuspid aortic valves, found a good correlation between estimates of peak velocity obtained by echocardiography and by MR imaging but did not question the assumption that measurements obtained using the highest velocity would be the most accurate and clinically useful. Of course, velocity varies temporally during systolic ejection, but it will also vary spatially across stenotic valves depending on the flow characteristics related to irregularly shaped orifices and stiff or rigid leaflets; thus, from a theoretical perspective, the approach of Donati et al seems more appropriate. Both studies also demonstrated that 4D...
flow MR is more accurate for quantifying aortic stenosis than phase-contrast MR because of its suboptimal spatiotemporal resolution; 4D flow gave velocities that were higher by 23%. The new method used by Donati et al17 to derive pressure gradients from MR is called work-energy relative pressure, or “WERP.” They have also developed a “simplified advective WERP” model, or SAW, and this too gave more accurate results than were obtained by simulated Doppler echocardiographic data. Their study is certainly interesting, but it leaves many questions unanswered. From a clinical perspective, it is very small, including only 12 subjects with aortic stenosis and none with severe disease (all had mean Doppler gradients <50 mm Hg). It is possible that differences between echocardiography and MR imaging become greater at higher velocities, as turbulence increases; another report suggested that methods using computational fluid dynamics are more accurate than the simplified Bernoulli equation in patients with more severe stenoses.8,9 MR techniques may underestimate peak pressure drops because of undersampling related to limited temporal resolution, which was 25 s−1 or ≈8 frames during systole; this would be a particular problem in patients with faster heart rates. The segmentation of the blood pool in the outflow tract and the aorta is based on thresholding the magnitude of the velocity field itself, rather than on an anatomic image, which leaves some room for error because of noisy measurements of boundary velocity. The spatial resolution of the technique is suboptimal, with voxel sizes of ≈2 mm3, which is above the axial resolution of echocardiography. Although the MR images are acquired in 4D, the accuracy of the work-energy relative pressure technique will depend on correct definition of the particular planes in which to apply the algorithm. This calls for interobserver reproducibility studies, including independent acquisition of images, and for intermachine comparisons, neither has yet been reported. A preliminary report, only of the reanalysis of images from 15 patients, suggested that 4D flow MR is reproducible with coefficients of variation of ≈6%.9

The investigators did not take into consideration the possible influence of downstream aortic wall function on the pressure recovery. It has been recognized recently that it is not peak systolic pressure that drives the development of heart failure in the overloaded left ventricle so much as end-systolic pressure.10 After aortic valve replacement, persistent arterial hypertension predicts lack of regression of left ventricular hypertrophy.11 Patients with bicuspid aortic valves are reported to have abnormal function of the ascending aorta.12 The clinical outcome of severe aortic stenosis is strongly influenced by left ventricular function, and in that context, all these studies imply that measurements of end-systolic load may be most important; it is likely to be influenced by aortic compliance and late-systolic wave reflections, which would not be assessed by measuring peak systolic velocity at the vena contracta. Thus, the optimal target for the new MR method has yet to be determined, but in silico simulations, using computational fluid dynamics could demonstrate the influence of aortic compliance and pressure recovery.

In conclusion, the report by Donati et al17 is an interesting proof of principle that needs to be evaluated in more detail. Given current MR acquisition sequences, obtaining the data sets with respiratory gating and then post-processing and analyzing the images are quite time-consuming compared with a Doppler echocardiographic study. Ultimately, the clinical application of the new method would depend on the demonstration of benefit over established investigations, necessitating much larger studies incorporating clinical end points based on decisions taken using the new measurements. Until then, high-quality echocardiography will clearly remain the primary noninvasive hemodynamic investigation in patients with heart valve disease,13,14 and MR will remain a research tool—but nonetheless useful for that. Both Doppler and Bernoulli will be with us for some time to come.

Disclosures

None.

References


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