Clin Physiol Funct Imaging (2006) **26,** pp1–8

Right ventricular myocardial isovolumic relaxation time and pulmonary pressure

Pulsed Doppler tissue imaging in resurrection of Burstin's nomogram

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Accepted for publication

Received 10 March 2005; accepted 22 August 2005

Key words

Doppler tissue imaging; isovolumic relaxation time; pulmonary artery systolic pressure; right ventricular function

Summary

Aims: Non-invasive assessment of pulmonary artery systolic pressure (PASP) has several limitations. As previously described by Burstin, the right ventricular (RV) isovolumic relaxation time (IVRt) is sensitive to changes in PASP. We therefore compared RV myocardial IVRt, derived by Doppler tissue imaging (DTI), with simultaneously measured invasive PASP.

Methods and results: Twenty-six consecutive patients (18 males, mean age 52 ± 12 years, range 23–75) underwent a simultaneous Doppler echocardiography, including DTI, and cardiac catheterization examination for measurement of PASP and right atrial mean pressures. IVRt was measured using the myocardial velocities by pulsed DTI at both basal and mid cavity segments of the RV free wall. As diastolic time intervals are influenced by heart rate IVRt was corrected for heart rate (IVRt/RR%). A significant correlation was found between PASP and regional IVRt/RR% at both the basal ($r = 0{\cdot}42$, $P<0{\cdot}05$) and mid cavity segment ($r = 0{\cdot}71$, $P<0{\cdot}001$). Furthermore, when only patients with normal right atrial pressures (<7 mmHg) were taken into account, the correlation coefficient improved at both basal and mid cavity segments ($r = 0{\cdot}74$, $P<0{\cdot}05$ and $r = 0{\cdot}83$, $P<0{\cdot}01$).

Conclusion: Pulsed Doppler-derived IVRt correlates well with PASP. The use of pulsed DTI for measurement of IVRt is simple, reproducible and easy to obtain. We propose this method as an additional non-invasive tool in the assessment of PASP.

Introduction

Right ventricular (RV) function as well as RV and pulmonary artery systolic pressures (PASPs) are important to determine because persistent pulmonary hypertension (PHT) and right heart failure are related to a substantially increased risk for death (Ghio *et al.*, 2001; Raymond *et al.*, 2002; Gavazzi *et al.*, 2003). Therefore, early detection of elevated PASP is crucial (Steen, 2003). By using Doppler echocardiography to assess the tricuspid regurgitation peak pressure gradient it has been possible to determine the PASP (Burgess *et al.*, 2002; Raymond *et al.*, 2002). This is the most widely used method but a substantial amount of patients do not show an accurate flow signal and the actual pressure level may be both over- and underestimated (Brecker *et al.*, 1994; Raeside *et al.*, 1998; Homma *et al.*, 2001). Right heart catheterization remains the golden standard technique for measurement of PASP.

Burstin (1967) showed, by using phonocardiogram (PCG) and external pulse curves, that the isovolumic relaxation time (IVRt) could accurately estimate the PASP. Doppler tissue imaging (DTI) is a relatively new technique in cardiac imaging, which allows characterization of myocardial motion and time intervals throughout the cardiac cycle. To our knowledge, no study has evaluated the regional myocardial RV IVRt in relation to PASP by using pulsed DTI and simultaneous cardiac catheterization. The aim of the present study was to investigate the feasibility to use pulsed DTI for estimation of PASP.

Methods

Study population

Twenty-six consecutive patients (18 males) referred for routine cardiac characterization due to different cardiac

diseases were studied. Their mean age was 52 ± 12 years (range 23–75). Two patients had hypertrophic cardiomyopathy, 10 had dilated cardiomyopathy, four were heart transplanted, one had systemic hypertension, one had mitral valve prosthesis dysfunction, four had primary pulmonary hypertension, one had heart failure caused by aortic stenosis, two had mitral valve disease, and one had ischaemic heart disease (Table 1). All patients were in sinus rhythm and patients with complete right bundle branch block (RBBB) were excluded. Nine patients were on diuretics, 12 on angiotensin-converting enzyme inhibitors, 12 on beta-blockers, one on digitalis and six on calcium antagonists. All patients gave their written consent to participate in the study, which was approved by the local ethics committee.

Echocardiography

Doppler echocardiographic examinations were carried out simultaneously with cardiac catheterization while patients were in the supine position. All patients were in a stable haemodynamic condition. A commercially available ultrasound system (HP, Sonos 5500; Andover, Massachusets, MA, USA) equipped with a multi-frequency phased array transducer (S3, 1–3 MHz and S4, 2–4 MHz) and pulsed DTI technique was used. Parasternal and apical views were obtained according to the recommendations of the American Society of Echocardiography (Schiller *et al.*, 1989). All recordings were made with a simultaneous superimposed ECG and PCG (HP 2105A, Andover) to detect the pulmonary component of second heart sound (S_2) (Garcia-Fernandez *et al.*, 1999; Sutherland & Hatle, 2000). Recordings were made at a sweep speed of 50 and 100 mm s^{-1} and stored on a magnetic optical disc. Values are presented as mean of three beats. As IVRt is heart rate dependent, it was divided by RR time interval (IVRt/RR%).

Conventional Doppler echocardiography

Presence of valvular regurgitation was detected by colour Doppler and trans-tricuspid peak retrograde velocities were recorded using the continuous wave Doppler technique and Bernoulli's modified equation was used to calculate the RV–right atrial (RA) peak pressure gradient.

Right ventricular myocardial pulsed Doppler tissue imaging

Myocardial systolic and diastolic velocities and the time intervals were recorded using the pulsed DTI technique. The sample volume was 6 mm. The acoustic power and filter frequencies were adjusted for detecting myocardial velocities. Measurements were made at two levels of the RV free wall, basal and mid cavity levels (Fig. 1).

Cardiac catheterization

One experienced investigator (G.W.) performed all the cardiac catheterization studies. Briefly, a balloon catheter was inserted through the right internal jugular vein or right brachial vein (Becton Dickinson Criticath SP 5107 HTD catheter, Irvine, California, USA). Pressures were registered with a Cathcor® system 3.3 (Siemens Elema AB, Electromedical Systems Divisions, Solna, Sweden).

Measurements

Left ventricular (LV) internal diameter at end-diastole (onset of the Q wave) and at end-systole (the shortest distance between septal nadir to the posterior wall) were measured as recommended by the American Society of Echocardiography (Sahn *et al.*, 1978). Ejection fraction was derived from Simpson's

Table 1 Patient characteristics.

	DCM	Transplanted	sPHT	pPHT	HCM
n	10	4	6	4	2
Age (years)	49 ± 9	56 ± 8	60 ± 8	30 ± 9	64 ± 6
HR (b min^{-1})	62 ± 12	76 ± 14	89 ± 16	74 ± 14	73 ± 1
SBP (mmHg)	118 ± 21	152 ± 31	131 ± 26	120 ± 30	128 ± 16
DBP (mmHg)	76 ± 11	92 ± 2	77 ± 13	68 ± 13	85 ± 7
Gender (m/f)	8/2	4/0	3/3	1/3	2/0
BSA (m^2)	2·07 ± 0·26	2·15 ± 0·17	1·88 ± 0·31	1·75 ± 0·21	2·15 ± 0·21
NYHA (I/II/III/IV)	0/4/5/1	2/2/0/0	0/2/2/2	0/2/2/0	0/0/0/2
PASP (mmHg)	47 ± 32	32 ± 3	71 ± 39	90 ± 26	42 ± 0
RAMP (mmHg)	7 ± 5	6 ± 2	12 ± 7	14 ± 10	8 ± 4
LVEF (%)	35 ± 11	54 ± 15	31 ± 23	72 ± 7	43 ± 19
LVDD (mm)	71 ± 11	52 ± 11	50 ± 7	43 ± 12	54 ± 18
RVS long axis (mm)	18 ± 5	17 ± 2	16 ± 9	13 ± 7	13 ± 1

DCM, dilated cardiomyopathy; sPHT, secondary pulmonary hypertension; pPHT, primary hypertension; HCM, hypertrophy cardiomyopathy; HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; BSA; body surface area; PASP, pulmonary artery systolic pressure; RAMP; right atrial mean pressure; LVEF, left ventricular ejection fraction; LVDD, left ventricular diastolic diameter; RVS, right ventricular systolic.

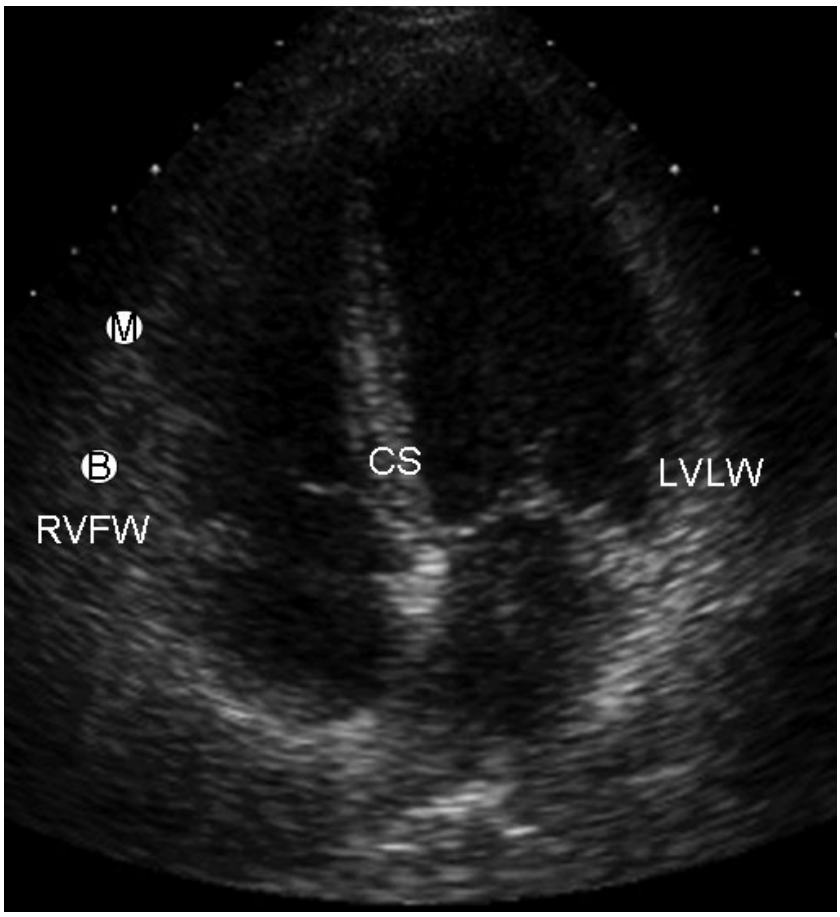

Figure 1 Sample volume position in the RV free wall. B, basal level; M, mid segmental level; RVFW, right ventricular free wall; CS, common septum; LVLW, left ventricular lateral wall.

modified single plane method using the four-chamber view. RV outflow tract fractional shortening (RVOT fs) was calculated as the percentage fall in RV outflow tract diameter in systole, as was previously described (Lindqvist *et al.*, 2003). Right ventricular systolic long axis amplitude (RVS long axis) was recorded from the apical four-chamber view with the M-mode cursor positioned at the free wall of the tricuspid valve anulus (Henein *et al.*, 1995). Furthermore, RV end-diastolic and systolic area was manually measured and RV fractional area change (RV FAC) was calculated. Tricuspid peak retrograde velocities were detected by colour Doppler and recorded using a continuous wave Doppler technique; RV–RA peak pressure gradient was calculated using the modified Bernoulli equation (Quinones *et al.*, 2002).

Right ventricular myocardial pulsed Doppler tissue imaging measurements

Doppler tissue imaging was used to measure RV longitudinal myocardial segmental function (Isaaz *et al.*, 1993; Garcia *et al.*, 1996). From the basal and mid cavity level the peak systolic (Sv) and IVRt were measured as the time interval between the pulmonary component of S_2 to onset of myocardial early diastolic velocity (Ev) (Fig. 2).

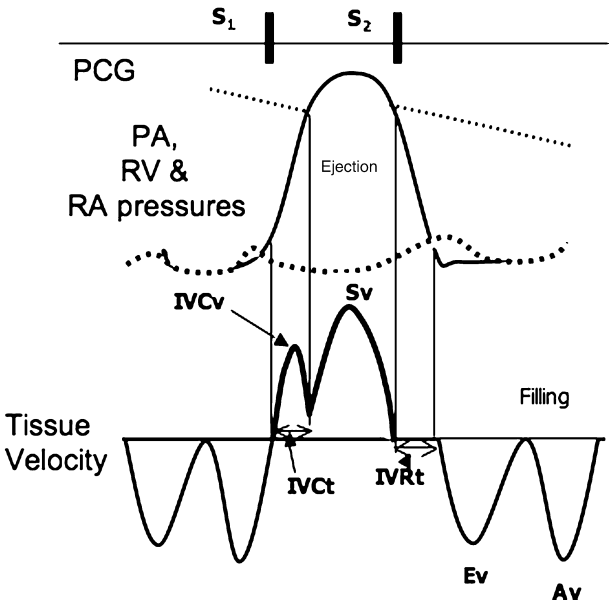

Figure 2 Schematic relationship between Doppler tissue imaging tracings and invasive haemodynamic variables: PCG, phonocardiogram; ECG, electrocardiogram; Sv, peak systolic myocardial velocity; Ev, peak early diastolic myocardial velocity; Av, peak late atrial myocardial velocity; IVCt, isovolumic contraction time; IVRt, isovolumic relaxation time; S2, second heart sound; PA, pulmonary artery, RV, right ventricular, RA, right atrial.

Cardiac catheterization

From cardiac catheterization recordings PASP and right atrial mean pressure were measured and the mean of five consecutive beats was used.

Statistical analysis

A commercially available statistical program (SPSS 10.1 and 11.1; SPSS Inc., Chicago, IL, USA) was used. All data are presented as the mean ± SD. Pearson's correlation and linear regression analyses were plotted when appropriate. Furthermore, a stepwise linear regression analysis was also performed. A P value <0·05 was considered significant.

Results

Right ventricular systolic function and pulmonary artery systolic pressure

Right ventricular systolic function and PASP RVOT fs ($r = 0{\cdot}49$, $P<0{\cdot}05$) and Sv ($r = 0{\cdot}43$, $P<0{\cdot}05$) correlated to pulmonary artery pressure. However, RV FAC and RVS long axis amplitude did not. After including RVOT fs, Sv and IVRt/RR% in a stepwise linear regression analysis, PASP was the strongest independent variable related to IVRt/RR% (standardized β coefficient = 0·78, P = 0·004). Standardized β coefficient for RVOT fs was −0·50, P = 0·22.

Right ventricular diastolic function and pulmonary artery systolic pressure

A significant correlation was found between PASP and regional IVRt at the mid cavity segment ($r = 0{\cdot}52$, $P<0{\cdot}05$) which was improved at both the basal and mid cavity levels ($r = 0{\cdot}42$, $P<0{\cdot}05$ and $r = 0{\cdot}71$, $P<0{\cdot}01$ respectively) after correcting fort heart rate, IVRt/RR% (Fig. 3). When studying the relationship between IVRt and PASP in case of normal or moderately elevated right atrial pressure (right atrial pressures below 8 mmHg), we found a higher correlation coefficient for both basal IVRt/RR% and mid cavity IVRt/RR% ($r = 0{\cdot}65$, $P<0{\cdot}05$; $r = 0{\cdot}76$, $P<0{\cdot}01$) (Fig. 4). Furthermore, when only patients with normal right atrial pressures (<7 mmHg) were taken into account, the correlation further improved at both base and mid cavity level IVRt/RR% ($r = 0{\cdot}74$, $P<0{\cdot}05$ and $r = 0{\cdot}83$, $P<0{\cdot}01$) (Fig. 5). Furthermore, RV–RA peak pressure gradient ($r = 0{\cdot}90$, $P<0{\cdot}001$) was highly significantly correlated to PASP. Importantly, RV–RA pressure gradient could only be calculated in 73% of the cases by conventional echo technique while DTI-derived IVRt was obtained in almost all patients (96%). An example of increased IVRt in a patient with elevated PASP (65 mmHg) is shown in Fig. 6. When a cut off value of 10% of IVRt/RR% was used to detect a PASP above 30 mmHg the sensitivity and specificity was 86% and 75% respectively.

Reproducibility of the data

Intra-observer and inter-observer variability in IVRt measurements were tested by repeated measurements in 10 consecutive

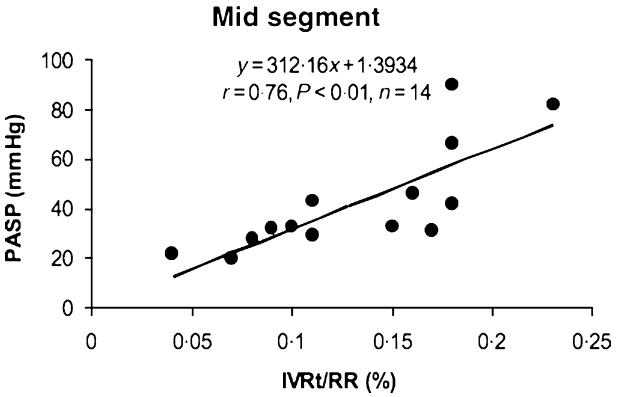

Figure 4 The relationship (in patients with right atrial pressure <8 mmHg) between the IVRt/RR% at the mid cavity of the right ventricle and pulmonary artery systolic pressure. Abbreviations as Figure 3.

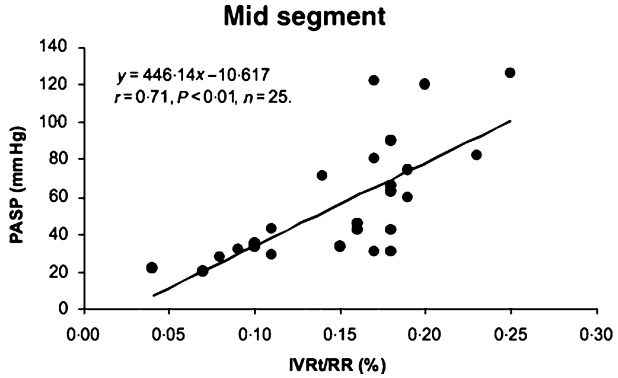

Figure 3 The relationship (in all patients) between the IVRt/RR% at the mid cavity of the right ventricle and pulmonary artery systolic pressure. PASP, pulmonary artery systolic pressure; IVRt, isovolumic relaxations time.

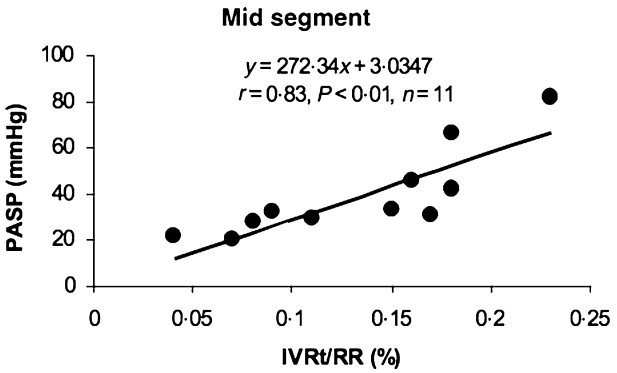

Figure 5 The relationship (in patients with right atrial pressure <7 mmHg) between the IVRt/RR% at the mid cavity of the right ventricle and pulmonary artery systolic pressure. Abbreviations as Figure 3.

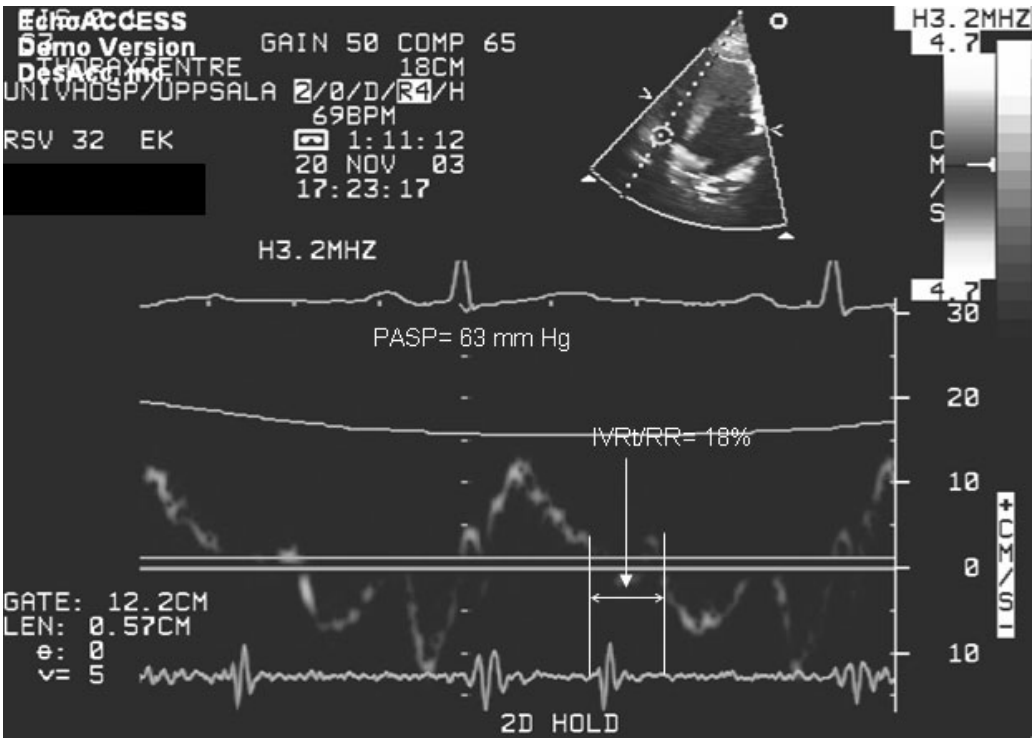

Figure 6 Prolonged IVRt/RR in patient with elevated pulmonary artery systolic pressure.

tracings. Variability is expressed as the coefficient of variation. The inter- and intra-observer variability of DTI-IVRt was 12·2% for both.

Discussion

By using Doppler echocardiography it is possible to estimate the pulmonary artery pressure from tricuspid regurgitation peak velocity (Chan *et al.*, 1987). Reports suggest that this method is appropriate in 60–86% of the patients (Borgeson *et al.*, 1996) and may be improved by using contrast media (Waggoner *et al.*, 1990). In clinical practice, the quality of the signal is often poor and the determination of peak velocity is thus difficult, especially in patients with mild to moderate PHT. Furthermore, PASP is often underestimated when using this method (Brecker *et al.*, 1994). The pulmonary artery acceleration time is proposed to be accurate in estimating PASP when heart rate is between 60 and 100 b min^{-1} (Chan *et al.*, 1987). Previously we reported that RVOT fs was more sensitive in detecting PHT than RV systolic long axis amplitude (Lindqvist *et al.*, 2003). This observation is confirmed in the present combined invasive and non-invasive study.

Burstin (1967) showed that PASP could be estimated non-invasively by measuring the time interval between the pulmonary valve closure to the onset of tricuspid flow (IVRt). Fourteen years later, Hatle *et al.* (1981) using PCG and pulsed Doppler tricuspid flow velocities confirmed this observation. Myocardial diastolic function can easily be assessed by pulsed DTI. This has been shown in hypertrophic cardiomyopathy (Severino *et al.*, 2000), systemic arterial hypertension (Cicala *et al.*, 2002), RV infarction (Oguzhan *et al.*, 2003), chronic obstructive lung disease and PHT (Marangoni *et al.*, 1992). Recently, pulsed DTI was used to distinguish subsets of patients affected by lung disease with or without echocardiographic evidence of PHT (Caso *et al.*, 2001).

The duration of IVRt is determined by: (i) right atrial pressure which, in the absence of tricuspid stenosis or insufficiency or right heart failure, remains normal; (ii) systolic pulmonary artery pressure which when raised, delays the opening of tricuspid valves and proportionately prolongs IVRt; and (iii) and heart rate (HR) is inversely related to the duration of IVRt (Yu *et al.*, 2003).

As it is well demonstrated that HR influences IVRt, all measurements were corrected for HR (IVRt/RR%). Previous studies have shown that measurement of RV IVRt may not be appropriate in patients with dysrhythmias (Chan *et al.*, 1987). It is also known that bundle branch block influence IVRt (Henein & Gibson, 1999). Therefore, patients with atrial fibrillation and complete RBBB were excluded from the study.

Increased right atrial pressure leads to a premature opening of the tricuspid valve and thereby shortens the IVRt. We took this into consideration and did a stepwise analysis by first including all patients, then those with atrial pressures below 8 and finally those with normal atrial pressures (<7 mmHg). The correlation for the total material was good but improved considerably after excluding patients with elevated right atrial pressures, as has been suggested by others (Burstin, 1967; Hatle *et al.*, 1981). The correlation between IVRt/RR% and

PASP was highest when the right atrial pressure was within normal limits.

In the case of PHT, the rate of the pressure fall is reduced and onset of RV filling may occur more than 100 ms after closure of pulmonary valves. The protracted early relaxation can be assessed with pulsed DTI where the onset of relaxation seems to be dependent on the pressure gradient across the tricuspid valve (Fig. 7).

Dyspnoea of unknown cause is a common and important problem in clinical medicine. Exclusion of PHT is a routine part of the clinical investigation. PHT is considered to be an indicator of poor prognosis (Abramson *et al.*, 1992). However, despite elevated PASP, well-preserved RV systolic function and normal right atrial pressures predict a better outcome (Ghio *et al.*, 2001) and preserved exercise tolerance (Gudjonsson & Rahko, 2002). Over the last 25 years, there has been a rapid progress in the understanding of the pathophysiology and pathogenesis of PHT, which resulted in improvement of treatment strategies (Hoeper *et al.*, 2002). Successful pharmacological treatment of PHT makes early diagnosis and follow-up even more relevant. This treatment supposedly leads to less tricuspid valve regurgitation, consequently RA–RV peak gradient assessment of PASP will be less reliable emphasizing a need for a better non-invasive method. Assessment of PASP is thought to be accurately determined only by cardiac catheterization, but this is not feasible in all cases for practical reasons.

The present study was performed in patients with a broad range of invasively measured PASP in order to calculate the correlation between the pulsed DTI-derived IVRt and PASP. By the use of pulsed DTI technique we confirmed the known relationship between IVRt and PASP (see above). This has potential clinical implications as the technique is available in modern equipment and registrations are easy to obtain in almost all patients. While RA–RV peak pressure gradient was only

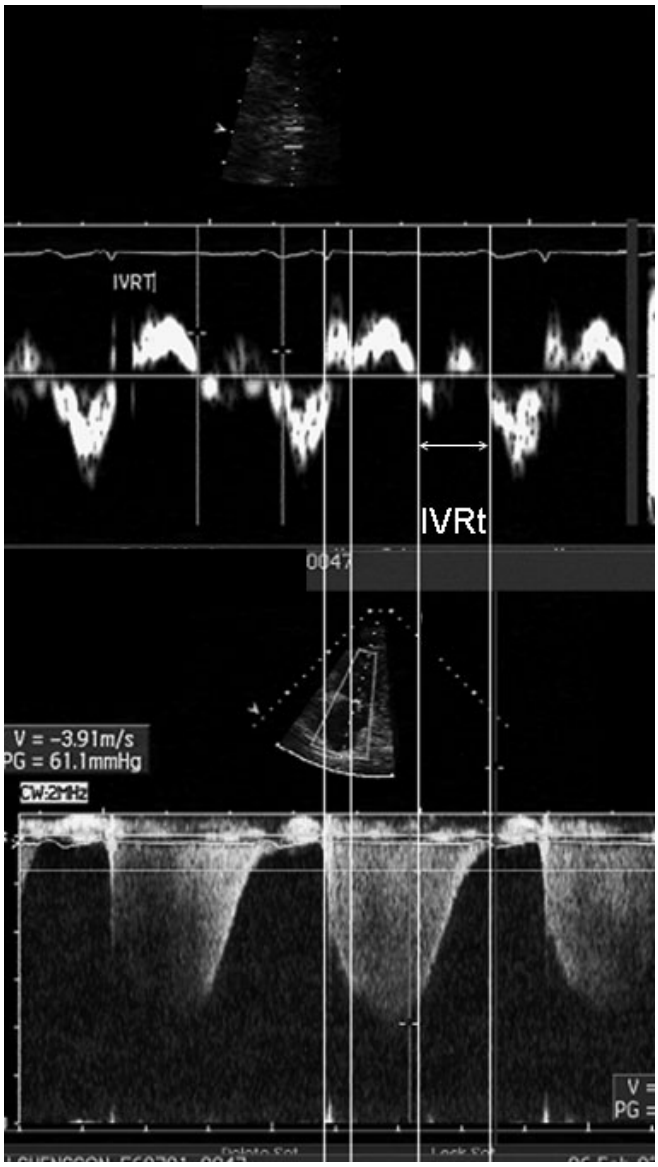

Figure 7 Simultaneously superimposed pulsed Doppler tissue imaging and continuous Doppler echocardiography. The onset of relaxation is dependent on the time for regurgitation in the tricuspid valve. In this case, the gradient between right ventricular and right atrial pressure drop was 65 mmHg. Note also the impaired filling time for the right ventricle.

measurable in 73% of our patients, IVRt was measurable by using DTI in almost all patients. Consequently, IVRt/RR% measured by using pulsed DTI, can serve as an additional non-invasive, easy method with good reproducibility for estimating PASP.

Study limitations

Relatively few patients were studied. Still a close relationship between IVRt and PASP was demonstrated. Many of the patients did suffer from severe heart failure, and therefore only 14 patients showed RA pressures below 8 mmHg and 11 patients below 7 mmHg. The equation of the curve (IVRt vs. PASP relationship) was essentially the same irrespective of how the material was defined (all, <8 mmHg, <7 mmHg respectively). To provide with a more reliable nomogram, more patients with PHT and normal RA pressure should be investigated.

The use of PCG to assess the starting point of IVRt and pulsed DTI to determine the end-point could be criticized as it combines mechanical myocardial and hydraulic aspects of motion in the measurement. However PCG is a very helpful tool to determine cardiac cycle timing as it displays the time of the second heart sound superimposed on Doppler tracings and therefore allows accurate measurements and assessment of cardiac physiology during different phases of the cardiac cycle. This is important as wall motion or postsystolic motion during IVRt is common in cardiac disease. In this study, we found it more accurate to define end of systole from PCG than from DTI tracings of end-ejection.

Conclusion

Pulsed DTI-derived IVRt/PP% correlates well with PASP. The use of DTI for measurement of IVRt is simple, reproducible and easy to obtain. We propose this method as an additional non-invasive tool in the assessment of PASP.

Acknowledgments

This study was supported by the Swedish Heart and Lung Foundation, The Heart Foundation of Northern Sweden. Ulla-Marie Andersson, Mona Andrén, Karin Fagerbrink, Kjell Karlström, Berit Lowén and Elisabeth Lindström are acknowledged for their skilful assistance during the catheterization procedure. Dr J. Landelius is appreciated for his support.

References

Abramson SV, Burke JF, Kelly JJ Jr., Kitchen JG 3rd., Dougherty MJ, Yih DF, McGeehin FC 3rd., Shuck JW, Phiambolis TP. Pulmonary hypertension predicts mortality and morbidity in patients with dilated cardiomyopathy. *Ann Intern Med* (1992); **116**: 888–895.

Borgeson DD, Seward JB, Miller FA Jr, Oh JK, Tajik AJ. Frequency of Doppler measurable pulmonary artery pressures. *J Am Soc Echocardiogr* (1996); **9**: 832–837.

Brecker SJ, Gibbs JS, Fox KM, Yacoub MH, Gibson DG. Comparison of Doppler derived haemodynamic variables and simultaneous high fidelity pressure measurements in severe pulmonary hypertension. *Br Heart J* (1994); **72**: 384–389.

Burgess MI, Bright-Thomas RJ, Ray SG. Echocardiographic evaluation of right ventricular function. *Eur J Echocardiogr* (2002); **3**: 252–262.

Burstin L. Determination of pressure in the pulmonary artery by external graphic recordings. *Br Heart J* (1967); **29**: 396–404.

Caso P, Galderisi M, Cicala S, Cioppa C, D'Andrea A, Lagioia G, Liccardo B, Martiniello AR, Mininni N. Association between myocardial right ventricular relaxation time and pulmonary arterial pressure in chronic obstructive lung disease: analysis by pulsed Doppler tissue imaging. *J Am Soc Echocardiogr* (2001); **14**: 970–977.

Chan KL, Currie PJ, Seward JB, Hagler DJ, Mair DD, Tajik AJ. Comparison of three Doppler ultrasound methods in the prediction of pulmonary artery pressure. *J Am Coll Cardiol* (1987); **9**: 549–554.

Cicala S, Galderisi M, Caso P, Petrocelli A, D'Errico A, de Divitiis O, Calabro R. Right ventricular diastolic dysfunction in arterial systemic hypertension: analysis by pulsed tissue Doppler. *Eur J Echocardiogr* (2002); **3**: 135–142.

Garcia MJ, Rodriguez L, Ares M, Griffin BP, Klein AL, Stewart WJ, Thomas JD. Myocardial wall velocity assessment by pulsed Doppler tissue imaging: characteristic findings in normal subjects. *Am Heart J* (1996); **132**: 648–656.

Garcia-Fernandez MA, Azevedo J, Moreno M, Bermejo J, Perez-Castellano N, Puerta P, Desco M, Antoranz C, Serrano JA, Garcia E, Delcan JL. Regional diastolic function in ischaemic heart disease using pulsed wave Doppler tissue imaging. *Eur Heart J* (1999); **20**: 496–505.

Gavazzi A, Ghio S, Scelsi L, Campana C, Klersy C, Serio A, Raineri C, Tavazzi L. Response of the right ventricle to acute pulmonary vasodilation predicts the outcome in patients with advanced heart failure and pulmonary hypertension. *Am Heart J* (2003); **145**: 310–316.

Ghio S, Gavazzi A, Campana C, Inserra C, Klersy C, Sebastiani R, Arbustini E, Recusani F, Tavazzi L. Independent and additive prognostic value of right ventricular systolic function and pulmonary artery pressure in patients with chronic heart failure. *J Am Coll Cardiol* (2001); **37**: 183–188.

Gudjonsson T, Rahko PS. Relation of "inotropic reserve" to functional capacity in heart failure secondary to ischemic or nonischemic cardiomyopathy. *Am J Cardiol* (2002); **89**: 1057–1061.

Hatle L, Angelsen BA, Tromsdal A. Non-invasive estimation of pulmonary artery systolic pressure with Doppler ultrasound. *Br Heart J* (1981); **45**: 157–165.

Henein MY, Cailes J, O'Sullivan C, du Bois RM, Gibson DG. Abnormal ventricular long-axis function in systemic sclerosis. *Chest* (1995); **108**: 1533–1540.

Henein MY, Gibson DG. Normal long axis function. *Heart* (1999); **81**: 111–113.

Hoeper MM, Galie N, Simonneau G, Rubin LJ. New treatments for pulmonary arterial hypertension. *Am J Respir Crit Care Med* (2002); **165**: 1209–1216.

Homma A, Anzueto A, Peters JI, Susanto I, Sako E, Zabalgoitia M, Bryan CL, Levine SM. Pulmonary artery systolic pressures estimated by echocardiogram vs cardiac catheterization in patients awaiting lung transplantation. *J Heart Lung Transplant* (2001); **20**: 833–839.

Isaaz K, Munoz del Romeral L, Lee E, Schiller NB. Quantitation of the motion of the cardiac base in normal subjects by Doppler echocardiography. *J Am Soc Echocardiogr* (1993); **6**: 166–176.

Lindqvist P, Henein M, Kazzam E. Right ventricular outflow-tract fractional shortening: an applicable measure of right ventricular systolic function. *Eur J Echocardiogr* (2003); **4**: 29–35.

Marangoni S, Scalvini S, Schena M, Vitacca M, Quadri A, Levi G. Right ventricular diastolic function in chronic obstructive lung disease. *Eur Respir J* (1992); **5**: 438–443.

Oguzhan A, Abaci A, Eryol NK, Topsakal R, Seyfeli E. Colour tissue Doppler echocardiographic evaluation of right ventricular function in patients with right ventricular infarction. *Cardiology* (2003); **100**: 41–46.

Quinones MA, Otto CM, Stoddard M, Waggoner A, Zoghbi WA. Recommendations for quantification of Doppler echocardiography: a report from the Doppler Quantification Task Force of the Nomenclature and Standards Committee of the American Society of Echocardiography. *J Am Soc Echocardiogr* (2002); **15**: 167–184.

Raeside DA, Chalmers G, Clelland J, Madhok R, Peacock AJ. Pulmonary artery pressure variation in patients with connective tissue disease: 24 hour ambulatory pulmonary artery pressure monitoring. *Thorax* (1998); **53**: 857–862.

Raymond RJ, Hinderliter AL, Willis PW, Ralph D, Caldwell EJ, Williams W, Ettinger NA, Hill NS, Summer WR, de Boisblanc B, Schwartz T, Koch G, Clayton LM, Jobsis MM, Crow JW, Long W. Echocardiographic predictors of adverse outcomes in primary pulmonary hypertension. *J Am Coll Cardiol* (2002); **39**: 1214–1219.

Sahn DJ, DeMaria A, Kisslo J, Weyman A. Recommendations regarding quantitation in M-mode echocardiography: results of a survey of echocardiographic measurements. *Circulation* (1978); **58**: 1072–1083.

Schiller NB, Shah PM, Crawford M, DeMaria A, Devereux R, Feigenbaum H, Gutgesell H, Reichek N, Sahn D, Schnittger I, *et al.* Recommendations for quantitation of the left ventricle by two-dimensional echocardiography. American Society of Echocardiography Committee on Standards, Subcommittee on Quantitation of Two-Dimensional Echocardiograms. *J Am Soc Echocardiogr* (1989); **2**: 358–367.

Severino S, Caso P, Cicala S, Galderisi M, de Simone L, D'Andrea A, D'Errico A, Mininni N. Involvement of right ventricle in left ventricular hypertrophic cardiomyopathy: analysis by pulsed Doppler tissue imaging. *Eur J Echocardiogr* (2000); **1**: 281–288.

Steen V. Predictors of end stage lung disease in systemic sclerosis. *Ann Rheum Dis* (2003); **62**: 97–99.

Sutherland GR, Hatle L. Pulsed Doppler myocardial imaging. A new approach to regional longitudinal function? *Eur J Echocardiogr* (2000); **1**: 81–83.

Waggoner AD, Barzilai B, Perez JE. Saline contrast enhancement of tricuspid regurgitant jets detected by Doppler color flow imaging. *Am J Cardiol* (1990); **65**: 1368–1371.

Yu CM, Lin H, Ho PC, Yang H. Assessment of left and right ventricular systolic and diastolic synchronicity in normal subjects by tissue Doppler echocardiography and the effects of age and heart rate. *Echocardiography* (2003); **20**: 19–27.