ORIGINAL ARTICLE

Prediction of Right Atrial Pressure from Inferior Vena Cava Parameters Derived by Three-Dimensional Echocardiography

Pantitra Pipatsawadwut, MD[1], Kamol Udol, MD, MSc[2], Decho Jakrapanichakul, MD[1]

[1] Division of Cardiology, Department of Medicine, Faculty of Medicine, Siriraj Hospital, Mahidol University, Bangkok, Thailand; [2] Division of Cardiovascular and Metabolic Disease Prevention, Department of Preventive and Social Medicine, Faculty of Medicine, Siriraj Hospital, Mahidol University, Bangkok, Thailand

Background: Right atrial pressure (RAP) is crucial for pulmonary pressure estimation by echocardiography, particularly in the assessment of pulmonary hypertension.

Objective: To evaluate the correlation between RAP measured by right heart catheterization and parameters derived from three-dimensional (3D) echocardiographic imaging of the inferior vena cava (IVC), and to develop an equation to predict RAP from these IVC parameters.

Materials and Methods: Patients scheduled for right heart catheterization or electrophysiologic study in the cardiac catheterization laboratory of the Division of Cardiology, Department of Medicine, Faculty of Medicine, Siriraj Hospital, Mahidol University, Bangkok, Thailand, between October 2019 and February 2020 were prospectively enrolled. RAP was measured invasively via right heart catheterization. Two- and three-dimensional echocardiography were performed to acquire IVC images. The IVC parameters of interest included the maximal and minimal diameters of the longitudinal IVC, cross-sectional dimensions obtained from multiplanar 3D image analysis, and the collapsibility index.

Results: Seventy-four patients, with a mean age of 50 years, were included in the study. Preexisting cardiac conditions included valvular heart disease in 45.9%, congenital heart disease in 36.5%, arrhythmia in 60.8%, and coronary heart disease in 6.8%. All IVC parameters were significantly correlated with RAP (r-value range of 0.31 to 0.67). The minimal cross-sectional area of the 3D IVC (IVC3DminCSA) showed the strongest correlation with RAP ($r=0.67$, $p<0.001$). The validated equation for estimating RAP was RAP = 5.57 + (2.10 × IVC3DminCSA).

Conclusion: Predicting RAP using the IVC3DminCSA is a novel parameter that can mitigate the translational effects of respiration and facilitate more accurate, earlier detection of pulmonary hypertension.

Keywords: Prediction; Right atrial pressure; Three-dimensional echocardiography; Inferior vena cava; Parameters

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Right atrial pressure (RAP) is essential for calculating right heart pressure by echocardiography. The reliability of pulmonary pressure depends on the precise determination of RAP. The American Society of Echocardiography (ASE) in 2010 published guidelines for the echocardiographic assessment of the right heart in adults, providing a scheme using two-dimensional (2D) inferior vena cava (IVC) diameter in longitudinal view and the IVC collapsibility index (IVCCI) for estimation of RAP(1). The authors' previous research investigated the relationship between IVC diameter and mean RAP. The findings indicated that the minimal IVC diameter showed a superior correlation with the mean RAP compared to the IVCCI, and a formula to predict mean RAP based on the minimal IVC diameter was derived(2). The authors integrated their predicted RAP to downgrade or upgrade the RAP obtained according to the ASE guideline to a lower or higher value in their echocardiography laboratory. It was later noted that the 2D IVC diameter was occasionally measured smaller during inspiration due to the translational effects of respiration, potentially leading to inaccurate RAP assessment. To mitigate this limitation, the authors proposed that measuring the cross-sectional area (CSA) of the IVC, which should not be affected by translational effects, would

Correspondence to:

Jakrapanichakul D.

Division of Cardiology, Department of Medicine, Faculty of Medicine, Siriraj Hospital, Mahidol University, 2 Wanglang Road, Bangkoknoi, Bangkok 10700, Thailand.

Phone: +66-2-4196104

Email: decho.jak@mahidol.ac.th

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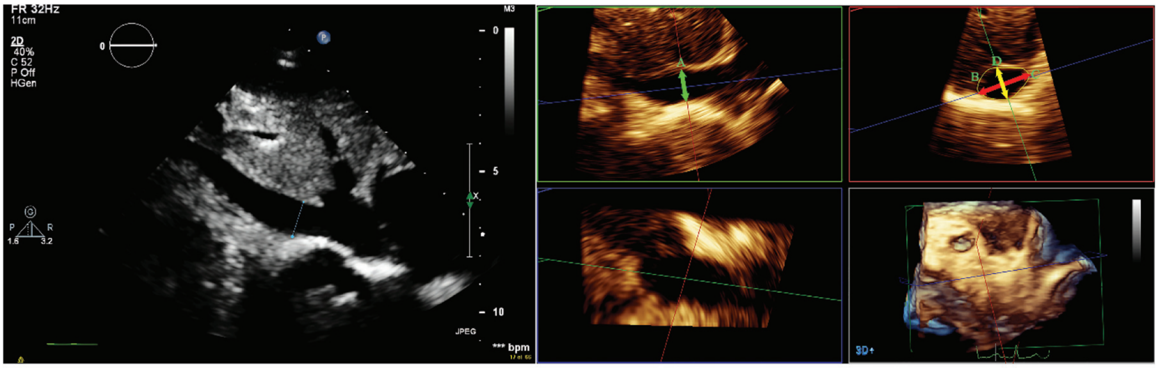

(1) (2)

Figure 1. Images of the inferior vena cava (IVC). The IVC parameters were measured approximately 2-3 cm from the right atrium to the IVC junction. (1) 2D image of longitudinal IVC. The 2D length measurement tool in ISCV measured the minimum (IVC2Dmin) and maximum (IVC2Dmax) diameters. (2) Multiplanar analysis of the 3D IVC image. The green frame represents the IVC in a longitudinal view, while the red frame shows its cross-sectional view. (A) Diameter of the longitudinal IVC, (B) Cross-sectional area, (C) Major diameter of the cross-sectional area, (D) Minor diameter of the cross-sectional area.

offer a more accurate IVC size for predicting RAP. Therefore, three-dimensional (3D) echocardiography was employed to evaluate CSA of the IVC.

The present study aimed to examine the correlation between RAP obtained from right heart catheterization and the parameters derived from 3D imaging of the IVC and formulate an equation for predicting RAP.

Materials and Methods

Population

The study prospectively included 74 consecutive patients, aged 18 and older, who were scheduled for either right heart catheterization or electrophysiologic study for various clinical indications between October 2019 and February 2020 at the cardiac catheterization laboratory of the Division of Cardiology, Department of Medicine, Faculty of Medicine, Siriraj Hospital, Mahidol University, Bangkok, Thailand. RAP was routinely done during an electrophysiologic study. Patients with pregnancy, abdominal compartment syndrome, post-heart transplantation, and those who required invasive or non-invasive ventilation were excluded. The Siriraj Institutional Review Board (SIRB) approved the present research protocol, certificate approval number 349/2562(EC3), and written informed consent was obtained from each participant. The study adhered to the 1964 Declaration of Helsinki principles and subsequent amendments.

Study design

All patients fasted for at least eight hours before their scheduled procedure, as outlined in the preprocedural cardiac catheterization protocol. The operators performing right heart catheterization were blinded to the IVC parameter measurements. In order to have RAP data from cardiac catheterization and echocardiogram less affected by the volume status of the patient, the 2D and 3D images of the IVC were acquired within six hours before or after the invasive measurement of RAP from the subcostal long-axis window during quiet respiration without sniffing, using a Philips iE33 or Philips CVx 3D system with an X5-1 probe. The 3D images were acquired with 3D zoom mode, placing the elevation plane in the center. All echocardiographic data were stored in the IntelliSpace Cardiovascular System (ISCV) version 2.3 (Philips NV, Eindhoven, the Netherlands).

Inferior vena cava measurements

IVC parameters were measured offline using a 2D length measurement tool and Philips QLAB software in ISCV. The IVC size was measured at 2 to 3 cm from the right atrium to the IVC junction.

The 2D length measurement tool in ISCV measured the minimum (IVC2Dmin) and maximum (IVC2Dmax) diameters of the longitudinal IVC from 2D images as shown in Figure 1, left panel.

The 3D images of the IVC were analyzed using multiplanar analysis in the QLAB program, as shown in Figure 1, right panel. Minimal (IVC3DminDiam) and maximal (IVC3DmaxDiam) diameters in the longitudinal plane and dimensions of IVC CSAs were measured. The measurements of the IVC CSA included the major axis at maximum (IVC3DmaxMajor) and minimum (IVC3DminMajor) phases, the minor axis at maximum (IVC3DmaxMinor) and minimum (IVC3DminMinor) phases, and the CSA at its minimum (IVC3DminCSA) and maximum (IVC3DmaxCSA). The IVCCI, defined as the percent decrease in the diameter of the IVC, was calculated from all the IVC parameters.

Right atrial pressure measurements

RAP was measured using a Swan-Ganz catheter (Edwards Lifesciences, Irvine, CA, USA) during right heart catheterization or before an electrophysiologic study. The data had been recorded as digitized mean RAP.

Statistical analysis

Continuous variables were presented as mean ± standard deviation (SD), and categorical variables were given as numbers and percentages. Pearson's correlation coefficient (r) was used to evaluate the correlation between RAP and each IVC parameter. With a power of 90% at a 2-sided significance level of 0.05, the authors required at least 62 subjects to demonstrate a correlation between RAP and each IVC parameter with a Pearson's correlation coefficient of at least 0.4 based on the null hypothesis that there was no correlation between RAP and each IVC parameter[3].

The equation to predict RAP from IVC parameters was developed using stepwise multiple linear regression analysis, and all IVC parameters derived from 2D and 3D images were included in the model. The equation was internally validated for optimism and overfitting by the bootstrap resampling method using the validation function in the Regression Modeling Strategies package of R software (the R Foundation for Statistical Computing, Vienna, Austria). Bootstrap resampling was repeated 400 times to estimate the optimism, which was then used to adjust the original model to obtain the final model. The agreement between measured RAP from catheterization and echocardiographic-derived RAP was evaluated with the Bland-Altman method[4].

The area under the receiver operating characteristic (ROC) curve was used to evaluate the ability of the final model to discriminate between subjects with RAP greater than 10 mmHg and those with RAP of 10 mmHg or less. The authors estimated the sensitivity and specificity of the final model at various cut-off points for predicting RAP >10 mmHg to determine the most appropriate cut-off point.

Table 1. Baseline characteristics and procedures (n=74)

Characteristics and procedures	
Age (years); mean±SD	50±20
Female sex; n (%)	50 (67.6)
Weight (kg); mean±SD	65±16
Height (cm); mean±SD	160±9
Body surface area (m^2); mean±SD	1.68±0.24
Underlying disease; n (%)	
Valvular heart disease	34 (45.9)
Arrhythmia	45 (60.8)
Congenital heart disease	27 (36.5)
Coronary heart disease	5 (6.8)
Hypertension	21 (28.4)
Diabetes mellitus	13 (17.6)
Chronic kidney disease	6 (8.1)
Procedure; n (%)	
Right heart catheterization	35 (47.3)
Electrophysiologic study	39 (52.7)
Time between RAP measurement and echocardiography (minutes); mean±SD	93±64

SD=standard deviation; RAP=right atrial pressure

Results

Table 1 showed the baseline characteristics and procedures performed in the 74 study patients. The mean age of patients was 50 years, and 67.6% were female. Preexisting cardiac conditions included valvular heart disease in 45.9%, congenital heart disease in 36.5%, arrhythmia in 60.8%, and coronary heart disease in 6.8%. The mean duration between RAP measurement and echocardiography was 93 minutes.

The mean RAP was 8.8±4.2 mmHg (Table 2). All IVC echocardiographic parameters were significantly correlated with RAP, with correlation coefficients ranging from 0.31 to 0.67 (Table 3). The minimal cross-sectional area of the 3D IVC (IVC3DminCSA) was most strongly correlated with RAP (r=0.67, p<0.001).

2D-IVC and RAP

Both IVC2Dmin and IVC2Dmax were significantly correlated with RAP. However, the correlation with IVC2Dmin was stronger (r=0.629) than with IVC2Dmax (r=0.600). The IVCCI of longitudinal 2D IVC diameter had an r-value of –0.418 (Table 3). Using stepwise multiple linear regression analysis that included IVC2Dmin and IVC2Dmax in the model, only IVC2Dmin was independently correlated with RAP. The derived equation to predict RAP by 2D image is as

Table 2. RAP and echocardiographic parameters of IVC

Parameters	Mean±SD
RAP (mmHg)	8.8±4.2
2D IVC	
IVC2Dmin (cm)	1.04±0.56
IVC2Dmax (cm)	1.56±0.54
3D IVC	
IVC3DminDiam (cm)	1.11±0.60
IVC3DmaxDiam (cm)	1.64±0.58
Minimal cross-sectional diameter (cm)	
• IVC3DminMajor	1.65±0.73
• IVC3DminMinor	0.97±0.54
Maximal cross-sectional diameter (cm)	
• IVC3DmaxMajor	2.22±0.67
• IVC3DmaxMinor	1.45±0.52
IVC3DminCSA (cm^2)	1.56±1.40
IVC3DmaxCSA (cm^2)	2.85±1.62

SD=standard deviation; RAP=right atrial pressure; IVC=inferior vena cava

follows: RAP = 3.84 + (4.80 × IVC2Dmin) (r^2=0.395) (Figure 2A).

3D-IVC and RAP

The IVC3DminCSA had the strongest correlation with RAP (r=0.670, p<0.001), and the mean IVC3DminCSA was 1.56±1.40 cm^2. The IVCCI of 3D CSA had an r-value of –0.448, p<0.001. The parameter with the lowest correlation with RAP was the IVCCI of the diameter in the minor axis of the 3D CSA (r=0.305, p=0.008) (Table 3). Using stepwise multiple linear regression with all 2D and 3D derived IVC parameters included in the model, only IVC3DminCSA was independently correlated with RAP. The derived equation to predict RAP by 3DE is as follows: RAP = 5.70 + (2.02 × IVC3DminCSA) (r^2=0.449) (Figure 2B).

Internal validation of the derived equation

The original equation obtained from the stepwise multiple linear regression analysis was internally validated for optimism and overfitting using the bootstrap resampling method with 400 repetitions. After correction for optimism, the final equation was RAP = 5.57 + (2.10 × IVC3DminCSA) (r^2=0.427) (Figure 3).

The Bland-Altman analysis compared the measured RAP from catheterization to the echocardiographic-derived RAP. The analysis showed satisfactory limits of agreement, with a mean difference of –0.006±3.15 mmHg and limits of agreement of ±6.17 mmHg (Figure 4).

Table 3. Correlation between RAP and echocardiographic parameters of IVC

	Correlation coefficient (r) (95% CI)	p-value
2D-IVC		
IVC2Dmin	0.629 (0.468 to 0.750)	<0.001
IVC2Dmax	0.600 (0.431 to 0.729)	<0.001
Collapsibility index, diameter of longitudinal 2D-IVC	–0.418 (–0.590 to –0.210)	<0.001
3D-IVC		
IVC3DminDiam	0.591 (0.419 to 0.722)	<0.001
IVC3DmaxDiam	0.587 (0.414 to 0.719)	<0.001
Minimal cross-sectional diameter		
• IVC3DminMajor	0.588 (0.415 to 0.720)	<0.001
• IVC3DminMinor	0.603 (0.434 to 0.731)	<0.001
Maximal cross-sectional diameter		
• IVC3DminMajor	0.458 (0.256 to 0.621)	<0.001
• IVC3DmaxMinor	0.573 (0.396 to 0.709)	<0.001
IVC3DminCSA	0.670 (0.521 to 0.779)	<0.001
IVC3DmaxCSA	0.583 (0.409 to 0.716)	<0.001
Collapsibility index, diameter of longitudinal 3D-IVC	–0.341 (–0.528 to –0.122)	0.003
Collapsibility index, 3D cross-sectional diameter, major axis	–0.322 (–0.513 to –0.101)	0.005
Collapsibility index, 3D cross-sectional diameter, minor axis	–0.305 (–0.499 to –0.082)	0.008
Collapsibility index, 3D cross-sectional area	–0.448 (–0.614 to –0.245)	<0.001

CI=confidence interval; IVC=inferior vena cava

p<0.05, statistical significance

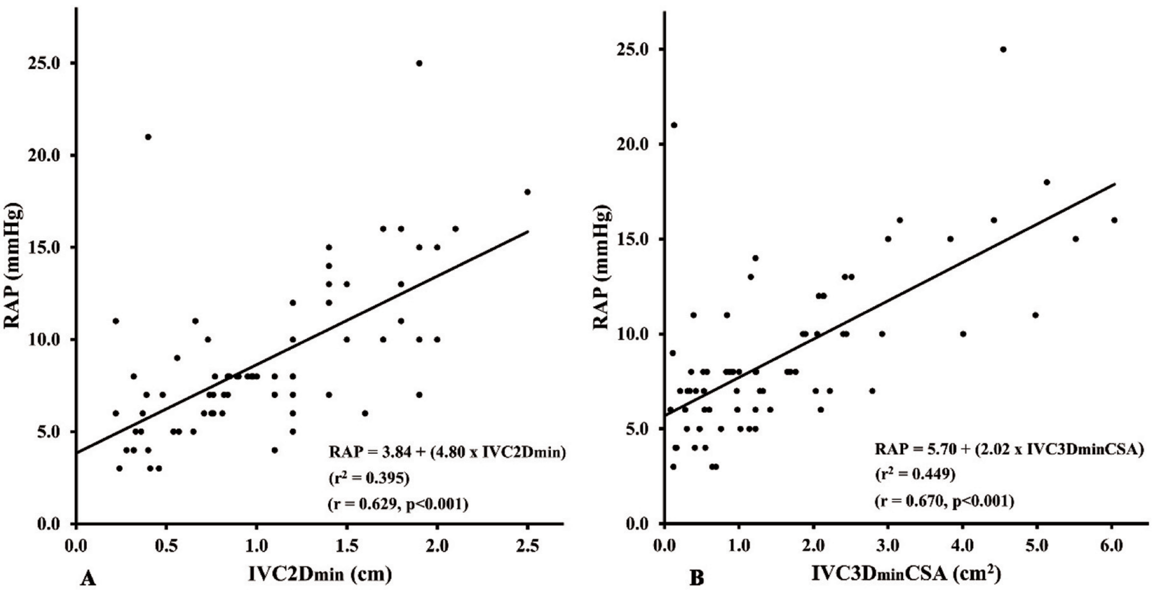

Figure 2. Linear regression analysis and derived equation between RAP and 2D minimal diameter (IVC2Dmin) (r^2=0.395) (A), and minimal cross-sectional area of 3D IVC (IVC3DminCSA) (r^2=0.449) (B).

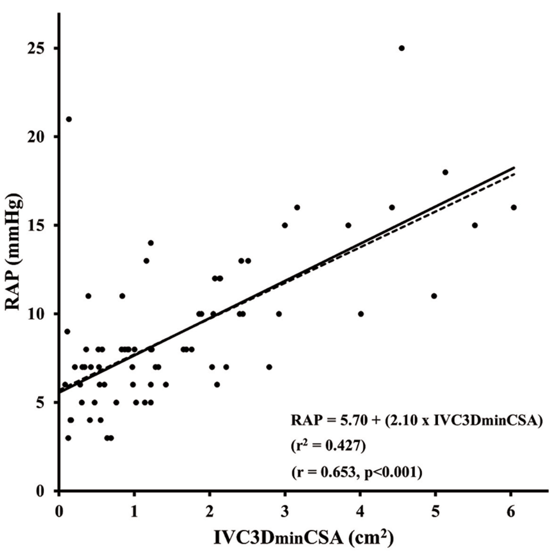

Figure 3. Linear regression analysis of RAP and 3D minimal cross-sectional area (IVC3DminCSA). After being internally validated for optimism and overfitting using the bootstrap resampling method with 400 repetitions, the linear regression and derived equation are given as predicted RAP = 5.70 + (2.1 × IVC3DminCSA) with an r^2 of 0.427. The dashed line represents the original equation before adjusting for optimism, and the solid line represents the final equation.

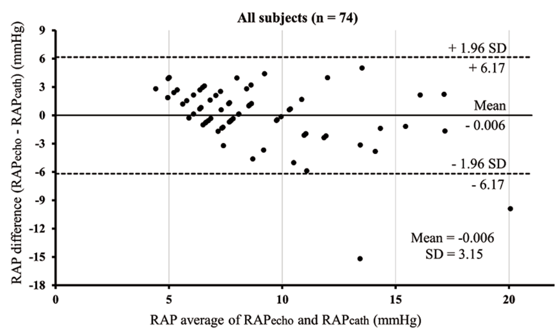

Figure 4. Bland-Altman analysis shows the limits of agreement between RAP by echocardiography and catheterization. The mean difference is –0.006±3.15 mmHg, and the limits of agreement are ±6.17 mmHg.

RAPecho: right atrial pressure predicted by echocardiography, RAPcath: right atrial pressure measured by catheterization

Discriminative ability of the final model

The final model was evaluated for its ability to discriminate between subjects with RAP greater than 10 mmHg and those with RAP of 10 mmHg or less using a receiver-operating characteristic (ROC) curve (Figure 5). The area under the curve was 0.81 [95% confidence interval (CI) 0.68 to 0.95]. Various cut-off values for predicting RAP using the final model and their corresponding IVC3DminCSA values demonstrate different sensitivities and specificities for predicting elevated RAP at RAP greater than 10 mmHg (Table 4). The cut-off value of greater than 9.89 mmHg for RAP prediction, which corresponded with the IVC3DminCSA value of greater than 2.06 cm^2, was determined to be the most appropriate cut-off for predicting elevated RAP at RAP greater than 10 mmHg, with a sensitivity of 73.7% and a specificity of 87.3% (Table 4, Figure 5).

Table 4. Sensitivity and specificity of various cut-off values for predicting RAP and their corresponding IVC3DminCSA values for predicting elevated RAP (RAP >10 mmHg)

Elevated RAP prediction values (mmHg)	IVC3DminCSA cut-off values (cm^2)	Sensitivity (%)	Specificity (%)
6.36	0.38	94.7	21.8
7.32	0.84	89.5	45.5
7.98	1.15	84.2	61.8
9.89	2.06	73.7	87.3
10.01	2.12	68.4	89.1
10.63	2.41	57.9	92.7
10.77	2.48	52.6	94.5
12.04	3.08	42.1	98.2
13.81	3.93	31.6	98.2

RAP=right atrial pressure

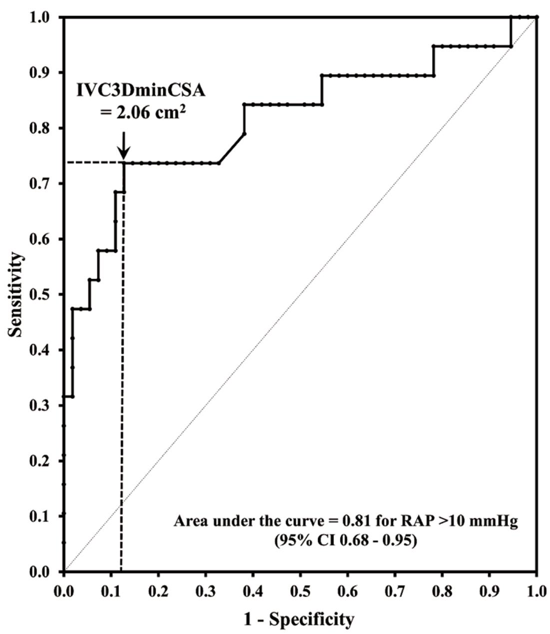

Figure 5. Receiver-operating characteristics curve. A minimal cross-sectional area of IVC (IVC3DminCSA) value of >2.06 cm^2 was determined to be the most appropriate cut-off for predicting elevated RAP (RAP >10 mmHg) with a sensitivity of 73.7% and a specificity of 87.3% (area under the curve 0.81).

Discussion

Simonson & Schiller[5] demonstrated that IVC diameter change during respiration can approximate the mean RAP. The IVC segment most responsive to respiration is 5 to 30 mm from the right atrium and the IVC junction. The minimal IVC diameter is related to the mean RAP with a good correlation (r=0.56). Kircher et al.[6] later demonstrated that the IVCCI best correlates (r=0.75) with RAP. The 2010 ASE[1] guidelines for the echocardiographic assessment of the right heart in adults provided a scheme based on IVCCI for estimating RAP. The previous study on the correlation between IVC diameter and mean RAP demonstrated that minimal IVC diameter had a stronger correlation (r=0.76, p<0.001) compared to the IVCCI (r=0.68, p<0.001)[2]. The authors derived the equation RAP = 4.8 + (4.6 × minimal IVC diameter in cm) and integrated it into the echocardiography laboratory as an index to downgrade or upgrade the predicted RAP obtained according to the ASE guideline to a lower or higher value. The authors observed that the translational effect of respiration caused inaccuracies in IVC measurements in certain patients, leading to incorrect RAP estimates. Patel et al.[7] demonstrated the benefit of 3D echocardiography of the right atrial volume index for predicting RAP in acutely decompensated heart failure. Huguet et al.[8] studied the IVCCI to assess central venous pressure (CVP) in patients with cardiogenic shock using 2D diameters and 3D CSAs of IVC. They demonstrated that IVCCI derived from 3D CSA is reproducible and more accurate (r=–0.82) for evaluating CVP than 2D diameters (r=–0.69).

The authors hypothesized that utilizing the CSA or diameters derived from 3D data of the IVC would mitigate the translational effect of respiration. The authors prospectively enrolled patients with a mean interval of 93±64 minutes between catheterization and echocardiography. Through multiplanar analysis of the 3D images of the IVC, we obtained both longitudinal and cross-sectional views of the IVC. All IVC parameters were analyzed. The IVCCI of longitudinal 2D IVC diameter and IVCCI of 3D CSA are inversely correlated with RAP, with r-values of –0.418 (95% CI –0.590 to –0.210), and –0.448 (95% CI –0.614 to –0.245), respectively. The IVCCI of 3D IVC diameters performed poorly, with r values ranging from –0.305 to –0.341 and p-values between 0.003 and 0.008. The IVC3DminCSA is the highest correlation (r=0.670, 95% CI 0.521 to 0.779, p<0.001) and higher than the IVCCI of 3D CSA (Table 3).

IVC2Dmin and IVC3DminCSA correlate more with measured RAP from catheterization than other IVC parameters. The authors analyzed linear regression and derived equations from both variables (Figure 2). IVC2Dmin had a good correlation with the RAP (r=0.629) and better than IVCCI of longitudinal 2D IVC diameter (r=–0.418). The IVC3DminCSA had the strongest correlation with and better predictive power for the RAP (r^2=0.449). The equation was internally validated for optimism and overfitting using the bootstrap resampling method with 400 repetitions. The final equation was RAP = 5.57 + (2.10 × IVC3DminCSA) (r^2=0.427) (Figure 3). The 3D CSA of the IVC shows the best correlation with RAP and overcomes the translational effect of respiration, but the r-value indicates only moderate correlation.

Bland-Altman analysis shows good agreement between RAP by echocardiography and catheterization. The mean difference is –0.006±3.15 mmHg, and the limits of agreement are ±6.17 mmHg (Figure 4), indicating that the range of discrepancy is 6.17 mmHg. Using the final formula as a fine-tuning parameter of the RAP predicted according to the ASE guideline scheme will bring the value closer to the RAP measured by right heart catheterization without the translational effect of respiration.

From ROC curve analysis, the IVC3DminCSA value greater than 2.06 cm^2 is the most appropriate cut-off for predicting elevated RAP at RAP greater than 10 mmHg, with a sensitivity of 73.7% and a specificity of 87.3% (Figure 4).

The present study demonstrates that using the CSA of the IVC by 3D echocardiography is simple and feasible, more accurately predicts RAP, and overcomes the translational effect of respiration.

Abbas et al.[9] demonstrated that the mean pulmonary pressure can be directly derived from echocardiography by calculation from peak pulmonary regurgitation velocity and RAP. Improved RAP determination increases the accuracy of mean pulmonary pressure by echocardiography, which is crucial for diagnosing pulmonary hypertension. Abbas et al.[10,11] also demonstrated that pulmonary vascular resistance can be obtained by echocardiography. Utilizing both parameters is beneficial for identifying patients with pulmonary hypertension who should undergo an extensive workup for pulmonary arterial hypertension. The authors can reduce the discrepancy between pulmonary pressure determined by echocardiography and right heart catheterization, and when combined with pulmonary vascular resistance, increase our awareness of patients with combined pre- and post-capillary pulmonary hypertension during screening for this condition.

Strength and limitation

The 2D and 3D IVC images were acquired in the supine position with quiet respiration without sniffing. This well represents a normal physiological state and is easy to apply in non-cooperative patients. Although minimal CSA from 3D echocardiography had the strongest correlation with RAP, RAP prediction equations were developed for 2D and 3D techniques for improved applicability, depending on equipment availability and clinician preference.

The present study also has notable limitations. Because of technical difficulties in the catheterization laboratory, IVC images could not be acquired simultaneously with RAP measurements. The accuracy of IVC measurements in small patients was sometimes compromised. Since this study did not include critically ill patients and fewer patients with very high RAP, such as severe pulmonary hypertension with right heart failure, using the derived equation in critically ill patients must be validated in future research. Most of the authors' RAP data ranged between 5 and 15 mmHg, suggesting that the accuracy of the corrected equation may be greater in patients with RAP of 10 mmHg or less. More research may be needed on patients with severe tricuspid regurgitation and right-sided heart failure.

Conclusion

The best predictor of RAP from 2D or 3D echocardiography is the IVC3DminCSA, using the formula RAP = 5.57 + (2.10 × IVC3DminCSA). This novel parameter can reduce the translational effects of respiration on IVC dimension measurements and facilitate early detection of pulmonary hypertension, whether from heart failure or pulmonary arterial hypertension.

What is already known about this topic?

The 2D IVC diameter in longitudinal view and the IVCCI were used to estimate RAP according to the ASE guideline.

What does this study add?

In Thai patients, the minimal size of IVC is better correlated with RAP than the collapsibility index, either IVC diameter or CSA. The best predictor of RAP was the IVC3DminCSA, using the formula RAP = 5.57 + (2.10 × IVC3DminCSA). Physicians can use the IVC3DminCSA as a novel RAP predictor in Thai patients or as an index to downgrade or upgrade the predicted RAP obtained according to the ASE guideline to a lower or higher value.

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Authors' contribution

PP recruited patients, collected data, and prepared data for analysis. KU provided statistical analysis and interpretation. DJ provided the research concept and study design.

Data availability statement

The datasets analyzed during the current study are not publicly available due to hospital privacy policies and ethical restrictions regarding patient confidentiality but are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

The Siriraj Institutional Review Board (SIRB) approved the present research protocol, certificate approval number 349/2562(EC3), and written informed consent was obtained from each participant. The study adhered to the 1964 Declaration of Helsinki principles and subsequent amendments.

Use of artificial intelligence

No artificial intelligence (AI) tools were used in any part of the research process.

Funding disclosure

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Conflicts of interest

All authors declare no personal or professional conflicts of interest relating to this study.

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