3D ECHOCARDIOGRAPHY: A NEW PARADIGM IN HEART VALVE DISEASE

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BACKGROUND

The technology for three-dimensional echocardiography (3D echo) has been in development for more than 30 years.[1] An important milestone along char path was the development of real-time 3D (RT-3D) echo in the early 1990s.2 This new, and for the first rime commercially viable, ultrasound format acquired volumetric image data with sufficient frame rate co display and analyze cardiac motion. The last several years have seen a remarkable increase in 3D imaging technology and potential clinical applications.

However, despite an impressive array of new applications, 3D echo imaging has not radically changed our approach to many areas of diagnostic cardiac imaging. This relatively slow wave of change is largely due to che excellent image quality generally afforded by current cwo-dimensional (2D) echocardiography techniques. The advent of harmonic imaging, contrast imaging, and ultrasound probe refinements have made 2D ultrasound imaging a difficult standard to improve upon. Nevertheless, rwo important technical advancements have recently changed the imaging landscape and will undoubtedly lead to the widespread adoption of at least some of these new 3D echo tools. The first advance was the creation of the 3D live marrix ultrasound transducer, typically containing more than 3,000 imaging elements. This new cool has made it possible co capture large volumetric data secs that can be interrogated to define cardiac chamber volumes, volume change (ejection fraction) and, most recently, left ventricular (LV) systolic strain and synchrony.3 The second and very recent advance was the further miniaturization of the macrix crystal cechnology to create a rransesophageal echo (TEE) probe able to capture and display live 3D images as well as 3D color Doppler data.

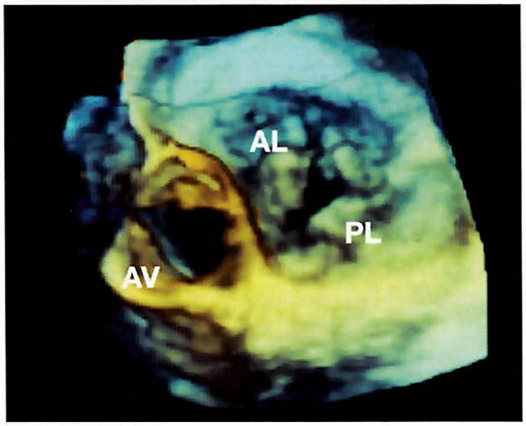

Figure 1. Real-time 3D TEE demonstrating aortic and mitral valve continuity. Systolic image depicting a normal aortic valve (AV) with three open cusps and an abnormal mitral valve with severe prolapse of both the anterior (A) and posterior (P) leaflets.

While 3D echo has proven useful in the quantification of chamber dimension and function, perhaps the greatest impact of these new technologies has been in the assessment of heart valve structure and function. The 2D echo technique relies upon an interpreting physician to make assumptions about ventricular and atrial geometry and to extrapolate an assessment of volume and function from multiple 2D image slices. For the assessment of cardiac chambers, these geometric assumptions are largely true. On the ocher hand, the geometric complexicies and nonplanar anatomy of both normal and abnormal valve function are becrer appreciated by 3D echo interrogation, which permits cropping and analysis in any image plane (Figure 1). Perhaps the best illuscracion of chis imaging potential is in the recent clinical and research fucus on 3D echo assessment of the mitral valve.

MITRAL VALVE

Anatomic Insight

The recent proliferation of publications describing some aspect of mitral valve anatomic function can be credited to the widespread availability of RT-3D tools.[4,7] One of the first applications of transchoracic 3D echo was for the direct assessment of valve area in micral stenosis. Several investigators have now demonstrated that chis method is comparable to carhecer-based assessment of stenoric area and usually superior co 2D echo assessment.[8,9] Three-dimensional echo has facilitated easy recognition of the mitral annular "saddle" shape, and our group along with others have been able to exploit this wealth of 3D data co describe che dynamic conformation change of the mitral annulus throughout the cardiac cyde.5,7,[1]O

Anocher important funccional relationship revealed by RT-3D imaging is the dynamic structural associations of the submitral apparatus. We are now able to accurately identify papillary muscle position, chordae insertion, chordae length, and the effect of this geometry on mitral leaflet closure during systole (Figure 2). Indeed, these anatomic insights are clearly evident when comparing the mechanism of "functional" mitral regurgitation (MR) with altered papillary muscle geometry creating secondary MR co chat ofa primary leaflet pathology such as myxomacous valve disease.[4,6,11] Already there is a growing research and commercial interest in the characterization and quantification of leaflet stresses under both normal and pathologic conditions. Undoubtedly, as this work continues we will discover clear associations between 3D geometry and valve-apparatus stress and hopefully be able co refine and apply chat knowledge co improve our predictions about both clinical and surgical management of mitral valve disease.

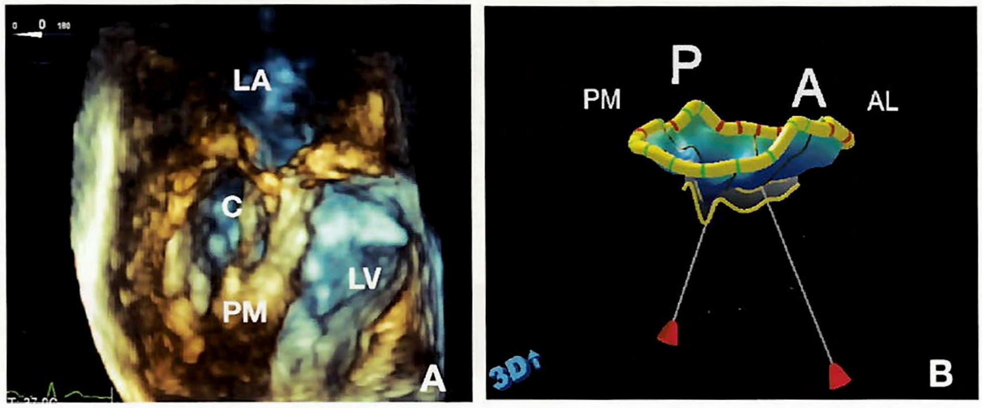

Figure 2. Live 3D transesophageal image of the mitral valve complex. Panel A shows the postero-medial papillary muscle (P}, chordae tendinae (C), and mitral leaflets. Quantitative analysis (panel B) can be performed to assess a host of novel valve parameters including mitral annulus area and geometry, leaflet area and tenting volume, and tethering distance to papillary muscles. These parameters are becoming increasingly important for surgical valve repair procedures.

Quantification of Flow

An exciting application of 30 rechnology is the use of 3D color Doppler (30-CD) for the quantification of color flow events. Classically, lesions such as MR have been quantified based on color Doppler parameters including the proximal flow convergence zone, vena contracta diameter, and regurgitant color jet volume.12 However, these 2D color Doppler applications must rely upon imporcant and often limiting geometric assumptions about the regurgitant flow characteristics. The use of 3D-CD interrogation permits a unique perspective on these abnormal flow events and allows novel mechanisms of quantification.

Our group has recently described che quantification of MR using 30 vena contracta area (not just 2D diameter) in both an imaging flow loop model of MR as well as a description of our initial clinical experience {Figure 3).[13] We demonstrated char measurement of vena contracta area is feasible with 30-CD and provides a simple parameter that accurately reflects MR severity, particularly in eccentric and clinically significant MR in which geomecric assumptions may be challenging.[13] Our group and ochers have also described the use of 3D flow convergence analysis (PISA method) as an attractive Doppler quantification tool for MR severity.[14-16]

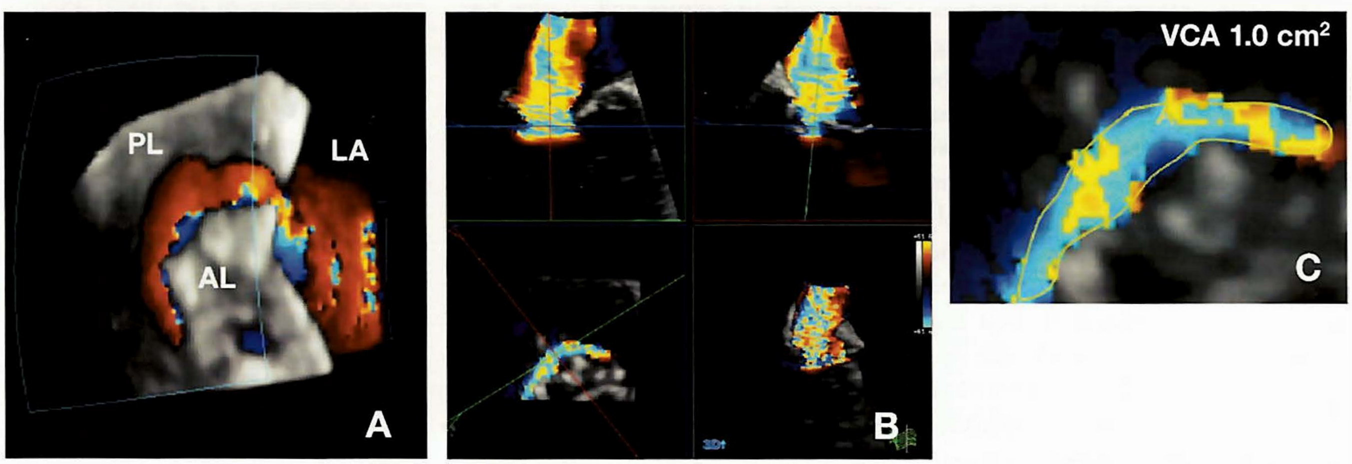

Figure 3. 3D color Doppler for the quantification of asymmetric regurgitant flow. Panel A shows the crescent-shaped proximal flow convergence zone created by an extensive coaptation defect in "functional" mitral regurgitation. The 30 color Doppler data is cropped to reveal the true short-axis of the vena contracta zone (panel B, upper images are long-axis views, lower left is short-axis). The highly asymmetric vena contracta (VG) area is traced to provide a quantitative measure of MR severity. In this case the VC area is 1.0 cm^2, which is consistent with severe MR (panel C, zoomed image of lower-left image in B).

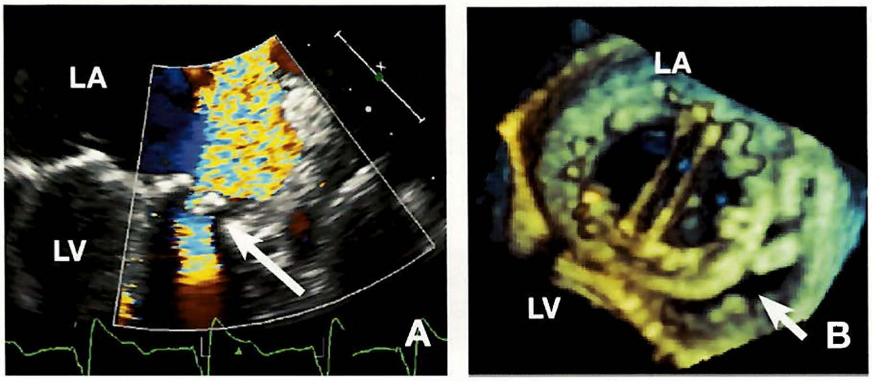

Figure 4. Anatomic insight into the 30 geometry of paravalvular defects. A bi-leaflet (St. Jude) mechanical mitral *valve* with 20 and color Doppler TEE assessment of a large paravalvular defect along the antero-lateral portion of the annulus (panel A. shown in systole). *Live* 30 TEE cropped to create a lateral view of the defect (arrow) at the origin of the LA appendage (Panel B, shown in diastole). Left atrium (LA); left ventricle (LV). Precise localization of the paravalvular defect as well as live 30 catheter guidance is now making percutaneous paravalvular repair an alternative to reoperation for some patients with significant paravalvular regurgitation.

Mitral Valve Repair

Three-dimensional echo has enhanced our understanding of the geometric distortions (affecting papillary muscle, leaflets, and mirral annulus) and asymmetric flow characteristics responsible for significant MR.[17-19] This anatomic insight has already influenced the surgical approach co mitral valve repair. Perhaps the most impressive early application of the new matrix 3D TEE has been in the intra-operative environment. With real-rime acquisition and image display, we now have the ability to view the mitral valve leaflets in an en-face perspective from the left atrium. This live beating image of the mirral leaflets can be readily rotated to create a perspective familiar to the surgeon (with che aortic valve displayed as ancerior). Compared to standard 2D TEE images, live 3D TEE increases operator confidence in identifying leaflet prolapse and improves sensitivity for the detection of flail chordae and leaflet scallops (Figure 4).

AORTIC VALVE

The use of RT-3D for the quamificarion of aortic stenosis severity has been well validated. Several groups have demonstrated that any-plane cropping of the RT-3D data set improves direct visualization and accurate planimetry of a stenosis aortic valve orifice.[20-22] Recently, Poh and colleagues also demonstrated that rhe LV outflow stroke volume assessment is more accurate using a novel 3D-CD application when compared co 2D Doppler method, the lacter being dependent upon an assumption (often incorrect) of a circular outflow trace geometry. Applying the continuity equation, with use of 3D-CD LV stroke volume assessment, leads co improved correlation with aortic valve area defined by direct planimetry of the stenoric valve area.[22] Quantitative applications of 30-C0 flow have also been validated for the assessment of aortic regurgitation severity.[23,24]

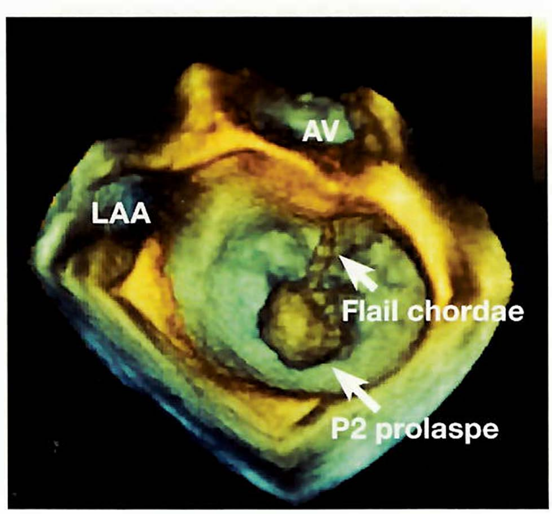

Figure 5. Live 30 TEE during mitral valve repair surgery. This systolic image clearly demonstrates isolated prolapse of the middle scallop of the posterior mitral leaflet (P2) as well as flail chordae tendinae.

PROSTHETIC VALVES

Another early and impressive application of the 3D matrix TEE is in the evaluation of prosthetic valve function. Although associated with significant morbidity, prosthetic paravalvular regurgitation is sometimes difficult to identify and always difficult to quantify by 20 TEE. The unique imaging perspective afforded by 3D TEE has had an immediate impact on our ability to differentiate valvular (through the prosthesis) from paravalvular (around the prosthesis) regurgitation (Figure 5). In addition, 3D-CD permits a novel view of the regurgitant jet flow, and 30 measures of regurgirant severity are being explored. Coupled with this diagnostic power is a new and exciting role in assisting with percutaneous closure of significant paravalvular leaks. Our group was one of the first ro describe the role of 3D TEE to guide these catheter-based repair procedures.[25]

Looking forward, 30 echocardiography will undoubtedly continue co define and refine its role in guiding interventional catheter-based procedures. As percutaneous aortic valve scenting works its way inco mainstream clinical practice, it is very likely chat 30 matrix TEE will become an integral tool for both imaging and intervemional cardiologists.

CONCLUSIONS

The complex geometry and nonplanar motion of cardiac valve function creates a unique problem for diagnostic imaging. Three-dimensional echocardiography has undergone significant refinement and, in its present form, is currently emerging as the best imaging solution. For the assessment of heart valve disease, the future of 3D echocardiography appears assured.

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