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REVIEW ARTICLE

Echocardiographic Evaluation of Tricuspid Prosthetic Valves: An Update

Dimitrios Maragiannis, MD, FASE, FACC [a,*], Constantina Aggeli, MD [b], Sherif F. Nagueh, MD, FASE [c]

[a] *Cardiovascular Imaging Section, 401 General Army Hospital of Athens, Athens, Greece*
[b] *1st Department of Cardiology, National and Kapodistrian University of Athens, Hippokration General Hospital, Athens, Greece*
[c] *Houston Methodist DeBakey Heart and Vascular Center, Houston, TX, USA*

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Abstract This review focuses on the diagnostic value of novel echocardiographic techniques and the clinical application of recently described algorithms to assess tricuspid prosthetic valve function.

1. Introduction

Accurate prosthetic valve assessment is of great importance for clinical decisions. Current guidelines recommend noninvasive evaluation in patients with tricuspid prosthetic valves (TPV) with Doppler echocardiography.[1] Normal Doppler derived indices such as transprosthetic peak velocity, mean transprosthetic pressure gradient and pressure half time (PHT) have been reported, although not validated. Studies using large series of early postoperative data have proposed additional parameters and clinically helpful algorithms to evaluate both bioprosthetic and mechanical valves in the tricuspid position.[2,3] The addition of newer techniques such as three-dimensional echocardiography may also add value to traditional tricuspid prosthetic valve evaluation. The purpose of this review is to focus on these new proposed indices to better describe the nature of pathologic TPV dysfunction.

2. Echocardiographic Evaluation of Tricuspid Prosthetic Valve Function

2.1. 2D Echocardiography

Comprehensive evaluation either with transthoracic echocardiography (TTE) or transesophageal echocardiography

* Corresponding author. Dimitrios Maragiannis, MD, FASE, FACC, Cardiovascular Imaging Section, 401 General Army Hospital of Athens, Athens, Greece. Tel.: +306937303553.
E-mail address: dmarajohn@gmail.com (D. Maragiannis).
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(TEE) has been traditionally used to assess TPV function and structure. Standard transthoracic (RV inflow, four chamber, RV inflow-outflow and subcostal views) and transesophageal views (mid-esophageal (ME) 4 chamber, the ME inflow-outflow, the ME-modified bicaval TV and the transgastric (TG) RV inflow-outflow view)[4] can visualize the appropriate seating of the TPV in the annulus, diagnose TPV degeneration due to leaflet calcification and thickening and possibly identify causes of obstruction (thrombus, pannus, vegetation) or regurgitation (vegetation, dehiscence). Transthoracic imaging can provide excellent quality images because the tricuspid valve is an anterior structure. 2D echocardiography may also provide additional information about RV and RA size and function, which results in an integrated approach to evaluate the presence and severity of TPV dysfunction.

2.2. Color Doppler Imaging

Color Doppler shows the blood flow pattern across the prostheses. In bioprosthetic TPVs the diastolic flow jet is smooth and wide, with no apparent aliasing. In mechanical TPVs, the antegrade color Doppler jet direction and pattern may differ among variable valve types (ball cage, bileaflet valves). Color Doppler is also the preferred method for assessing TPV transprosthetic and periprosthetic regurgitation. Mild regurgitant washing jets are apparent in normally functioning mechanical TPVs, while mild regurgitant transprosthetic jets might be rarely seen in normally functioning bioprosthetic TPVs early post-surgery. Acoustic shadowing from the valve's metallic elements may interfere with color Doppler interrogation, and views with minimal shadowing are preferred with TTE (the RV inflow and the subcostal views). Multiplane TEE may offer additional views, avoiding acoustic shadowing, especially in cases when significant transprosthetic or periprosthetic regurgitation is suspected.

2.3. Spectral Doppler Echocardiography

Doppler echocardiography is currently recommended for TPV evaluation early post implantation.[1] The transprosthetic velocity can be noninvasively estimated with continuous wave (CW) Doppler and pressure gradient (peak and mean) can be estimated by applying the simplified Bernoulli equation. Adequate Doppler alignment with flow appears to be superior with traditional TTE views, whereas valve interrogation with CW by the TEE approach might be challenging in some cases. Current guidelines[1] report normal transprosthetic gradient and pressure half time values; however, additional Doppler derived parameters such as the effective orifice area (EOA) and time velocity integral (TVI) ratio have been recently described in larger population studies[2,3] to provide a comprehensive evaluation of TPV function.

Respiratory transprosthetic velocities may vary during the respiratory cycle; therefore, Doppler measurements from at least five cycles have been proposed to be averaged in current guidelines whether the patient is in sinus rhythm or atrial fibrillation. In cases of significant Doppler velocity variation, more cycles might be averaged.[1]

2.4. Mean Gradient

Current guidelines state that normally functioning tricuspid prostheses have a mean gradient <6mmHg.[1] Recently, Blawet et al. have shown that a transvalvular mean gradient <9mmHg identifies normally functioning bioprosthetic tricuspid valves.[2] They included a variety of different types of valves and sizes (Carpentier-Edwards Duraflex, Medtronic Mosaic, St. Jude Medical Biocor, Carpentier-Edwards Perimount and Medtronic Hancock II). In another study evaluating mechanical tricuspid bileaflet valves, a mean gradient <6 mmHg reflected normally functioning valves.[3] However, it should be noted that the mean gradient may be altered significantly in high flow states (anemia, hyperthyroidism, sepsis), where the valves are still functioning normally despite higher reported gradients.[1] Other conditions such as constrictive pericarditis or elevated right ventricular diastolic pressures can also affect transprosthetic gradients. Although high right atrial pressure or a noncompliant right atrium can affect the contour of the continuous wave Doppler in cases of tricuspid regurgitation reflecting the relation of pressures across the prosthesis, their contribution to the transvalvular diastolic mean gradient assessment remains unclear.

2.5. Pressure Half-Time

Pressure half time (PHT) is the time it takes for the transprosthetic peak gradient measured by Doppler to decline to half of its initial value. Current guidelines recommend that a PHT<230 msec indicates the absence of significant valve stenosis.[1] It should be noted, that rounded spectral Doppler contours are not uncommon and PHT cannot be reliably evaluated in these cases. The normal value of 200-238 msec has been proposed as an upper limit for bioprosthetic TVPs.[5,6] Blawet et al recently showed that normally operating bioprostheses in the tricuspid position have a PHT <200 msec.[2] Different values have been published for the normal mechanical tricuspid prostheses. In a recent study, a PHT<130 msec was associated with normal function in bileaflet mechanical tricuspid prostheses (St. Jude Medical Standard, CarboMedics Standard).[3] This is consistent with previously published reports, where the mean PHT ranged between 102-120 msec for St Jude bileaflet mechanical valves (St. Jude Medical Standard).[7,8] In a past study in which older prostheses types were used, Conolly et al. demonstrated that mean PHT for normal ball caged valves was 144 ± 46 msec.[5]

2.6. TVI Ratio for Tricuspid Prosthetic Valves

Similar to mitral mechanical prosthetic valves, a ratio of (TVI_{TPV}) to the left ventricle outflow tract TVI (TVI_{LVOT}) has been investigated as a useful index of tricuspid prosthetic valve function. Blauwet et al. demonstrated that a peak tricuspid E velocity <2.1 m/sec, $TVI_{TPV}/TVI_{LVOT}<3.3$ and PHT<200msec were predictive of normal TPV function in tricuspid valve bioprostheses.[2] The same group has also proposed the use of the TVI ratio for the evaluation of mechanical tricuspid valve prostheses. A peak tricuspid E velocity <1.9 m/sec, $TVI_{TPV}/TVI_{LVOT}<2.0$ and PHT<130 msec was found to be predictive of normal mechanical TPV function.[3]

2.7. Effective Orifice Area (EOA)

Effective orifice area (EOA) represents the area through which streamline or frictionless flow occurs, and it has been traditionally evaluated by echocardiography either using the pressure half time or the continuity equation method. However, the use of either the continuity equation or the pressure half time method to calculate EOA for TPVs has not been validated with *in vitro* data. In a small study including only five TPVs, Fawsy et al., using both echocardiography and catheterization data, demonstrated that EOA = 190/PHT by echocardiography compares well with the invasively derived EOA.[9] Recent comprehensive Doppler echocardiography retrospective studies have shown that EOA calculated by the pressure half time method was larger than the one calculated with the continuity equation.[2,3] Those studies have also proposed normal reference values for bioprosthetic and mechanical valve EOA in the tricuspid position.

3. Tricuspid Prosthetic Valve Obstruction

Both tricuspid bioprostheses and tricuspid mechanical valves may fail early or late after implantation. Common mechanisms of valve obstruction include leaflet degeneration, pannus formation, thrombus or vegetation obstructing transvalvular flow (Figure 1). Bioprosthetic TPV obstruction is not uncommon and occurs due to leaflet thickening and calcification. It has been reported that leaflet degeneration varies between 0.4 and 2.2% patient-years in previously published studies.[10,11] Mechanical TPVs are commonly obstructed by thrombus or pannus formation, and thrombosis has been reported at 0.5%-3.3% patient-years in earlier studies.[11–13] Doppler measurements have been shown to accurately predict TPV stenosis when compared with invasive hemodynamic data.[14,15] Current guidelines recommend 2D echocardiography and Doppler derived parameters to assess TPV dysfunction due to valve stenosis.[1]

3.1. 2D Echocardiography

Both TTE and TEE may verify abnormal leaflet structure due to degeneration with calcification and abnormal motion,

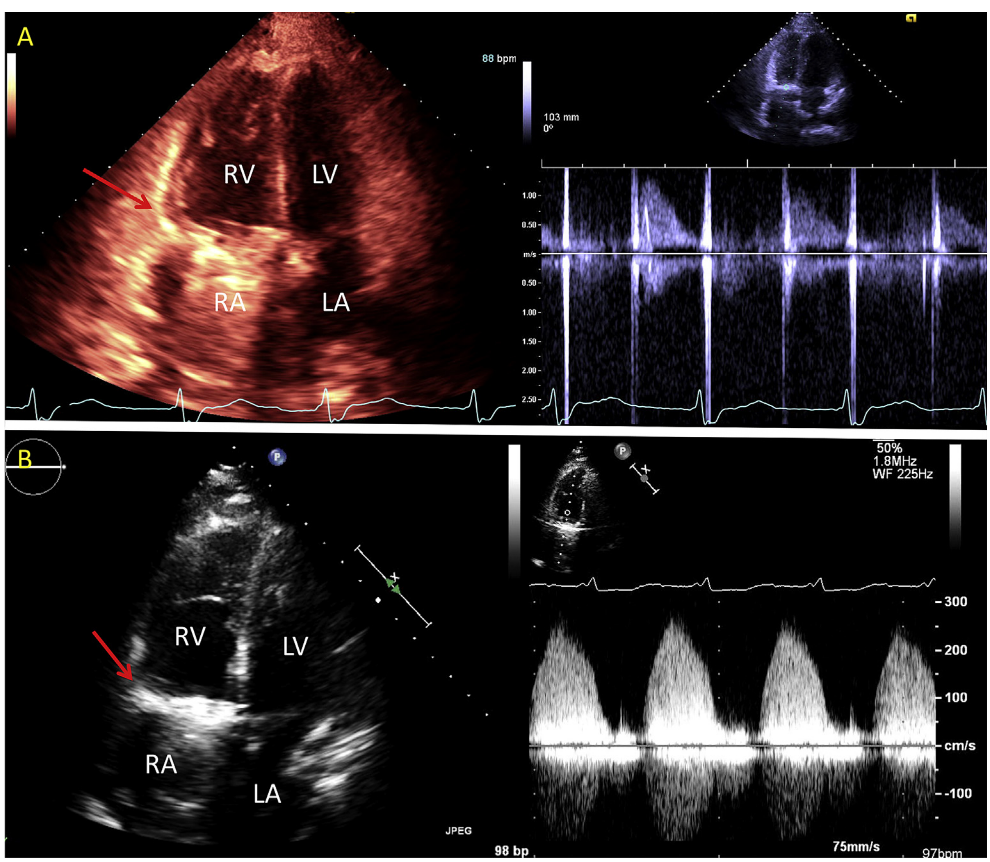

Figure 1 The figure shows a two-dimensional (2D) and continuous-wave (CW) examination of a normal mechanical tricuspid valve (red arrow) in a 66-year-old female and the same valve one month later after acute thrombosis. *Panel A*: 2D and CW examination of a normal mechanical tricuspid valve in the apical four-chamber view. Normal transprosthetic mean gradient of 2.8 mmHg was measured at a heart rate of 86 bpm. *Panel B*: 2D and CW in an obstructed mechanical tricuspid valve (red arrow) of the same female one month later due to valve thrombosis. Severely elevated transprosthetic mean gradient of 15 mmHg was measured at a heart rate of 97 bpm.

with visualization of vegetations or thrombi when present. TEE may also measure thrombus size and impact the decision on whether to use thrombolytic therapy.[16]

3.2. Color Flow Imaging

Color Doppler may add supportive information to TPV evaluation. Obstructive flow is usually turbulent and appears as a high velocity narrow color jet with aliasing. A flow convergence zone may be noted proximal to the right atrium, although acoustic shadowing may conceal this finding.

3.3. Spectral Doppler

In a large series of patients with different types of tricuspid bioprostheses during the early postoperative period, Blawet et al. have demonstrated that a PHT $\geq$200 msec is predictive of valve stenosis.[2] These findings are in line with current guidelines (PHT>230 msec).[1] In another study, the same group has reported that a PHT$\geq$130 msec identifies obstructed bileaflet tricuspid mechanical valves.[3] Additive parameters to the diagnosis of TPV obstruction are elevated mean gradient $\geq$9 mmHg, which is highly suggestive of tricuspid bioprosthetic valve stenosis, and $\geq$6 mmHg in mechanical TPVs, an elevated velocity $\geq$2.1 m/sec in tricuspid bioprostheses, whereas an abnormal value for mechanical bileaflet prostheses has been reported to be $\geq$1.9 m/sec. An abnormal EOA is also supportive of TPV obstruction.[2,3]

4. Tricuspid Valve Patient Prosthesis Mismatch

Patient prosthesis mismatch (PPM) occurs when the prosthesis is small for a patients' body size. Clinically, it presents with an elevated transprosthetic valve gradient and a small valve EOA. Blawet et al. defined PPM as an indexed EOA (iEOA) <1.2 cm^2/m^2. Severe PPM was defined as iEOA $\leq$0.9 cm^2/m^2.[2,3] A PHT$\geq$200 msec for bioprosthetic and $\geq$130 msec for mechanical tricuspid valve prostheses can differentiate the obstructed TPV from one with PPM.

5. Tricuspid Prosthetic Valve Regurgitation

TTE is the primary technique to diagnose pathologic tricuspid prosthetic valve regurgitation. TEE may offer additional information, showing the cause and the location of regurgitation when TTE is not diagnostic. Current guidelines recommend an integrated approach to quantify regurgitation using 2D, color Doppler and spectral Doppler parameters.[1] Pathologic regurgitation can occur in both bioprosthetic and mechanical tricuspid prostheses (Figure 2). However, no echocardiographic parameters associated with significant pathologic prosthetic tricuspid paravalvular or transprosthetic regurgitation have been reported in clinical studies. In bioprosthetic valves, transprosthetic regurgitation is usually caused by valve degeneration with thickening and calcification of valve leaflets or leaflet perforation due to endocarditis. In mechanical prostheses, pathologic regurgitation may occur when pannus, thrombus or vegetation prevent complete leaflet closure. Paravalvular tricuspid regurgitation, although rare, occurs when blood leaks backward during systole outside the prosthetic ring. Paravalvular regurgitation reflects usually suture loosening or infective endocarditis with the presence or absence of abscess formation.

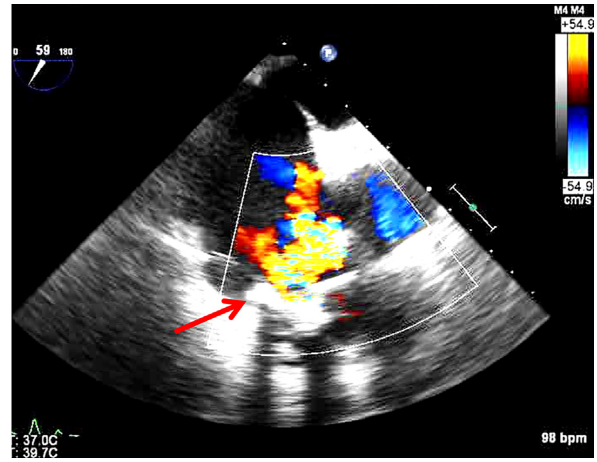

Figure 2 The figure shows the transesophageal echocardiogram (TEE) images from a 40-year-old woman with moderate prosthetic valve regurgitation. Severely thickened and calcified leaflets and moderate tricuspid regurgitation in a degenerated tricuspid bioprosthesis (red arrow).

A limited amount of regurgitation is normal in mechanical tricuspid prostheses. Regurgitant jets have a low velocity profile, they appear smooth and homogenous with color Doppler, and they are of short duration. Their flow pattern varies within different valve types. Regurgitation is not usually present in bioprosthetic valves; however, in the early postoperative period, some trace of backflow may be seen.

5.1. 2D Echocardiography

2D echocardiography using standard views with either TTE or TEE may provide a clear delineation of prosthetic valve pathology and etiology of regurgitation (dehiscence, degeneration, endocarditis, mechanical leaflet fixed in an open position). Identifying the cause of regurgitation is extremely important because clinical decisions will be based upon the echocardiographic diagnosis. The presence of substantial enlargement in the right chamber is supportive of significant prosthetic valve regurgitation although other causes may commonly affect the size of the right chamber. Inferior vena cava dilatation is also associated with significant TPV regurgitation.

5.2. Color Flow Imaging

Although color Doppler has proven to be a useful method for quantifying regurgitant lesion severity in native tricuspid valves, its value in pathologic TPV regurgitation may be more limited due to acoustic attenuation and reverberations by the prosthesis. Importantly, TTE can identify transprosthetic or paravalvular regurgitation, assess qualitatively and quantitatively the severity of regurgitation by using the radius of flow convergence and vena contracta measurements. Similar to native valves, a vena contracta width >0.7 cm is highly specific and sensitive for severe TR.[1] An alternative strategy involving TEE may add more precise information about regurgitant jet location and its direction and size, especially when TTE is not conclusive.

5.3. Spectral Doppler

Spectral Doppler derived parameters should be considered in addition to 2D and color flow imaging. An elevated tricuspid peak E velocity (≥1.9 m/sec in bioprosthetic or ≥2.1 m/sec in mechanical TPVs) and a holosystolic flow reversal in hepatic venous flow by Pulse Wave (PW) Doppler are associated with significant regurgitation. However, existing data suggest that both parameters may not be always specific for severe TR. Another common feature of severity by continuous wave (CW) Doppler is a dense, early peaking jet. Recently, Blawet et al. have reported that spectral Doppler parameters increase the confidence of identifying severe regurgitant lesions. With severe bioprosthetic TR, peak tricuspid E velocity is usually ≥2.1 m/sec, with TVI_{TPV}/TVI_{LVOT} ratio ≥3.3 and PHT<200 msec.[2] For severe mechanical TR, peak tricuspid E velocity is ≥1.9 m/sec, TVI_{TPV}/TVI_{LVOT} ratio ≥2.0 and PHT<130 msec.[3]

In summary, dehiscence of the prosthesis by 2D echocardiography, a wide vena contracta width (≥0.7 cm) and /or the presence of significant flow convergence zone when combined with dilated right heart chambers are all supportive of severe tricuspid prosthetic valvular or paravalvular regurgitation. Spectral Doppler parameters previously described may enhance the confidence of the diagnosis.

6. 3D Echocardiography

Multiplane TEE is indicated for the evaluation of prosthetic valve regurgitation (severity and mechanism), the evaluation of suspected valve obstruction (presence of thrombus or pannus), the evaluation of endocarditis and associated abnormalities (vegetation, valve abscess, fistula, pseudoaneurysm) and for guidance of transcatheter procedures.[4] 3D TTE and TEE offer additional diagnostic value in identifying pathologic TPVs (Figure 3). A very limited number of studies have addressed the role of novel technology in

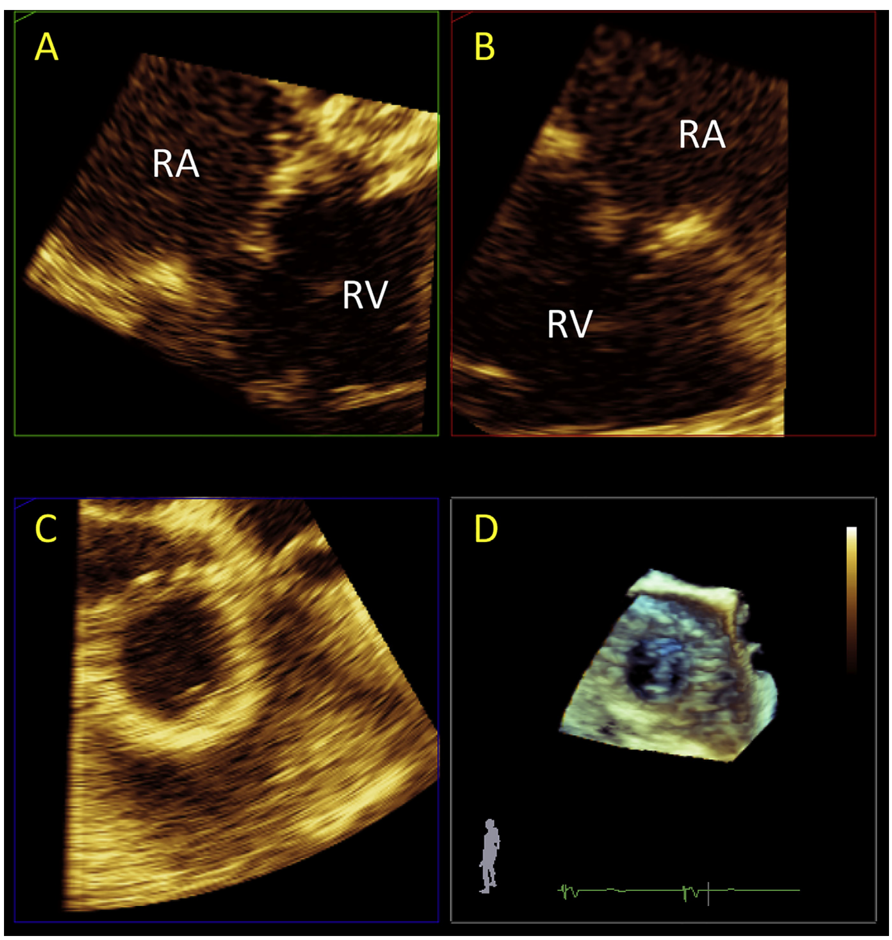

Figure 3 Three-dimensional transesophageal echocardiography (TEE) of a normally functioning 10-year-old bioprosthetic valve in the tricuspid position. *Panel A, B*: Two-dimensional orthogonal long planes of the bioprosthetic valve, created by the volumetric data. *Panel C*: Short axis (en face) view of the valve surgical ring. *Panel D*: 3D volume data, showing the thin leaflets of the tricuspid bioprosthetic valve.

prosthetic valve evaluation in the last decade, but the number of the TPVs evaluated in these studies was very small.[17,18] According to recently published guidelines, the native tricuspid valve's evaluation is enhanced by 3D echocardiography at the mid-esophageal 4 chamber-view from 0° to 30° or at the 40° transgastric view using a narrow-angle or a wide-angle acquisition with either a single-beat or multiple-beat acquisition.[4,19] Dehiscence locations, regurgitant jet sites, vegetations, degenerative leaflets, thrombi and immobile leaflets can be identified by 3D TEE.[20,21] The limited temporal and spatial resolution are inherent limitations of 3D echocardiography. Stitching artifacts are also prominent in patients with arrhythmias. Further research is needed to investigate the diagnostic role of 3D echocardiography in evaluating TPV structure and function.

7. Tricuspid Transcatheter Valve-in-valve Implantation

2D and 3D TEE have been successfully used for the deployment of percutaneous transcatheter valves in severely dysfunctional bioprosthetic TPVs in high surgical risk patients using the transatrial, transjugular or transfemoral approach. TEE is the modality of choice during transcatheter valve in valve implantation.[4] Only a few cases in literature[22–29] have been reported, mostly describing implantation of either the Melody valve (Medtronic, Inc., Minneapolis, MN, USA) or Edwards SAPIEN transcatheter valve (Edwards Lifesciences, Irvine, CA, USA). Currently, Doppler parameters and normal reference values from surgical prosthetic valves are used in clinical practice to assess percutaneous valve function; however, additional data on the hemodynamic performance of these valves using Doppler derived parameters in larger patient populations are needed.

8. The role of other modalities

An ECG gated multidetector computed tomography collecting 3D dataset may reconstruct and visualize the valve anatomy, paravalvular regurgitation on any plane, identify abscesses, thrombus or pannus in most cases on an offline analysis system. MDCT is an accurate modality for identifying the mechanism of valve obstruction; however, radiation, contrast use and artifacts from the prostheses are still a concern.

CMR may provide anatomic (anatomic orifice area by planimetry) and functional information (peak velocity through the valve, calculation of regurgitant volume/fraction). By using volumetric data from the right ventricle ejection fraction calculation and the phase contrast measurement of flow through the pulmonary artery, CMR may evaluate tricuspid regurgitant volume/fraction. However, both bioprosthetic and (especially) mechanical valves generate significant metallic artifacts, which creates difficulties in interpretation. Phase contrast measurement of through plane velocity can be underestimated if it is not perpendicular to the flow direction and should be measured at the location of maximal velocity. The temporal resolution of CMR is lower than continuous wave Doppler, and annular motion during cardiac cycle generates additional sources of error for velocity measurements. To our knowledge, there are no published reports describing the accuracy of CMR measurements for tricuspid valve prostheses.

9. Conclusion

Echocardiography is the primary diagnostic modality for the evaluation of tricuspid prosthetic valve function. Early postoperative examination and comparative echocardiographic follow-up studies may unmask possible valve dysfunction. In the era of multimodality imaging, echocardiography remains a widely available inexpensive method with enough evidence incorporated in current guidelines to accurately evaluate tricuspid prosthetic valve function. The diagnostic role of 3D echocardiography to the routine assessment of tricuspid prosthetic valves warrants further investigation in larger population studies.

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