EDITORIAL

Measuring Pressure Gradients After Transcatheter Aortic Valve Implantation: Rethinking the Bernoulli Principle

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Noninvasive assessment of pressure gradients by echo-Doppler has revolutionized the assessment of aortic stenosis. Before this, patients were diagnosed primarily based on the history and physical exam, with cardiac catheterization required in all cases to directly measure pressure gradients across the valve. With the validation of the simplified Bernoulli equation for pressure gradients using Doppler velocity, most patients are now diagnosed and referred for definitive therapies based on noninvasive data. The original validation studies found highly significant correlations between simultaneous echo-Doppler and catheterization systolic gradients in patients with native[1] and surgical prosthetic aortic stenosis.[2] However, with transcatheter aortic valve implantation (TAVI) now representing the dominant form of aortic stenosis therapy, and given their unique structural features, contemporary data on the validity of echo-Doppler gradients in TAVI is needed. To date, the primary limitation of Doppler-derived gradients has been underestimation due to suboptimal alignment with the direction of flow, but there is little recognition in clinical practice about potential overestimation of gradients using echocardiography.

ECHO-CATHETERIZATION CORRELATION IN TAVI

A single-center study found evidence of overestimation of echo gradients immediately post TAVI[3] but the clinical implications, predictors, and long-term outcomes of such discrepant echo-catheterization gradients was unclear. In this issue of the *Journal of the American Heart Association (JAHA)*, Abbas et al[4] now present a follow-up to their initial single-center study, with a multicenter evaluation of pre- and post-TAVI correlations of invasive and echo-Doppler systolic mean gradients across the aortic valve. The authors recruited 808 patients undergoing TAVI (78% with balloon expandable valve and 22% with self-expanding valves) of whom 547 had intraprocedural Doppler and invasive gradients measured. Pre-TAVI there was modest echo-catheterization correlation of gradients ($r=0.6$) even though there was overall a systematic lower gradient by catheterization compared with Doppler even with truly severe aortic stenosis (catheterization gradient 35 versus Doppler gradient 41 mm Hg with valve area of 0.7 cm^2). Although reported gradients after TAVI were small and clinically insignificant, there remained systematic overestimation by echo compared with the true gradient directly measured at the time of catheterization (catheterization gradient of 0 mm Hg versus echo gradient of 4 mm Hg). The authors then evaluated gradients

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stratified by valve type and size and found that smaller balloon expandable valves had the highest Doppler gradients compared with larger or self-expanding valves. Of particular interest, although the smallest balloon expandable valves had the highest Doppler gradients (median 8 mm Hg), this occurred despite negligible gradients measured by catheterization (median 1 mm Hg). This increased further to 16 mm Hg before dismissal. In terms of prognostic significance, the authors found that clinical valve dysfunction and short-term survival was not related to these measured Doppler gradients, with the important caveat that follow-up extended to only 2 years.

INTERPRETATION OF RESULTS

This is a rigorously performed multicenter study with a much larger sample size than the original echo-catheterization validation studies[1,2] or prior work by the authors in TAVI,[3] thus providing a much better representation of real-world echo-cath correlations. Therefore, the observed systematic bias toward higher gradients by Doppler both pre- and post-TAVI is an important and credible finding that requires further exploration.

We must now reflect on what might explain this and prior work[3,4] suggesting that Doppler gradients might be systematically higher in TAVI valves compared with the direct pressure gradient when invasively measured. The simplified Bernoulli equation for Doppler gradient calculation relies on measuring the velocity of blood across the stenotic valve and then uses this velocity to calculate the pressure gradient (ie, energy lost) during systole. Central to this calculation is the assumption that the increase in convective velocity across the valve is all driven by pressure loss due to the valvular stenosis. Other important assumptions for the simplified Bernoulli equation is the ignoring of local acceleration and viscous forces, along with omission of the proximal left ventricular outflow tract velocity allowing simplification of the Bernoulli equation to $4*(velocity)$.[2] It is unclear whether aortic valve gradient calculation incorporated left ventricular outflow tract velocities in the present study. Guidelines recommend inclusion of proximal velocities into the Bernoulli equation when they are >1.5 m/s or transvalvular peak velocities are <3.0 m/s. This might have accounted for some of reported discrepancies between invasively and noninvasively measured gradients, especially given the low transvalvular gradients/velocities.

It is important to point out that in the absence of a clinically significant obstruction, this simplified Bernoulli equation should not be applied for determination of an aortic valve gradient as forces other than the convective velocity from a pressure drop predominate. Thus, the small difference in the Doppler versus catheterization gradients post TAVI in most patients can be explained and is not of clinical significance. However, what is important is that there may be some patients who do have true obstruction after TAVI and that there indeed may be a clinically significant overestimation in these gradients primarily because of the concept of pressure recovery.[5–7] The phenomenon of pressure recovery reflects the fact that some of the velocity generated in flow across the valve is reconverted back to pressure energy in the proximal aorta (without a true loss in energy from the stenosis). In this case, the high velocity across the valve does not completely reflect energy lost during systole, and this portion not lost is then recovered as pressure distally in the aorta. The pressure difference between the left ventricular pressure and that "recovered" aortic pressure best reflects true energy loss during ejection and valvular stenosis burden.[8,9] In contrast, echo-Doppler picks up the highest gradient before this pressure recovery and overestimates the true degree of stenosis/energy loss (Figure). Such pressure recovery is exacerbated in the setting of high flow states, small noncompliant aortas and geometric alterations where there is not the normal outward turbulent expansion of blood past the valve in the sinuses.[5,8–10] Flow characteristics of TAVI are different from both native valve and surgical aortic valve replacement potentially affecting pressure recovery.[10] In addition, proximal aortic impedance has been shown to worsen immediately after TAVI[11] and this may also contribute to greater pressure recovery and overestimated Doppler gradients immediately post TAVI.

CLINICAL IMPLICATIONS

It is critical to evaluate valve hemodynamics following TAVI to rule out significant obstruction from either patient-prosthesis mismatch or abnormal valve function. There are several important takeaways from this study. The first is that Doppler echocardiography gradients should be interpreted critically in the absence of significant obstruction, acknowledging the limitations of the Bernoulli equation in this scenario. However, if there are more substantial gradients after TAVI, there should be caution in relying on echo-Doppler alone to diagnose true obstruction given the potential for overestimation of the true gradient. If there is clinical discrepancy and suspicion of true obstruction, direct pressure measurement by catheterization may be warranted. In follow-up, it is always important to compare with a "footprint" of a Doppler velocity after the procedure to determine whether there is a significant change with time.
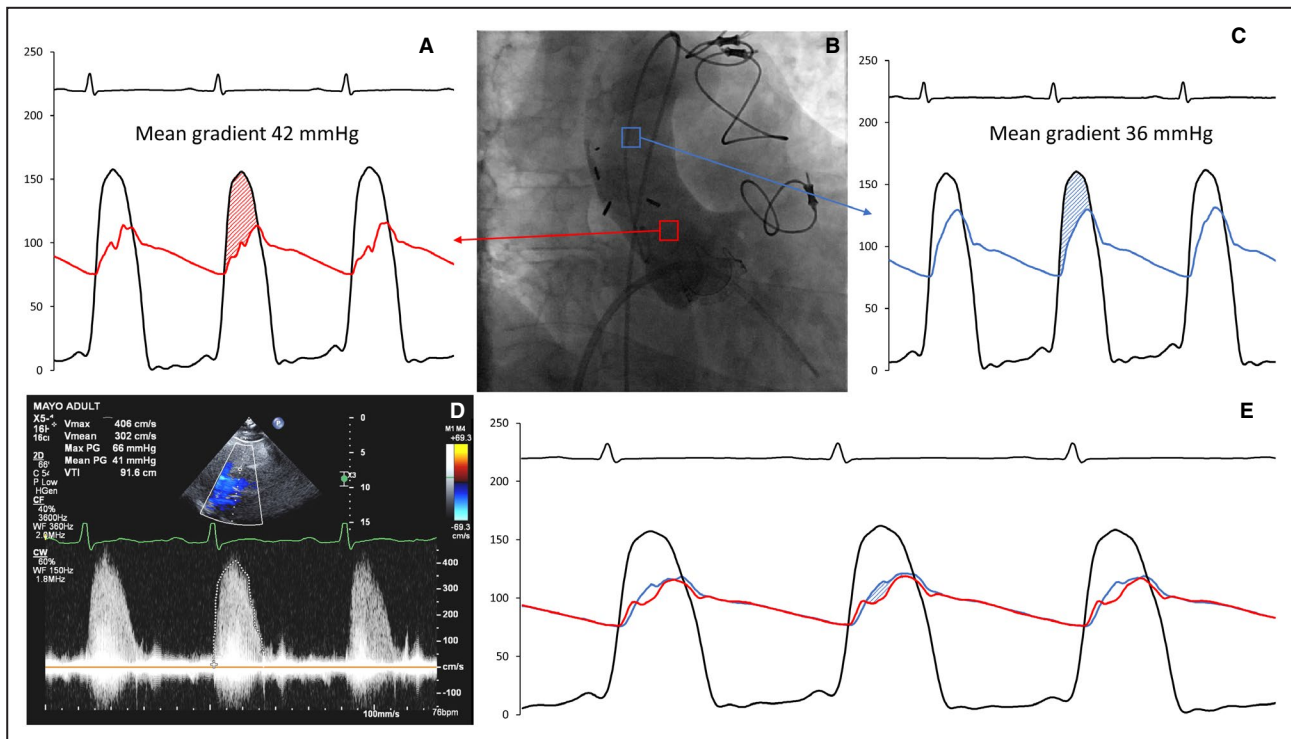
Figure. Illustrative hemodynamic data via transseptal catheterization in a patient with aortic bioprosthesis and pressure-recovery phenomenon.

Panel **A** depicts aortic pressure tracings (red) and aortic prosthesis systolic mean gradients (red shaded area) measured at the level of the sinus of Valsalva (red box, Panel **B**); left ventricular tracings are presented in black. Simultaneous continuous-wave Doppler data (right parasternal window) is shown in Panel **D**, which demonstrates similar noninvasive systolic mean gradients. Lower transaortic gradients (blue shaded area, Panel **C**) were obtained with the aortic catheter at the distal ascending aorta (blue box, Panel **B**). Panel **E** shows simultaneous proximal (red) and distal (blue) ascending aortic tracings measured using a high-fidelity manometer and fluid-filled catheter, respectively, illustrating the systolic pressure gradient between the 2 (blue shaded area). A still frame from the patient's aortogram is shown in Panel **B**; note the left ventricular catheter, placed via transseptal approach.

It is clear from randomized trials of balloon expandable versus self-expanding valves that the echo gradients post procedure tend to be higher with balloon expandable valves. Even though the difference in the gradients are small and may be related to factors other than true obstruction, their effect on long-term outcome is unknown. These differences in Doppler gradients has thus far not translated into worse outcomes with balloon expandable TAVI valves either in the randomized trials[12,13] or observational studies,[14] including the current one by Abbas et al.[4] It is possible that some of these post-TAVI gradients may be artifacts of pressure recovery and assumptions inherent to the simplified Bernoulli equation, as opposed to true patient-prosthesis mismatch or valve dysfunction. However, the effect of modest differences in the afterload on a left ventricle may not show up for many years and thus we require more rigorous long-term data on the trajectory and clinical significance of these observed gradients post TAVI and how they relate to outcomes and clinical valve dysfunction. This study by Abbas et al is an important reminder that pressure recovery is probably a more important clinical factor in TAVI than we previously thought and we should more consistently consider its potential for clinical echo-Doppler gradient overestimation.

ARTICLE INFORMATION

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Disclosures

None.

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