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Original Article

How best to assess right ventricular function by echocardiography*

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Abstract Right ventricular function is a crucial determinant of long-term outcomes of children with heart disease. Quantification of right ventricular systolic and diastolic performance by echocardiography is of paramount importance, given the prevalence of children with heart disease, particularly those with involvement of the right heart, such as single or systemic right ventricles, tetralogy of Fallot, and pulmonary arterial hypertension. Identification of poor right ventricular performance can provide an opportunity to intervene. In this review, we will go through the different systolic and diastolic indices, as well as their application in practice. Quantification of right ventricular function is possible and should be routinely performed using a combination of different measures, taking into account each disease state. Quantification is extremely useful for individual patient follow-up. Laboratories should continue to strive to optimise reproducibility through quality improvement and quality assurance efforts in addition to investing in technology and training for new, promising techniques, such as three-dimensional echocardiography.

Keywords: Echocardiography; right ventricle; right ventricular function; systolic function; diastolic function

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RIGHT VENTRICULAR FUNCTION IS A CRUCIAL determinant of long-term outcomes of children with heart disease. Quantification of right ventricular systolic and diastolic performance by echocardiography is of paramount importance, given the prevalence of children with heart disease, particularly those with involvement of the right heart, such as single or systemic right ventricles, tetralogy of Fallot, and pulmonary arterial hypertension. Identification of poor right ventricular performance can provide an opportunity to intervene.

In order to properly assess right ventricular function, it is important to highlight some of the features that differentiate the normal right ventricle from the left ventricle. The very anterior position of the right ventricle in the chest limits its visualisation by echocardiography. Its complex geometric shape, in contrast to the ellipsoid shape of the left ventricle, precludes the easy assessment of function by traditional echocardiography.[1] The right ventricle has prominent trabeculations, making border definition challenging when clear endocardial borders are required for some calculations, including fractional area change, as detailed later in the text. Finally, the muscle fibres of the right ventricle are arranged mainly longitudinally, such that most of the contraction occurs in that plane, as opposed to the oblique, longitudinal, and circular myofibres of the left ventricle.[1] Therefore, the contraction pattern of the right ventricle is characterised by a bellow-like motion of the free wall towards the septum, a longitudinal motion of the base towards the apex, and bulging of the ventricular septum into the right ventricular cavity.[2–4] In disease states, however, the right ventricle shifts from the mainly longitudinal contraction pattern even in conditions in which the right ventricle is not the most affected chamber.[5] By way of example, patients with tetralogy of Fallot show a change in the right ventricular fibres with presence of a

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circular middle layer that resembles that of the left ventricle.[6] In systemic right ventricles, circumferential over longitudinal free-wall shortening is seen, similarly to the left ventricle.[7] Owing to these factors, the assessment of right ventricular function by echocardiography is challenging and no single echocardiographic measure of function is devoid of limitations. Therefore, proper assessment should include various measures, taking into consideration different disease states. Despite these difficulties, there are guidelines for the functional assessment of the right ventricle by echocardiography in children.[8] In this review, we will go through the different systolic and diastolic indices, as well as their applications in practice. We will not review measures that assess global right ventricular function.

Systolic function

Qualitative assessment

The most commonly used method for the assessment of right ventricular systolic function is qualitative assessment or the "eyeball" method. Usually, abnormal function is reported as mildly, moderately, or severely diminished; however, the subjective estimation of right ventricular systolic function is highly dependent on the radiologist interpreting the study and can result in marked variability, and therefore poor inter-observer agreement.[9] Moreover, qualitative assessment lacks sensitivity, as it does not distinguish well between mild-to-moderate and between moderate-to-severe systolic dysfunction when compared with cardiac magnetic resonance imaging studies.[10] Qualitative assessment should, therefore, be avoided as a single method or it should be used in conjunction with other quantitative measures and include several views to thoroughly examine right ventricular contractility.

Fractional area change

The fractional area change is a two-dimensional measure of right ventricular global systolic function. It is obtained from the apical four-chamber view, and is calculated as the difference in end-diastolic area and end-systolic area divided by the end-diastolic area (Fig 1).[11] The image must be optimised with focus on maximising the right ventricular area and clearly delineating the border of the endocardium in the setting of trabeculations, particularly the free wall, to ensure accurate tracing of the right ventricular cavity.[12] A percentage of fractional area change >35% is considered normal in adults.[13] The fractional area change has been found to correlate with magnetic resonance-derived right ventricular ejection fraction, as well as to predict outcome in adult patients with myocardial infarction and pulmonary hypertension.[14,15] Fractional area change is preserved after pericardiotomy, as opposed to other measures of right ventricular function, such as tricuspid annular plane systolic excursion, which is discussed below, and therefore is a preferable method with which to assess right ventricular function post-operatively in the setting of an altered right ventricular contractile pattern.[5] Fractional area change has not been extensively used in congenital heart disease, but some studies have reported on its use. In patients with surgically repaired tetralogy of Fallot, for example, the right ventricular outflow tract

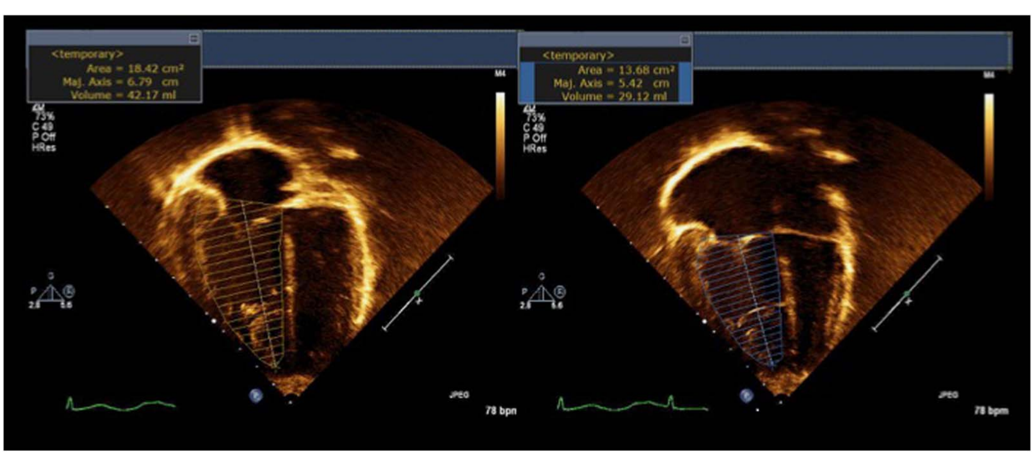

Figure 1.
The fractional area change is obtained by tracing the right ventricular endocardial border at end diastole and end systole. The difference in the area at end diastole and end systole is divided by the area at end diastole. This is a reproducible measure of function that is not affected by pericardiotomy. Normal fractional area change is above 35%. In this example, the fractional area change is diminished (26%), indicating impaired right ventricular function.

is patched and often dysfunctional. Given that fractional area change does not include the contribution of the right ventricular outflow tract to ejection, it is thought that the fractional area change may overestimate global right ventricular function in this subset of patients.[12] On the other hand, in adult patients with repaired tetralogy of Fallot, fractional area change demonstrates good correlation with ejection fraction measured by cardiac magnetic resonance imaging, whereas correlations with other echocardiographic measures such as tricuspid annular plane systolic excursion, tricuspid S' velocity, and the myocardial performance index are poor. Finally, fractional area change can predict impaired right ventricular function before and after pulmonary valve replacement in this patient population.[16] Fractional area change is reproducible in adult studies.[17] Although normative values are lacking in the paediatric population, the fractional area change should be incorporated in paediatric studies, with attention to acquiring an adequate four-chamber view of the right ventricle for proper tracing of the endocardial borders.[8]

Tricuspid Annular Plane Systolic Excursion (TAPSE)

Tricuspid annular plane systolic excursion is another two-dimensional measure with which one can assess systolic right ventricular function. It is obtained by placing the M-mode cursor through the lateral portion of the tricuspid valve annulus in the apical four-chamber view. The excursion of the tricuspid valve from the base of the heart towards the apex is measured as the distance from the annulus to the apex at end diastole minus that distance at end systole. This distance can also be simply measured using two-dimensional imaging techniques, with equally reproducible results (Fig 2).[18,19] Limitations include load and angle dependence, as well as the potential influence of the functional status of the left ventricle. Moreover, this measure does not take into account the contribution of the ventricular septum and/or the right ventricular outflow tract to right ventricular performance.[20,21] Tricuspid annular plane systolic excursion has proven utility in the adult population with pulmonary hypertension and heart failure, with good correlation with other indices of systolic function, such as radionucleotide angiography.[22–24] Given the change in contractile pattern of the right ventricle in disease states, even after pericardiotomy for aortic valve replacement, this measure has poor correlation with ejection fraction measured by cardiac magnetic resonance and should be used with caution in paediatric conditions that result in right ventricular volume load and in single ventricles. Preferably, it should be reserved for the individual longitudinal follow-up in such cases.[19,25–27] Similar to adults, this measure is especially useful in children with pulmonary arterial hypertension, where tricuspid annular plane systolic excursion values <15 mm are associated with a threefold event rate compared with those with normal values.[18,28,29] Normative values for age are available for the premature, neonatal, and paediatric populations, with normal values ranging from 0.9 to 2.5 mm.[30,31]

Tissue Doppler-derived right ventricular systolic excursion velocity S'

Tissue Doppler systolic velocity of the tricuspid annulus is another measure of longitudinal right

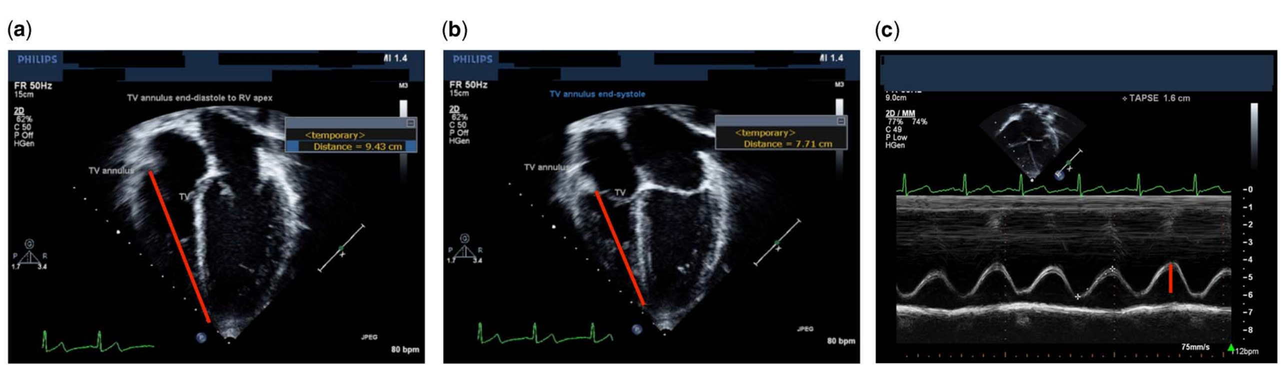

Figure 2.
*Tricuspid annular plane systolic excursion can be obtained using two-dimensional imaging (**a** and **b**) or by placing the M-mode cursor at the level of the tricuspid valve annulus (**c**). The electrocardiogram tracing can be used to determine the optimal frame to be measured. This measure reflects the longitudinal shortening of the right ventricle. In adults, normal values are greater than 1.6 centimetres. Normative data for age are available for children. Tricuspid annular plane systolic excursion is helpful for the assessment of right ventriuclar function in patients with pulmonary hypertension and those with unoperated hearts. Although reproducible, this measure correlates poorly with ejection fraction by magnetic resonance and shodul be used with caution in congenital heart defects involving the right ventricle, such as single and systemic right ventricles, and tetralogy of Fallot.*

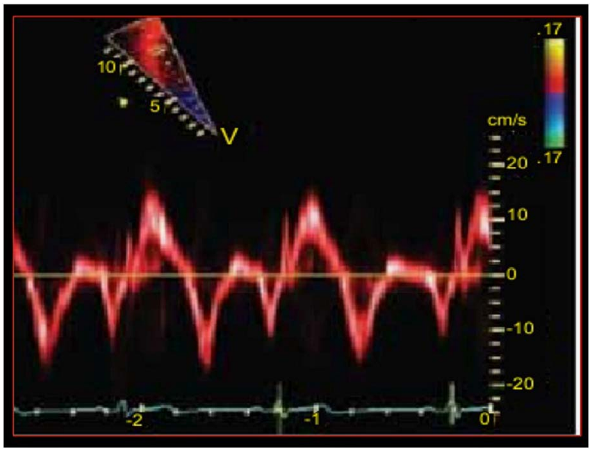

Figure 3.
Pulsed tissue Doppler can be used to calculate the tissue Doppler velocities of the tricuspid annulus. The S' wave represents the systolic velocity, which assesses the right ventricular longitudinal function. The e' wave represents the tricuspid annular early diastolic velocity, whereas the a' wave represents the annular velocity with atrial contraction. E' and a' velocities are used in the assessment of right ventricular diastolic function.

ventricular systolic performance, similar to tricuspid annular plane systolic excursion. This is a reproducible and easily obtainable measure of right ventricular systolic function with normal reference values available for the paediatric population (Fig 3).[32,33] A value <11.5 cm per second is associated with global right ventricular dysfunction with ejection fraction <45%.[22,32,34] The S' velocity is diminished and inversely associated with end-diastolic volume in patients with repaired tetralogy of Fallot.[28,33,35,36] Limitations of this technique are similar to tricuspid annular plane systolic excursion and include angle and load dependency.[12] An additional intrinsic limitation to tissue velocity imaging is a phenomenon called "tethering" by which the passive motion of the normal myocardium surrounding the diseased myocardium can result in falsely normal tissue velocities of the diseased segment in question.[12]

Speckle tracking – strain and strain rate

Strain and strain rate together have recently emerged as a novel technique to quantitate myocardial contractility. Strain is defined as the degree of myocardial deformation compared with its original length, and is expressed as a percentage – where lengthening and thickening result in a positive value and shortening and thinning result in a negative value. Strain rate measures the rate of deformation, and is expressed as $seconds^{-1}$. Its measurements can be obtained using Doppler and non-Doppler two-dimensional imaging, via speckle tracking or the tracking of natural myocardial acoustic markers (Fig 4). In addition, two-dimensional strain has the advantage of being angle independent. Strain also has the advantage of overcoming "tethering" or the movement of the diseased myocardium via pulling by the healthy myocardium surrounding it.[12] Secondary to their dependence on both extrinsic loading and intrinsic contractile force, strain and strain rate are load dependent, demonstrating increasing values in the setting of increased preload and decreasing values with increased ventricular size and afterload.[37]

In the left ventricle, strain is a useful tool to assess regional myocardial function in ischaemic heart disease and in cardiomyopathies.[37–41] It also appears to be a prognostic marker in adults with significant cardiovascular disease.[42] Strain has been used to assess right ventricular function in conditions such as pulmonary arterial hypertension, arrhythmogenic right ventricular cardiomyopathy, and tetralogy of Fallot.[20,43] It correlates well with ejection fraction measured by cardiac magnetic resonance, and may serve as a better predictor of outcome and functional capacity than ejection fraction.[44,45] In adults and children with pulmonary hypertension, lower strain, especially in the apical and free wall regions, has a strong correlation with mean pulmonary artery pressures, right ventricular size and function, exercise capacity, and mortality.[46–49] Global longitudinal strain is decreased in children and adults with repaired tetralogy of Fallot, and declines in strain appear to precede overt declines in right ventricular ejection fraction.[40,50–53] Although strain appears to be reproducible, is angle independent, and easy to obtain, normative values are lacking, and therefore its utility at present lies in its use for individual patient follow-up.[54]

Myocardial acceleration during isovolumic contraction

Myocardial acceleration during isovolumic contraction is a load-independent measure of ventricular contractile function. This Doppler-derived index is measured as the ratio of systolic velocity to the time to peak systolic velocity, with normal values in the right ventricular free wall of $>1.1\ m/s^2$ (Fig 5).[20] Although the isovolumic acceleration is heart rate dependent, and therefore useful to assess myocardial contractile reserve during exercise stress testing, normative data are available in children with adjustment for heart rate. Mean values in children are $2.3\ m/s^2$ (range 1.1–3.6). Isovolumic acceleration is strongly associated with tricuspid annular plane systolic excursion and tricuspid myocardial systolic velocity (S'). Isovolumic acceleration is diminished in conditions such as transposition of the great arteries with systemic right ventricles, tetralogy of Fallot, and acute pulmonary embolism.[55–58]

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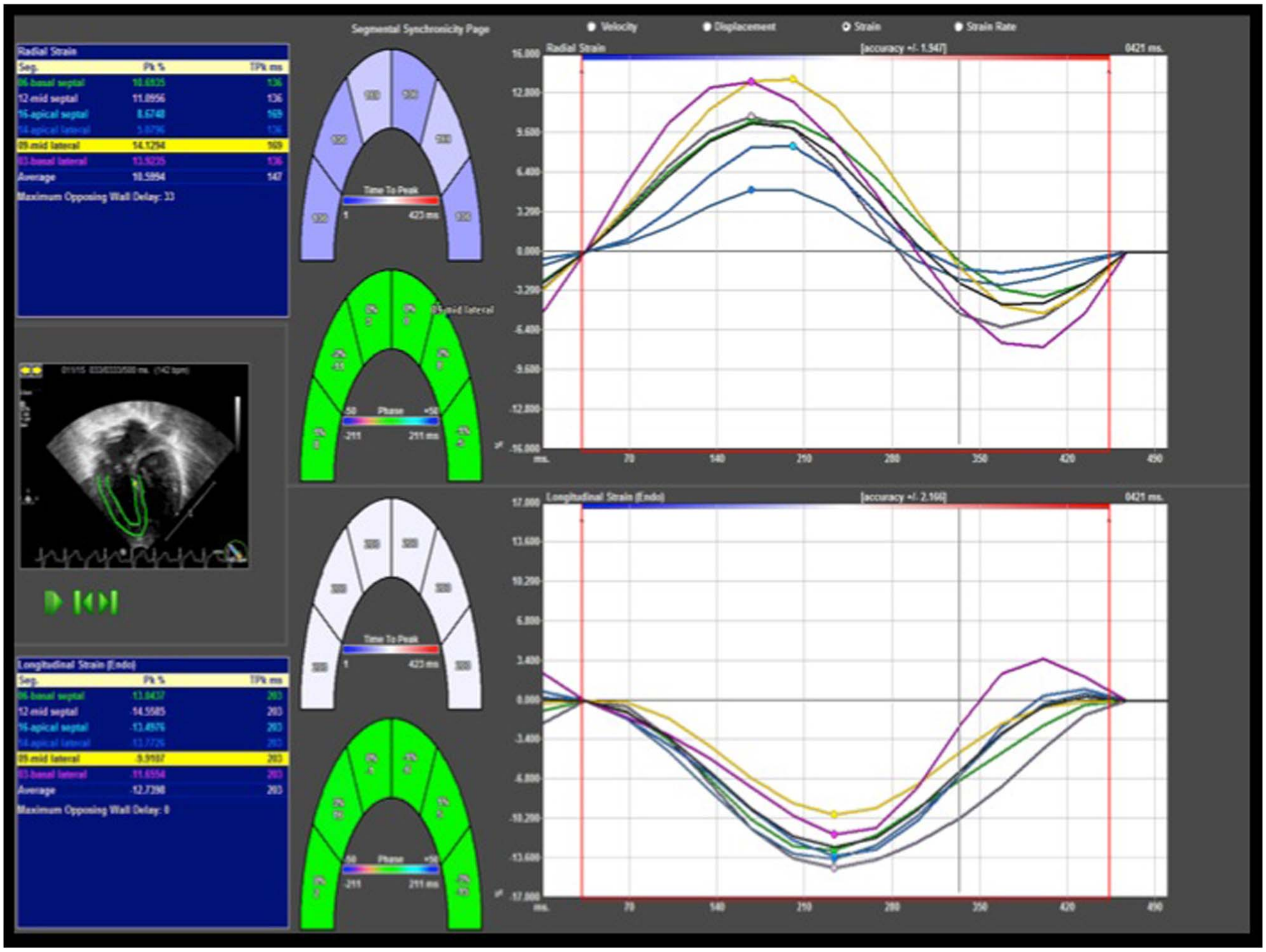

Figure 4.

Speckle tracking technology allows for the assessment of strain and strain rate as measures of the longitudinal function of the right ventricle. Image optimisation is required to demonstrate the entire right ventricular cavity in the imaging sector. Strain is a negative value, with more negative values indicating better function. Decreased strain appears to precede overt declines in right ventricular ejection fraction. Normal value in adults is −26 ± 4%.

Three-dimensional echocardiography

In brief, three-dimensional calculation of right ventricular volumes is possible with the use of specific softwares.[59,60] This method typically involves manual tracing of the RV endocardial border in different planes, therefore adequate two-dimensional views of the right ventricle are required.[61] Multiple studies comparing right ventricular volumes and ejection fraction with values obtained by cardiac magnetic resonance imaging show consistent underestimation of volumes measured by three-dimensional echocardiography. Importantly, this underestimation appears to be more pronounced as the right ventricular volume increases (Fig 6).[59,60,62,63] Nevertheless, due to its availability and cost-effectiveness, three-dimensional echocardiography is an attractive alternative to magnetic resonance imaging to assess right ventricular volumes in function. Further studies are required in order to establish normative data and improve accuracy in the paediatric population

Diastolic function

Assessment of right ventricular diastolic function should be included in routine echocardiograms, particularly in those performed for conditions in which diastolic dysfunction can precede declines in systolic function, such as in pulmonary arterial hypertension.[64] In tetralogy of Fallot, measures of diastolic dysfunction appear to correlate with risk factors for future re-interventions, such as greater degree of right ventricular dilatation.[65]

The assessment of right ventricular diastolic function is obtained by Doppler interrogation of the tricuspid inflow, tissue Doppler interrogation of the lateral tricuspid valve annulus, Doppler interrogation

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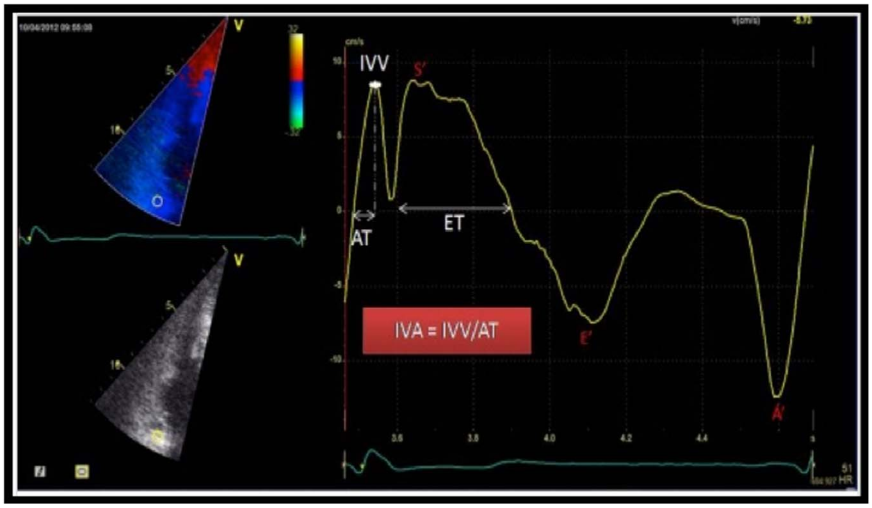

Figure 5.
Colour tissue Doppler interrogation of the tricuspid valve annulus for measurement of the isovolumic acceleration. Isovolumic acceleration is calculated by dividing the peak velocity at isovolumic contraction by the time from the onset of the wave to its peak velocity, also measured by tissue Doppler interrogation at the tricuspid valve annulus. Normal values are >1.1 m/s^2.

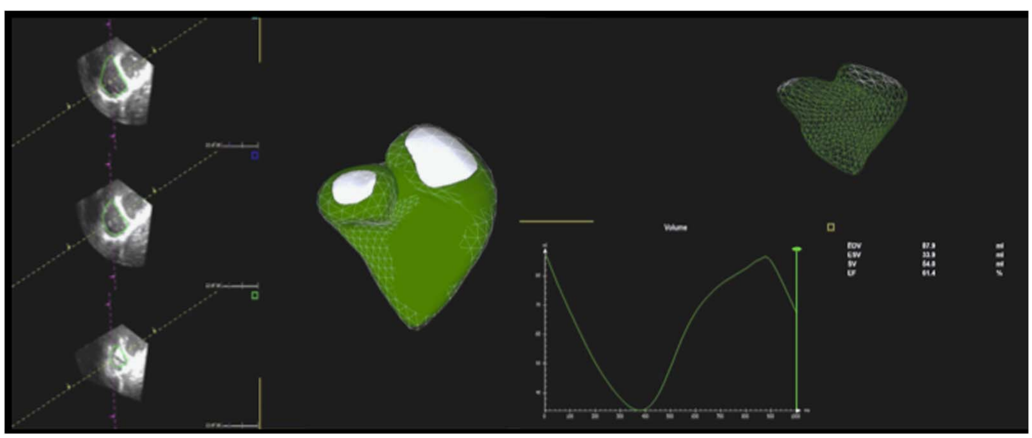

Figure 6.
Three-dimensional calculation of right ventricular volumes and ejection fraction. Three-dimensional image acquisition is performed from the apical four-chamber view in order to maximise visualisation of the right ventricle. Data sets are analysed offline using a dedicated software. Manual tracing of the endocardial border in three planes – sagittal, frontal, and coronal – is required for this calculation. The figure on the right depicts normal ejection fraction (61%).

of the hepatic veins, assessment of the right atrium, as well as assessment of the size and collapsibility of the inferior caval vein. Owing to the different phases of diastole, the evaluation of diastolic function should include multiple parameters. Doppler signals should be obtained at end-expiration during quiet breathing – a task that can be quite challenging in children. Alternatively, five to seven beats should be acquired to account for the effect of respiration on the inflow velocities.[66]

Right ventricular diastolic dysfunction can result in increased right atrial pressures. As such, the collapsibility of the inferior caval vein might be decreased or absent. This is easily identified by two-dimensional imaging or by interrogating the caval vein using M-mode (Fig 7). Impaired right ventricular compliance and increased end-diastolic pressures can result in reversal of flow with atrial contraction in the hepatic veins and/or the inferior caval vein.

Tricuspid inflow and myocardial velocities

The early, rapid filling phase of diastole is represented by the E-wave. The E-wave deceleration time reflects right ventricular relaxation. Atrial contraction occurs

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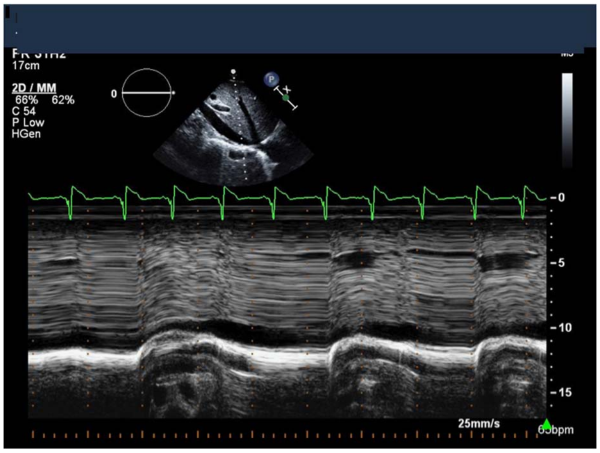

Figure 7.
Inferior caval vein collapse can be identified by simple two-dimensional observation or using M-mode. The figure shows M-mode interrogation of normal inferior caval vein collapse with respiration, suggesting normal right atrial pressure.

in late diastole, and is represented by the A-wave. The early diastolic tissue Doppler velocity, commonly denoted as e', represents right ventricular relaxation. Increased E/e' ratios represent increased right ventricular filling pressures. Normal values in adults have recently been published. E/e' ratios <15 are considered normal.[67] With normal diastolic function, the early filling velocity is higher than the atrial contraction velocity; therefore, reversal of the E/A ratio (<0.8) with increased deceleration time represents impaired ventricular relaxation. An accentuated relationship of the rapid filling and the atrial contraction velocities (E/A > 2.1) with decreased deceleration time (<120 ms) represents restrictive physiology – a late phase of diastolic dysfunction. Short deceleration time helps discern between normal diastolic function and "pseudo-normalisation" – the intermediate phase of diastolic dysfunction characterised by preserved E/A relationship (E/A ratio between 0.8 and 2.1 with E/e' ratio >6) (Fig 3). Increased deceleration time is directly associated with tau in subjects with pulmonary arterial hypertension.[49]

In summary, the echocardiographic assessment of right ventricular function is challenging due to limitations inherent to the right ventricle and due to paucity of normative data in children. Nevertheless, quantification of right ventricular function is possible and should be routinely performed using a combination of different measures, taking into account each disease state. Quantification is extremely useful for individual patient follow-up. Laboratories should continue to strive to optimise reproducibility through quality improvement and quality assurance efforts in addition to investing in technology and training for new, promising techniques, such as three-dimensional echocardiography.

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Conflicts of Interest

None.

Ethical Standards

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national guidelines and with the Helsinki Declaration of 1975, as revised in 2008.

References

1. Ho SY, Nihoyannopoulos P. Anatomy, echocardiography, and normal right ventricular dimensions. Heart 2006; 92 (Suppl 1): i2–i13.
2. Haber I, Metaxas DN, Geva T, Axel L. Three-dimensional systolic kinematics of the right ventricle. Am J Physiol Heart Circ Physiol 2005; 289: H1826–H1833.
3. Meier GD, Bove AA, Santamore WP, Lynch PR. Contractile function in canine right ventricle. Am J Physiol 1980; 239: H794–H804.
4. Rushmer RF, Crystal DK, Wagner C. The functional anatomy of ventricular contraction. Circ Res 1953; 1: 162–170.
5. Okada DR, Rahmouni HW, Herrmann HC, Bavaria JE, Forfia PR, Han Y. Assessment of right ventricular function by transthoracic echocardiography following aortic valve replacement. Echocardiography 2014; 31: 552–557.
6. Sanchez-Quintana D, Anderson RH, Ho SY. Ventricular myoarchitecture in tetralogy of Fallot. Heart 1996; 76: 280–286.
7. Pettersen E, Helle-Valle T, Edvardsen T, et al. Contraction pattern of the systemic right ventricle shift from longitudinal to circumferential shortening and absent global ventricular torsion. J Am Coll Cardiol 2007; 49: 2450–2456.
8. Lopez L, Colan SD, Frommelt PC, et al. Recommendations for quantification methods during the performance of a pediatric echocardiogram: a report from the pediatric measurements writing group of the American Society of Echocardiography Pediatric and Congenital Heart Disease Council. J Am Soc Echocardiogr 2010; 23: 465–495.
9. Srinivasan C, Sachdeva R, Morrow WR, Greenberg SB, Vyas HV. Limitations of standard echocardiographic methods for quantification of right ventricular size and function in children and young adults. J Ultrasound Med 2011; 30: 487–493.
10. Puchalski MD, Williams RV, Askovich B, Minich LL, Mart C, Tani LY. Assessment of right ventricular size and function: echo versus magnetic resonance imaging. Congenit Heart Dis 2007; 2: 27–31.
11. Solomon SD, Skali H, Anavekar NS, et al. Changes in ventricular size and function in patients treated with valsartan, captopril, or both after myocardial infarction. Circulation 2005; 111: 3411–3419.
12. Mertens LL, Friedberg MK. Imaging the right ventricle–current state of the art. Nat Rev Cardiol 2010; 7: 551–563.
13. Lopez-Candales A, Dohi K, Rajagopalan N, Edelman K, Gulyasy B, Bazaz R. Defining normal variables of right ventricular size and function in pulmonary hypertension: an echocardiographic study. Postgrad Med J 2008; 84: 40–45.
14. Anavekar NS, Gerson D, Skali H, Kwong RY, Yucel EK, Solomon SD. Two-dimensional assessment of right ventricular function: an echocardiographic-MRI correlative study. Echocardiography 2007; 24: 452–456.

https://doi.org/10.1017/S1047951115002255 Published online by Cambridge University Press

15. Anavekar NS, Skali H, Bourgoun M, et al. Usefulness of right ventricular fractional area change to predict death, heart failure, and stroke following myocardial infarction (from the VALIANT ECHO Study). Am J Cardiol 2008; 101: 607–612.
16. Selly JB, Iriart X, Roubertie F, et al. Multivariable assessment of the right ventricle by echocardiography in patients with repaired tetralogy of Fallot undergoing pulmonary valve replacement: a comparative study with magnetic resonance imaging. Arch Cardiovasc Dis 2015; 108: 5–15.
17. Shiran H, Zamanian RT, McConnell MV, et al. Relationship between echocardiographic and magnetic resonance derived measures of right ventricular size and function in patients with pulmonary hypertension. J Am Soc Echocardiogr 2014; 27: 405–412.
18. Forfia PR, Fisher MR, Mathai SC, et al. Tricuspid annular displacement predicts survival in pulmonary hypertension. Am J Respir Crit Care Med 2006; 174: 1034–1041.
19. Mercer-Rosa L, Parnell A, Forfia PR, Yang W, Goldmuntz E, Kawut SM. Tricuspid annular plane systolic excursion in the assessment of right ventricular function in children and adolescents after repair of tetralogy of fallot. J Am Soc Echocardiogr 2013; 26: 1322–1329.
20. Jurcut R, Giusca S, La Gerche A, Vasile S, Ginghina C, Voigt J-U. The echocardiographic assessment of the right ventricle: what to do in 2010? Eur J Echocardiogr 2010; 11: 81–96.
21. López-Candales A, Rajagopalan N, Saxena N, Gulyasy B, Edelman K, Bazaz R. Right ventricular systolic function is not the sole determinant of tricuspid annular motion. Am J Cardiol 2006; 98: 973–977.
22. Saxena N, Rajagopalan N, Edelman K, Lopez-Candales A. Tricuspid annular systolic velocity: a useful measurement in determining right ventricular systolic function regardless of pulmonary artery pressures. Echocardiography 2006; 23: 750–755.
23. Kaul S, Tei C, Hopkins JM, Shah PM. Assessment of right ventricular function using two-dimensional echocardiography. Am Heart J 1984; 107: 526–531.
24. Dini FL, Conti U, Fontanive P, et al. Right ventricular dysfunction is a major predictor of outcome in patients with moderate to severe mitral regurgitation and left ventricular dysfunction. Am Heart J 2007; 154: 172–179.
25. Avitabile CM, Whitehead K, Fogel M, Mercer-Rosa L. Tricuspid annular plane systolic excursion does not correlate with right ventricular ejection fraction in patients with hypoplastic left heart syndrome after fontan palliation. Pediatr Cardiol 2014; 35: 1253–1258.
26. Koestenberger M, Nagel B, Avian A, et al. Systolic right ventricular function in children and young adults with pulmonary artery hypertension secondary to congenital heart disease and tetralogy of Fallot: Tricuspid Annular Plane Systolic Excursion (TAPSE) and magnetic resonance imaging data. Congenit Heart Dis 2012; 7: 250–258.
27. Koestenberger M, Nagel B, Ravekes W, et al. Systolic right ventricular function in pediatric and adolescent patients with tetralogy of Fallot: echocardiography versus magnetic resonance imaging. J Am Soc Echocardiogr 2011; 24: 45–52.
28. Ghio S, Klersy C, Magrini G, et al. Prognostic relevance of the echocardiographic assessment of right ventricular function in patients with idiopathic pulmonary arterial hypertension. Int J Cardiol 2010; 140: 272–278.
29. Sato T, Tsujino I, Ohira H, et al. Validation study on the accuracy of echocardiographic measurements of right ventricular systolic function in pulmonary hypertension. J Am Soc Echocardiogr 2012; 25: 280–286.
30. Koestenberger M, Ravekes W, Everett AD, et al. Right ventricular function in infants, children and adolescents: reference values of the Tricuspid Annular Plane Systolic Excursion (TAPSE) in 640 healthy patients and calculation of z score values. J Am Soc Echocardiogr 2009; 22: 715–719.
31. Koestenberger M, Nagel B, Ravekes W, et al. Systolic right ventricular function in preterm and term neonates: reference values of the Tricuspid Annular Plane Systolic Excursion (TAPSE) in 258 Patients and calculation of Z-score values. Neonatology 2011; 100: 85–92.
32. Pavlicek M, Wahl A, Rutz T, et al. Right ventricular systolic function assessment: rank of echocardiographic methods vs. cardiac magnetic resonance imaging. Eur J Echocardiogr 2011; 12: 871–880.
33. Koestenberger M, Nagel B, Ravekes W, et al. Reference values of tricuspid annular peak systolic velocity in healthy pediatric patients, calculation of z score, and comparison to tricuspid annular plane systolic excursion. Am J Cardiol 2012; 109: 116–121.
34. Meluzin J, Spinarova L, Bakala J, et al. Pulsed Doppler tissue imaging of the velocity of tricuspid annular systolic motion; a new, rapid, and non-invasive method of evaluating right ventricular systolic function. Eur Heart J 2001; 22: 340–348.
35. Harada K, Toyono M, Yamamoto F. Assessment of right ventricular function during exercise with quantitative Doppler tissue imaging in children late after repair of tetralogy of Fallot. J Am Soc Echocardiogr 2004; 17: 863–869.
36. Koestenberger M, Ravekes W. Value of tricuspid annular plane systolic excursion and peak systolic velocity in children with pulmonary hypertension. J Am Soc Echocardiogr 2012; 25: 1357, author reply 1357–1358.
37. Sutherland GR, Di Salvo G, Claus P, D'Hooge J, Bijnens B. Strain and strain rate imaging: a new clinical approach to quantifying regional myocardial function. J Am Soc Echocardiogr 2004; 17: 788–802.
38. Nesbitt GC, Mankad S, Oh JK. Strain imaging in echocardiography: methods and clinical applications. Int J Cardiovasc Imaging 2009; 25 (Suppl 1): 9–22.
39. Weidemann F, Kowalski M, D'Hooge J, Bijnens B, Sutherland GR. Doppler myocardial imaging. A new tool to assess regional inhomogeneity in cardiac function. Basic Res Cardiol 2001; 96: 595–605.
40. Weidemann F, Mertens L, Gewillig M, Sutherland GR. Quantitation of localized abnormal deformation in asymmetric non-obstructive hypertrophic cardiomyopathy: a velocity, strain rate, and strain Doppler myocardial imaging study. Pediatr Cardiol 2001; 22: 534–537.
41. Weidemann F, Wacker C, Rauch A, et al. Sequential changes of myocardial function during acute myocardial infarction, in the early and chronic phase after coronary intervention described by ultrasonic strain rate imaging. J Am Soc Echocardiogr 2006; 19: 839–847.
42. Kalam K, Otahal P, Marwick TH. Prognostic implications of global LV dysfunction: a systematic review and meta-analysis of global longitudinal strain and ejection fraction. Heart 2014; 100: 1673–1680.
43. Teske AJ, Cox MG, De Boeck BW, Doevendans PA, Hauer RN, Cramer MJ. Echocardiographic tissue deformation imaging quantifies abnormal regional right ventricular function in arrhythmogenic right ventricular dysplasia/cardiomyopathy. J Am Soc Echocardiogr 2009; 22: 920–927.
44. Leong DP, Grover S, Molaee P, et al. Nonvolumetric echocardiographic indices of right ventricular systolic function: validation with cardiovascular magnetic resonance and relationship with functional capacity. Echocardiography 2012; 29: 455–463.
45. Park J-H, Negishi K, Kwon DH, Popovic ZB, Grimm RA, Marwick TH. Validation of global longitudinal strain and strain rate as reliable markers of right ventricular dysfunction: comparison with cardiac magnetic resonance and outcome. J Cardiovasc Ultrasound 2014; 22: 113–120.
46. Dambrauskaite V, Delcroix M, Claus P, et al. Regional right ventricular dysfunction in chronic pulmonary hypertension. J Am Soc Echocardiogr 2007; 20: 1172–1180.

47. Sachdev A, Villarraga HR, Frantz RP, et al. Right ventricular strain for prediction of survival in patients with pulmonary arterial hypertension. Chest 2011; 139: 1299–1309.
48. Vitarelli A, Mangieri E, Terzano C, et al. Three-dimensional echocardiography and 2D-3D speckle-tracking imaging in chronic pulmonary hypertension: diagnostic accuracy in detecting hemodynamic signs of right ventricular (RV) failure. *J Am Heart Assoc* 2015; 4: e001584.
49. Okumura K, Humpl T, Dragulescu A, Mertens L, Friedberg MK. Longitudinal assessment of right ventricular myocardial strain in relation to transplant-free survival in children with idiopathic pulmonary hypertension. J Am Soc Echocardiogr 2014; 27: 1344–1351.
50. Li Y, Xie M, Wang X, Lu Q, Zhang L, Ren P. Impaired right and left ventricular function in asymptomatic children with repaired tetralogy of Fallot by two-dimensional speckle tracking echocardiography study. Echocardiography 2015; 32: 135–143.
51. Ye J-J, Shu Q, Liu X-W, Gu W-z, Yu J, Jiang G-p. Noninvasive perioperative evaluation of right ventricular function in children with tetralogy of Fallot. Artif Organs 2014; 38: 41–47.
52. Bernard Y, Morel M, Descotes-Genon V, Jehl J, Meneveau N, Schiele F. Value of speckle tracking for the assessment of right ventricular function in patients operated on for tetralogy of fallot. Comparison with magnetic resonance imaging. Echocardiography 2014; 31: 474–482.
53. Scherptong RWC, Mollema SA, Blom NA, et al. Right ventricular peak systolic longitudinal strain is a sensitive marker for right ventricular deterioration in adult patients with tetralogy of Fallot. Int J Cardiovasc Imaging 2009; 25: 669–676.
54. Levy PT, Sanchez Mejia AA, Machefsky A, Fowler S, Holland MR, Singh GK. Normal ranges of right ventricular systolic and diastolic strain measures in children: a systematic review and meta-analysis. J Am Soc Echocardiogr 2014; 27: 549–560, e543.
55. Cetiner MA, Sayin MR, Yildirim N, et al. Right ventricular isovolumic acceleration in acute pulmonary embolism. Echocardiography 2014; 31: 1253–1258.
56. Selcuk M, Sayar N, Demir S, Rodi Tosua A, Aslan V. The value of isovolumic acceleration for the assessment of right ventricular function in acute pulmonary embolism. Revista Portuguesa de Cardiologia 2014; 33: 591–596.
57. Frigiola A. Pulmonary regurgitation is an important determinant of right ventricular contractile dysfunction in patients with surgically repaired tetralogy of Fallot. Circulation 2004; 110 (Suppl 1): II-153–II-157.
58. Vogel M. Validation of myocardial acceleration during isovolumic contraction as a novel noninvasive index of right ventricular contractility: comparison with ventricular pressure-volume relations in an animal model. Circulation 2002; 105: 1693–1699.
59. Khoo NS, Young A, Occleshaw C, Cowan B, Zeng IS, Gentles TL. Assessments of right ventricular volume and function using three-dimensional echocardiography in older children and adults with congenital heart disease: comparison with cardiac magnetic resonance imaging. J Am Soc Echocardiogr 2009; 22: 1279–1288.
60. van der Zwaan HB, Helbing WA, McGhie JS, et al. Clinical value of real-time three-dimensional echocardiography for right ventricular quantification in congenital heart disease: validation with cardiac magnetic resonance imaging. J Am Soc Echocardiogr 2010; 23: 134–140.
61. Leary PJ, Kurtz CE, Hough CL, Waiss MP, Ralph DD, Sheehan FH. Three-dimensional analysis of right ventricular shape and function in pulmonary hypertension. Pulm Circ 2012; 2: 34–40.
62. Grewal J, Majdalany D, Syed I, Pellikka P, Warnes CA. Three-dimensional echocardiographic assessment of right ventricular volume and function in adult patients with congenital heart disease: comparison with magnetic resonance imaging. J Am Soc Echocardiogr 2010; 23: 127–133.
63. Niemann PS, Pinho L, Balbach T, et al. Anatomically oriented right ventricular volume measurements with dynamic three-dimensional echocardiography validated by 3-Tesla magnetic resonance imaging. J Am Coll Cardiol 2007; 50: 1668–1676.
64. Shiina Y, Funabashi N, Lee K, et al. Right atrium contractility and right ventricular diastolic function assessed by pulsed tissue Doppler imaging can predict brain natriuretic peptide in adults with acquired pulmonary hypertension. Int J Cardiol 2009; 135: 53–59.
65. Maskatia SA, Morris SA, Spinner JA, Krishnamurthy R, Altman CA. Echocardiographic parameters of right ventricular diastolic function in repaired tetralogy of fallot are associated with important findings on magnetic resonance imaging. Congenit Heart Dis 2015; 10: E113–E122.
66. Zoghbi WA, Habib GB, Quinones MA. Doppler assessment of right ventricular filling in a normal population. Comparison with left ventricular filling dynamics. Circulation 1990; 82: 1316–1324.
67. Caballero L, Kou S, Dulgheru R, et al. Echocardiographic reference ranges for normal cardiac Doppler data: results from the NORRE Study. *Eur Heart J Cardiovasc Imaging* 2015; 16: 1031–1041.