Comparison of the Right Atrial Expansion Index with Inferior Vena Cava Assessment for Echocardiographic Estimation of the Right Atrial Pressure

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Background: Evaluating right atrial pressure (RAP) is essential for managing cardiac diseases. Right heart catheterization (RHC) measures RAP directly but is invasive. In contrast, transthoracic echocardiography (TTE) provides a noninvasive estimate of RAP through inferior vena cava (IVC) assessment despite some limitations. The right atrial expansion index (RAEI) reflects right atrial compliance by measuring the relative increase in volume during the reservoir phase. This study aimed to validate RAEI as a noninvasive parameter for estimating RAP.

Methods: We retrospectively enrolled 1,020 patients (728 in the derivation and 292 in the validation cohort) with various chronic cardiac diseases who underwent clinically indicated RHC and TTE within 24 hours. Right atrial pressure was measured during the RHC and defined as elevated when above 10 mm Hg. Right atrial expansion index and other TTE parameters were measured offline and blinded to RHC results.

Results: In the derivation cohort, RAEI showed a logarithmic correlation with RAP (lnRAEI-RAP: $r = -0.65$, $P < .001$). The natural log of RAEI was an independent and additive predictor of RAP, outperforming clinical, hemodynamic, and echocardiographic parameters, including IVC assessment. The natural log of RAEI was more accurate than IVC assessment for identifying RAP $\geq$10 mm Hg (area under the curve lnRAEI, 0.840,; $P < .001$; optimal cutoff, lnRAEI <3.53); this finding was replicated in the validation cohort (area under the curve lnRAEI, 0.826; $P < .001$). Furthermore, lnRAEI <3.53 was confirmed as an optimal cutoff for identifying RAP $\geq$10 mm Hg in the validation cohort as well (sensitivity, 74%; specificity, 79%; accuracy, 78%). Finally, the equation RAP = 19.3 – (3.29 $\times$ lnRAEI) derived from the derivation cohort estimated RAP more accurately (-0.2 ± 3.1 mm Hg) than IVC assessment (1.5 ± 4.2 mm Hg) in the validation cohort.

Conclusions: In this patient cohort, lnRAEI was more accurate than IVC assessment for noninvasive RAP estimation. (J Am Soc Echocardiogr 2026;39:167-78.)

Keywords: Right atrial reservoir function, Right atrial compliance, Central venous pressure, Right atrial pressure, Echocardiography

BACKGROUND

The increase in right atrial (RA) pressure (RAP) represents the hemodynamic hallmark of right heart failure (HF), is responsible for systemic venous congestion,[1] and reflects the cumulative hemodynamic burden on the right heart chambers.[2] Normal mean RAP values range from 2 to 6 mm Hg.[3] Although a precise cutoff for elevated RAP has not been univocally defined, values exceeding 10 mm Hg have been considered as a reasonable threshold.[4-6] Increased RAP is independently associated with all-cause mortality in patients with cardiovascular disease.[2,7-9] Furthermore, RAP assessment helps manage critically ill patients[10] and estimate the pulmonary arterial systolic pressure (PASP) when added to the right atrioventricular gradient in systole in the absence of pulmonary stenosis/right ventricular (RV) outflow tract obstruction.[11]

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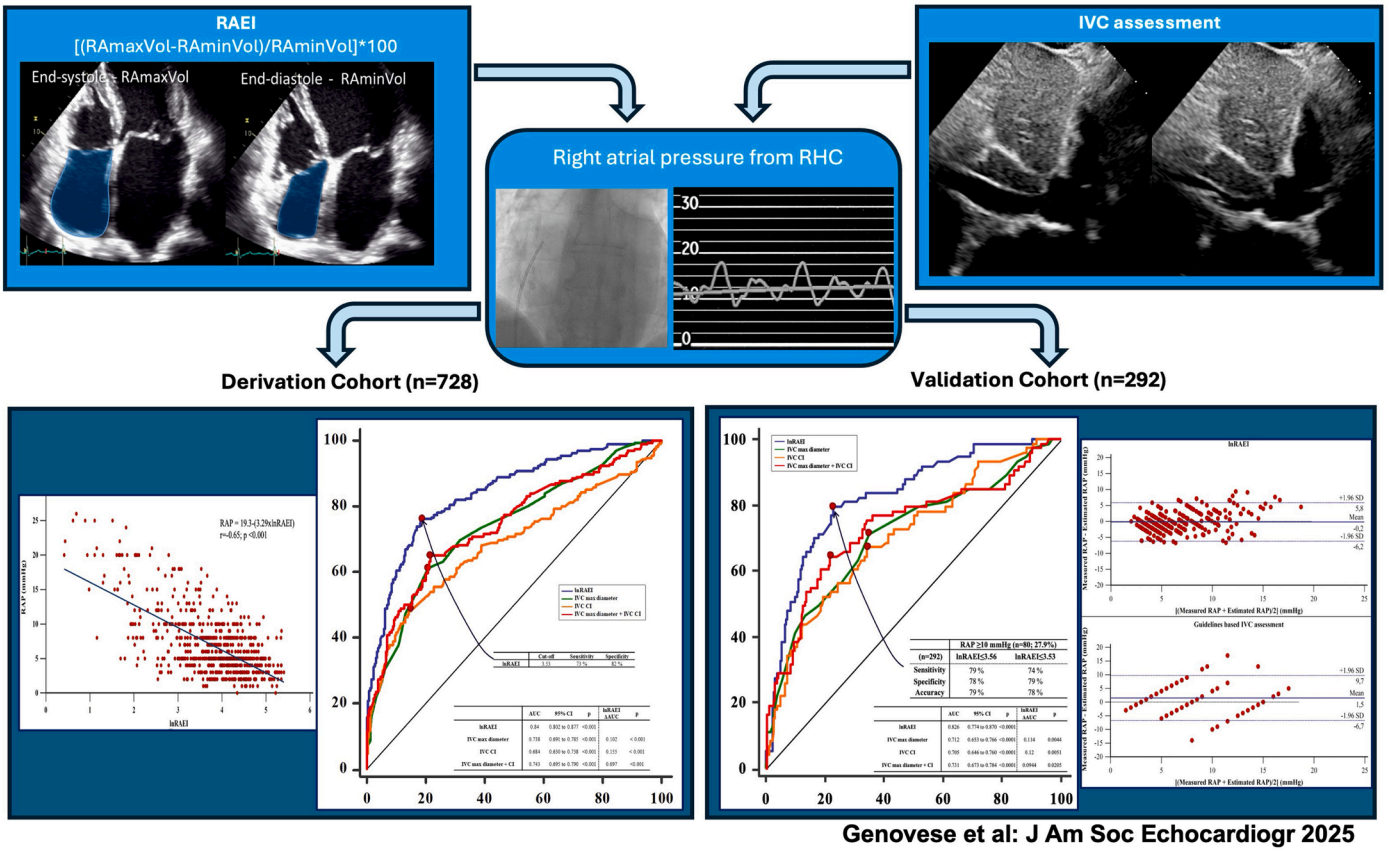

Central Illustration Echocardiographic evaluation of the RAEI more accurately estimates RAP than conventional IVC assessment.

Right heart catheterization (RHC) provides accurate measurement of RAP. However, it is an invasive procedure with some procedural risk,[12,13] requires a catheterization laboratory or an intensive care unit room, and is impractical for evaluating patients during multiple follow-up visits. Therefore, RAP is routinely estimated by measuring the maximal diameter of the inferior vena cava (IVCDmax) and the extent of IVC collapse during rapid inspiration or sniffs with transthoracic echocardiography (TTE).[4-6,14] Unfortunately, the accuracy of RAP estimation through IVC assessment is modest and can be inconsistent.[6]

The left atrial (LA) expansion index (LAEI), a volume-based index of LA compliance, has proven to be a valuable parameter for the noninvasive estimation of the LA pressure (LAP).[15-17] However, the RA expansion index (RAEI) had never been previously used for RAP assessment. Therefore, we hypothesize that RAEI, which describes RA compliance through the relative RA volume increase during the reservoir phase, could serve as a valuable parameter for noninvasive RAP estimation. This study aimed to (1) explore the correlation between RAEI and RAP; (2) evaluate the independent and additional value of RAEI for predicting RAP, accounting for clinical, hemodynamic, and echocardiographic parameters; (3) compare the accuracy of RAEI in identifying elevated RAP against IVC assessment; and (4) derive and validate a simple equation for predicting RAP based on RAEI.

METHODS

Study Population

We performed a single-center, retrospective, observational, cross-sectional study. We screened patients with chronic cardiac diseases who underwent a clinically indicated RHC from December 2019 to March 2023 at the Department of Cardiac, Thoracic, Vascular Sciences, and Public Health, University of Padua Hospital. We included the 1,065 patients who underwent RHC and TTE exams within 24 hours during this period. All patients were electively admitted and had no change in clinical status or medications between the 2 exams. We excluded patients without adequate TTE image quality or RA-dedicated views ($n = 25$) and those with tricuspid valve prosthesis ($n = 8$), surgical tricuspid valve repair ($n = 10$), and tricuspid valve stenosis ($n = 2$). The final study population included 1,020 subjects. The local ethics committee approved the study (protocol no. 521n/AO/24), and enrolled patients provided informed consent. The datasets for the current study are available from the corresponding author upon reasonable request.

Right Heart Catheterization

Right heart catheterization was performed with a Swan-Ganz catheter (SGC) through a femoral transvenous approach, following

Abbreviations

AF = Atrial fibrillation

AUC = Area under the curve

BMI = Body mass index

CoV = Coefficient of variation

EDA = End-diastolic area

FAC = Fractional area change

HF = Heart failure

HR = Heart rate

ICC = Intraclass correlation coefficient

IVC = Inferior vena cava

IVCDmax = Inferior vena cava maximal diameter

IVCCI = Inferior vena cava collapsibility index

LA = Left atrial

LAEI = Left atrial expansion index

LAP = Left atrial pressure

LV = Left ventricular

LVEF = Left ventricular ejection fraction

MPAP = Mean pulmonary arterial pressure

PASP = Pulmonary arterial systolic pressure

RA = Right atrial, atrium

RAEI = Right atrial expansion index

RAmaxVol = Right atrial maximal volume

RAminVol = Right atrial minimal volume

RAP = Right atrial pressure

RHC = Right heart catheterization

ROC = Receiver operating characteristic

RV = Right ventricular

SGC = Swan-Ganz catheter

TAPSE = Tricuspid annulus plane systolic excursion

TR = Tricuspid regurgitation

conventional methodology.[3] The procedure was preceded by a 6-hour fasting period, performed without sedation during the patient's spontaneous breathing. The external fluid-filled pressure transducer was zeroed with the supine patient's heart level at the midthoracic line. The SGC balloon was inflated and advanced until it reached the pulmonary capillary wedge position. Subsequently, the SGC balloon was deflated, and the tip was progressively retracted to the pulmonary artery, right ventricle, and finally into the right atrium (RA). The position of the SGC in the RA was identified by fluoroscopy and pressure waveform. Mean RAP measurement was obtained from the pressure-time recordings at the end of a normal expiration by averaging at least 3 cardiac cycles, as currently recommended.[18,19] Right atrial pressure was considered elevated when ≥10 mm Hg.[4,14]

Echocardiography

Transthoracic echocardiography was performed using a Vivid E9 imaging system (GE Vingmed Ultrasound) with an M5S probe. Transthoracic echocardiography measurements were performed offline according to American Society of Echocardiography guidelines[4,20,21] by a reader blinded to clinical and RHC data using a vendor-independent software package (ComPACS; MediMatic Srl). The values of RAmaxVol and RAminVol were measured with the monoplane disks-summation method from RA area tracings at end systole and end diastole in an atrial dedicated apical 4-chamber view. Finally, RAEI was calculated as RAEI = [(RAmaxVol − RAminVol)/RAminVol] * 100. In atrial fibrillation (AF) patients, measurements were averaged from 3 consecutive cardiac cycles. Additional TTE measurements included RV end-diastolic area (EDA), fractional area change (FAC), tricuspid annulus plane systolic excursion (TAPSE), tricuspid regurgitation (TR) severity, PASP, IVCDmax, and IVC collapsibility index (IVCCI), calculated as IVCCI = [(IVCmax diameter − IVCmin diameter during rapid inspiration)/IVCmax diameter] * 100. The RAP estimation with IVC assessment was performed following current TTE guidelines,[4,5] defining 3 ranges of RAP: normal RAP (3 mm Hg) with IVCDmax ≤2.1 cm and IVCCI >50%, intermediate RAP (8 mm Hg) with IVCDmax ≤2.1 cm and IVCCI <50% or IVCDmax >2.1 cm, and IVCCI >50%, elevated RAP (15 mm Hg) with IVCDmax >2.1 cm and IVCCI <50%.

Reproducibility Analysis

Right atrial expansion index reproducibility assessment included inter- and intrareader variability in repeated analysis of 50 randomly selected cases. At least 2 months later, the same reader and a second independent reader, blinded to all prior measurements, performed repeated measurements on the same images.

Statistical Analysis

Continuous variables were reported as mean ± SD and categorical variables as absolute number with percentage (%). Independent samples *t* test, chi-square analysis, and Pearson correlation coefficients were applied as appropriate. The natural log of RAEI was derived by the log transformation of RAEI. Multivariate hierarchical linear regression analyses and *F* test were used to explore the independent and additive predictive role of lnRAEI for RAP estimation over clinical, hemodynamic, and TTE parameters. The diagnostic accuracy of lnRAEI for elevated RAP identification was assessed using receiving operating characteristic (ROC) curves. The areas under the curves (AUCs) were compared using the DeLong method. The optimal lnRAEI cutoff was identified with the Youden index. Diagnostic accuracy for the identified cutoff was tested using 2 × 2 tables for standard diagnostic tests. The lnRAEI linear regression equations and IVC assessment for RAP estimation were analyzed using Bland-Altman analysis. Inter- and intrareader variability was assessed using the coefficient of variation (CoV) and intraclass correlation coefficient (ICC). A P value $< .05$ was considered statistically significant. Statistical analysis was performed using SPSS 26.0 (SPSS) and Medcalc 19.6.1 (MedCalc).

RESULTS

Population Characteristics

We included 1,020 patients with different chronic cardiac pathologies, randomly divided into derivation ($n = 728$) and validation ($n = 292$) cohorts with comparable clinical, hemodynamic, and TTE characteristics (Table 1).

Derivation Cohort Analysis

Comparison Between Normal and Elevated RAP. The derivation cohort was divided into RAP ≥10 mm Hg ($n = 160$) and RAP <10 mm Hg ($n = 568$) subgroups. Higher RAP was associated with male gender, AF, higher body mass index (BMI), lower systolic blood pressure, faster heart rate (HR), and higher mean pulmonary arterial pressure (MPAP). Moreover, RAP ≥10 mm Hg was associated with lower RAEI, larger RA, larger and more

HIGHLIGHTS

- RAEI describes the relative increase in RA volume during the reservoir phase.
- RAEI correlates logarithmically with RAP.
- lnRAEI is more accurate than IVC assessment for estimating RAP.
- lnRAEI is a simple echocardiographic parameter for noninvasive RAP assessment.

dysfunctional right ventricle, lower left ventricular (LV) ejection fraction (LVEF), and more severe TR (Table 2).

RAEI and RAP Correlation. The RAEI had the highest correlation with RAP ($r = -0.49$; $P < .001$; Figure 1, top) among the other clinical, hemodynamic, and TTE parameters (Table 3, first column), including IVC assessment (Figure 2). However, a logarithmic curve best fitted the RAEI-RAP correlation, and the log-transformed LAEI (lnRAEI) showed a further improvement in the linear correlation with RAP ($r = -0.65$; $P < .001$, Figure 1, bottom).

Univariate and Multivariate Analysis for RAP Estimation. The multivariate hierarchical linear regression for predicting RAP included 3 models. The first model included gender, BMI, HR, AF, RHC MPAP, EDA, FAC, RAmaxVol, TAPSE, and TR severity (first model: adjusted $R^2 = 0.45$). The addition of IVC assessment (IVCDmax, IVCCI) to the parameters of the first model provided a small but significant improvement in the predictive power of the second model (adjusted $R^2 = 0.47$; $P < .001$ from the first model). Finally, the addition of lnRAEI to the parameters of the second model provided a further significant improvement of the predictive power of the third model (adjusted $R^2 = 0.57$; $P < .001$ from the second model). In addition, lnRAEI resulted in an independent RAP predictor along with BMI, RHC MPAP, EDA, IVCCI, and TR severity (Table 3).

ROC Curve Analysis. The natural log of RAEI showed good accuracy for identification of RAP ≥10 mm Hg (lnRAEI AUC = 0.84, $P < .001$), significantly higher than IVCDmax (ΔAUC from lnRAEI = 0.102, $P < .001$), IVCCI (ΔAUC from lnRAEI = 0.155, $P < .001$), and a model that accounted together for IVCDmax + IVCCI (ΔAUC from lnRAEI = 0.097, $P < .001$; Figure 3). The derived optimal cutoff lnRAEI ≤3.53 had 73% sensitivity and 82% specificity for discriminating RAP ≥10 mm Hg in the derivation cohort. Furthermore, the diagnostic performance and optimal cutoffs of lnRAEI had been identified also for RAP≥15 mm Hg (AUC = 0.94, $P < .001$; cutoff lnRAEI = 3.23; sensitivity, 88%; specificity, 83%) and RAP ≥20 mm Hg (AUC = 0.98; $P < .001$; cutoff lnRAEI = 2.7; sensitivity, 96%; specificity, 91%; Supplemental Table 1).

Subgroup Analysis. The diagnostic performance of lnRAEI for identifying RAP ≥10 mm Hg was assessed across different groups, including obesity, AF, moderate or more TR, reduced RV function, reduced LVEF, and dilated RA. The natural log of RAEI showed good diagnostic accuracy in all these groups, with the highest performance in patients with LVEF <50% (AUC = 0.884) and the lowest in patients with AF (AUC = 0.761), demonstrating the robustness of this parameter (Supplemental Table 2 and Supplemental Figure 1).

Validation Cohort

ROC Curve Analysis. In the validation cohort, the diagnostic accuracy of lnRAEI for RAP ≥10 mm Hg identification was confirmed to be higher than IVCDmax, IVCCI, and the model IVCDmax + IVCCI (lnRAEI AUC = 0.826, $P < .001$; ΔAUC lnRAEI-IVCDmax = 0.114, $P = .004$; ΔAUC lnRAEI-IVCCI = 0.120, $P = .005$; ΔAUC lnRAEI-IVCDmax + IVCCI = 0.094, $P = .021$). Of note, the IVC assessment was not feasible in 31 patients (11% of the validation cohort) due to an inadequate subcostal view. Furthermore, the cutoff lnRAEI ≤3.53 obtained from the derivation cohort was superimposable to the optimal cutoff identified from the validation cohort (lnRAEI ≤3.56), confirming its reproducibility and accuracy for discriminating RAP ≥10 mm Hg also in an independent cohort of patients (lnRAEI ≤3.56; accuracy, 79%; lnRAEI ≤3.53; accuracy, 78%; Figure 4). Similarly, comparable or higher accuracy was also confirmed for the corresponding lnRAEI cutoffs derived for RAP ≥15 mm Hg (lnRAEI = 3.23; accuracy, 79%) and ≥20 mm Hg (lnRAEI = 2.7; accuracy 87%; Supplemental Table 1).

The lnRAEI Equation for RAP and PASP Prediction. The lnRAEI regression equation for RAP estimation obtained in the derivation cohort (RAP = 19.3 − 3.29 × lnRAEI) predicted invasively measured RAP in the validation cohort (RHC RAP − lnRAEI RAP estimated = −0.2 ± 3.1 mm Hg; Figure 5). Of note, the lnRAEI equation was more accurate than the guidelines-based IVC assessment for RAP estimation (RHC RAP − IVC assessment RAP = 1.5 ± 4.2 mm Hg). Finally, when adding the estimated RAP to the right atrioventricular gradient, the use of lnRAEI resulted in a mean difference of −0.9 ± 10.6 mm Hg compared to invasive PASP, while the use of IVC-based RAP resulted in a mean difference of 0.4 ± 11.6 mm Hg.

Reproducibility Analysis

Right atrial volumes and RAEI showed good inter- and intrareader reproducibility (Table 4).

DISCUSSION

In this large cohort of patients with chronic cardiac diseases, we found that (1) RAEI was logarithmically correlated to RAP; (2) lnRAEI was an independent and additive predictor of RAP beyond clinical, hemodynamic, and other TTE parameters, including the assessment of the IVC; (3) lnRAEI ≤3.53 cutoff, obtained from the derivation cohort, demonstrated 78% accuracy in identifying RAP above 10 mm Hg in the validation cohort; (4) the equation RAP = 19.3 − 3.29 × lnRAEI, obtained from the derivation cohort, estimated RAP more accurately (−0.2 ± 3.1 mm Hg) than the guidelines-based IVC assessment (1.5 ± 4.2 mm Hg) in the validation cohort (Central Illustration).

Transthoracic echocardiography guidelines recommend IVC evaluation for RAP assessment[4,5] despite modest accuracy and inconsistency in the results.[6] Indeed, IVC assessment has several limitations since it systematically underestimates RAP >15 mm Hg due to classification constraints;[4] is unreliable in mechanically ventilated patients[22] and young athletes;[23] is influenced by BSA

Table 1 Clinical, RHC, and echocardiographic parameters in the study population, derivation, and validation cohorts

	All *n* = 1,020	Derivation, *n* = 728	Validation, *n* = 292	*P*
Age, years	66.9 ± 14.2	67.3 ± 13.7	65.8 ± 15.1	.118
Gender, male	586 (57.5)	417 (57.3)	169 (57.9)	.862
BMI, kg/m^2	26.3 ± 4.5	26.3 ± 4.6	26.3 ± 4.5	.876
Systolic blood pressure, mm Hg	131.2 ± 26.3	131.7 ± 26.0	130 ± 27.3	.368
Diastolic blood pressure, mm Hg	71.9 ± 12.4	72.2 ± 12.5	71.1 ± 12.0	.192
HR, bpm	75.3 ± 14.8	75.7 ± 15.2	74.4 ± 13.8	.207
Main cardiac diagnosis*				
IHD	137.0 (13.4)	102.0 (14.0)	35.0 (12.0)	.913
DCM	133.0 (13.0)	93.0 (12.8)	40.0 (13.7)	
PH	97.0 (9.5)	69.0 (9.5)	28.0 (9.6)	
AVD	368.0 (36.1)	267.0 (36.7)	101.0 (34.6)	
MVD	137.0 (13.4)	95.0 (13.0)	42.0 (14.4)	
TR	26.0 (2.5)	16.0 (2.2)	10.0 (3.4)	
CM (others)	65.0 (6.4)	44.0 (6.0)	21.0 (7.2)	
PD	37.0 (3.6)	28.0 (3.8)	9.0 (3.1)	
Others	20.0 (2.0)	14.0 (1.9)	6.0 (2.1)	
AF	252 (24.7)	178 (24.5)	74 (25.3)	.765
RHC RAP, mm Hg	6.9 ± 4.5	6.8 ± 4.5	7 ± 4.4	.684
RHC MPAP, mm Hg	23.9 ± 11.2	23.8 ± 11.2	24.2 ± 11.2	.548
RV EDA, cm^2/m^2	12.4 ± 4.1	12.4 ± 4.1	12.4 ± 4.0	.923
RV FAC, %	39.7 ± 9.7	39.7 ± 9.7	39.7 ± 9.7	.979
IVCDmax, cm	1.6 ± 0.6	1.6 ± 0.6	1.6 ± 0.6	.855
IVCCI, %	58 ± 18.2	57.9 ± 18.6	58.2 ± 17.2	.842
RAmaxVol, mL/m^2	39.1 ± 24.6	38.7 ± 22.5	40.3 ± 29.3	.359
RAEI, %	60.4 ± 44.2	61.2 ± 43.7	58.3 ± 45.3	.339
TAPSE, cm	2.1 ± 1.1	2.1 ± 1.3	2.0 ± 0.6	.184
LAmaxVol, mL/m^2	51.7 ± 28.4	51.4 ± 27.4	52.5 ± 31.0	.593
LVEDV, mL/m^2	73.6 ± 37.3	73.5 ± 37.8	73.6 ± 36.1	.988
LVEF, %	50.8 ± 14.8	50.9 ± 14.8	50.8 ± 15.0	.953
TR†				
None	351 (34.4)	264 (36.3)	87 (29.8)	.400
Mild	385 (37.7)	264 (36.3)	121 (41.4)	
Mild-moderate	85 (8.3)	63 (8.7)	22 (7.5)	
Moderate	101 (9.9)	70 (9.6)	31 (10.6)	
Moderate-severe	28 (2.7)	20 (2.7)	8 (2.7)	
Severe	70 (6.9)	47 (6.5)	23 (7.9)	

Values are reported as mean ± SD or *n* (%). *AVD*, Aortic valve diseases; *DCM*, dilated cardiomyopathy; *MVD*, mitral valve diseases; *IHD*, ischemic heart disease; *PD*, valvular prosthesis dysfunction; *LAmaxVol*, left atrial maximal volume; *LVEDV*, LV end-diastolic volume; *PH*, pulmonary hypertension.

*In patients with multiple cardiac diseases, only the primary condition leading to an RHC exam was reported for each patient.

†The TR severity was determined based on the current American Society of Echocardiography guidelines on native valvular regurgitation.[21]

differences;[24] is affected by intra-abdominal pressure, which induces IVC changes from the supine to the left lateral decubitus;[25] and requires collaborative patients and standardization of the sniff maneuver in routine clinical practice. Then the IVC might translate out of the TTE plane during the rapid inspiration, showing false IVC collapse.[5,26] Finally, IVC cannot be assessed in about 10% of patients due to insufficient subcostal view.[14] To refine RAP evaluation, other secondary parameters could be evaluated (i.e., RA enlargement, RV hypertrophy, hepatic veins flow). However, the multiparametric assessments did not improve accuracy over the IVC assessment alone.[27,28]

Right atrial echocardiographic evaluation currently relies on RA static dimensions (RA diameters RAmaxArea and RAmaxVol), despite the fact that the RA is a dynamic structure.[5,29] The RA

Table 2 High and low RAP subgroups comparison in the derivation cohort

Derivation cohort *n* = 728	RAP <10 mm Hg *n* = 568	RAP ≥10 mm Hg *n* = 160	*P*
Age, years	67.6 ± 13.9	66.4 ± 13.0	.308
Gender, male	3.9 (54)	108 (68)	**.003**
BMI, kg/m^2	26 ± 4.5	27.6 ± 4.8	**<.001**
Systolic blood pressure, mm Hg	132.8 ± 25.9	127.6 ± 25.6	**.025**
Diastolic blood pressure, mm Hg	72.2 ± 12.3	72.5 ± 13.4	.738
HR, bpm	74.9 ± 14.5	78.5 ± 17.3	**.009**
AF	102 (18)	76 (48)	**<.001**
RHC RAP, mm Hg	4.9 ± 2.1	13.7 ± 4.2	**<.001**
RHC MPAP, mm Hg	21.1 ± 10.0	33.4 ± 9.7	**<.001**
RV EDA, cm^2/m^2	11.8 ± 3.6	14.6 ± 5.6	**<.001**
RV FAC, %	41.4 ± 8.9	33.2 ± 9.8	**<.001**
IVCDmax, cm	1.5 ± 0.5	2.0 ± 0.6	**<.001**
IVCCI, %	61.3 ± 15.4	46.7 ± 23.4	**<.001**
RAmaxVol, mL/m^2	34.7 ± 17.8	52.9 ± 30.4	**<.001**
RAEI, %	70.4 ± 43.3	28.8 ± 26.8	**<.001**
TAPSE, cm	2.2 ± 1.4	1.8 ± 0.5	**<.001**
LAmaxVol, mL/m^2	49 ± 22.2	59.7 ± 39.7	**<.001**
LVEDV, mL/m^2	72.8 ± 37.3	76.4 ± 39.5	.283
LVEF, %	52.5 ± 14.0	44.9 ± 16.1	**<.001**
TR*			
None	233 (41)	31 (19)	**<.001**
Mild	211 (37)	53 (33)	
Mild-moderate	47 (8)	16 (10)	
Moderate	47 (8.3)	23 (14)	
Moderate-severe	11 (1.9)	9 (5.6)	
Severe	19 (3.3)	28 (18)	

LAmaxVol, left atrial maximal volume; *LVEDV*, LV end-diastolic volume.
Values are reported as mean ± SD or *n* (%).
Bold values indicate $P < .05$.
*The TR severity was determined based on the current American Society of Echocardiography guidelines on native valvular regurgitation.[21]

stores the blood from both superior and inferior cava veins during the reservoir phase; the relative RA volume increase during this phase could be described with the RAEI and could theoretically provide RAP insight as the LAEI demonstrated for the LAP.[15-17] Indeed, RA reservoir function is reduced in patients with pulmonary arterial hypertension,[30] predicting clinical worsening[31,32] and outcomes.[33-36]

In our study, we found that RAEI had a significant logarithmic association with RAP ($r = -0.65$; $P < .001$), as previously found for LAEI with LAP.[15] Of note, lnRAEI remained an independent predictor of RAP after accounting for IVCDmax and IVCCI, the current TTE cornerstone for RAP evaluation using echocardiography. Moreover, lnRAEI improved RAP evaluation also after accounting for several other right heart TTE parameters such as RV dilatation (RV EDA), RV systolic function (RV FAC and TAPSE), RA dilatation (RAmaxVol) and TR severity, and hemodynamic parameters such as MPAP measured by RHC, which represents the backward hemodynamic burden of the left heart on the right heart, and other clinical determinants such as BMI, HR, and AF. Our population exhibited a wide range of RAP measured by RHC, spanning from 0 to 26 mm Hg, enabling us to assess lnRAEI performance across a broad spectrum of values.

It is noteworthy that the optimal cutoff identified in the derivation cohort (lnRAEI ≤3.53) was superimposable to that in the validation cohort (lnRAEI ≤3.56). This finding confirms the robustness and reproducibility of the cutoff value identified in our study. Furthermore, the diagnostic accuracy of lnRAEI for detecting elevated RAP remained consistent across various RAP thresholds (10, 15, and 20 mm Hg) and different subgroups, including obesity, AF, severe TR, dilated RA, and reduced RV and LV function. The natural log of RAEI confirmed its high diagnostic accuracy for elevated RAP identification also in the validation cohort, outperforming IVCDmax, IVCCI, and their association. Additionally, 11% of patients in the validation cohort had an inadequate subcostal view, and RAP estimation from IVC assessment was impossible in these cases.

Finally, since RAP is a continuous parameter, a quantitative estimation would be more appropriate than the proposed estimation in 3 broad categories (i.e., 3, 8, 15 mm Hg) as recommended by current guidelines.[4,5] The equation RAP = 19.3 − 3.29 × lnRAEI

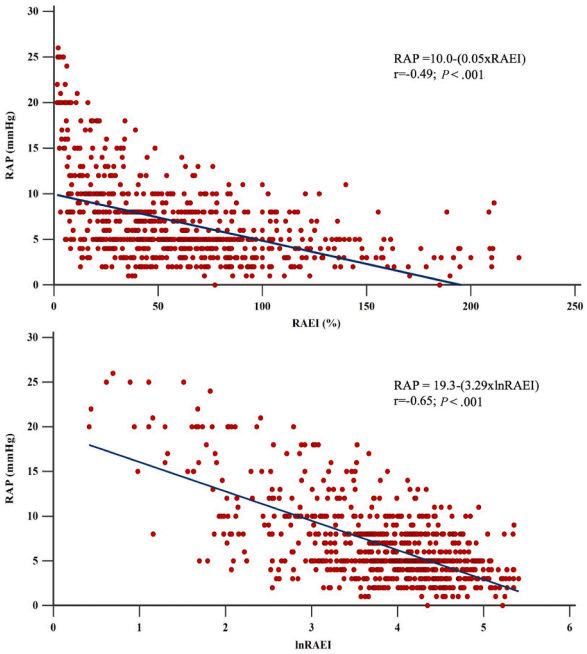

Figure 1 Right atrial pressure scatterplot linear correlation analysis in the derivation cohort (n = 728) for RAEI *(top)* and lnRAEI *(bottom)*.

obtained from the derivation cohort was more accurate than the guidelines' IVC assessment (3, 8, 15 mm Hg) for RAP prediction in the validation cohort, proving the superiority of the equation based on lnRAEI over current guidelines' IVC assessment. However, despite the higher performance of lnRAEI over IVC assessment, the limits of agreement for the equation based on lnRAEI were still suboptimal, meaning that the equation could still provide some inaccurate results in a minority of patients. These discrepancies were more pronounced at the highest RAP ranges and the lowest lnRAEI ranges. The reduced number of patients with very high RAP may contribute to wider prediction intervals and greater variability of RAEI at its lower values. In addition, despite that RAEI improved PASP estimation when combined with the right atrioventricular gradient in systole in comparison to IVC, the limits of agreement for PASP estimation with echocardiography remained large, as previously reported in the literature.[37-39] The improved accuracy of the lnRAEI-based RAP estimate did not translate into a proportionally better PASP prediction. This could be explained by the remaining variability in the right atrioventricular gradient calculation, where any minor inaccuracies in the TR velocity are mathematically squared in the Bernoulli equation, thus limiting the overall impact of a more accurate RAP value.

We believe that RAEI could be extensively utilized in regular TTE exams as a quick and easy method to assess RA reservoir function and estimate RAP. It is a simple calculation that only requires the additional RAminVol measurement over the standard TTE protocol and does not necessitate any specific training or software package for analysis.

Finally, we suggest the following practical approach to implement our findings in clinical practice. We recommend using both lnRAEI and IVC assessment as complementary tools. The superior accuracy of RAEI serves as the primary quantitative tool, while IVC assessment is used for confirmation analysis. This approach shifts the noninvasive estimation of RAP from a categorical to a quantitative assessment. When both methods are feasible (both adequate RA-focused apical 4-chamber and subcostal views), we suggest calculating quantitative RAP from the RAEI formula; this numerical value serves as the initial anchor, whereas IVC assessment acts as a secondary, confirmatory step. Concordant findings provide strong synergistic evidence for the quantitative RAP estimation. Discordant findings should trigger a reassessment of measurements. If discordant measurements are confirmed, the RAEI method should be preferred due to its higher accuracy, albeit with a lower level of certainty. In this case, relying solely on a dichotomized lnRAEI approach (i.e., lnRAEI cutoffs for RAP $\geq$10, 15, 20 mm Hg) might be an option to improve result consistency, albeit at the expense of losing quantitative detail. If only RAEI or IVC assessment is available, RAP should be estimated using that modality only, while recognizing its inherent limitations. By adopting this structured approach, clinicians can leverage the strengths of both modalities to achieve a more confident and nuanced TTE estimation of RAP.

Limitations

Our study had some limitations that should be acknowledged: (1) It is a single tertiary center study subject to potential selection bias (i.e., some cardiac conditions, such as aortic stenosis, were more represented than others). However, since the study population was large and had a wide range of RAP values, we were able

Table 3 Correlation, univariate, and multivariate analysis for RAP estimation in the derivation cohort

	Correlation analysis		Univariate analysis			Multivariate analysis								
						Model 1 (Adj-R^2 = 0.45; F = 33.8)			Model 2 (Adj-R^2 = 0.47; F = 49.6; P < .001 from model 1)			Model 3 (Adj-R^2 = 0.57; F = 182.8; P < .001 from model 2)		
	r	*P*	Estimate	SE	*P*	Estimate	SE	*P*	Estimate	SE	*P*	Estimate	SE	*P*
Age, years	−0.03	.39	−0.01	0.01	.39									
Gender, male			0.92	0.34	**.006**	0.51	0.3	.097	0.3	0.3	.324	−0.06	0.27	.83
BMI, kg/m^2	0.2	**<.001**	0.19	0.04	**<.001**	0.18	0.03	**<.001**	0.17	0.03	**<.001**	0.13	0.03	**<.001**
HR, bpm	0.07	**.048**	0.02	0.01	**.048**	−0.01	0.01	.524	−0.01	0.01	.403	0	0.01	.74
AF			3.35	0.37	**<.001**	1.43	0.38	**<.001**	1.14	0.38	**.003**	0.23	0.35	.517
RHC MPAP, mm Hg	0.55	**<.001**	0.22	0.01	**<.001**	0.14	0.01	**<.001**	0.13	0.01	**<.001**	0.1	0.01	**<.001**
RV EDA, cm^2/m^2	0.31	**<.001**	0.34	0.04	**<.001**	0.09	0.04	**.046**	0.06	0.04	.147	0.1	0.04	**.01**
RV FAC, %	−0.37	**<.001**	−0.17	0.02	**<.001**	−0.05	0.02	**.003**	−0.04	0.02	**.015**	−0.02	0.02	.231
RAmaxVol, mL/m^2	0.35	**<.001**	0.07	0.01	**<.001**	0.00	0.01	.966	0.00	0.01	.595	−0.01	0.01	.23
TAPSE, cm	−0.17	**<.001**	−0.6	0.13	**<.001**	−0.17	0.11	.115	−0.13	0.11	.21	−0.08	0.1	.391
TR*†														
Mild	0.25	**<.001**	0.55	0.36	.133	−0.12	0.35	.724	−0.12	0.34	.719	−0.22	0.31	.476
Mild-moderate			1.62	0.58	**.006**	0.32	0.56	.56	0.4	0.54	.467	−0.2	0.49	.688
Moderate			2.53	0.56	**<.001**	0.79	0.55	.146	0.68	0.54	.208	−0.37	0.49	.45
Moderate-severe			4.28	0.97	**<.001**	2.19	0.91	**.017**	1.53	0.9	.089	0.87	0.81	.288
Severe			6.65	0.66	**<.001**	3.81	0.74	**<.001**	2.86	0.75	**<.001**	1.55	0.68	**.024**
IVCDmax, cm	0.46	**<.001**	3.68	0.27	**<.001**				0.73	0.32	**.023**	0.36	0.29	.219
IVCCI, %	−0.40	**<.001**	−0.10	0.01	**<.001**				−0.04	0.01	**<.001**	−0.02	0.01	**.009**
RAEI, %	−0.49	**<.001**	−0.05	0.00	**<.001**									
lnRAEI	−0.65	**<.001**	−3.29	0.14	**<.001**							−2.11	0.18	**<.001**
Intercept						−0.54	1.66	.745	1.33	1.79	.46	9.87	1.78	**<.001**

Adj-R^2, Coefficient of determination; *F*, explained and unexplained variance ratio; *r*, Pearson coefficient.
Bold values indicate $P < .05$.
*None/trivial TR as the reference.
†The TR severity was determined based on the current American Society of Echocardiography guidelines on native valvular regurgitation.[21]

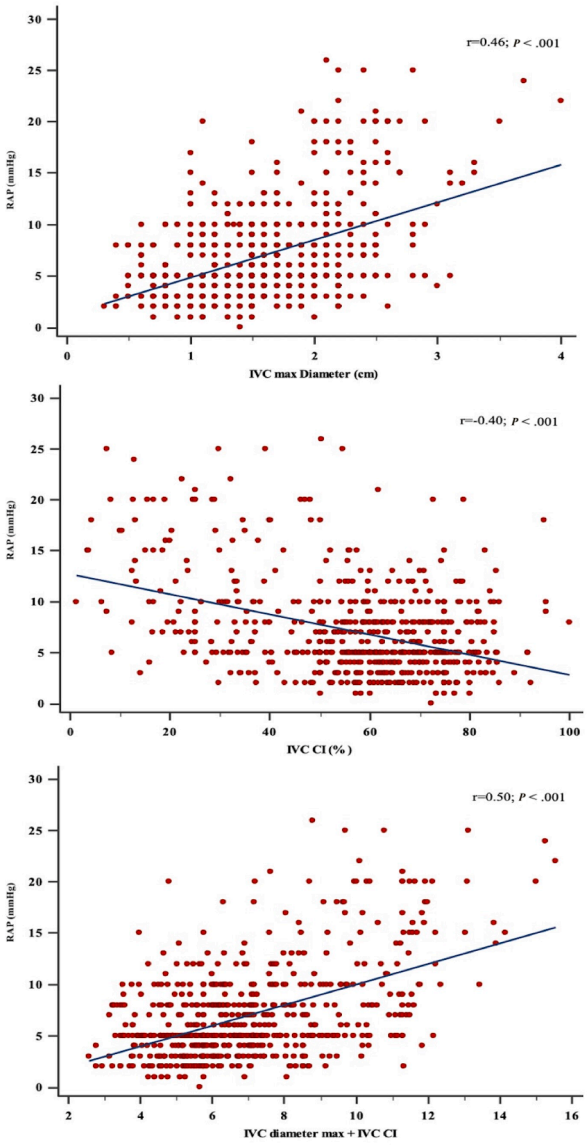

Figure 2 Right atrial pressure scatterplot correlation analysis in the derivation cohort (n = 728) for IVCDmax *(top)*, IVCCI *(middle)*, and a model that accounted together IVCDmax + IVCCI *(bottom)*.

to assess the performance of RAEI over a wide range of RAP values, thereby increasing the robustness of our findings. Nonetheless, the reduced number of patients with very high RAP may limit the applicability of lnRAEI quantitative estimation in this patient group. Furthermore, despite being superior to IVC assessment, the correlation between lnRAEI and RAP was still modest, and there was still significant variation between RAEI-derived and invasively measured RAP values. (2) It has a retrospective design. However, we performed a cross-sectional analysis where TTE exams were reanalyzed offline by a reader blinded to clinical and RHC data. Furthermore, we validated our findings in an independent cohort to increase the robustness of our results.

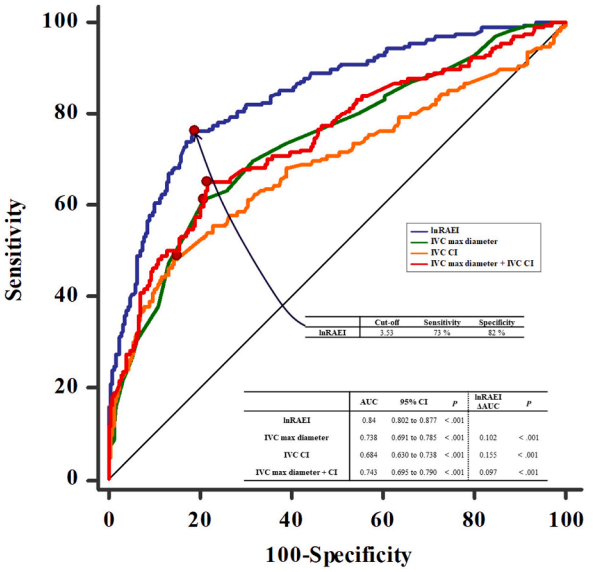

Figure 3 Derivation cohort (n = 728). The ROC analysis for identification of RAP≥10 mm Hg comparing AUC for lnRAEI, IVCDmax, IVCCI, and both (IVCDmax + IVCCI). The optimal cutoff for RAP ≥10 mm Hg was lnRAEI ≤3.53.

(3) It made use of nonsimultaneous RHC and TTE exams. However, the exams were performed within a very short time span of 24 hours from each other, and all patients enrolled were elective admissions with chronic cardiac conditions and did not undergo any intervening changes in clinical status or

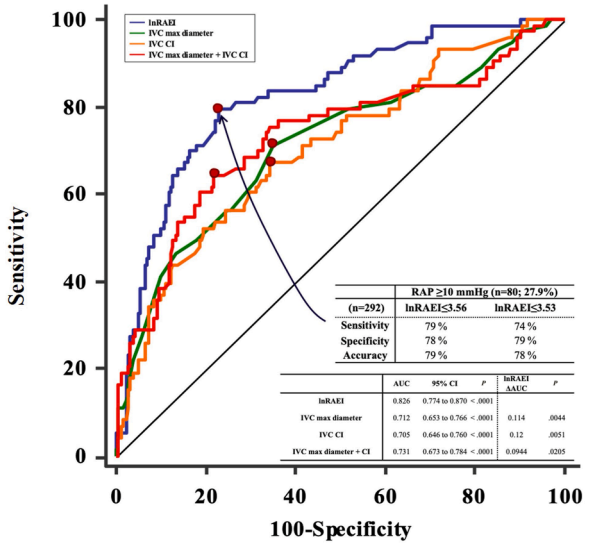

Figure 4 Validation cohort (n = 292). The ROC analysis for identification of RAP ≥10 mm Hg comparing AUC for lnRAEI, IVCDmax, IVCCI, and the model (IVCDmax + IVCCI). The accuracy for identification of RAP≥10 mm Hg of lnRAEI ≤3.53 was superimposable to the performance optimal cutoff obtained from the derivation cohort (lnRAEI ≤3.56).

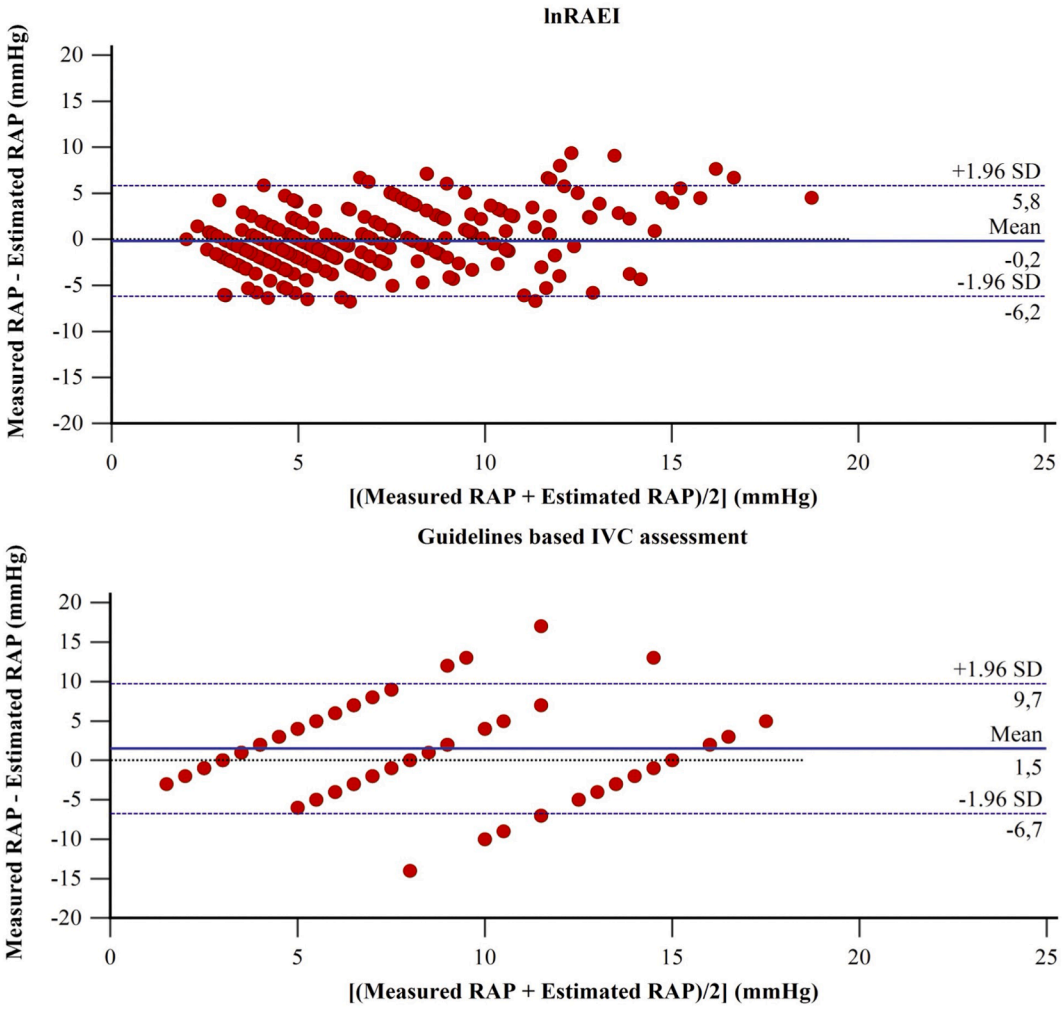

Figure 5 Bland-Altman plot comparing RAP predicted through lnRAEI equation *(top)* and guidelines IVC assessment *(bottom)* against RAP invasively measured during RHC in the validation cohort.

medications between the exams. (4) We used RHC end-expiratory RAP measurements as our reference, in line with current recommendations.[18,19] Therefore, the performance of lnRAEI cannot be directly extrapolated to respiratory-averaged RAP values. (5) Our results were obtained from chronic cardiac patients, and therefore, the potential usefulness of RAEI in acute settings must be evaluated in future studies. (6) Finally, prospective studies are needed for external validation of our findings and to compare lnRAEI performance for RAP evaluation with other RA reservoir function parameters such as RA reservoir strain.

Table 4 Intra- and interreader variability analysis on 50 randomly selected patients

	Intra-reader			Inter-reader		
	CoV (%)	(CI)	ICC	CoV (%)	(CI)	ICC
RAmaxVol	4.6	(3.7 to 5.6)	0.97	5.3	(4.3 to 6.5)	0.95
RAminVol	5.6	(4.5 to 6.7)	0.97	6.9	(5.4 to 8.3)	0.94
RAEI	9.3	(7.4 to 11.3)	0.96	11.0	(8.8 to 13.5)	0.95

CONCLUSIONS

In this cohort of chronic cardiac patients, we found that RAEI was more accurate than IVC assessment for the noninvasive estimation of RAP with echocardiography.

REVIEW STATEMENT

Given her role as *JASE* Editor-in-Chief, Patricia A. Pellikka, MD, and given his role as *JASE* Associate Editor, Luigi Paolo Badano, MD, PhD, had no involvement in the peer review of this article and have no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to guest editor William R. Miranda, MD.

CONFLICTS OF INTEREST

None.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found at https://doi.org/10.1016/j.echo.2025.09.005.

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