

Review Article

Clinical Implications of the Echocardiographic Evaluation of Right Ventricular Function on the Long Axis Using Newer Techniques

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The assessment of right heart function remains difficult, despite rapid technological developments in echocardiography.¹ This is due to the fact that there are limitations to each of the echocardiographic techniques currently used in clinical and academic practice. The volume calculation and estimation of ejection fraction are not ideal for the clinical assessment of right ventricular (RV) function. However, regional myocardial wall motion detection by M-mode and tissue Doppler velocities are probably the most useful methods in clinical practice. One-dimensional (1D) and two-dimensional (2D) strain, velocity vector imaging, and four-dimensional (4D) echocardiography need further evaluation before they can be considered as routine investigations. Global attention needs to be paid to a very important, but neglected entity, the right ventricle, whose functional performance has been shown to predict exercise tolerance and outcome in a number of syndromes.²

Right ventricular dysfunction

There are numerous reasons for RV dysfunction (Figure 1). The echocardiographic assessment, especially of RV systolic function, is not easy. In contrast with the left

ventricle, the usefulness of the echocardiographic “eyeball” method to estimate RV size and systolic function in patients with right heart disease has limitations, specifically related to variability among echocardiographers.³ However, functional estimation on the long axis has shown particular promise for assessing RV performance and has accordingly resulted in numerous studies from which valuable conclusions were derived. The assessment of RV function on the long axis started with the M-mode technique (Figure 2). Tissue Doppler imaging (TDI) (Figure 3), a novel technique, was subsequently found to outperform M-mode study of the tricuspid annulus motion (Table 1).⁴ By RV function estimation with TDI, and using as index the tricuspid annulus peak systolic velocity (TAPSV), systolic RV dysfunction can be accurately assessed. With RV dysfunction defined as RV ejection fraction <40%, a TAPSV cut-off value of 9.5 cm/s yielded the best compromise between sensitivity, specificity, positive and negative predictive value.⁵ Wang et al determined which echocardiographic variable or variables best correlated with RV ejection fraction as assessed by cardiac magnetic resonance imaging (cMRI).⁶ Right ventricular fractional area change, Tei index, isovolumic acceleration,

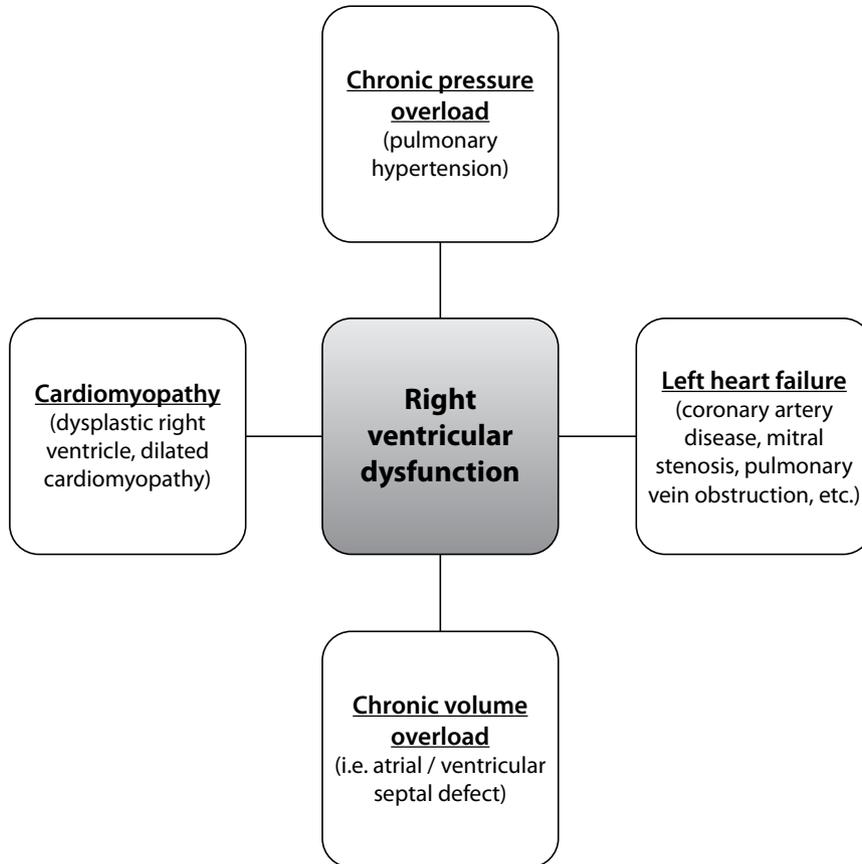


Figure 1. Possible causes of right ventricular dysfunction.

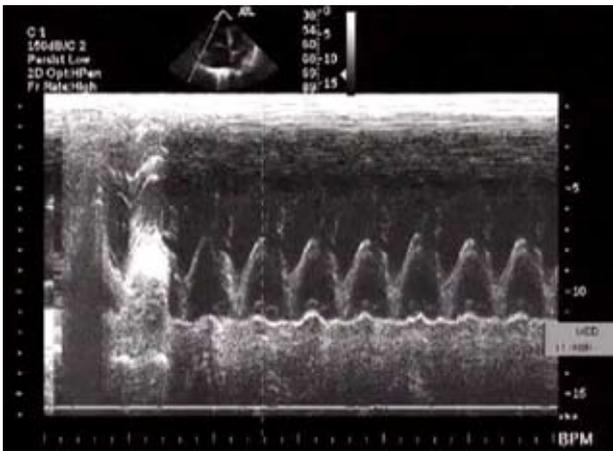


Figure 2. M-mode recording of tricuspid annulus motion.

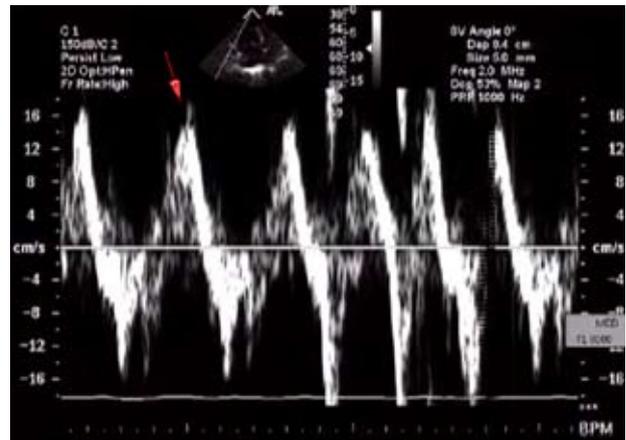


Figure 3. Tissue Doppler imaging (TDI) technique. Recording of velocities of tricuspid annulus movement. The arrow indicates tricuspid annulus peak systolic velocity (TAPSV).

TAPSV, tissue displacement, systolic strain rate, and systolic strain were measured. Multivariate analysis demonstrated a persistent significant relationship between both TAPSV and RV fractional area change, and RV ejection fraction. However, feasibility, as well

as intra-observer and inter-observer agreement, were substantially lower for RV fractional area change.⁶ Nevertheless, it has been emphasized that TAPSV values are not useful in further evaluating the severity of RV dysfunction.⁵

Table 1. Functional and hemodynamic information derived by right ventricular interrogation with tissue Doppler imaging on the long axis.

1. RV systolic function	TAPSV < 9.5 cm/s correlates with RV ejection fraction < 40% ⁵ (it is not however useful in evaluating RV dysfunction severity).
2. RV diastolic function	$E/E' \geq 4$ correlates with RAP ≥ 10 mmHg with sensitivity 88% & specificity 85% (but not in status post-cardiac surgery). ²⁴
3. PAP	Tricuspid annulus IVRT strongly correlates ($r=0.83$) to systolic PAP (alternative to TR derived systolic PAP when TR jet not recordable, but not for patients with severe RV dysfunction). ²⁵ TAPSV has an inverse relationship with invasively derived mean pulmonary artery pressure. ²⁶
4. PVR	TAPSV is inversely related to invasively derived PVR ($PVR = 3698 - 1227 \times \ln TAPSV$). ²⁶

IVRT – isovolumic relaxation time; PAP – pulmonary artery pressure; PVR – pulmonary valve resistance; RAP – right atrial pressure; RV – right ventricle; TAPSV – tricuspid annulus peak systolic velocity; TR – tricuspid regurgitation.

Frequently, RV function impairment can be found in heart failure of ischemic origin and in dilated cardiomyopathy. By studying RV function on the long axis with the TDI method, Parcharidou et al recently demonstrated that RV dysfunction is more pronounced in patients with ischemic than in those with dilated cardiomyopathy (Table 2).⁷ Patients with ischemic cardiomyopathy exhibited significantly lower systolic and diastolic velocities of tricuspid and mitral septal annular motion and a higher ratio of peak early trans-tricuspid filling velocity to peak early diastolic velocity of the tricuspid annulus, compared to patients with dilated cardiomyopathy. Moreover, the tricuspid peak systolic velocity was found to be a significant predictor of the cause of cardiomyopathy, independently of the influence of age, gender, presence of left bundle branch block and other echocardiographic parameters.⁷ Some possible explanations were proposed for the abovementioned findings. The overall RV performance depends not only on the right free wall, but also on septal contractility, which is irreversibly impaired in ischemic cardiomyopathy. Moreover, patients with ischemic exhibited worse pulmonary hypertension than patients with dilated cardiomyopathy in this cohort, which could explain the worse RV systolic and diastolic function in the former group. Additionally, contraction on the longitudinal axis is mainly caused by subendocardial fibers that are sensitive to ischemia. Therefore, TDI velocity measurements in the free wall of the RV are affected more in cardiomyopathy of ischemic origin.⁷ Mitral valve annuloplasty frequently becomes necessary in ischemic or dilated cardiomyopathy, because of significant mitral regurgitation. Preoperative assessment of longitudinal RV systolic function seems to be easy, low cost, and provides accurate information about RV performance.⁸

It has been mentioned that the TDI and strain

rate methods enable the detection of conditions with impaired RV function, such as arrhythmogenic right ventricular dysplasia/cardiomyopathy (ARVD/C) (Table 2). This fact may have potential clinical value since TAPSV < 7.5 cm/s and peak RV strain < 18% best identify patients with ARVD/C. Consequently, it seems that TDI and strain rate methods (Figure 4) can make an important contribution, along with other methods such as cMRI, to the sometimes difficult diagnosis of ARVD/C, even in the subset of patients with an apparently normal RV by conventional echocardiography.⁹

It is known that, in pathologic conditions with pulmonary hypertension, the RV myocardial systolic activation delay assessed by TDI could offer a unique approach to predict RV dysfunction (Table 2).¹⁰ RV myocardial systolic activation delay was defined as the difference in time to peak TDI systolic velocities between the RV basal lateral and the basal septal wall segment. In patients with pulmonary arterial hypertension, a strong correlation between RV myocardial systolic activation delay and RV fractional area change was shown.¹⁰ Another study of RV lateral wall function on the long axis with the strain rate technique found that RV myocardial strain correlates significantly with pulmonary hemodynamics in patients with pulmonary hypertension and normal left ventricular function. It should be noted, though, that there was no correlation with RV performance in patients with left ventricular dysfunction.¹¹ Lately the regional longitudinal deformation in the RV free wall has been studied using strain rate imaging. The deformation parameters in the apical segment were reduced more than in the basal segment in a patient group with pulmonary hypertension. The reduction of the apical deformation was related to the severity of RV afterload. Strong correlations were found between the apical strain and invasively measured

Table 2. Information about various disease states derived by assessment of right ventricular function assessment on the long axis.

Disease	Method	Information
1. Cardiomyopathy	TDI	RV dysfunction is more pronounced in ischemic than in dilated cardiomyopathy. ⁷
2. ARVD/C	TDI, strain/ strain rate	ARVD/C is identified if TAPSV <7.5 cm/s and peak RV strain <18%. ⁹
3. PAH	TDI, strain/ strain rate	<ul style="list-style-type: none"> • Increased RV systolic activation delay and RV lateral wall strain correlates with hemodynamics when LV function is normal.¹⁰ • Apical strain inversely correlates with PASP and PVR.¹¹ • In severe PAH systolic and diastolic RV dysfunction as well as diastolic LV dysfunction are detected by TDI.¹²
4. Mitral stenosis	TDI	TDI assessment predicts exercise capacity. ¹⁴
5. Pulmonary embolism in CHF	TDI	SmLV/SmRV ≤ 1.2 related to pulmonary embolism with 76% sensitivity and 93.3% specificity. ¹⁵ Peak systolic strain in the middle segment of right ventricular free wall was reduced in patients with perfusion defect greater than 25%. ¹⁶
6. Diabetes mellitus	Strain / strain rate	Detection of subclinical RV dysfunction. ¹⁷
7. β -thalassemia	TDI	Early detection of RV/LV dysfunction. ¹⁹
8. Amyloidosis	M-mode	TAPSE <17 mm marker of RV dysfunction. ²⁰
9. Repaired Fallot tetralogy	TDI	Follow up of RV function ²¹ , TAPSV predictive of exercise capacity. ²²
10. Heart failure	TDI	TAPSV superior to two-dimensional ultrasound assessment of RV function in predicting re-hospitalization for heart failure. ²⁸
11. Resynchronization therapy	TDI	Biventricular pacing improves RV function independently of LV ejection fraction improvement. ²⁹
12. After Senning or Mustard operation for cTGA	TDI	Detection of systemic RV dyssynchrony which correlates with impaired exercise capacity. ³⁰

ARVD/C – arrhythmogenic right ventricular dysplasia/cardiomyopathy; CHF – congestive heart failure; cTGA – corrected transposition of great arteries; LV – left ventricle; PAH – pulmonary arterial hypertension; PASP – pulmonary artery systolic pressure; PVR – pulmonary valve resistance; RV – right ventricle; SmLV – mitral annular lateral longitudinal systolic velocity; SmRV – tricuspid annular lateral longitudinal systolic velocity; TAPSE – tricuspid annular plane systolic excursion; TAPSV – tricuspid annulus peak systolic velocity.

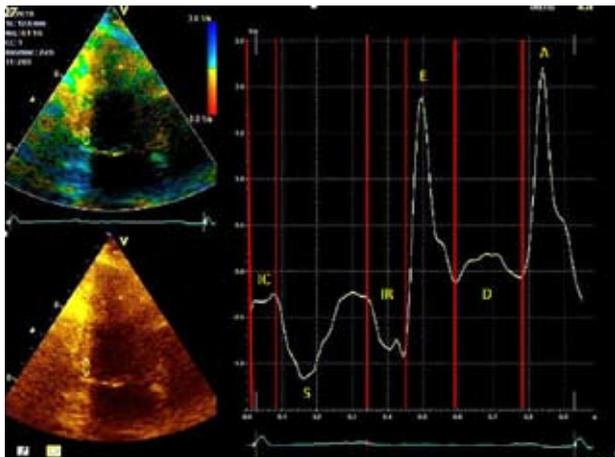


Figure 4. Strain rate curve on the long axis during one cardiac cycle. A – late diastolic filling, atrial contraction; D – diastasis; E – early diastolic filling; IC – isovolumic contraction; IR – isovolumic relaxation; S – systole.

mean pulmonary arterial pressure and pulmonary vascular resistance.¹² In the abovementioned studies

impaired RV function was found in pulmonary hypertension, but in the case of pulmonary hypertension RV dysfunction is not the only abnormality. It has been found that cardiac function was abnormal in patients with severe pulmonary hypertension because of a combination of alterations in both diastolic and systolic RV function, and left ventricular diastolic function, abnormalities that are in any case assessed with TDI. Thus it seems that TDI is a particularly useful method for examining patients with pulmonary hypertension.¹³

In cases of severe mitral valve stenosis with pulmonary hypertension and subsequent RV dysfunction, TDI assessment of RV function on the long axis has been shown to provide important information about the patients' exercise capacity.¹⁴

Pulmonary embolism, a disease that is linked to increased pulmonary artery pressure and therefore to RV dysfunction, seems to be a not unusual complication among patients with congestive heart failure.

It has been found for this patient group that studying the left and right ventricle on the long axis can contribute to the diagnosis of pulmonary embolism. To be specific, after measurement of the mitral annulus lateral (SmLV) and tricuspid annulus lateral (SmRV) longitudinal systolic velocities, a ratio SmRV/SmLV ≤ 1.2 can distinguish patients with pulmonary embolism with a sensitivity of 76% and a specificity of 93.3%, as derived from analysis of the receiver operator characteristic curve.¹⁵ Regarding the assessment of pulmonary embolism severity, where quantification plays an important role in therapeutic management, it has been found by assessment of RV function on the long axis using the strain rate technique, that peak systolic strain in the middle segment of the RV free wall was reduced in patients with a perfusion defect greater than 25%.¹⁶

It has been reported that diabetes mellitus causes subclinical left ventricular dysfunction. It seems, however, that it also affects RV function. Subclinical RV dysfunction has been demonstrated by the strain/strain rate technique in diabetes mellitus.¹⁷

Iron overload impairs systolic and diastolic function in both ventricles of β -thalassemia patients and in fact it impairs systolic function earlier than diastolic.¹⁸ The functional assessment of longitudinal fibers in both ventricles by TDI is an easy and reliable method for the early determination of ventricular dysfunction.¹⁹ Another infiltrative cardiomyopathy, amyloidosis, often presents with signs of congestive heart failure. When RV function on the long axis is assessed by M-mode echocardiography, a tricuspid annular plane systolic excursion (TAPSE) < 17 mm was taken as a marker of RV dysfunction. It was found that RV dysfunction is associated with more severe involvement of the left ventricle, higher plasma levels of N-terminal pro-brain natriuretic peptide (BNP), and a poor prognosis.²⁰

Dysfunction of the RV is common in congenital heart diseases. Regarding surgically repaired Fallot tetralogy, it has been found in a cohort of asymptomatic patients with this condition that the use of TDI, as well as BNP, enables us to easily discriminate them from healthy controls. The ability of TDI to assess ventricular function on the long axis, even in the presence of valvular lesions, such as in patients with surgically repaired Fallot tetralogy, makes it a valuable tool in the investigation and follow up of these patients.²¹ Other authors agree on that last point, also finding abnormalities of RV systolic and diastolic function by studying RV function on the long axis in patients with

repaired Fallot tetralogy.²² Additionally, they found that the TAPSV is predictive of exercise capacity in these patients. Among Senning-operated patients with systemic right ventricles, of particular interest is the information, derived from studying strain, that in the systemic RV, as in the normal LV, circumferential predominated over longitudinal free wall shortening, the opposite of findings in the normal RV. This may represent an adaptive response to the systemic load. Notably, however, the systemic RV did not display the torsion found in the normal LV.²³

Diastolic RV dysfunction

Few data are available concerning the evaluation of RV diastolic function and filling pressures by echocardiography (Table 1). Sade et al determined whether the ratio of early tricuspid inflow to annular diastolic velocity (E/E') could be used to estimate RV filling pressure in patients with and without recent cardiac surgery.²⁴ They found that E/E' correlated only moderately with pulmonary artery pressure early after cardiac surgery. However they confirmed that E/E' correlated strongly with pulmonary artery pressure in patients without cardiac surgery. The sensitivity and specificity of E/E' ≥ 4 were 88% and 85% for a right atrial pressure ≥ 10 mm Hg in patients who were not in the post-cardiac surgery status. They concluded that E/E' is useful for the noninvasive estimation of RV filling pressure and for detecting serial changes under a wide range of clinical conditions, but is a weak correlate of pulmonary artery pressure early after cardiac surgery and in patients with normal right ventricular function.

Pulmonary systolic pressure and resistance estimation

In several disease states, the systolic pulmonary pressure calculation is traditionally performed by using the tricuspid regurgitation and applying the Bernoulli formula. Recently, however, Fahmy Elnoamany and Abdelraouf Dawood found that tricuspid annular pulse wave TDI-derived RV isovolumic relaxation time correlates very strongly with invasively measured pulmonary artery systolic pressure (Table 1).²⁵ They proposed that this variable can be used to predict pulmonary artery systolic pressure. It can even be considered as an alternative to tricuspid regurgitation-derived pulmonary artery systolic pressure when tricuspid regurgitation is non-recordable. They recommended, though, that caution should be exercised

while examining patients with significantly reduced RV function.

For the noninvasive assessment of pulmonary resistance it seems that the TDI method can provide some solutions. Gurudevan et al studied 50 consecutive patients with suspected chronic thromboembolic pulmonary hypertension.²⁶ They performed preoperative transthoracic echocardiography with TDI of the tricuspid annulus. All patients then underwent cardiac catheterization with invasive determination of mean pulmonary pressure and pulmonary valve resistance. These investigators found that TAPSV had an inverse relationship with catheterization-derived mean pulmonary artery pressure, with a correlation coefficient of -0.493 ($p=0.0003$). The inverse correlation of TAPSV with catheterization-derived pulmonary valve resistance was more striking, with a correlation coefficient of -0.710 ($p<0.0001$). Based on their data, they derived the following logarithmic regression equation: pulmonary valve resistance = $3698 - 1227 \times \ln \text{TAPSV}$.

Right ventricular dysfunction and prognosis

It would be rather unexpected if RV function assessment did not have a role in the prognosis of cardiac disease. As shown by Karatasakis et al, shortening of the RV, measured as the difference between the end-diastolic and end-systolic distances between the tricuspid annulus and the RV apex, can be a reliable predictor of outcome in congestive heart failure (Table 2). Over a follow-up period of 14 ± 10 months a value >1.25 cm had a sensitivity of 90%, specificity of 80%, and overall predictive accuracy of 83% in distinguishing survivors from non-survivors.²⁷ Recently, Dokainish et al have demonstrated by assessment of RV function on the long axis that the RV systolic velocity derived with TDI is an independent predictor of cardiac death or rehospitalization for heart failure patients and appears to be superior to conventional two-dimensional parameters of right ventricular function.²⁸

Cardiac resynchronization therapy

Biventricular pacing favorably affects left and right ventricular function. After biventricular pacemaker implantation in patients with left ventricular dyssynchrony it has been found by functional interrogation on the long axis with TDI that ventricular resynchronization has beneficial effects on RV function, which seem to be independent of the improvement in left

ventricular ejection fraction (Table 2).²⁹ Additionally, recent data suggest potential benefits of cardiac resynchronization therapy in the management of RV dysfunction in congenital heart disease, such as corrected transposition of the great arteries after Senning or Mustard procedures. In this study the cardiac dyssynchrony was detected using TDI for the study of ventricular function on the long axis.³⁰ In these patients, the magnitude of right ventricular intra- and interventricular mechanical delay was correlated with cardiac magnetic resonance-derived RV volumes and ejection fractions, as well as treadmill exercise testing parameters. The right ventricular intra- and interventricular mechanical delay was correlated negatively with the RV ejection fraction and the percentage of predicted maximum oxygen consumption, and positively with the minute ventilation/carbon dioxide production slope. The investigators concluded that RV dyssynchrony is common in young adults after atrial switch operations and is associated with RV systolic dysfunction and impaired exercise performance.³⁰

Conclusions

The RV position, geometry, structure, and unique functional characteristics render its echocardiographic study especially challenging. Traditional echocardiographic techniques are far from being perfect when accurate RV function assessment is required. Novel techniques that examine the RV on the long axis provide useful additional information concerning pathophysiology and hemodynamics, which can subsequently be considered in the clinical management of numerous disease states affecting the right heart.

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