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# The accuracy and influencing factors of Doppler echocardiography in estimating pulmonary artery systolic pressure: comparison with right heart catheterization: a retrospective cross-sectional study

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## Abstract

**Background:** Noninvasive assessment of pulmonary artery systolic pressure by Doppler echocardiography ($sPAP_{ECHO}$) has been widely adopted to screen for pulmonary hypertension (PH), but there is still a high proportion of overestimation or underestimation of $sPAP_{ECHO}$. We therefore aimed to explore the accuracy and influencing factors of $sPAP_{ECHO}$ with right heart catheterization (RHC) as a reference.

**Methods:** A total of 218 highly suspected PH patients who underwent RHC and echocardiography within 7 days were included. The correlation and consistency between tricuspid regurgitation (TR)-related methods and RHC results were tested by Pearson and Bland–Altman methods. TR-related methods included peak velocity of TR (TR Vmax), TR pressure gradient (TR-PG), TR mean pressure gradient (TR-mPG), estimated mean pulmonary artery pressure ($mPAP_{ECHO}$), and $sPAP_{ECHO}$. With $mPAP \geq 25$ mm Hg measured by RHC as the standard diagnostic criterion of PH, the ROC curve was used to compare the diagnostic efficacy of $sPAP_{ECHO}$ with other TR-derived parameters. The ratio ($sPAP_{ECHO}$–$sPAP_{RHC}$)/$sPAP_{RHC}$ was calculated and divided into three groups as follows: patients with an estimation error between $-10\%$ and $+10\%$ were defined as the accurate group; patients with an estimated difference greater than $+10\%$ were classified as the overestimated group; and patients with an estimation error greater than $-10\%$ were classified as the underestimated group. The influencing factors of $sPAP_{ECHO}$ were analyzed by ordinal regression analysis.

**Results:** $sPAP_{ECHO}$ had the highest correlation coefficient (r = 0.781, $P < 0.001$), best diagnostic efficiency (AUC = 0.98), and lowest bias (mean bias = 0.07 mm Hg; 95% limits of agreement, $-32.08$ to $+32.22$ mm Hg) compared with other TR-related methods. Ordinal regression analysis showed that TR signal quality, $sPAP_{RHC}$ level, and pulmonary artery wedge pressure (PAWP) affected the accuracy of $sPAP_{ECHO}$ ($P < 0.05$). Relative to the good signal quality, the OR values of medium and poor signal quality were 0.26 (95% CI: 0.14, 0.48) and 0.23 (95% CI: 0.07, 0.73), respectively. Compared with high $sPAP_{RHC}$ level, the OR values of low and medium $sPAP_{RHC}$ levels were 21.56 (95% CI: 9.57, 48.55) and 5.13

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(95% CI: 2.55, 10.32), respectively. The OR value of PAWP was 0.94 (95% CI: 0.89, 0.99). TR severity and right ventricular systolic function had no significant effect on the accuracy of $sPAP_{ECHO}$.

**Conclusions:** In this study, we found that all TR-related methods, including $sPAP_{ECHO}$, had comparable and good efficiency in PH screening. To make the assessment of $sPAP_{ECHO}$ more accurate, attention should be paid to TR signal quality, $sPAP_{RHC}$ level, and PAWP.

## Background

Right heart catheterization (RHC) is recognized as the gold standard for measuring pulmonary artery pressure, but its invasiveness limits its general applicability. Doppler echocardiography (DE) can noninvasively assess pulmonary artery pressure by peak velocity of tricuspid regurgitation (TR Vmax) and its derived parameters, including TR pressure gradient (TR-PG), TR mean pressure gradient (TR-mPG), estimated mean pulmonary artery pressure ($mPAP_{ECHO}$), and pulmonary artery systolic pressure ($sPAP_{ECHO}$). The current guidelines recommend TR Vmax to avoid additional error in the estimated right atrial pressure (RAP) [1]. Furthermore, mPAP has been found to be superior to TR Vmax in identifying pulmonary hypertension (PH) [2]. As the most well-adopted approach in PH screening, $sPAP_{ECHO}$ has also been shown to be a reliable method [3]; however, it has not yet been examined whether $sPAP_{ECHO}$ is superior to other parameters in determining the probability of PH. $sPAP_{ECHO}$ can also provide valuable information for evaluating treatment response and even predicting prognosis [4, 5]; however, there is still a high proportion of overestimation or underestimation of $sPAP_{ECHO}$ [6]. To evaluate PH patients' condition appropriately and avoid too invasive examination, we need to understand situations in which $sPAP_{ECHO}$ is under/overestimated. Based on clinical experience and review of previous literature, we assumed that right ventricular systolic function, pulmonary artery pressure level, TR severity, and signal quality would affect the accuracy of $sPAP_{ECHO}$. In addition, as an important parameter to distinguish pre- and post-capillary PH, pulmonary artery wedge pressure (PAWP) was also included in the analysis to examine whether there would be any difference in the accuracy of $sPAP_{ECHO}$. Therefore, the first aim of this study was to compare the efficiency of $sPAP_{ECHO}$ and other parameters in PH screening, while the second aim was to find influencing factors that account for the inaccuracy of $sPAP_{ECHO}$.

## Methods

Between October 2015 and October 2020, a total of 430 patients admitted to our center with known or suspected PH were evaluated. The inclusion criteria were age $\geq 18$ years and the interval between echocardiography and RHC $\leq 7$ days. The exclusion criteria were as follows: lack of TR, pulmonary artery stenosis or right ventricular outflow tract stenosis, poor image quality not suitable for analysis, ventricular septal defect, or patent ductus arteriosus. Patients' demographic and clinical data were obtained from the electronic medical records. The institutional review board of the China–Japan Friendship Hospital waived the need for written informed consent as the study involved the retrospective analysis of clinically acquired data. The data underlying this article will be shared upon a reasonable request to the corresponding author.

### Clinical data

Baseline assessment of the eligible patients included WHO functional class, the level of N-terminal pro B-type natriuretic peptide (NT-proBNP), and a 6-min walk test (6MWT).

### RHC

Hemodynamic measurements were performed with a 7F Swan-Ganz catheter Philips Allura X-PER FD20 flat-plate angiography system (Baxter Inc.). The system was zeroed and referenced at patients' heart level as previously described [7]. Right atrial pressure (RAP), pulmonary systolic artery pressure ($sPAP_{RHC}$), and PAWP were recorded at end-expiration at baseline over at least three heart cycles. Cardiac output (CO) was obtained using Fick's method. Pulmonary vascular resistance (PVR), cardiac index, stroke volume, pulse pressure, and diastolic pressure gradient were calculated using standard formulas. Pulmonary artery pressure was classified into low, medium, and high levels according to the tertiles of $sPAP_{RHC}$.

### Echocardiography

Echocardiographic images were acquired using a GE Vivid E95 machine (GE Healthcare, General Electric Healthcare) equipped with M5S phased-array transducers. Analysis was performed independently by two blinded investigators using EchoPAC software (GE Healthcare version 201). Two-dimensional echocardiography and Doppler echocardiography (DE) were performed based on current guidelines. TR-PG was calculated from the TR Vmax obtained from continuous-wave Doppler by the simplified Bernoulli equation:

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TR-PG $= 4$ (TR Vmax)$^2$. TR-mPG was obtained by tracing the time–velocity integral of TR. sPAP$_{ECHO}$ and mPAP$_{ECHO}$ were calculated by adding the estimated RAP to TR-PG and TR-mPG, respectively. RAP was divided into three categories (3, 8, and 15 mm Hg) based on the inferior vena cava (IVC) diameter and its respiratory variation [1]. The ratio (sPAP$_{ECHO}$−sPAP$_{RHC}$)/sPAP$_{RHC}$ was calculated and divided into three groups as follows: patients with an estimation error between $-10\%$ and $+10\%$ were defined as the accurate group; patients with an estimated difference greater than $+10\%$ were classified as the overestimated group; and patients with an estimation error greater than $-10\%$ were classified as the underestimated group. The severity of TR was classified into three grades by comprehensively evaluating the regurgitation jet area and vena contracta (VC) width. The mild group was defined as jet area $< 5$ cm$^2$, VC TR $\leq 3$ mm; the moderate group as jet area $5$–$10$ cm$^2$, $3$ mm $<$ VC TR $< 7$ mm; and the severe group as jet area $> 10$ cm$^2$, VC TR $\geq 7$ mm. TR signal quality was classified into three types according to the extension of the signal for more than half of the systole and well-defined border. Good signal quality was defined as the one that met both criteria. Medium signal quality met only one of these criteria, while poor signal quality did not meet any of the criteria [8] (Fig. 1). RV systolic function was assessed using multiple parameters, including RV wall thickness (RV WT), tricuspid annular plane systolic excursion (TAPSE), systolic annular tissue velocity of the lateral tricuspid annulus (S'), and RV fractional area change (FAC). All of these parameters were repeatedly measured and averaged. To determine the reproducibility of sPAP$_{ECHO}$ measurements, a total of 34 randomly



**Fig. 1** Classification of the TR signal quality using continuous-wave Doppler. Good signal quality, complete envelope; Medium signal quality, partial envelope; Poor signal quality, unreliable envelope or no signal

selected examinations were analyzed twice by the first investigator at a 1-week interval and once by the second investigator.

## Statistical analysis
Standard statistical software (SPSS version 26 for Windows, SPSS, Chicago, IL, USA) was used for the statistical analysis. Data are expressed as mean $\pm$ standard deviation for quantitative variables with normal distribution, or as median (interquartile range) for variables not complying with normal distribution. The correlation and consistency between TR-derived parameters and RHC results were tested by Pearson and Bland–Altman methods. With mPAP $\geq 25$ mm Hg measured by RHC as the standard diagnostic criterion of PH, a receiver operating characteristic (ROC) curve was used to compare the diagnostic efficacy of sPAP$_{ECHO}$ and other TR-related methods. The influencing factors of sPAP$_{ECHO}$ were analyzed by ordinal regression analysis. The intraclass correlation coefficient was used to determine inter- and intra-observer reproducibility for sPAP$_{ECHO}$ from 34 randomly selected patients using an identical cine-loop for each view. For all statistical tests, a *P* value $< 0.05$ was used to indicate significance.

## Results
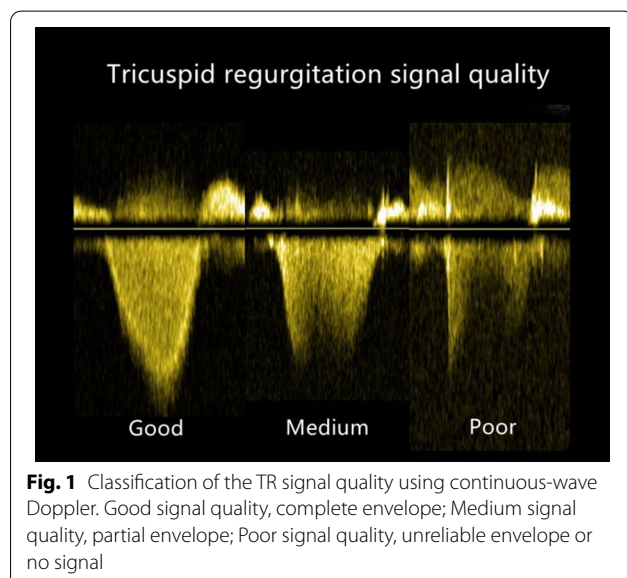
### Patients' characteristics
A total of 218 patients were finally identified and analyzed, as shown in Fig. 2. Baseline demographic and clinical characteristics are provided in Table 1. The mean age of the patients was $50.9 \pm 13.3$ years; 40.3% of them were men; 197 (90.4%) patients had PH. None of the patients experienced major cardiac events between DE and RHC examinations. Table 2 lists the DE and RHC variables grouped by estimated accuracy.
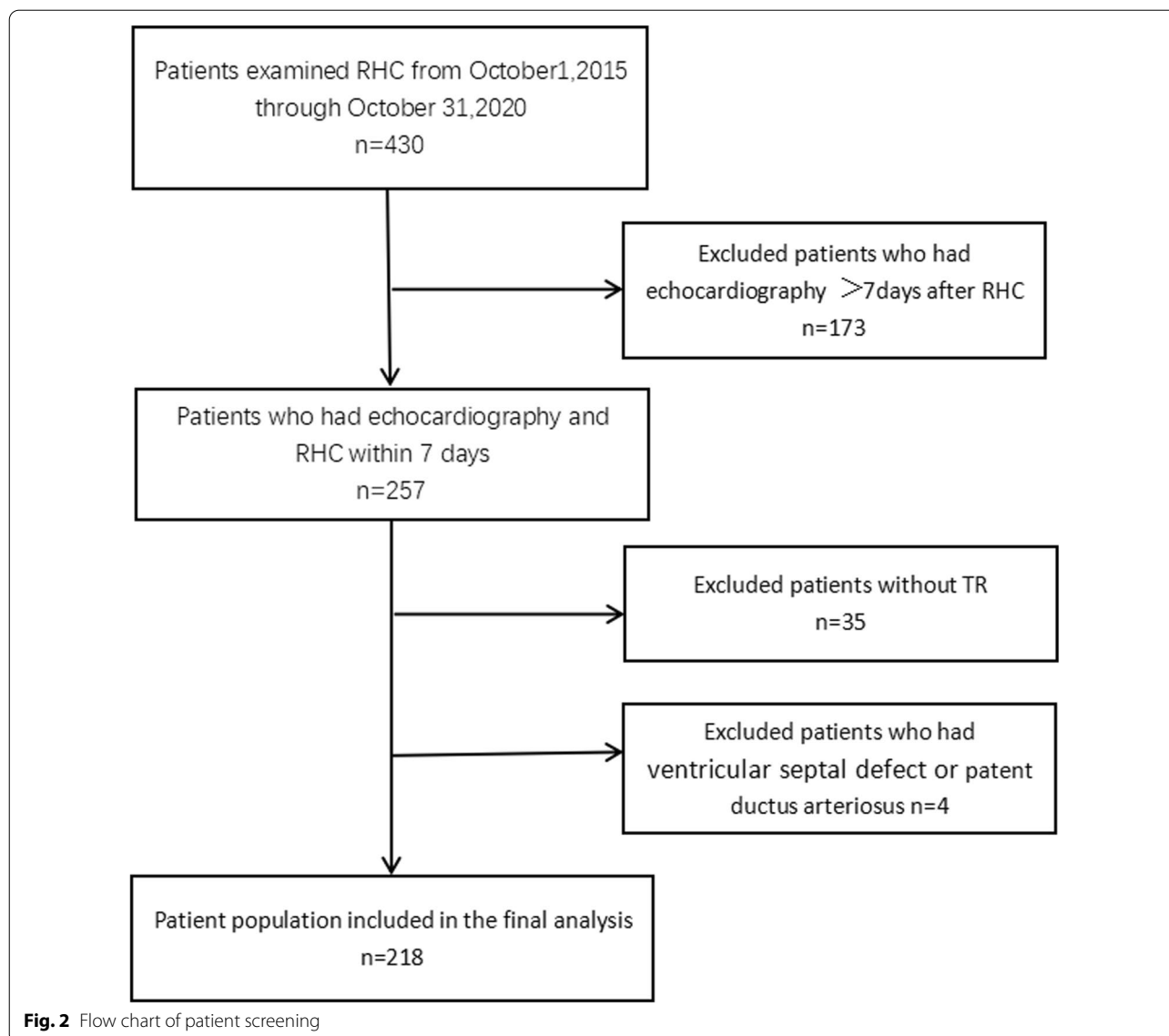
### Observer variability of sPAP$_{ECHO}$ estimation
The intraclass correlation coefficient for interobserver reproducibility of sPAP$_{ECHO}$ was 0.988 (95% CI: 0.977–0.994), and the intraclass correlation coefficient for intra-observer reproducibility of sPAP$_{ECHO}$ was 0.992 (95% CI, 0.984–0.996).

### Association between invasively determined parameters and TR-derived parameters
All of the TR-derived parameters, including TR Vmax, TR-PG, TR-mPG, mPAP$_{ECHO}$, and sPAP$_{ECHO}$, showed a positive correlation with related RHC results (Fig. 3). sPAP$_{ECHO}$ had the highest correlation coefficient (r $=$ 0.782, *P* $< 0.001$). Bland–Altman analysis demonstrated low bias between RHC and echocardiographic results,

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**Fig. 2** Flow chart of patient screening

with wide limits of agreements (Fig. 4). The bias of $sPAP_{ECHO}$ (mean bias = 0.1 mm Hg; 95% limits of agreement: −32.1 to +32.2 mm Hg) was lower than that of TR-PG (mean bias = 5.9 mm Hg; 95% limits of agreement: −26.5 to +38.2 mm Hg). The mean deviations of $mPAP_{ECHO}$ and TR-mPG from $mPAP_{RHC}$ were −2.6 mm Hg (95% limits of agreement: −26.3 to +21.1 mm Hg) and 3.3 mm Hg (95% limits of agreement: −20.1 to +26.7 mm Hg), respectively.

**Performance of different TR methods for predicting PH**

The ROC analysis showed that $sPAP_{ECHO}$ had better predictive efficiency and sensitivity for determining the possibility of PH than other TR-related methods, including TR Vmax, TR-PG, TR-mPG, and $mPAP_{ECHO}$ (Table 3),

but their differences were not significant ($P > 0.05$). Using Youden index quantification, the optimal cutoff value for our cohort was 49.5 mm Hg for the $sPAP_{ECHO}$ method with a sensitivity of 94.9% and a specificity of 85.7%.

**Factors affecting the accuracy of $sPAP_{ECHO}$ estimation**

There were 79 patients (36.2%) in the overestimated group, 81 patients (37.2%) in the accurate group, and 58 patients (26.6%) in the underestimated group. $sPAP_{RHC}$ was divided into three levels according to its tertiles (63 mm Hg, 85 mm Hg). The low-level group was defined $sPAP_{RHC}$ less than 63 mm Hg. Patients with $sPAP_{RHC}$ between 63 mm Hg and 85 mm Hg were considered the medium-level group, while patients with $sPAP_{RHC}$ higher than 85 mmHg were classified as the high-level group.

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**Table 1** Clinical and demographic characteristics

| Variables | Value |
|---|---|
| Age (years) | 50.9 ± 13.3 |
| Males (%) | 90 (41.3) |
| BMI | 1.67 (1.57, 1.84) |
| Systolic BP (mmHg) | 120 (108, 132) |
| Diastolic BP (mmHg) | 77 (70, 87) |
| Heart rate (bpm) | 76 (68.65, 80) |
| Interval between TTE and RHC, days | 2.5 (1, 5) |
| NT-pro BNP (pg/ml) | 451 (175, 1043) |
| 6 M WT (m) | 365.5 ± 104.6 |
| WHO functional class | |
| I Class (%) | 20 (9.2) |
| II Class (%) | 93 (42.7) |
| III Class (%) | 89 (40.8) |
| IV Class (%) | 16 (7.3) |
| PH (n) | 197 (90.4%) |
| Idiopathic, heritable, drug and toxic induced | 37 |
| Associated with Connective tissue disease | 25 |
| Portal hypertension | 2 |
| Congenital heart disease | 8 |
| PH due to left heart disease | 6 |
| PH due to lung disease and/or hypoxia | 6 |
| Chronic thromboembolic PH | 95 |
| PH with unclear and/or multifactorial mechanisms | 13 |
| Pulmonary veno-occlusive disease and/or pulmonary capillary haemangiomatosis | 5 |
| Non-PH (n) | 21 (9.6%) |

Values are presented as mean ± SD, median (IQR), or n (%)

*BMI* body mass index; *TTE*, transthoracic echocardiography; *RHC* right heart catheterization; *BP* blood pressure; *NT-pro BNP* N-terminal pro B-type natriuretic peptide; *6 M WT* 6-min walk test; *PH* pulmonary hypertension

The univariate ordinal analysis demonstrated that RV WT, FAC, TR signal quality, sPAP$_{RHC}$ level, RAP, PVR, PAWP, and mPAP were associated with the inaccuracy of sPAP$_{ECHO}$ estimation (Table 2). After multivariate ordinal regression analysis, we found that TR signal quality, PAWP, and sPAP$_{RHC}$ level significantly affected the accuracy of sPAP$_{ECHO}$ ($P < 0.05$). Relative to good signal quality, the OR values of medium and poor signal quality were 0.26 (95% CI: 0.14, 0.48) and 0.23 (95% CI: 0.07, 0.73), respectively. Compared with high sPAP$_{RHC}$ level, the OR values of low and medium sPAP$_{RHC}$ levels were 21.56 (95% CI: 9.57, 48.55) and 5.13 (95% CI: 2.55, 10.32), respectively. The OR value of PAWP was 0.94 (95% CI: 0.89, 0.99). In contrast, TR severity and RV systolic function parameters (such as TAPSE, S′, and FAC) did not remain in the final equation.

## Discussion

Key findings of our study are as follows: (1) All TR-related methods, including sPAP$_{ECHO}$, have comparable and good efficiency in PH screening. (2) The assessment of sPAP$_{ECHO}$ would be more reliable after taking TR signal quality, sPAP$_{RHC}$ levels, and PAWP into account.

### Performance of sPAP$_{ECHO}$ in PH screening

In our study, sPAP$_{ECHO}$ showed comparable efficiency to other TR-related methods in PH screening. Compared with mPAP$_{ECHO}$, sPAP$_{ECHO}$ is more convenient to measure. As a derived variable of TR Vmax, sPAP$_{ECHO}$ did not amplify measurement errors in assessing pulmonary artery pressure as indicated by the current guidelines; on the contrary, it showed better sensitivity while maintaining similar specificity. Relative to TR Vmax, TR-PG, and TR-mPG, sPAP$_{ECHO}$ contains more information from RAP, which may account for its better accuracy and lower bias. RAP elevates with the increase of RV overload [9], so it is an important measurement that provides heart failure and prognostic information [10]. Hellenkamp's study [2] on mPAP$_{ECHO}$ also supported that RAP is of additional diagnostic value in predicting PH. Compared with mPAP$_{ECHO}$, sPAP$_{ECHO}$ has the advantage of being simple and convenient. Taken together, sPAP$_{ECHO}$ can be a convenient and effective measurement for clinical application in PH screening.

### Reasons for the inaccuracy in sPAP$_{ECHO}$ estimation

First, our findings confirmed previous reports that the TR signal quality would affect the accuracy of sPAP$_{ECHO}$ [11]. Poor signal quality leads to the underestimation of sPAP$_{ECHO}$, because interpretation error of peak velocity is further amplified by the square of the Bernoulli equation. We also found that good signal quality could bring overestimation of sPAP$_{ECHO}$ for some cases. In our cohort, sPAP$_{ECHO}$ was still overestimated in 41% of the patients who obtained good signal quality of TR. After further analysis, we found that the lower sPAP$_{RHC}$ level and PAWP were significantly associated with the overestimation of sPAP$_{ECHO}$ in patients with good signal quality. This phenomenon suggests that we cannot simply rely on good signal quality, and attention should also be paid to sPAP$_{RHC}$ level and PAWP because they both affect the accuracy of sPAP$_{ECHO}$.

Second, as for the effect of sPAP$_{RHC}$ level on the accuracy of sPAP$_{ECHO}$, Groh et al. [12] found that echocardiography inaccurately estimated right ventricular pressure in children with elevated right heart pressure. Our results provided further evidence that sPAP$_{ECHO}$ tends to be underestimated at a high sPAP$_{RHC}$ level. We assumed that the coupling mechanism between

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**Table 2** Univariable and multivariable ordered analysis for accuracy of sPAP$_{ECHO}$

| Variables | Overestimation (n = 79) | Accurate (n = 81) | Underestimation (n = 58) | Univariable analysis | | Multivariable analysis | |
|---|---|---|---|---|---|---|---|
| | | | | P | OR (95% CI) | P | OR (95% CI) |
| *Echocardiographic parameters* | | | | | | | |
| RAD (mm) | 49.1 ± 10.2 | 49.9 ± 11.1 | 49.4 ± 10.0 | 0.816 | 0.997 (0.974, 1.021) | | |
| RVDD (mm) | 45.4 ± 7.3 | 46.2 ± 7.6 | 46.5 ± 6.5 | 0.323 | 0.984 (0.952,1.016) | | |
| RV WT (mm) | 5.3 ± 1.5 | 5.4 ± 1.4 | 5.8 ± 1.6 | 0.055 | 0.845 (0.712,1.003) | | |
| TAPSE(mm) | 16.8 ± 3.9 | 16.3 ± 3.4 | 15.9 ± 3.7 | 0.110 | 1.057 (0.988,1.130) | | |
| FAC (%) | 30.6 ± 9.3 | 29.8 ± 8.3 | 27.7 ± 7.6 | 0.064 | 1.029 (0.998,1.061) | | |
| TR severity | | | | 0.546 | | | |
| Mild | 44 (20.2%) | 51 (23.5%) | 36 (16.5%) | 0.944 | 1.031 (0.441,2.408) | | |
| Moderate | 28 (12.8%) | 22 (10.1%) | 16 (7.3%) | 0.480 | 1.386 (0.560,3.431) | | |
| Severe | 7 (3.2%) | 8 (3.7%) | 6 (2.8%) | | | | |
| TR signal quality | | | | 0.020 | | | |
| Good | 53 (24.3%) | 49 (22.5%) | 25 (11.5%) | | | | |
| Medium | 23 (10.6%) | 26 (11.9%) | 27 (12.4%) | 0.017 | 0.525 (0.309,0.892) | 0.000 | 0.258 (0.138,0438) |
| Poor | 3 (1.4%) | 6 (2.8%) | 6 (2.8%) | 0.055 | 0.375 (0.138,1.020) | 0.013 | 0.233 (0.074,0.734) |
| *Catheterization parameters* | | | | | | | |
| sPAP$_{RHC}$ level | | | | 0.000 | | | |
| Low | 43 (19.7%) | 25 (11.5%) | 2 (0.9%) | 0.000 | 15.574 (7.563,31.961) | 0.000 | 21.561 (9.574,48.554) |
| Medium | 30 (13.8%) | 27 (12.4%) | 17 (7.9%) | 0.000 | 5.279 (2.752.10.125) | 0.000 | 5.125 (2.545,10.321) |
| High | 6 (2.8%) | 29 (13.3%) | 39 (17.9%) | | | | |
| sPAP$_{RHC}$ (mmHg) | 60.5 ± 19.6 | 74.4 ± 23.1 | 92.4 ± 23.1 | 0.000 | 0.958 (0.947,0.970) | | |
| RAP (mmHg) | 2.2 ± 4.2 | 3.3 ± 4.7 | 5.2 ± 6.1 | 0.002 | 0.921 (0.875,0.970) | | |
| PVR (Wood Units) | 8.4 ± 5.9 | 11.2 ± 6.2 | 14.0 ± 8.5 | 0.000 | 0.912 (0.878,0.947) | | |
| PAWP (mmHg) | 6.9 ± 5.2 | 7.5 ± 5.2 | 10.1 ± 7.0 | 0.003 | 0.932 (0.889,0.977) | 0.018 | 0.939 (0.892,0.989) |
| mPAP (mmHg) | 38.6 ± 35.6 | 43.3 ± 14.7 | 53.9 ± 15.5 | 0.000 | 0.961 (0.944,0.978) | | |
| *Clinical parameters* | | | | | | | |
| 6 M WT (m) | 370.9 ± 105.7 | 355.9 ± 123.0 | 367.8 ± 84.1 | 0.868 | 1.000 (0.996,1.005) | | |
| WHO functional class | | | | 0.907 | | | |
| I | 5 (2.3%) | 10 (4.6%) | 5 (2.3%) | 0.805 | 0.858 (0.256,2.880) | | |
| II | 38 (17.4%) | 29 (13.3%) | 26 (11.9%) | 0.745 | 1.176 (0.443,3.127) | | |
| III | 30 (13.8%) | 37 (17.0%) | 22 (10.1%) | 0.919 | 1.052 (0.395,2.805) | | |
| VI | 6 (2.8%) | 5 (2.3%) | 5 (2.3%) | | | | |

*RAD* right atrial diameter; *RVDD* right ventricle diastolic diameter; *RV WT* right ventricle wall thickness; *TAPSE* tricuspid annular plane systolic excursion; *RV FAC* right ventricle fractional area change; *RAP* right atrial pressure; *PVR* pulmonary vascular resistance; *PAWP* pulmonary artery wedge pressure; *mPAP* mean pulmonary artery pressure; *6 M WT* 6-min walk test

RV contractility and its load may account for this phenomenon. When sPAP$_{RHC}$ mildly elevates during the initial phase of PH, RV coupling could be maintained by enhanced RV contractility [13, 14], and the estimation of sPAP$_{RHC}$ by DE is relatively reliable. However, as PH progresses and RV uncoupling occurs, CO would decrease and RV preload would increase, along with elevated RAP, so the right atrioventricular pressure gradient would decrease, and DE would underestimate sPAP$_{RHC}$. sPAP$_{RHC}$ level may affect the accuracy of sPAP$_{ECHO}$ through the coupling mechanism between RV contractility and its load. This finding suggests that we should synthesize more echocardiographic

signs when evaluating the efficacy of PH, because the decrease in sPAP$_{ECHO}$ at this time is not necessarily a result of disease improvement, but may also be a sign of underestimation of sPAP$_{ECHO}$ caused by RV decoupling.

Third, we found that echocardiography tended to underestimate pulmonary artery pressure when PAWP increased. We speculated that the underestimation of sPAP$_{ECHO}$ due to the higher PAWP may be related to the lower threshold in post-capillary PH patients. Amsallem et al. [15] found that higher PAWP was associated with lower sPAP$_{ECHO}$ threshold for PH diagnosis, which is consistent with our findings. The optimal cutoff value of our cohort was 49.5 mm Hg, which is higher than the cutoff
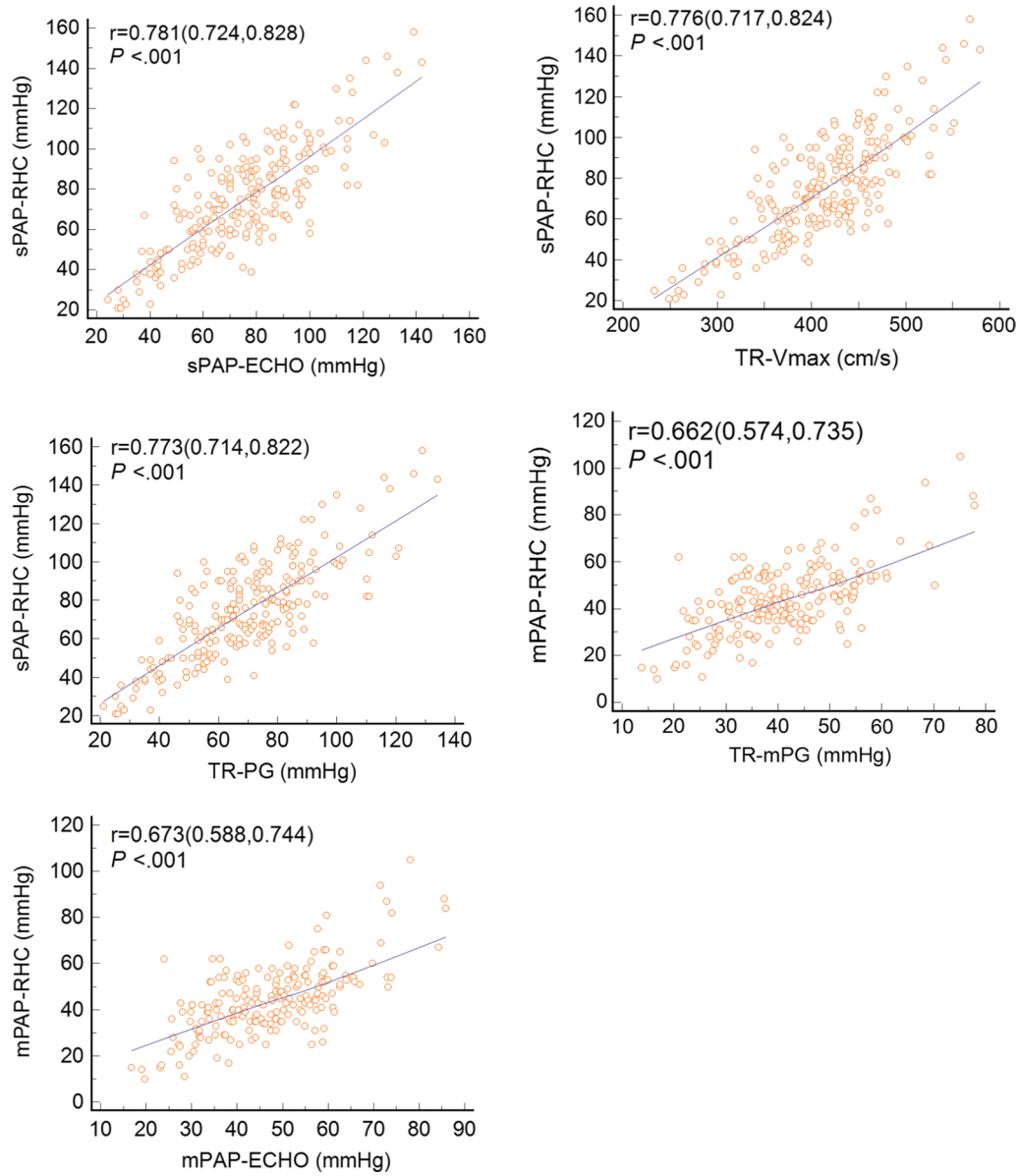
**Fig. 3** Correlation of invasively determined parameters with TR derived parameters. pearson's rank correlation coefficients are presented with 95% CI in brackets

values in previous studies that had focused on post-capillary PH patients with higher PAWP [16, 17]. Pre-capillary PH patients with lower PAWP accounted for 85.8% of the cohort, which may explain this phenomenon. Finkelhor et al. [18] also found that PAWP had a strong inverse correlation with the difference between $sPAP_{RHC}$ and $sPAP_{ECHO}$. They speculated that elevated left atrial pressure can be transmitted to the right atrium via the shared interatrial septum as well as through pericardial constraint and limit TR velocities, thereby also affecting the accuracy of $sPAP_{ECHO}$. Until now, the mechanism

by which PAWP affects the accuracy of $sPAP_{ECHO}$ is still unclear, so more multicenter studies are needed to validate this deduction. Based on the above findings, we think that the accuracy of $sPAP_{ECHO}$ would be improved if combined with the assessment of left ventricular filling pressure by echocardiography. Although RHC is the gold standard for PAWP or left ventricular filling pressure, whether PAWP is elevated can be assessed by indirect signs of echocardiography, such as the ratio of mitral E peak velocity and averaged e'velocity (E/e'm ratio), TR Vmax, and left atrium volume index. Echocardiologists

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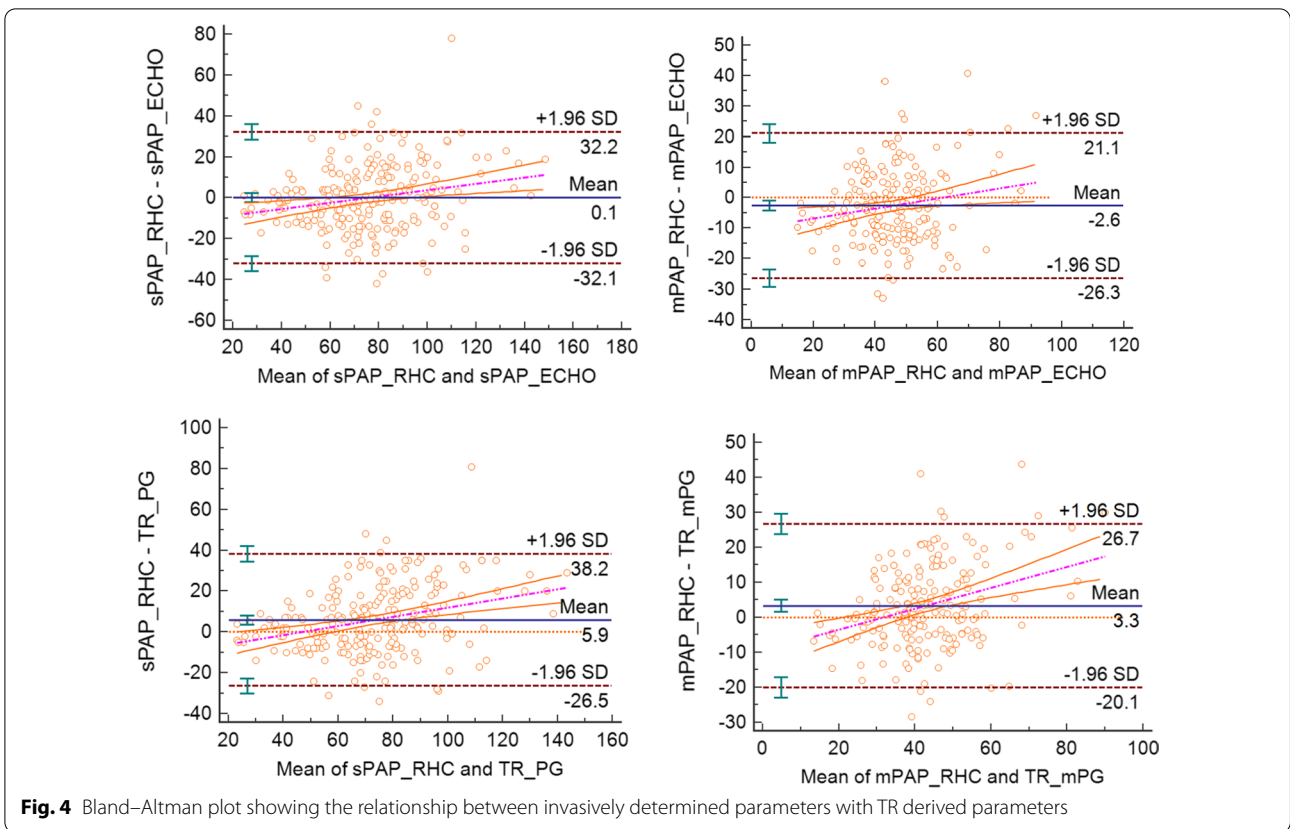


**Fig. 4** Bland–Altman plot showing the relationship between invasively determined parameters with TR derived parameters

can synthesize such information to determine whether patients have PAWP elevation, to assess the $sPAP_{ECHO}$ and the possibility of PH more reasonably.

Furthermore, there is no consensus as to how TR severity would interfere with the accuracy of the $sPAP_{ECHO}$. Hioka et al. [19] reported that echocardiography increasingly overestimated the TR PG with the advance of TR severity, as was theoretically predicted by the pressure recovery phenomenon associated with the laminar regurgitant flow. However, Parasuraman et al. [20] reported that severe TR could cause equalization of right atrial and ventricular pressures, which may cause the TR Doppler envelope to be cut short, thereby leading to

underestimation of $sPAP_{ECHO}$. Our study differed from other studies in that the TR severity did not significantly affect the accuracy of $sPAP_{ECHO}$. It should be noted that only 9.6% of patients in our cohort had severe TR, which was in line with the actual clinical situation that severe TR only appears in the minority of patients. However, in patients with mild or moderate TR, we could also obtain good signal quality and estimate $sPAP_{ECHO}$ appropriately (Fig. 5). TR severity was also affected by RV contractility and dimension. Thus, the overall impact of TR severity on the accuracy of $sPAP_{ECHO}$ is not as significant as that of TR signal quality.

**Table 3** Receiver operating characteristic curve analysis of DE parameters for detecting PH (mPAP $\geq$ 25 mmHg)

|  | AUC | Cut-off value | Sensitivity (%) | Specificity (%) | Accuracy (%) | PPV (%) | NPV (%) |
|---|---|---|---|---|---|---|---|
| $sPAP_{ECHO}$ | 0.981 | 49.5 mmHg | 94.9 | 85.7 | 94.0 | 98.4 | 64.3 |
| TR Vmax | 0.977 | 350.0 cm/s | 91.9 | 90.5 | 91.7 | 98.9 | 54.3 |
| TR-PG | 0.978 | 46.5 mmHg | 94.4 | 85.7 | 93.6 | 98.4 | 62.1 |
| $mPAP_{ECHO}$ | 0.956 | 30.6 mmHg | 94.4 | 84.6 | 93.7 | 98.8 | 52.4 |
| TR-mPG | 0.945 | 27.6 mmHg | 92.7 | 84.6 | 92.2 | 98.8 | 45.8 |

*PPV* Positive predictive value; *NPV* Negative predictive value; *sPAP_ECHO*: pulmonary systolic pressure estimated by echocardiography; *TR Vmax*: maximum velocity of tricuspid regurgitation; *TR-PG* tricuspid regurgitation pressure gradient; *mPAP_ECHO* mean pulmonary artery pressure estimated by echocardiography; *TR-mPG* tricuspid regurgitation mean pressure gradient

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We found that none of the RV systolic parameters had a significant impact on the accuracy of sPAP$_{ECHO}$. Theoretically, RV systolic function would gradually decrease [21], but RV can remain coupled for the large increase in load by increasing contractility until heart failure [13]. Therefore, RV systolic parameters are relatively stable before the end-stage of PH. In addition, the heart movement and measurement angle dependence also affect the accuracy of the relevant parameters. Although RV systolic parameters had clinical significance for the assessment of PH, they did not have a significant effect on the accuracy of sPAP$_{ECHO}$.

Finally, incorporating TR signal quality, sPAP$_{RHC}$ level, and PAWP into the assessment of sPAP$_{ECHO}$

would improve its accuracy and avoid overly invasive examination.

## Limitations

This study has several limitations. First, this was a retrospective study with a small sample size. Although 90.5% of our patients had PH, and in 47.7% of them, PH was due to chronic pulmonary thromboembolism, the sample size of other types of PH was relatively small. Thus, we could not give specific suggestions for each type of PH. Second, we included patients who had undergone RHC and echocardiography within 7 days due to the restriction of clinical actual conditions. However, the average interval time was 3 days in this study, and the majority
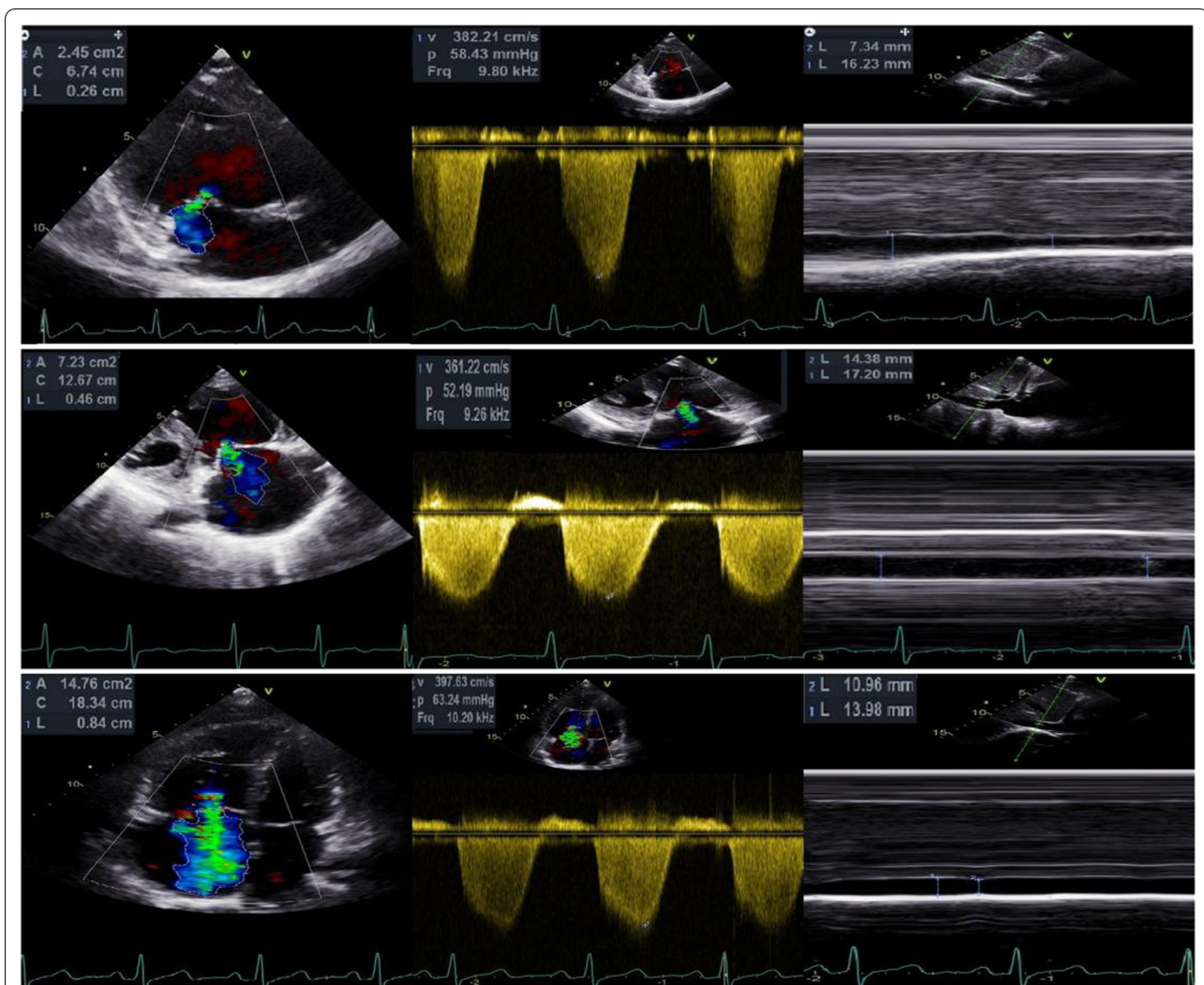


**Fig. 5** Examples of different severity of TR with good signal quality and accurate sPAP$_{ECHO}$. The upper image presents a 40 years old female with mild TR whose sPAP$_{ECHO}$ and sPAP$_{RHC}$ were 59 and 61 mmHg, respectively. The medium image shows a 50 years old female with moderate TR whose sPAP$_{ECHO}$ and sPAP$_{RHC}$ were 60 and 60 mmHg, respectively. The lower image demonstrates a 34 years old female with severe TR whose sPAP$_{ECHO}$ and sPAP$_{RHC}$ were 71 and 73 mmHg, respectively

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of patients had pre-capillary PH, which indicated that the patients' hemodynamics was relatively stable and did not change dramatically during this short time. Furthermore, contrast microbubbles were not adopted to enhance the tricuspid regurgitation jet for patients with mild regurgitation or poor signal quality. Finally, the single-center nature of the present study limited generalization.

## Conclusions

In this study, we found that all TR-related methods, including $sPAP_{ECHO}$, had comparable and good efficiency in PH screening. To make the assessment of $sPAP_{ECHO}$ more accurate, attention should be paid to TR signal quality, $sPAP_{RHC}$ level, and PAWP.

### Abbreviations

PH: Pulmonary hypertension; RHC: Right heart catheterization; DE: Doppler echocardiography; TR: Tricuspid regurgitation; $sPAP_{RHC}$: Pulmonary artery systolic pressure measured by RHC; $sPAP_{ECHO}$: Pulmonary artery systolic pressure estimated by DE; mPAP: Mean pulmonary artery pressure measured by RHC; $mPAP_{ECHO}$: Mean pulmonary artery pressure estimated by DE; PAWP: Pulmonary artery wedge pressure; RAP: Right atrial pressure; CO: Cardiac output; TR PG: TR pressure gradient; TR-mPG: TR mean pressure gradient; PVR: Pulmonary vascular resistance; RV: Right ventricle; RV WT: RV wall thickness; TAPSE: Tricuspid annular plane systolic excursion; S': Systolic annular tissue velocity of the lateral tricuspid annulus; FAC: RV Fractional area change; IVC: Inferior vena cava.

### Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

### Ethics approval and consent to participate

This study complied with the Declaration of Helsinki. Ethical approval number was 2020-95-K59. The protocol was approved by the Ethic Committee of China-Japan Friendship Hospital. The institutional review board of the China-Japan Friendship Hospital waived the need for written patient informed consent as this study involved the retrospective analysis of clinically acquired data.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

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