



# Echocardiographic surrogates of right atrial pressure in pulmonary hypertension

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Received: 18 July 2018 / Accepted: 14 September 2018 / Published online: 22 September 2018  
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## Abstract

Right atrial pressure (RAP), a representative parameter of right heart failure, is very important for prognostic evaluation and risk assessment in pulmonary hypertension. However, its measurement requires invasive cardiac catheterization. In this study, we determined the most accurate echocardiographic surrogate of catheterization-based RAP. In 23 patients with pulmonary hypertension, a total of 66 cardiac catheterization procedures were performed along with 2-dimensional echocardiography. We evaluated tricuspid  $E/A$ ,  $E'$ ,  $A'$  and  $E/E'$ , and estimated RAP by the respirophasic variation of the inferior vena cava diameter (eRAP-IVCd) as possible surrogates of catheterization-based RAP. In simple linear regression analysis,  $E/A$  ( $R=0.452$ ,  $P=0.0001$ ) and eRAP-IVCd ( $R=0.505$ ,  $P<0.0001$ ) were positively correlated with catheterization-based RAP, whereas  $A'$  ( $R=-0.512$ ,  $P<0.0001$ ) was negatively correlated with RAP. In multiple regression analysis,  $A'$  was the most significant independent predictor of catheterization-based RAP ( $R=-0.375$ ,  $P=0.0007$ ). In 16 patients who had multiple measurements, there were a total of 43 measurements before and after medication changes. The absolute change in catheterization-based RAP was negatively correlated with the percent change in  $A'$ . Receiver operating characteristic curve analysis indicated that the optimal cut-off value of  $A'$  to predict a catheterization-based RAP  $> 10$  mmHg was 11.3 cm/s (area under the curve = 0.782, sensitivity = 0.70, specificity = 0.78). In 20 measurements of 20 patients with left heart failure, catheterization-based RAP was not correlated with any of 5 echocardiographic parameters. However, it was closely correlated with catheterization-based pulmonary capillary wedge pressure. The echocardiographic parameter,  $A'$ , was the best surrogate of catheterization-based RAP in patients with pulmonary hypertension.

**Keywords** Right atrial pressure · Cardiac catheterization · Echocardiography ·  $A'$  · Pulmonary hypertension

## Introduction

Pulmonary hypertension is defined as a mean pulmonary artery pressure (mPAP) over 25 mmHg. Pathophysiological deterioration of pulmonary hypertension can cause an increase in pulmonary artery pressure (PAP) over the long-term, and subsequent continuous right cardiac overload leads to right heart failure. The presence of the right heart failure greatly contributes to the prognosis of patients with pulmonary hypertension [1, 2]. In patients who have right heart failure, decreased cardiac output causes PAP to reach a limit

or even decrease because PAP is greatly affected by cardiac output [3]. A paradoxical decrease in the PAP, often seen in patients with advanced-stage pulmonary hypertension, is due to this pathophysiological mechanism. Right atrial pressure (RAP) is a representative parameter of right heart failure, but its measurement requires invasive cardiac catheterization. On the other hand, several studies have estimated RAP in pulmonary hypertension using echocardiographic parameters [2, 4–7]. Two-dimensional (2D) echocardiography is a simpler, noninvasive and less expensive method that is frequently performed, even in outpatient clinics; thus, the American Society of Echocardiography (ASE) has suggested several right heart function parameters [4]. In the present study, we assessed the relationship between several echocardiographic right cardiac function parameters and catheterization-based RAP to determine the most accurate echocardiographic surrogate.

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## Methods

### Subjects

Subjects included 23 patients (6 males and 17 females aged  $59 \pm 17$  years old) with pulmonary hypertension. Pulmonary hypertension was diagnosed using right cardiac catheterization and pulmonary angiography based on the 2012 guidelines of the Japanese Circulation Society (JCS 2012). Basal diseases were idiopathic pulmonary artery hypertension in 11 patients and chronic thromboembolic pulmonary hypertension in 12. The severity of dyspnea based on the World Health Organization (WHO) functional classification was class II in 17 patients, class III in 4 and class IV in 2. Twenty patients (8 males and 12 females aged  $69 \pm 17$  years) with left heart failure (coronary artery disease;  $n = 5$ , cardiomyopathy;  $n = 5$ , and valvular heart disease;  $n = 10$ ), who developed pulmonary hypertension, were also included as a control. Patients with atrial fibrillation were not included. This study was approved by the ethics committee of Dokkyo Medical University, and all patients provided written informed consent before participation.

### Methods

In the 23 patients with pulmonary hypertension, a total of 66 cardiac catheterization procedures were performed (16 patients underwent multiple procedures with a maximum of 7 procedures per patient) (Table 1). 2D echocardiography was also performed within several days of each cardiac catheterization procedure. Patients were on the following medications at the time of the 66 measurements: none in 10 measurements, prostacyclin (prostaglandin I<sub>2</sub>, PGI<sub>2</sub>) drugs alone in 11, phosphodiesterase 5 (PDE-5) inhibitors alone in 2, endothelin (ET) receptor antagonists alone in 1, PGI<sub>2</sub> plus PDE-5 inhibitors in 12, PGI<sub>2</sub> plus ET receptor antagonists in 4, PGI<sub>2</sub> plus PDE-5 inhibitors plus ET receptor antagonists in 25, and a PGI<sub>2</sub> plus ET receptor antagonist along with a soluble guanylate cyclase (sGC) stimulant in 1 (Table 1). In the 20 left heart failure patients, data for single procedure of right cardiac catheterization procedures along with 2D echocardiography performed within several days, i.e., the 20 measurement data, were analyzed.

### Right cardiac catheterization

Right cardiac catheterization was performed using a 6F Swan-Ganz catheter (Fukuda Denshi, Tokyo, Japan) via the right femoral approach. All of the measurements were performed at the end-expiratory phase. We measured RAP,

**Table 1** Baseline characteristics of the 23 study patients

Age, years	59 ± 17
Male gender, <i>n</i> (%)	6 (26)
Basal disease, <i>n</i> (%)	
Idiopathic pulmonary artery hypertension	11 (49)
Chronic thromboembolic pulmonary hypertension	12 (51)
WHO functional class, <i>n</i> (%)	
I	0 (0)
II	17 (74)
III	4 (17)
IV	2 (9)
Measurement, <i>n</i> (%)	
1	7 (31)
2	5 (22)
3	3 (13)
4	3 (13)
5	3 (13)
6	1 (4)
7	1 (4)
Total measurements: <i>n</i>	66

WHO World Health Organization

systolic pulmonary artery pressure (sPAP), diastolic pulmonary artery pressure (dPAP), pulmonary capillary wedge pressure (PCWP), and cardiac output (CO). The CO was measured more than 3 times by the thermodilution method, and 3 measurements that agreed within 10% were averaged. The mean PAP (mPAP) was calculated as:  $mPAP = [dPAP + 1/3(sPAP - dPAP)]$ , and the pulmonary vascular resistance (PVR) as:  $PVR = [(mPAP - PCWP)/CO] \times 80$  (dyne s cm<sup>-5</sup>).

### 2D echocardiography

Transthoracic echocardiography was performed to assess right cardiac function, and the images were analyzed by two experienced echocardiographers using commercially available equipment (Vivid 7, GE Medical Systems, Horton, Norway). Right ventricular diastolic inflow was recorded at the tricuspid valve leaflet in the apical view using pulsed Doppler. The peak early diastolic flow velocity (*E*), *E*-wave deceleration time and peak atrial systolic flow velocity (*A*) were determined based on the blood flow patterns, and the ratio of the *E*-wave to *A*-wave (*E/A*) was calculated. The early diastolic (*E'*) and atrial systolic tricuspid annular motion velocity (*A'*) were determined at the tricuspid annular septum in the four-chamber apical view using tissue Doppler imaging, and the *E* to *E'* ratio (*E/E'*) was calculated. These parameters were determined by recording 3 cardiac cycles under stable conditions, and the mean of the measurements was used for analysis. In addition, the inferior vena cava (IVC) diameter was measured in the image from

the subxiphoid approach, and we estimated RAP using the respirophasic variation of the IVC diameter (eRAP-IVCd) (Table 2) [4]. In this study, we selected the following 5 parameters as possible surrogates of catheterization-based RAP:  $E/A$ ,  $E'$ ,  $A'$ ,  $E/E'$ , and eRAP-IVCd [2, 4].

### Statistical analysis

Data are expressed as the mean  $\pm$  standard deviation and  $n$  (%). All statistical analyses were performed using statistical software (Stat Mate IV, ATMS, Tokyo, Japan). Inter-group comparisons for continuous variables was performed using unpaired  $t$  test. The correlation between catheterization-based RAP and each of the five echocardiographic variables or catheterization-based PCWP was determined by simple linear regression analysis. Multiple regression analysis was performed to assess the independent correlation of catheterization-based RAP with the echocardiographic right cardiac function parameters. Receiver operating characteristic (ROC) curve analysis was performed to predict a catheterization-based RAP  $> 10$  mmHg using  $A'$ , and sensitivity,

specificity and area under the curve (AUC) were calculated.  $P$  values  $< 0.05$  were considered significant.

### Results

Cardiac catheterization and echocardiographic parameters for the 66 measurements in 23 pulmonary hypertension patients are compared with those for 20 measurements in 20 left heart failure patients (Table 3). The RAP measured by cardiac catheterization was  $6.6 \pm 3.5$  mmHg in pulmonary hypertension, which was lower than the value of  $11.1 \pm 5.2$  mmHg in left heart failure, although the mPAP value was comparable. The values of PVR was higher and those of PCWP was lower in pulmonary hypertension, compared with left heart failure. The CO was comparable in both diseases. In addition, the selected 5 echocardiographic parameters were also comparative between both diseases.

Among the 5 echocardiographic parameters,  $E/A$  ( $R = 0.452$ ,  $P = 0.0001$ ) and eRAP-IVCd ( $R = 0.505$ ,  $P < 0.0001$ ) were positively correlated with catheterization-based RAP, whereas  $A'$  ( $R = -0.512$ ,  $P < 0.0001$ ) was negatively correlated with RAP in simple linear regression analysis in 66 measurements of patients with pulmonary hypertension, although  $E'$  and  $E/E'$  were not correlated with catheterization-based RAP (Table 4, Fig. 1a). In multiple regression analysis,  $A'$  was the most significant independent predictor of catheterization-based RAP ( $R = -0.375$ ,  $P = 0.0007$ ) (Table 5). In the 16 pulmonary hypertension patients who had multiple measurements to assess the effects of new or additional medical treatments, we assessed the relationship between the change in catheterization-based RAP and that in  $A'$ . In case of measurements more than 3 times, the changes in the most recent 2 measurements were

**Table 2** The eRAP calculated by IVC diameter with its respirophasic variation

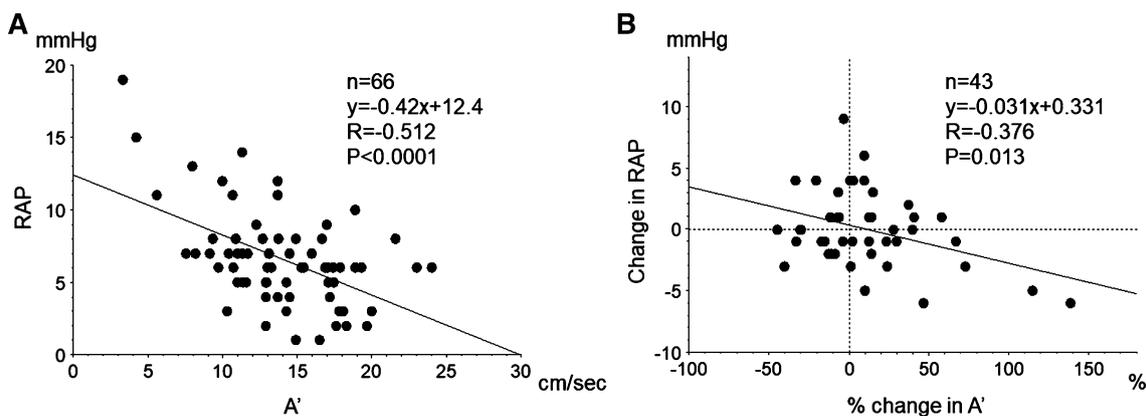
IVC diameter (mm)	Collapse (%)	eRAP (mmHg)
$\leq 21$	$\geq 50$	3
$\leq 21$	$< 50$	8
$> 21$	$\geq 50$	8
$> 21$	$< 50$	15

eRAP estimated right atrial pressure, IVC inferior vena cava

**Table 3** Cardiac catheterization and echocardiographic parameters

	Pulmonary hypertension (66 measurements)	Left heart failure (20 measurements)	$P$ value
Cardiac catheterization			
mPAP, mmHg	$33 \pm 10$	$31 \pm 6$	0.386
PVR, dyne $s\ cm^{-5}$	$407 \pm 264$	$174 \pm 109$	0.0002
RAP, mmHg	$6.6 \pm 3.5$	$11.1 \pm 5.2$	$< 0.0001$
PCWP, mmHg	$10.6 \pm 3.5$	$22.8 \pm 5.8$	$< 0.0001$
CO, L/min	$4.8 \pm 1.4$	$4.4 \pm 1.7$	0.324
Echocardiography			
$E/A$	$1.02 \pm 0.34$	$1.03 \pm 0.34$	0.934
$E'$ , cm/s	$8.8 \pm 2.8$	$8.3 \pm 2.6$	0.418
$A'$ , cm/s	$13.9 \pm 4.2$	$13.5 \pm 4.8$	0.682
$E/E'$	$5.4 \pm 2.0$	$6.0 \pm 2.9$	0.279
eRAP-IVCd: mmHg	$4.5 \pm 2.8$	$4.1 \pm 3.0$	0.584

mPAP mean pulmonary artery pressure, PVR pulmonary vascular resistance, RAP right atrial pressure, PCWP pulmonary capillary wedge pressure, CO cardiac output, eRAP estimated right atrial pressure, IVCd inferior vena cava diameter



**Fig. 1** Relationship between values of  $A'$  by echocardiogram and that of RAP by right cardiac catheterization in patients with pulmonary hypertension. Both values were negatively correlated in total of 66 measurements in 23 patients (a). In 16 patients undergoing multiple measurements, total of 43 changes in both parameters were assessed.

As a result, the absolute change in catheterization-based RAP (value after treatment – baseline value: mmHg) were negatively correlated with the percent change in  $A'$  ([value after treatment – baseline value]  $\times$  100/baseline value; %) (b)

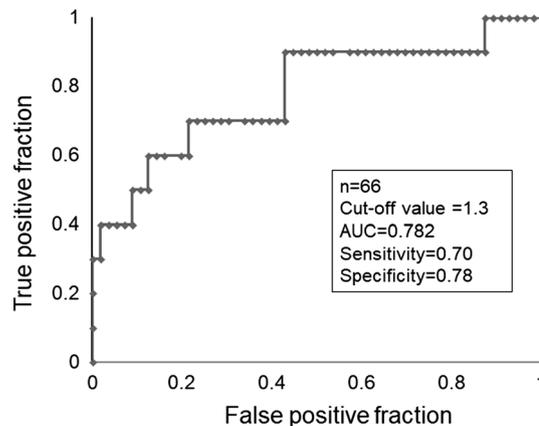
**Table 4** Relationship between cardiac catheterization-based RAP and echocardiographic parameters by simple linear regression analysis

Echocardiographic parameter	R	P value
Pulmonary hypertension (n=23; 66 measurements)		
E/A	0.452	0.00014
E'	0.155	0.411
A'	-0.512	0.000011
E/E'	0.183	0.304
eRAP-IVCd	0.505	0.000015
Left heart failure (n=20; 20 measurements)		
E/A	-0.210	0.374
E'	-0.211	0.372
A'	-0.075	0.754
E/E'	0.202	0.394
eRAP-IVCd	-0.035	0.885

**Table 5** Prediction of cardiac catheterization-based RAP using the echocardiographic parameters in multiple regression analysis

Echocardiographic parameter	R	P value
E/A	0.232	0.059
E'	0.102	0.499
A'	-0.375	0.0007
E/E'	0.082	0.527
eRAP-IVCd	0.276	0.013

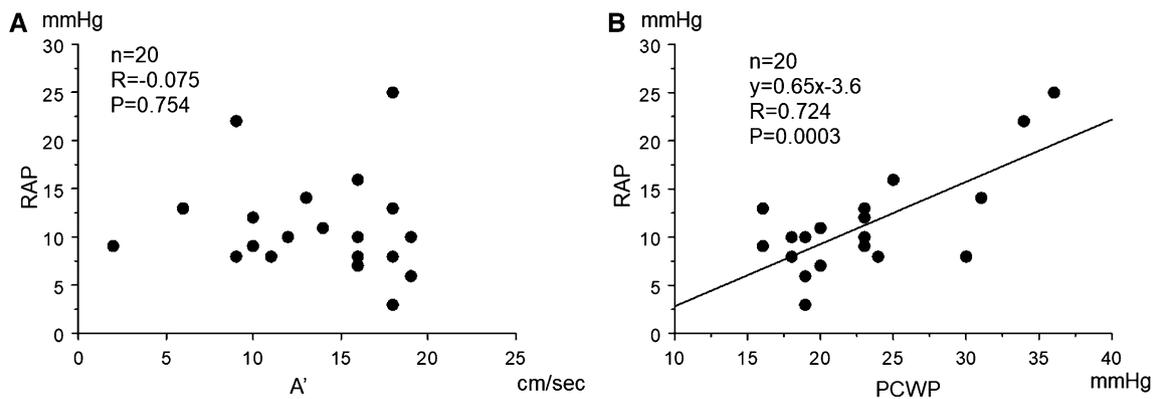
evaluated. There was a total of 43 measurements before and after medication changes. New or additionally prescribed drugs included PGI2 drugs in 11 patients, PDE-5 inhibitors in 10, ET receptor antagonists in 19, a sGC stimulant in 1, a



**Fig. 2** The ROC curve analysis to determine the cardiac catheterization-based RAP > 10, using the total of 66 measurements in patients with pulmonary hypertension. The analysis indicated that a cut-off value of  $A'$  was 11.3 cm/s (AUC=0.782, sensitivity=0.70, specificity=0.78)

PGI2 plus ET receptor antagonist in 1, and a PDE-5 inhibitor plus ET receptor antagonist in 1. Simple linear regression analysis showed that the change in catheterization-based RAP (value after treatment – baseline value: mmHg) was negatively correlated with the percent change in  $A'$  ([value after treatment – baseline value]  $\times$  100/baseline value; %) (Fig 1b). Finally, ROC curve analysis using the 66 measurements indicated that the optimal cut-off value of  $A'$  to predict a catheterization-based RAP > 10 mmHg was 11.3 cm/s (AUC = 0.782, sensitivity = 0.70, specificity = 0.78) (Fig. 2).

In 20 measurements of 20 patients with left heart failure, catheterization-based RAP was not correlated with any of 5 echocardiographic parameters (Table 4, Fig. 3a). However,



**Fig. 3** Factors related to RAP by right cardiac catheterization in patients with left heart failure, who developed pulmonary hypertension. The cardiac catheterization-based RAP was not correlated with the  $A'$  by echocardiogram (**a**), but with catheterization-based PCWP (**b**)

it was closely correlated with catheterization-based PCWP ( $R=0.724$ ,  $P=0.0003$ ) (Fig. 3b).

## Discussion

The major finding of the present study is that among several echocardiographic parameters,  $A'$  was the most powerful surrogate of catheterization-based RAP in patients with pulmonary hypertension such as idiopathic pulmonary artery hypertension and chronic thromboembolic pulmonary hypertension.

Right cardiac catheterization is essential to confirm the diagnosis of pulmonary hypertension, to assess right cardiac function or the severity of hemodynamic impairment and to perform vasoreactivity testing of the pulmonary circulation in selected patients. Although these procedures have low morbidity and mortality rates when performed at expert centers [8], the risk increases in patients with severe pulmonary hypertension (WHO or NYHA class IV) [9, 10]. In addition to cardiac catheterization, magnetic resonance imaging and radionuclide angiography are also available to assess right cardiac function. However, these modalities require large facilities and are expensive. In contrast, 2D echocardiography is a simpler, noninvasive and less expensive method that is frequently used to assess right cardiac function, and this method can even be used in outpatient clinics [11, 12].

We have been investigating surrogate echocardiographic parameters as an alternative to various indices measured by cardiac catheterization or radionuclide angiography for hemodynamic assessment in patients with pulmonary hypertension. Our previous results showed that the best surrogate of catheterization-based PAP was an echocardiographic parameter (PEP/AcT)/(PEP + ET), where PEP was pre-ejection period, AcT was acceleration time, and ET was ejection time [13]. In addition, the best echocardiographic alternative

to right ventricular ejection fraction measured by radionuclide angiography was right ventricular Tei index [14]. In the present study, we focused on RAP, because the recent European Society of Cardiology (ESC)/European Respiratory Society (ERS) guidelines indicated that comprehensive prognostic evaluation and risk assessment for pulmonary hypertension should be based on RAP. In these guidelines, patients with an RAP > 14 mmHg were considered high risk (estimated 1-year mortality > 10%), and those with an RAP of 8–14 mmHg were considered moderate risk (estimated 1-year mortality of 5–10%) [2]. Thus, RAP is considered the most important cardiac catheterization parameter to predict the prognosis of pulmonary hypertension, and we attempted to find the best echocardiographic surrogate of RAP.

In the present study, we selected 5 echocardiographic parameters as possible surrogates for catheterization-based RAP in pulmonary hypertension. Four of these surrogates ( $E/A$ ,  $E'$ ,  $A'$  and  $E/E'$ ) are recommended as indices of right ventricular diastolic function in the ASE guidelines [4]; and the fifth surrogate, eRAP-IVCd, is strongly recommended as an index of catheterization-based RAP in the ESC/ERS guidelines [2]. In total of 66 measurements in 23 patients with pulmonary hypertension, simple regression analysis showed that  $E/A$ ,  $A'$  and eRAP-IVCd were correlated with RAP. However, multiple regression analysis showed that  $A'$  was the most significant independent predictor of catheterization-based RAP. In addition, the absolute change in catheterization-based RAP was negatively correlated with the percent change in  $A'$ . Thus, we believe that  $A'$  is the best surrogate of catheterization-based RAP in patients with pulmonary hypertension.  $A'$  is thought to reflect atrial contraction [15], and it is strongly affected by preload in healthy subjects [16]. In pediatric patients with congenital heart disease,  $A'$  was strongly correlated with right ventricular end-diastolic pressure [17]. There is also a report that among various echocardiographic parameters, tricuspid annular  $E/E'$  was the best index of RAP in patients with cardiovascular

disease who had an elevated RAP ( $> 10$  mmHg) [7].  $E/E'$  was also correlated with right ventricular end-diastolic pressure in pediatric patients with congenital heart disease [17]. In contrast, the results of the present study showed that  $E/E'$  was not correlated with catheterization-based RAP in pulmonary hypertension patients with an average RAP of  $6.6 \pm 3.5$  mmHg. The discrepancy between the present study and other studies might be due to differences in baseline characteristics, such as age, the baseline level of RAP, or the type of disease present (i.e., cardiovascular disease, congenital heart disease or pulmonary hypertension). In our study, we included eRAP-IVCd using the respirophasic variation in IVC diameter because it is recommended as a possible surrogate of catheterization-based RAP in the ASE guidelines [4]. The eRAP-IVCd has been shown to discriminate among patients with an RAP of 3, 8 and 15 mmHg, and this parameter has a great advantage in that the IVC diameter can be simply measured from a subcostal window. However, the disadvantages are that it does not accurately reflect RAP when the IVC is collapsed in ventilator-dependent patients, and it is less reliable for intermediate values of RAP. The results of present study suggest that  $A'$  is a better surrogate of catheterization-based RAP than eRAP-IVCd. Using ROC curve analysis, we determined that the optimal cut-off value of  $A'$  was 11.3 cm/s to predict a catheterization-based RAP  $> 10$  mmHg. An RAP  $> 10$  mmHg has been shown to increase mortality rate in patients with pulmonary hypertension [2]. Our results suggest that pulmonary hypertension should be treated to achieve an  $A'$  value  $> 11.3$  cm/s.

In the present study, we also performed the same assessment in 20 measurements of 20 patients with left heart failure, who developed pulmonary hypertension. In these patients, RAP as well as PCWP was higher and PVR was lower, compared with 23 pulmonary hypertension patients, although mPAP was comparable. Interestingly, in these patients, catheterization-based RAP was not correlated with any of 5 echocardiographic parameters. In contrast, it was closely correlated with catheterization-based PCWP. The results suggest that RAP could be directly affected by left atrial pressure via atrial septum in case of left heart failure with left atrial overload, possibly leading to absence of correlation between RAP and 5 echocardiographic right cardiac function parameters, which we selected in the present study as surrogates of RAP. Anyway, unlike pulmonary hypertension, the  $A'$  might not be an echocardiographic surrogate of RAP in case of left heart failure.

### Study limitations

The present study has several potential limitations. First, the study included a small sample of 66 measurements in 23 patents, and the sample included multiple measurements (maximum of 7 measurements) in 16 patients. In the future,

we need to investigate the relationship between catheterization-based RAP and the echocardiographic parameter,  $A'$ , in a larger number of patients. In addition, we need to evaluate the relationship between  $A'$  and the therapeutic efficacy of the drugs used to treat pulmonary hypertension. Second, in the present study, there was a time lag of several days between right heart catheterization and echocardiography. To obtain more precise information on the relationships between invasive RAP and noninvasive  $A'$ , the simultaneous measurement of both parameters is required. Finally, in the present study, patients had either thromboembolic or idiopathic pulmonary hypertension. Since diastolic pulmonary artery pressure is commonly higher in thromboembolic than idiopathic pulmonary hypertension, this could potentially lead to a difference in right heart hemodynamics and RAP. Therefore, additional evaluation is needed separately in each type of pulmonary hypertension.

### Clinical implications/conclusion

In the present study, we found that an echocardiographic parameter,  $A'$  was a better surrogate of catheterization-based RAP than eRAP-IVCd, which has been recommended by the ESC/ERS guidelines, in patients with pulmonary hypertension. At the present time, right heart catheterization is essential for the diagnosis and treatment of pulmonary hypertension; however, 2D echocardiography should be considered as a method to assess right heart function because it is a simpler, less invasive and less expensive. We believe that the present study provides novel insight into pulmonary hypertension that can be used in routine clinical practice.

### Compliance with ethical standards

**Conflict of interest** The authors have no conflicts of interest to disclose

### References

1. Swiston JR, Johnson SR, Granton JT (2010) Factors that prognosticate mortality in idiopathic pulmonary arterial hypertension: a systematic review of the literature. *Respir Med* 104:1588–607
2. Galiè N, Humbert M, Vachiery JL, Gibbs S, Lang I, Torbicki A, Simonneau G, Peacock A, Vonk Noordegraaf A, Beghetti M, Ghofrani A, Gomez Sanchez MA, Hansmann G, Klepetko W, Lancellotti P, Matucci M, McDonagh T, Pierard LA, Trindade PT, Zompatori M, Hoeper M, ESC Scientific Document Group (2016) 2015 ESC/ERS Guidelines for the diagnosis and treatment of pulmonary hypertension: The Joint Task Force for the Diagnosis and Treatment of Pulmonary Hypertension of the European Society of Cardiology (ESC) and the European Respiratory Society (ERS): Endorsed by: Association for European Paediatric and Congenital Cardiology (AEPC), International Society for Heart and Lung Transplantation (ISHLT). *Eur Heart J* 37:67–119

3. Weinberger SE, Drazen JM (1998) Disturbances of respiratory function. In: Harrison TR (ed) A textbook of principles of internal medicine, 14th edn. McGraw-Hill, New-York, pp 1410–1407
4. Rudski LG, Lai WW, Afilalo J, Hua L, Handschumacher MD, Chandrasekaran K, Solomon SD, Louie EK, Schiller NB (2010) Guidelines for the echocardiographic assessment of the right heart in adults: a report from the American Society of Echocardiography endorsed by the European Association of Echocardiography, a registered branch of the European Society of Cardiology, and the Canadian Society of Echocardiography. *J Am Soc Echocardiogr* 23:685–713
5. Kircher BJ, Himelman RB, Schiller NB (1990) Noninvasive estimation of right atrial pressure from the inspiratory collapse of the inferior vena cava. *Am J Cardiol* 66:493–496
6. Sade LE, Gulmez O, Eroglu S, Sezgin A, Muderrisoglu H (2007) Noninvasive estimation of right ventricular filling pressure by ratio of early tricuspid inflow to annular diastolic velocity in patients with and without recent cardiac surgery. *J Am Soc Echocardiogr* 20:982–988
7. Said K, Shehata A, Ashour Z, El-Tobgi S (2012) Value of conventional and tissue Doppler echocardiography in the noninvasive measurement of right atrial pressure. *Echocardiography* 29:779–784
8. Hoepfer MM, Lee SH, Voswinckel R, Palazzini M, Jais X, Marinelli A, Barst RJ, Ghofrani HA, Jing ZC, Opitz C, Seyfarth HJ, Halank M, McLaughlin V, Oudiz RJ, Ewert R, Wilkens H, Kluge S, Bremer HC, Baroke E, Rubin LJ (2006) Complications of right heart catheterization procedures in patients with pulmonary hypertension in experienced centers. *J Am Coll Cardiol* 48:2546–2552
9. Ranu H, Smith K, Nimako K, Sheth A, Madden BP (2010) A retrospective review to evaluate the safety of right heart catheterization via internal jugular vein in the assessment of pulmonary hypertension. *Clin Cardiol* 33:303–306
10. Taylor CJ, Derrick G, McEwan A, Haworth SG, Sury MR (2007) Risk of cardiac catheterization under anesthesia in children with pulmonary hypertension. *Br J Anaesth* 98:657–661
11. Briongos Figuero S, Moya Mur JL, García-Lledó A, Centella T, Salido L, Aceña Navarro Á, García Martín A, García-Andrade I, Oliva E, Zamorano JL (2016) Predictors of persistent pulmonary hypertension after mitral valve replacement. *Heart Vessels* 31:1091–1099
12. Hioka T, Kaga S, Mikami T, Okada K, Murayama M, Masauzi N, Nakabachi M, Nishino H, Yokoyama S, Nishida M, Iwano H, Sakakibara M, Yamada S, Tsutsui H (2017) Overestimation by echocardiography of the peak systolic pressure gradient between the right ventricle and right atrium due to tricuspid regurgitation and the usefulness of the early diastolic transpulmonary valve pressure gradient for estimating pulmonary artery pressure. *Heart Vessels* 32:833–842
13. Fukuda R, Amano H, Nishida H, Yamauchi F, Inoue T (2016) Estimation of pulmonary vascular resistance by echocardiographic parameters in patients with pulmonary hypertension. *J Clin Physiol* 46:31–37 (in Japanese)
14. Amano H, Abe S, Hirose S, Waku R, Masuyama T, Sakuma M, Toyoda S, Taguchi I, Inoue T, Tei C (2017) Comparison of echocardiographic parameters to assess right ventricular function in pulmonary hypertension. *Heart Vessels* 32:1214–1219
15. Thomas L, Levett K, Boyd A, Leung DY, Schiller NB, Ross DL (2003) Changes in regional left atrial function with aging: evaluation by Doppler tissue imaging. *Eur J Echocardiogr* 4:92–100
16. Pelà G, Regolisti G, Coghi P, Cabassi A, Basile A, Cavatorta A, Manca C, Borghetti A (2004) Effects of the reduction of preload on left and right ventricular myocardial velocities analyzed by Doppler tissue echocardiography in healthy subjects. *Eur J Echocardiogr* 5:262–271
17. Nadorlik H, Stiver C, Khan S, Miao Y, Holzer R, Cheatham JP, Cua CL (2017) Echocardiographic right ventricular function correlations with cardiac catheterisation data in biventricular congenital heart patients. *Cardiol Young* 27:1186–1193
18. Sitbon O, Humbert M, Nunes H, Parent F, Garcia G, Hervé P, Rainisio M, Simonneau G (2002) Long-term intravenous epoprostenol infusion in primary pulmonary hypertension: prognostic factors and survival. *J Am Coll Cardiol* 40:780–788