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Two-and Three-Dimensional Echocardiographic Assessment of the Aortic Valve

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Aortic valve (AV) is a semilunar valve composed of three cusps and its orifice normally measures 3 to 4 cm^2. Degenerative calcific changes occurring in the elderly may lead to a stenotic orifice resulting in hypertrophy of the left ventricle and symptoms such as exertional dyspnea, angina and exertional syncope. In younger patients, rheumatic involvement may produce commissural fusion leading to stenosis. AV stenosis (AS) may be associated with varying degrees of regurgitation (AR). In approximately 1-2% of population the AV is congenitally bicuspid with only 2 leaflets. This has a greater predilection for developing stenosis in younger patients and may be associated with weakness of the ascending aortic wall leading to aneurysm formation and dissection, the so-called bicuspid AV syndrome. Other variants of AV including quadricuspid and unicuspid AV have also been reported but they are rare.

Table 1: Estimation of Aortic Valve (AV) Gradients (G) and Orifice Area (A) by Echo/Doppler

A. Maximum and mean AV G's are estimated by converting maximum and mean AV velocities (V) obtained with continuous wave Doppler using the modified Bernoulli formula: $G = 4 \times V^2$ (mmHg).

B. AVA is calculated using the Doppler principle (LVOT/AV flow= area x velocity) and continuity equation (flow volume same in LVOT and aortic root). Volume of flow in LVOT is calculated by multiplying LVOT area (obtained from 2D echo measured diameter assuming circular configuration) with velocity time integral (VTI) obtained by pulsed wave Doppler. AV VTI is obtained by continuous wave Doppler. AVA $= 0.785 \times (\text{LVOT diameter})^2 \times$ LVOT VTI/AV VTI. Since VTI is related to velocities, it can be substituted by either maximum or mean velocities in this equation.
LVOT= left ventricular outflow tract.

AV STENOSIS

This is most commonly assessed by two-dimensional transthoracic echocardiography (2DTTE) and Doppler. Tables 1-3 show the methods to do this and include pitfalls and several useful tips to overcome some of them.

It should be stressed that the pressure gradients and the continuity equation are flow-dependent and thus only provide an indirect estimate of the AVorifice area (A) and the severity of AS. Under- or over-estimation of the severity of AS can be seen in up to 15% of patients. Underestimation often stems from errors in Doppler interrogation of the AV, whereas overestimation is usually seen in cases of significant pressure recovery. To overcome this, direct planimetry of the AV has been proposed as another method to obtain accurate measurement of the AV. 2D TTE planimetry is hampered by the difficulty in identifying the flow limiting tips of AV leaflets where the orifice would be smallest. This is specially the case in patients with poor acoustic windows and those with extensively calcified leaflets which makes it difficult to visualize the AV leaflets and their motion. Two-dimensional transesophageal echoardiography (2D TEE) is more helpful in obtaining planimetry of AVA because of superior quality images provided by this modality but is less helpful in obtaining maximum pressure gradients because of the difficulty in aligning the Doppler beam parallel to the AS jet in the limited windows available in the transgastric approach which is commonly used to assess AS severity.

IMPORTANT SUBGROUPS OF AS

Low Flow Low Gradient AS

In some cases, both the pressure gradient across the AV

Table 2: Criteria for Determination of AS severity

Degree of severity	AVA (cm^2)	Mean AV gradient (mmHg)	Maximum AV velocity (m/s)	Dimensionless Index (DI)
Mild	>1.5	<20	<2	>0.50
Moderate	1-1.5	20-40	2-4	0.25-0.50
Severe	< 1 (AVAi< 0.6 cm^2/m^2)	>40	>4	<0.25

2DTTE: Two-dimensional transthoracic echocardiography; AVAi: Aortic valve area indexed to body surface area; other abbreviations as in the previous table. Dimensionless index = LVOT VTI/ AV VTI. This is a useful index since it bypasses potential errors in the measurement of LVOT diameter.

Table 3: Pitfalls and Useful Tips in the Assessment of AS Severity by 2D TTE.

1.	Poor acoustic window, calcification of mitral and/or aortic valve annulus may preclude accurate assessment of LVOT diameter. Tip: Optimizing transducer angulation and gain settings may help in the latter case.
2.	Poor acoustic window may preclude accurate assessment of AV pressure gradient. Tip: All windows which visualize the AV ((apical, left and right parasternal, suprasternal/supraclavicular and subcostal) should be utilized in a given patient to obtain maximum velocities. Consider TEE.
3.	Assumption that the LVOT is circular and its cross-sectional area remains constant throughout systole (when using the continuity equation). Tip: May consider using LV-Aortic junction for LVOT measurement since it does not change in size during the cardiac cycle and appears circular.
4.	The LVOT velocity profile is assumed to be laminar and flat. Tip: Does not appear to cause any significant error in clinical practice.
5.	Doppler cursor may not be aligned with the jet core leading to underestimation of the severity of AS. Tip: Use color Doppler guidance for alignment with AS jet flow and multiple transducer angulations.
6.	Difficulty in differentiating LVOT velocity by pulsed wave Doppler from higher velocity flow acceleration. Tip: Keep pulsed wave Doppler sample volume just outside the flow acceleration area identified by color Doppler, measure diameter in mid-systole.
7.	Continuity equation gives only indirect measurement of AVA. Also, overestimates AS severity in many patients especially if the LVOT is narrow or borderline narrow (around 20 mm). Tip: Preservation of A2 by auscultation, large AVA by 2D TTE/3D TTE planimetry and good opening of AV leaflets help exclude severe AS. Beware patients with congenital AS where the domed leaflets may appear to open normally because stenosis is located at the AV tip which may not be identified by 2D TTE. 3DE is helpful in these cases.
8.	Eccentric AS jet may preclude parallel alignment of the Doppler cursor in measurement of maximum AV velocity. Tip: Use multiple transducer angulations to obtain maximum jet velocity.
9.	Jet originating from mitral regurgitation may be mistaken for or "contaminate" jet of AS. Tip: Timing of onset of LVOT waveform in relation to the QRS complex of the EKG would be same as AS jet. MR jet would originate earlier.
10.	Low stroke volume may underestimate severity of AS. Similarly, high cardiac output may lead to its overestimation. Tip: Use low dose Dobutamine when low stroke volume or flow rate as explained in the text and mentioned in Figure 1. Evaluate for underlying significant anemia.
11.	Pressure recovery may lead to overestimation of severity of AS. Tip: Correction factors have been suggested but need further validation. Beware small LVOT and aorta as explained in the text.
12.	Co-existing supra or sub-valvular pathology of the AV may impact accurate assessment of severity of AS since CW Doppler will give the maximum gradient but cannot localize its origin. Tip: Planimetry by 2D/3D TTE will help differentiate.

3DE: Three-dimensional echocardiography; other abbreviations as in previous tables.

and the AVA (as calculated by the continuity equation) may be low. This is seen in patients with underlying low cardiac output and low ejection fraction (EF), such as significant left ventricular (LV) systolic dysfunction, mitral stenosis and dilated cardiomyopathy. In these cases, it is best to proceed with low dose Dobutamine stress test (maximum dose of 20 mcg/kg/min) to assess for underlying contractile reserve and distinguish between truly severe AS and pseudosevere AS (Figure 1).

Low Gradient Severe AS with normal LV function

Severe AS by the continuity equation may also be seen in association with paradoxically low gradients in a subgroup of patients with normal LV function and EF, especially elderly women with small and severely hypertrophied LV's and advanced diastolic dysfunction. This is attributed to low transvalvular stroke volume and low flow rate (<200mL/sec) across the AV which accounts for low gradients. In these cases also, low dose Dbutamine stress echocardiography can be used to distinguish true from pseudosevere AS (Figure 1).

Pressure Recovery

Occasionally, Doppler and invasive gradients may be discordant (Doppler-high, catheterization-normal-low) and this could be due to the phenomenon of pressure recovery. This phenomenon is based on the principle of conversion of potential energy (pressure) to kinetic energy (velocity), which occurs at the level of the stenosis. Some of the energy is also lost as heat, turbulence, friction

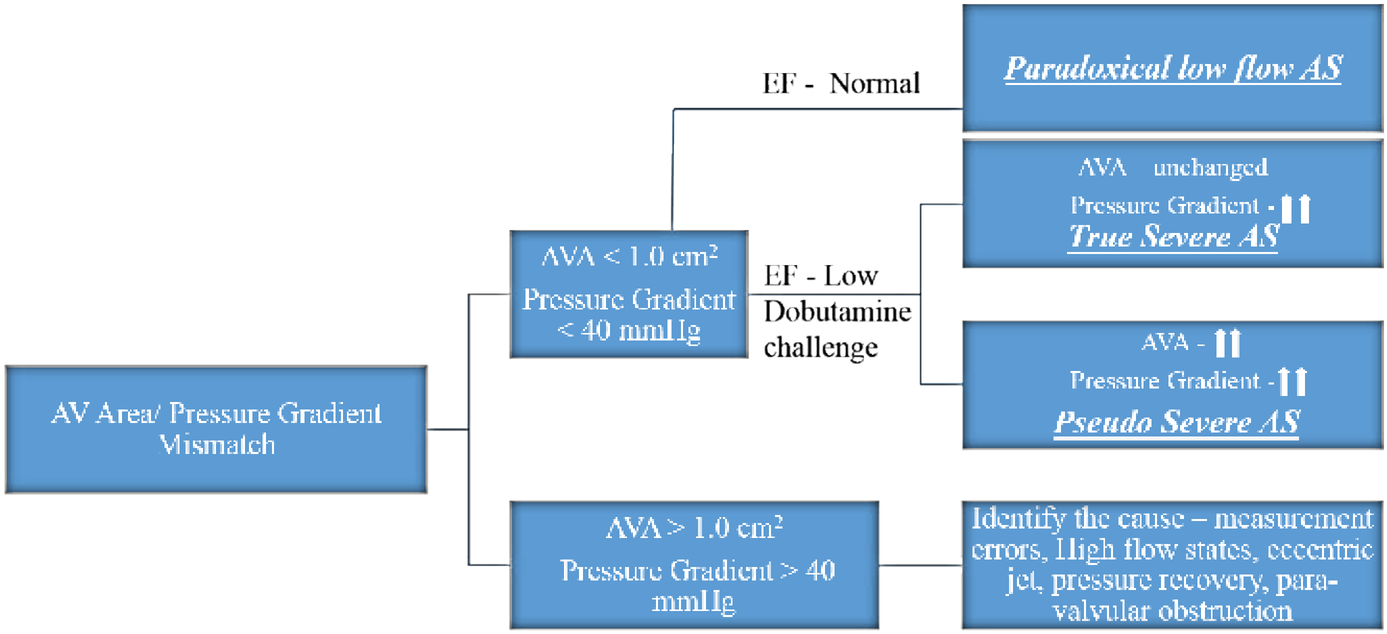

Fig. 1: Algorithm for approaching patients with severe aortic stenosis (AS) and mismatch between their aortic valve (AV) orifice area (A) and pressure gradient. When peforming a Dobutamine stress test in patients with AS, the presence (or absence thereof) of contractile reserve, defined as an increase in the stroke volume by >20% with Dobutamine, is an important prognostic marker, especially in patients undergoing evaluation for surgical replacement of the AV. Since AVA derived from the continuity equation is not reliable in many situations as explained in the text, it may be useful to assess it by two- or three- dimensional echo planimetry, preferably the latter. EF: left ventricular ejection fraction

or eddy currents. Distal to the stenosis, velocity is once again converted back to pressure ("pressure recovery"). Invasive assessment of pressure (catheterization) is always done at some distance from the stenosis (AS), which is after "pressure recovery" has already occurred. This is in contrast to Doppler measurements which are done at the level of stenosi, correlating with maximal drop in pressure. It should be noted that it is Doppler that gives the correct estimate of the gradient across the stenotic valve, however, the afterload "seen" by the LV more accurately correlates with the distal pressure as measured invasively, and therefore, catheterization-derived gradient may be more physiologic. Pressure recovery phenomenon is most often seen in patients with small LVOT (≤20mm), small diameters of the aorta (≤30mm at the level of the sinotubular junction), with long tubular AS (not discrete ones) and when there is systolic doming of the AV.

Of note, in some rare cases, AS might be severe by Doppler gradients, but not by catheterization and pressure recovery is not significant. In these cases, Doppler may be detecting focal areas of high gradients, through the heavily calcified AV. To best resolve these cases, one can directly measure the AVA by three-dimensional echocardiography (3DE) either 3D TTE or 3D TEE or even 2D-TEE and thus grade AS severity.

INCREMENTAL VALUE OF 3DE

A major advantage conferred by 3D echo over the 2D modality is its ability to acquire the entire extent of the AV and its surrounding structures in the 3D data set which facilitates cropping and sectioning using multiple planes and at any desired angulation including obtaining *en face* views of the AV. On the other hand, 2D provides only thin sections of the AV and its surrounding structures at any given time precluding comprehensive and accurate assessment. Because of this advantage, 3D provides more accurate assessment of AV morphology especially in patients with bicuspid valves with a prominent raphe which could be mistaken for a tricuspid AV on 2D imaging. Because of the ability to systemically and comprehensively section the AV data set, the flow limiting tips of the AV can also be more easily and reliably identified and the orifice area planimetered by 3D echo as compared to the 2D technique resulting in more accurate assessment of AVA. 3D TEE provides superior quality images as compared to 3D TTE but TEE is semi-invasive and not entirely devoid of risk and discomfort to the patient.

AORTIC REGURGITATION

AR can arise from abnormalities of the AV itself (degenerative calcification, bicuspid AV) or from primary dilation of the aortic root and proximal ascending aorta. In the developing world, rheumatic heart disease remains a common cause of AR. AR is primarily a state of volume overload, which over time leads to eccentric LV hypertrophy and initially an increased LV EF. As the LV slowly fails to continue adapting to the excess volume, pressure overload also develops, LV EF begins to drop and patients develop symptoms, commonly exercise intolerance and dyspnea.

Much like AS, 2DE and 3DE are the mainstay for the assessment of the presence and severity of AR. In clinical practice, this is most often done qualitatively by observing

Table 4: Echo Criteria for Grading Aortic Regurgitation (AR) Severity.

Degree of severity	AR Jet width/ LVOT width	VC* (cm^2)	PHT** (msec)	EROA*** (cm^2) by PISA method	RV+ (mL)	RF+	Holodiastolic flow reversal in isthmus/ proximal descending aorta#	LV dilation##	Density and contour of AR jet###
Mild	<25%	<0.3	>500	<0.1	<30	<30	No	No or mild	Low density, faint or incomplete contour
Moderate	25%-59%	0.3-0.6	200-500	0.1-0.29	30-59	30-49	No	Mild-moderate	Higher density compared to mild, more completely filled contour
Severe	>60%	>0.6	<200	≥0.3	≥60	≥50	Yes, Also prominent.	Severe	Similar to moderate, high density, contour spherical to triangular (very severe)

EROA: estimated regurgitant orifice area; LV: left ventricular; PHT: pressure half-time; PISA: proximal isovelocity surface area; RF: regurgitant fraction; RV: regurgitant volume. VC: vena contracta; other abbreviations as in previous tables. *VC measurements can be obtained by 3DE for greater accuracy. Add VCs if more than one jet. Potentially VC method ideal but suffers from many institutions not having 3D transducers. ** More useful in acute than chronic AR. Difficult to keep the ultrasonic beam parallel to AR jet throughout diastole and hence correct PHT may not be obtained. Also, affected by LV compliance. *** Suffers from inaccuracy because a mostly incorrect assumption is made that the flow acceleration is hemispherical. + Inaccurate in the presence of moderate/ severe MR. #Useful to confirm severe AR found by the jet width/LVOT width method and in cases with eccentric AR or where the AR jet is not well visualized. Color Doppler should be used to place the pulsed wave Doppler sample volume in the middle of the reversed flow signals (red in color) at the level of the aortic isthmus which is the junction of the aortic arch with the descending thoracic aorta (at the level of origin of the left subclavian artery) using suprasternal examination approach. Beware: pandiastolic backflow may be seen in patients with patent ductus arteriosus and other systemic arterio-venous shunts. Proximal abdominal aorta may be used if the suprasternal window is poor or unavailable but is less sensitive. ## Dilation of the LV may be seen in other conditions. ### Density and contour depend on the direction of the jet (inaccurate for eccentric AR) and their appearance might overlap for moderate-severe AR.

the proximal AR jet width in relation to LV outflow tract (OTO) diameter. Quantitative estimation requires more sophisticated 2DE and 3DE methods (See Tables 4 and 5).

TEE IN THE EVALUATION OF AR

TEE supplements TTE when the transthoracic acoustic window is poor and in the intra-operative setting. The TEE criteria used for severity assessment are essentially similar to TTE except the proximal jet width tends to be somewhat larger because of the higher resolution provided by the higher frequency TEE transducer.. Similar to AS, it is more challenging to properly align the Doppler beam and thus obtain reliable estimates of AR velocity needed for calculating, ARt volume and fraction.. However, use of TEE may improve visualization of different aortic segments and detect aneurysm or dissection which could be causing AR.

INCREMENTAL VALUE OF 3DE

As mentioned above, 3DE allows for direct, *en face*, visualization of the AV, which helps in reliable assessment of AV morphology. 3DE is superior to 2DE in evaluating other causes of AR such as vegetations, perforations and aortic fibroelastomas. 3DE has also been found more accurate in identifying mostly benign lesions such as Lambl's excrescences and thickened nodules of Arantius which can mimic tumor masses. In addition, it may facilitate grading the severity of AR by direct measurement of the area of AR vena contracta (VC), which essentially represents the "hole" or defect in the AV through which AR occurs. 3DE may also provide more

Table 5: Pitfalls and Tips in the Assessment of AR Severity by 2DTTE using AR Jet Width/LVOT Width Ratio

• Most widely used method in clinical practice.
• Preferably use parasternal long axis view since LVOT width is usually maximum in this view. Measure jet width at the origin of AR from AV (essentially the vena contracta, VC) and measure LVOT inner width in the same frame. AR jet may fan out immediately after its exit from the AV hence important not to measure the width further downstream otherwise overestimation will occur.
• Keep Nyquist limit in low fifties. Increasing the Nyquist limit which also changes the color filter tends to decrease AR jet width leading to underestimation of AR severity. Conversely, lower Nyquist limits will increase AR jet width leading to overestimation.
• Similar to the Nyquist limit, standardize color gain. Increase color gain till noise and artifacts appear, then slowly reduce it till they just disappear and use that setting for grading AR severity. Use very high Nyquist limits in eccentric jets to visualize origin and course of AR jet.
• Use multiple acoustic windows to optimize AR visualization. Short axis view not recommended to grade AR severity because cardiac motion makes it difficult to accurately identify AR jet origin.
• Severe AR found by this method may be further confirmed by suprasternal examination (see Table 4) to increase the confidence level.
• AR jet origin may be difficult to visualize in the presence of AV vegetations which may disperse the jet. Also, AR severity may be underestimated by one grade in the presence of aortic root aneurysm. In these cases, try different acoustic windows. Suprasternal examination would help in excluding severe AR

Abbreviations as in previous tables.

accurate quantification of LV volumes when following patients with chronic AR and trying to determine timing for surgery. Lastly, it might have potential in estimating the AR volume by quantifying the left and right sided stroke volumes. 3DTEE is also increasingly used in patients with prior AV replacement, both surgical and transcatheter, to more accurately diagnose paravalvular leaks by clearly demonstrating their location and size.

In conclusion, judicious use of multiple echocardiographic modalities including 2DE/Doppler, 3DE and low dose Dobutamine helps in the comprehensive assessment of the AV for stenosis and regurgitation.

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