Evaluation of the tricuspid valve morphology and function by transthoracic real-time three-dimensional echocardiography

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Assessment of tricuspid valve (TV) function plays an important role in a number of clinical disease states, including left-sided valve disease and heart failure. However, the TV is a complex structure that, unlike the aortic and mitral valve, it is not possible to visualize in one cross-sectional view using either transthoracic or transoesophageal two-dimensional echocardiography (i.e. imaging all three TV leaflets and their attachment in the annulus simultaneously). Conversely, three-dimensional echocardiography allows users to visualize the whole TV apparatus from any perspective. This may significantly improve our understanding of the pathophysiological mechanisms underlying the various TV diseases and functional tricuspid regurgitation, and potentially suggest ways to improve surgical treatment. This review details the current status of real-time three-dimensional echocardiography evaluation of TV morphology and function with its clinical applications and limitations.

KEYWORDS
Echocardiography; Three-dimensional; Real-time; Tricuspid valve; Tricuspid insufficiency; Tricuspid stenosis; Tricuspid regurgitation; Surgery

Introduction
Function of the tricuspid valve (TV) plays an important role in several heart diseases, including left-sided valve disease and heart failure, and the development of functional tricuspid regurgitation is directly associated with increased morbidity and mortality.1–5 These data have increased motivation to repair functional tricuspid regurgitation, especially at the time of concomitant surgery for left-sided disease.3 However, the unsatisfactory results of current approaches suggest an incomplete understanding of the underlying mechanisms.3,6 As in the case of mitral regurgitation, a better understanding of the pathophysiological mechanisms underlying functional tricuspid regurgitation could potentially suggest ways to improve surgical treatment.

The assessment of the TV is mostly done by two-dimensional echocardiography (2DE) despite unique configuration of tricuspid leaflets and annulus, and anatomic complexity of the right ventricle. As a result, simultaneous visualization of the three TV leaflets has not been achieved routinely from standard 2DE imaging views. Usually, only two leaflets can be imaged in one 2DE view and determination of individual leaflet involvement (especially the posterior leaflet) is challenging when a disease process is present.7 This limitation can be partially overcome with an anterior to posterior sweep to see both the anterior and the posterior leaflets using the apical 4-chamber or subcostal view. Afterwards, the echocardiographer starts a difficult mental process to reconstruct a stereoscopic image of the TV based on the interpretation of the multiple tomographic images obtained with the sweep. Sometimes, the mental exercise of reconstruction may be inadequate to obtain a precise diagnosis even for an experienced observer, particularly when dealing with complex valvular abnormalities.

The advent of real-time three-dimensional echocardiography (RT-3DE) may obviate for this exercise by allowing a more objective and quantitative evaluation of TV anatomy and function that would reduce the subjectivity in the interpretation of images. However, compared with the mitral and aortic valves, the TV has been less widely studied with 3D echocardiography.

This review details the current status of RT-3DE evaluation of TV morphology and function with its clinical applications and limitations.
Anatomy

The TV is a complex anatomic structure composed of leaflet tissue, chordae tendineae, papillary muscles, and the supporting annular ring, right atrium, and ventricular myocardium and it is the most apically placed valve with the largest orifice.

The TV leaflets (anterior, posterior, and septal) are attached to a fibrous annulus and are of unequal size: the anterior leaflet is usually the largest and extends from the infundibula region anteriorly to the inferolateral wall posteriorly; the septal leaflet extends from the interventricular septum from the infundibulum to the posterior ventricular border; the posterior leaflet attaches along the posterior margin of the annulus from the septum to the inferolateral wall. The insertion of the septal leaflet of the TV is characteristically apical relative to the septal insertion of the anterior mitral leaflet.

The tricuspid annulus shows a non-planar structure with an elliptical saddle-shaped pattern having two high points (oriented superiorly towards the right atrium) and two low points oriented inferiorly toward the right ventricle that is best seen in mid-systole.

Three papillary muscle groups usually support the TV leaflets and lie beneath each of the three commissures.

Approaches to three-dimensional imaging of the tricuspid valve

Unlike the aortic and mitral valve it is not possible to visualize all TV leaflets simultaneously in one cross-sectional view by standard 2DE either transthoracic or transoesophageal due to the position of the TV in the far field (Figure 1). RT-3DE supplements 2DE and transoesophageal echocardiography with detailed images of the morphology of the valve including leaflets size and thickness, annulus shape and size, myocardial walls, and their anatomic relationships. RT-3DE with its unique capability of obtaining a short-axis plane of the TV allows simultaneous visualization of the three leaflets moving during the cardiac cycle and their attachment in the tricuspid annulus (Figure 2). RT-3DE allows the echocardiographer to visualize leaflet coaptation and separation of the commissures. A detailed anatomic structure of the TV including unique description and measurement of tricuspid annulus shape and size, TV leaflets shape and mobility, and TV commissural width has been reported by Anwar et al.

Like 2DE, there are three main approaches to be used with RT-3DE: parasternal, apical, and subcostal. However, when trying to imagine a cardiac structure with RT-3DE we should take into account the point spread function of the system that describes the response of any imaging system to a point object. The degree of spreading (blurring) of any point object varies according to the dimension employed. In current RT-3DE systems it will be around 0.5 mm in the axial or azimuthal (y) dimension, around 2.5 mm in the lateral (x) dimension, and around 3 mm in the elevation (z) dimension. As a result we will obtain the best images (less degree of spreading, i.e. distortion) when using the axial dimension and the worst (greatest degree of spreading) when we use the elevation dimension. These concepts have an immediate practical application in the choice of the best approach to obtain an en-face view of the TV from the right atrium (the so called ‘surgical view’). According to the point spread function of RT-3DE, the best results are expected to be obtained by using the parasternal short-axis approach because structures are imaged by the axial and lateral dimensions. Conversely, the worst result is expected to be obtained by the apical approach which uses the lateral and elevation dimensions. An intermediate result will be obtained by using the
parasternal right ventricular inflow in which the axial and elevation dimensions are used.

An additional feature of matrix array 3D transducer is that they can acquire both in actual real-time (particularly in real-time zoom mode), and in full-volume (wide angled) acquisition (i.e. four consecutive cardiac cycles merged together). Both of these acquisition modalities are useful for imaging the TV. The real-time zoom mode has several advantages over the full-volume acquisition: (1) image resolution is much higher than that of full-volume mode; (2) since we do not need neither suspended respiration nor acquisition of multiple cardiac cycles, it is feasible also in dyspnoic patients and in patients with atrial fibrillation; (3) the possibility to electronically steer the 3D beam by rotating the ‘track ball’, with no need of moving the transducer, may be a major advantage for the purpose of imaging the TV from the parasternal approach, because this approach often requires a very acute angle between the transducer and the skin combined with the need to fit a large transducer footprint between a rib interspace. (4) by steering the 3D beam in order to place the long axis of the TV along the y-axis can facilitate visualization of the three leaflets and the full shape of the valve orifice from both atrial or ventricular side. Using full-volume acquisition allows a wider coverage of the region of interest. Therefore, most relevant structures and their spatial relationships (e.g. leaflets, chordae, and papillary muscles) can be more realistically delineated, and anatomic continuity can be assessed. But this approach has at least two major limitations: (1) a reduced spatial resolution of the structures with respect to the real-time zoom mode, and (2) the possible presence of artifacts due to rhythm disturbances and respiratory movements.

From the practical point of view, in order to acquire an RT-3DE data set of the TV, it is recommended to place the transducer in a modified parasternal long-axis position to visualize right ventricular inflow, set the overall gain control higher than normal, centre the TV in the 3D volume, steer the 3D beam, or manually adjust the transducer, to optimize the image to simultaneously view all three leaflets and acquire. From the apex, the TV can be imaged in a similar way as it is used for 2D imaging. Acquisition of a full-volume data set or real-time zoom mode from the apical approach optimized for right heart structures will yield the widest field of visualization for the TV complex (e.g. leaflets, annulus, chordae, papillary muscles, and right ventricle) allowing assessment of their spatial relationships and anatomic continuity. After acquisition, cropping from the apex towards the base, or from the atrial roof towards the apex will display the en face view of the TV from the ventricular and from atrial (‘surgical view’) side, respectively. Frequently, it is possible to visualize TV and mitral valve side-by-side by full volume modality. The subcostal approach can be used in some patients to obtain adequate views of the TV. Beam steering is very useful when using this approach because an acute angle between the abdomen surface and the transducer is frequently required to place the transducer close to the liver and below the costochondral junction.

In patients with good 2DE images, assessment of TV anatomy and function with RT-3DE is feasible in around 90% of normal subjects.7

Tricuspid regurgitation

The most common cause of tricuspid regurgitation is not a primary TV disease but rather an impaired valve coaptation caused by a dilation of the right ventricle and/or of the tricuspid annulus.11 A variety of primary disease processes can affect the TV complex directly and lead to valve incompetence: infective endocarditis, congenital disease like Ebstein anomaly or atrioventricular canal, rheumatic fever, carcinoid syndrome, endomyocardial fibrosis, myxomatous degeneration of the TV leading to prolapse, penetrating and non-penetrating trauma, and iatrogenic damages during cardiac surgery, biopsies, catheter placement in right heart chambers (Figure 3).12-18

As in the case of mitral regurgitation, a complete understanding of leaflet morphology and of the pathophysiological mechanisms underlying tricuspid regurgitation could potentially lead to improved techniques for valve repair and to design physiologically suitable annular rings.

Even though primary valve diseases are uncommon causes of TV regurgitation, RT-3DE can be useful for a better characterization of valve lesions in different aetiologies (Figure 3). Rheumatic involvement of the TV is less common than that of left-sided valves. Regurgitation is a consequence of deformity, shortening and retraction of

![Figure 2](https://example.com/figure2.jpg) Normal tricuspid valve leaflets visualized by real-time three-dimensional echocardiography from atrial (left panel) and ventricular side (right panel). ATL, anterior tricuspid leaflet; Ao, aorta; MV, mitral valve, PTL, posterior tricuspid leaflet; STL, septal tricuspid leaflet.
one or more leaflets of the TV as well as shortening and fusion of the chordae tendineae and papillary muscles. 2DE usually detects thickening and the distortion of the leaflets but cannot provide a comprehensive assessment of extension of valve apparatus involvement. The full-volume data set from apical approach usually provides a comprehensive assessment of the whole TV apparatus which can be examined from different perspectives. The ‘en face’ view of the TV obtained by RT-3DE allows the visualization of the commissural fusion which is helpful to establish a correct diagnosis of rheumatic aetiology of TV regurgitation (Figure 3F). TV leaflets’ involvement in degenerative myxomatous disease is visualized by RT-3DE as bulging or protrusion of one or more segments of a single or multiple TV leaflets (Figure 3A). In addition, the presence of chordal rupture and extension of the concomitant annular dilation can be assessed in the same view (Figure 3A). In the carcinoid disease, the valve appears thickened, fibrotic with markedly restricted motion during cardiac cycle, RT-3DE can show the regions of ineffective leaflet coaptation and the lack of commissural fusion (Figure 3C).

Tricuspid annular dilatation seems to be the underlying mechanism of functional TV regurgitation. The extent of TV annulus dilatation may be a more reliable indicator of TV pathology than the degree of regurgitation itself.3

Using RT-3DE, two independent groups10,19 were able to demonstrate that, similar to the mitral annulus, the normal TV annulus is saddle shaped, with the highest points located in an anterior–posterior orientation and the lowest points in a medio-lateral orientation (Figure 4). They also elucidated the mechanism of functional tricuspid regurgitation by showing that with the development of functional TR, the tricuspid annulus becomes dilated, more planar, and circular. In addition, they showed that as the annulus becomes more circular with tricuspid regurgitation, the increase of the anterior–posterior distance was greater than that of the medio-lateral distance. This may result from dilation of the tricuspid annulus preferentially along...
its free-wall distance. This latter finding has an important clinical implication.

Matsunaga et al.20 demonstrated that pre-operative tricuspid annular dilation was associated with the development of late post-operative tricuspid regurgitation after repair of ischaemic mitral regurgitation. Dreyfus et al.3 reported that when the decision to perform tricuspid annuloplasty was based on the extent of tricuspid annular dilation rather than the degree of tricuspid regurgitation at the time of surgery, the long-term outcome of patients was improved. Reference measures for TV repair include tricuspid annulus size $\geq 2.1$ cm/m² and tricuspid annulus fractional shortening $\leq 25\%$.21 However, both Matsunaga and Dreyfus used 2DE for decision-making surgery and this may have led to some inaccuracies in measuring the true annular size.

Anwar et al.22 demonstrated that the tricuspid annulus shape is not circular but oval, with a minor and a major diameter, both in normal sized and in dilated annulus. In addition, they showed that the currently used tricuspid annulus diameters measured with 2DE (both measured in apical 4-chamber view and in parasternal short-axis view) systematically underestimated the actual tricuspid annulus size (Figure 5). As a consequence, 65% of patients with normal tricuspid annulus diameter at 2DE showed grade 1–2 tricuspid regurgitation compared with 30% of patients with normal tricuspid annulus size at RT-3DE.22 Conversely, calculation of tricuspid annulus fractional shortening yielded the same results using 2DE and RT-3DE.22 This is because the extent of underestimation of tricuspid annulus diameter made by 2DE is comparable in diastole and in systole.

In addition to tricuspid annulus shape, size, and function, RT-3DE allows to assess TV leaflet geometry in functional tricuspid regurgitation. In patients with pulmonary hypertension (i.e. right ventricular to right atrium gradient $\geq 30$ mmHg), Sukmawan et al.23 reported that patients with tricuspid regurgitation showed a tethering of tricuspid leaflets into the right ventricle. The measured TV tenting volume was linearly correlated with right ventricular volume and with TV regurgitant jet area.

At the moment there are no data supporting the use of RT-3DE in selecting patients to be addressed to surgical repair of functional tricuspid regurgitation. However as in the case of mitral regurgitation, an improved assessment of valve anatomy and understanding of the pathophysiological mechanisms underlying the TV regurgitation could suggest new and more effective techniques for TV repair.

Finally, RT-3DE can help in estimating the severity of TV regurgitation using colour flow. Velayudhan et al.24 demonstrated the feasibility of obtaining the area of the vena contracta of the tricuspid regurgitant jet by cropping the RT-3DE colour Doppler data set with imaging planes
Tricuspid stenosis

Tricuspid stenosis is uncommon in adult patients. In nearly all cases it is due to rheumatic disease in association with rheumatic mitral and/or aortic valve involvement. Carcinoid heart disease can also lead to tricuspid stenosis.

2DE images show thickening and shortening of the TV leaflets. Doppler recordings of trans-tricuspid flow velocity allow calculation of mean gradient and pressure half-time valve area as described for the mitral valve.25 However, unlike what it is routinely done for mitral stenosis, neither transthoracic nor transesophageal 2DE can provide an en face view the stenotic orifice and visualize commissural fusion. Using RT-3DE, the orifice of TV stenosis can be clearly visualized and planimetered (Figures 3F and 6).26

Infective endocarditis of the tricuspid valve

In patients with TV endocarditis, RT-3DE may show the stereoscopic morphology and attachments of vegetations, mobility of vegetations with blood flow, and possible complications such as leaflet prolapse or perforation (Figure 7).

The size of a vegetation is an important predictor for embolic events and for response to treatment. Maximum diameter measurements from 2DE are routinely used to determine mass size. However, most vegetations are irregularly shaped, making it difficult to accurately image or select the largest diameter. The selection of a diameter that is not truly the largest may lead to underestimation of the true size of the vegetation and a misrepresentation of patients’ prognosis. RT-3DE images the entire volume of a vegetation allowing for accurate measurements in multiple planes.27

Congenital

Ebstein’s anomaly is a congenital defect of the TV in which the origins of the septal or posterior leaflets, or both, are displaced downward into the right ventricle with a large sail-like anterior leaflet that results in atrialization of the right ventricular inflow. There is a wide spectrum of severity. Although 2DE can show the characteristic displacement of the septal leaflet and the redundant and elongated anterior leaflet, the complex anatomy of the disease and the mechanisms of valve regurgitation are very difficult to assess. In adult patients with Ebstein anomaly of the TV, Patel et al.28 have reported that RT-3DE was particularly useful in delineating the chordal attachment of the three leaflets of the TV. This was accomplished by multiple systematic cropping and sectioning of the RT-3DE data sets, which shows the characteristic bubble-like appearance resulting from bulging of the non-tethered areas of the TV leaflets (Figure 8). In addition, an en face view of the valve obtained with RT-3DE can be used to measure the leaflet surface areas, and to visualize the regions of ineffective leaflet coaptation (Figure 8). Moreover, RT-3DE can be useful in evaluating the size of the functional right ventricle, and to obtain an en face view of the vena contracta of estimating severity of tricuspid regurgitation.

Present limitations and future perspectives

Despite all the data supporting the use of RT-3DE to assess TV morphology and function, especially in patients who are candidates to cardiac surgery for left-sided diseases, this technique has not been integrated into the clinical routine. There are several reasons to explain this: some pertaining the 3D technique per se, and they have been discussed elsewhere,8,9 and two others are related to the application of the technique to the study of the TV.

The first reason is a clinical one. At the moment, there is no evidence that 3D assessment of TV anatomy and function may improve surgical results. However, clinical research is active in this field and results are expected soon.

The second reason is the lack of standardized measures and specific software to be used to quantitate tricuspid annulus and leaflet size and shape, as it has been developed for the mitral valve. The increasing interest for the TV by both echocardiographers and surgeons will fuel development and implementation of such a tool.
The anterior leaflet (A) surface area can be visualized and the regions of ineffective leaflet coaptation easily identified. The aspect of septal (S, with arrows) and posterior (P, red arrows) leaflets as effect of tethering of the leaflet where the chordae are attached.

Conclusions

Imaging of the TV by 2DE is hampered by inability to visualize all three leaflets simultaneously. Conversely, RT-3DE provides a unique tool for a comprehensive assessment of morphology and function of the TV complex pre-operatively. Understanding the anatomy and the pathophysiological mechanisms underlying the various TV diseases will provide the basis for surgical planning in order to tailor the intervention to patient’s individual case.

Conflict of interest: none declared.

References


