Clinical utility of superior vena cava flow velocity waveform measured from the subcostal window for estimating right atrial pressure[1]

Michito Murayama, MS[a,b], Sanae Kaga, PhD[c]*, Kazunori Okada, PhD[c], Hiroyuki Iwano, MD, PhD[d,e], Masahiro Nakabachi, MS[a], Shinobu Yokoyama[a], Hisao Nishino[a], Shingo Tsujinaga, MD, PhD[d], Yasuyuki Chiba, MD[d], Suguru Ishizaka, MD[d], Ko Motoi, MD[d], Kiwamu Kamiya, MD, PhD[d], Mutsumi Nishida, PhD[a], Toshiyuki Nagai, MD, PhD[d], Toshihisa Anzai, MD, PhD[d]

[a] Diagnostic Center for Sonography, Hokkaido University Hospital, N14, W5, Kita-ku, Sapporo 060-8648, Japan

[b] Graduate School of Health Sciences, Hokkaido University, N12, W5, Kita-ku, Sapporo 060-0812, Japan

[c] Faculty of Health Sciences, Hokkaido University, N12, W5, Kita-ku, Sapporo 060-0812, Japan

[d] Department of Cardiovascular Medicine, Faculty of Medicine and Graduate School of Medicine, Hokkaido University, N15, W7, Kita-ku, Sapporo 060-8638, Japan

[e] Division of Cardiology, Hakodate Municipal Hospital, 1-10-1, Minatocho, Hakodate 041-8680, Japan

***Corresponding author:**

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[1] Abbreviations: RAP = Right atrial pressure; IVC = Inferior vena cava; SVC = Superior vena cava; ASE = American Society of Echocardiography; LV = Left ventricular; TR = Tricuspid regurgitation; RV = Right ventricular; Tricuspid E = Peak early-diastolic tricuspid inflow velocity; Tricuspid E/A = Ratio of tricuspid E to peak late-diastolic tricuspid inflow velocity; Tricuspid E/e′ = Ratio of tricuspid E to early-diastolic tricuspid annular velocity; RAP grading = Estimated RAP using IVC parameters according to the ASE guidelines; SVC-S = Peak systolic forward SVC flow; SVC-D = Peak diastolic forward SVC flow; SVC-S/D = Ratio of peak systolic to diastolic forward SVC flows

Sanae Kaga, PhD

Faculty of Health Sciences, Hokkaido University, N12, W5, Kita-ku, Sapporo 060-0812, Japan; Tel: +81-11-706-3405; Fax: +81-11-706-3405; Email: sanae@med.hokudai.ac.jp

Brief title: SVC flow from subcostal window for RAP estimation

ABSTRACT

Background: Superior vena cava (SVC) flow velocity waveform from the supraclavicular window reflects the right atrial pressure (RAP) status. Recent guidelines have stated that the subcostal window is an alternative view for recording SVC flow, but the validity of this approach remains unclear. This study aimed to determine the usefulness of SVC flow evaluation from the subcostal window for estimating RAP.

Methods: Differences in SVC flow characteristics between opposite approaches were examined in 38 healthy adults. In 115 patients with cardiovascular diseases who underwent cardiac catheterization and echocardiography within 48 h, the ratio of peak systolic to diastolic forward SVC flows was measured (SVC-S/D), and the diagnostic ability of SVC-S/D for elevated RAP was tested. A validation cohort was conducted to confirm the diagnostic ability of SVC-S/D in 48 patients who underwent both cardiac catheterization and echocardiography within 24 h. In 59 patients of derivation and validation cohorts, the relationship between SVC flow and RAP was compared between the opposite windows.

Results: Both systolic and diastolic SVC flow velocities were higher in the subcostal than in the

supraclavicular approach, and effect of position change on the subcostal SVC-S/D was smaller than that on the supraclavicular SVC-S/D in healthy adults. Measurement of SVC-S/D from the subcostal window was feasible in 98 patients (85%). RAP was inversely correlated with SVC-S/D (r=-0.50, P<.001), and was an independent determinant of SVC-S/D after the adjustment for right ventricular systolic function (β=-0.48, P<.001). A cutoff value of 1.9 for SVC-S/D showed 85% sensitivity and 74% specificity in identifying elevated RAP. Additionally, SVC-S/D showed an incremental diagnostic value combined with inferior vena cava size and collapsibility (P=.006). When the cutoff value, SVC-S/D<1.9, was applied to the validation cohort, it showed an acceptable accuracy of 72%, and an incremental diagnostic value combined with inferior vena cava parameters (P=.033). SVC-S/D from the subcostal window correlated better with RAP than that from the supraclavicular window (P<.001, Meng's test).

Conclusions: Measurement of SVC flow velocity from the subcostal window was feasible, and SVC-S/D from the subcostal window could be an additive parameter for estimating RAP.

Key words: echocardiography, right atrial pressure, right atrial pressure estimation, superior vena cava, subcostal approach, supraclavicular approach

INTRODUCTION

Right atrial pressure (RAP) provides important information about right-sided cardiac pressure loading, which is a critical component for optimal patient care.[1] In addition, RAP is the most important hemodynamic factor for systemic congestion,[2-4] and its elevation is an important determinant of poor clinical outcomes in patients with cardiovascular diseases.[2,3,5-9] Echocardiography of the inferior vena cava (IVC) and its respiratory changes is used to non-invasively estimate the RAP .[10] However, previous studies have shown limited accuracy of the IVC indices.[8,11]

Several studies have reported that the superior vena cava (SVC) flow velocity waveform evaluated from the right supraclavicular or suprasternal windows reflects the RAP.[12-18] However, the measurement of the SVC flow using this approach is not often used in daily practice, owing to its cumbersome nature. Recently, the use of the subcostal window was recommended in the American Society of Echocardiography (ASE) guidelines,[19] but the validity of the subcostal window approach for recording the SVC flow remains untested. Thus, this study aimed to: (1) investigate the differences in SVC flow characteristics between the subcostal and supraclavicular measurement approaches in healthy volunteers, and (2) evaluate the clinical utility of SVC flow measurement using the subcostal window to estimate RAP in patients with cardiovascular disease.

METHODS

Study protocols

Protocol 1 (basic investigations in healthy volunteers)

We recruited 38 adult healthy volunteers (35±12 years old, men, n=26) who had no clinical and echocardiographic evidence of cardiovascular disease. In this cohort, we investigated the differences in SVC flow characteristics between the subcostal and the right supraclavicular measurement approaches and tested the reproducibility of SVC flow evaluation from both windows.

Protocol 2 (detection of elevated RAP)

Derivation cohort

First, we prospectively enrolled 140 consecutive hospitalized patients who were scheduled for right-heart catheterization and echocardiography within 48 h between February 2018 and October 2020 in Hokkaido University Hospital. All patients underwent a standard echocardiogram performed by a single sonographer (M.M.) at our echocardiography laboratory. There were no patients who needed assistance with ventilation, such as BiPAP, or were intubated and mechanically ventilated. We excluded patients with mechanical circulatory support devices (n=13), those who had undergone a heart transplant (n=10), and those with potential hemodynamic changes (diuretic or vasodilator dose change and dialysis or hemofiltration) between cardiac catheterization and echocardiography (n=2). Ultimately, 115 patients were eligible for SVC flow evaluation for RAP estimation (**Supplemental Figure 1**).

Validation cohort

Second, we prospectively enrolled 67 consecutive adult patients who were scheduled for right-

heart catheterization and echocardiography within 24 h between November 2020 and September 2021. Patients were excluded if they met the exclusion criteria mentioned above (n=19). Ultimately, 48 patients were included in the final analysis to validate the SVC flow evaluation for RAP estimation (**Supplemental Figure 1**).

In 59 patients of Protocol 2 in whom the acquisition of SVC flow from both right supraclavicular and subcostal windows was successful, the relationship between the SVC flow and invasive RAP was compared from two opposite windows (supraclavicular vs subcostal) as a sub-analysis.

Protocol 1 was approved by the Ethics Committee of the Faculty of Health Sciences in Hokkaido University, and all volunteers provided written informed consent. Protocol 2 was approved by the Institutional Review Board of Hokkaido University Hospital (No. 019-0190). Since all examinations were performed within the scope of medical care, an opportunity to opt-out was given to each participant through a published disclosure document on the website of the institute and the requirement for informed consent was waived.

Echocardiography

Transthoracic echocardiography was performed using commercially available ultrasound machines: an Artida system equipped with a 3.0 MHz probe (Canon Medical Systems, Otawara, Japan); a Vivid E9 ultrasound system with an M5S probe (GE Healthcare, Chicago, Illinois, USA); an iE33 ultrasound system with an S5-1 probe (Philips Medical Systems, Andover, Massachusetts, USA); an

ACUSON SC2000 prime with a 4V1c probe (Siemens Healthineers, Erlangen, Germany); or a Prosound F-75 system with a 2.5 MHz probe (Hitachi Ltd., Tokyo, Japan). A comprehensive echocardiographic examination was performed in line with the ASE guidelines to evaluate the cardiac chamber morphology and left ventricular (LV) function.[20] The severity of valve regurgitation was determined according to the guidelines,[21] and significant tricuspid regurgitation (TR) was defined as more than moderate TR.[21] Right heart measurements were also performed according to the published ASE guidelines.[10] Basal right ventricular (RV) and mid-cavity diameter were measured at end diastole using RV-focused views, and RV systolic function was assessed based on tricuspid annular plane systolic excursion, systolic excursion velocity, and fractional area change. The ratio of peak early-diastolic tricuspid inflow velocity (tricuspid E) to peak late-diastolic tricuspid inflow velocity (tricuspid E/A) was measured using the RV modified apical four-chamber view, along with the early-diastolic peak of tricuspid annulus velocity; the ratio of tricuspid E to the tricuspid annulus velocity (tricuspid E/e′) was consequently calculated. The hepatic vein systolic filling fraction was calculated as the peak systolic wave velocity divided by the sum of peak systolic and diastolic velocities. Maximum right atrial area was measured at ventricular end systole in the apical four-chamber view. The IVC dimension and IVC respiratory changes were measured using the subcostal longitudinal image. We estimated the RAP as normal (3 mmHg) when the IVC diameter was ≤21 mm and collapsed >50%, and as high (15 mmHg) when the IVC diameter was >21 mm and collapsed <50% in line with the ASE guidelines (RAP grading).[10] In the cases where the IVC diameter and collapse

120 did not fit these criteria, RAP was classified as intermediate (8 mmHg).[10]

121 The SVC flow velocity waveform was recorded by pulsed-wave Doppler images from the
122 subcostal long-axis view (**Figure 1A**) or subcostal four-chamber view (**Figure 1B**) with the angle of the
123 transducer towards the head, and the patients in a supine position.[19] A 3- to 5-mm sample volume was
124 placed about 10 mm proximal to the junction of the right atrium and SVC. The peak systolic and diastolic
125 forward velocities of SVC flows (SVC-S and SVC-D, respectively) and the SVC-S/D ratio were measured
126 using the waveforms. For quantitative purposes, systolic flow reversal was assigned as SVC-S of 0 cm/s,
127 and SVC-S/D was calculated as 0 in line with the previous report.[22] In Protocol 1, the SVC flow was also
128 recorded from the right supraclavicular approach according to previous reports,[12,13,23] in the 45-degree
129 semi-sitting and supine positions. Echocardiographic data were acquired during a breath-hold at shallow
130 expiration or at the intermediate expiratory position under quiet respiration except for the IVC parameters.
131 In patients with atrial fibrillation, Doppler parameters were obtained from an index beat in which
132 preceding and pre-preceding RR intervals were similar.[24]

133 ***Cardiac catheterization***

134 Right-heart catheterization procedures were performed by trained physicians using 6F fluid-
135 filled balloon-tipped catheters. After calibration with the zero point at the mid-thoracic line, the catheters
136 were inserted through the internal jugular vein or the common femoral vein, and the waveforms for
137 pulmonary arterial wedge pressure, main pulmonary arterial pressure, and RAP were recorded at end

expiration. The cardiac output was measured using Fick's method in patients with severe TR or by the thermodilution method in those without TR. Pulmonary vascular resistance was calculated as (mean pulmonary arterial pressure − mean pulmonary arterial wedge pressure)/cardiac output. All measurements were obtained from three consecutive beats and the averaged values were used for final analysis. An elevated RAP was defined as a mean RAP of >8 mmHg.[2,13,22]

Statistical analysis

Continuous data were expressed as mean ± standard deviation or median (interquartile range) as appropriate. Student's t-test or Wilcoxon rank-sum test was used to compare continuous variables between the two groups. Categorical variables were presented as numbers (%) and compared using the Chi-square test or Fisher exact test, as appropriate. Parametric one-way analysis of variance with the Tukey-Kramer post hoc test was used for comparisons of catheterization-derived RAP among the different RAP grading. Relationships between two continuous variables were assessed by the linear correlation and regression analysis. A receiver operating characteristic curve analysis was performed to evaluate the ability to predict the elevation of the invasive RAP. Multiple linear regression analysis was used for assessing the associations between the SVC-S/D and invasive RAP after adjustment for several confounders, which were previously reported to influence the SVC and hepatic venous flow patterns.[14,27] Parameters with $P<.05$ in the univariable analysis were incorporated into the multivariable model to detect independent determinants of SVC-S/D. The performance of the RAP grading according to the ASE guidelines in

combination with the SVC flow in predicting elevated RAP was assessed using the c-index. Interobserver acquisition variability for SVC flow was assessed in the healthy volunteers in Protocol 1, and an intraclass correlation analysis was performed for interobserver comparison. All statistical analyses were conducted using JMP Pro 14.0.0 (SAS Institute Inc., Cary, NC, USA), and statistical significance was set at a P-value <.05.

RESULTS

Basic investigations in healthy volunteers

Difference between the subcostal and the right supraclavicular approaches

Of the 38 healthy volunteers, measurement of the SVC flow velocity was feasible in 32 subjects (84%) from the subcostal window and in all subjects (100%) from the right supraclavicular window. The supine SVC-S and D waves at expiration were significantly larger in the subcostal approach than in the supraclavicular approach (S: 57.8±14.2 vs. 41.5±9.8 cm/s, P<.001; D: 31.5±9.0 vs. 23.2±5.9 cm/s, P<.001, respectively), whereas S/D was similar in both approaches (1.9±0.7 vs. 1.9±0.7, P=.726). Although there was a significant increase in SVC-S and D in the semi-sitting position than in the supine position in the subcostal approach, S/D was not significantly affected by the position. Contrarily, in the supraclavicular approach, the semi-sitting position significantly increased the SVC-S and D, with a decreased S/D compared to that in the supine position (**Supplemental Table 1**). A representative case is shown in **Supplemental Figure 2**.

Reproducibility of SVC flow acquisition from subcostal and the right supraclavicular windows

Re-acquisition variability was tested by two observers (M.M. [>5 years' experience] and S.M. [beginner]) in the initial 18 participants of Protocol 1. In the subcostal approach, interobserver variability for SVC-S, D, and S/D showed good intraclass correlation coefficients of 0.85, 0.91, and 0.84, respectively, indicating satisfactory reproducibility of the measurement of SVC flow from the subcostal window. The supraclavicular approach also showed adequate intraclass correlation coefficients of 0.78, 0.68, and 0.80 for SVC-S, D, and S/D, respectively, but the reproducibility of SVC flow measurement was better in the subcostal approach.

Detection of elevated RAP

Derivation cohort

Patient characteristics

Of 115 patients who met the inclusion criteria, measurement of the SVC-S/D was feasible in 98 patients (85%). The characteristics of 17 patients in whom SVC flow could not be measured from the subcostal approach are summarized in **Supplemental Table 2**. These 17 patients were characterized as more frequently having the lowest quartile of body mass index ($\leq$20 kg/m^2) and higher prevalence of atrial fibrillation. The comparison between patients with normal and those with elevated RAP is presented in **Table 1**. Among the 98 participants, the mean age was 64 years, and half of the patients were men. Nonischemic dilated cardiomyopathy was the most frequently occurring cardiac disease, and one-third of

the patients presented with NYHA functional class III or IV. Pulmonary hypertension (mean pulmonary arterial pressure >20 mmHg) was observed in 48 subjects (49%) and 35–38% of the cohort showed right heart abnormalities detected based on a reduced fractional area change or enlarged RV. Significant TR was observed in 17 patients (17%).

The mean RAP was 6.0±2.3 mmHg (range: 1–22 mmHg) and 20 patients (20%) showed elevated RAP. More significant advanced remodeling of the right heart was observed in the elevated RAP group than that in the normal RAP group (**Table 1**). While the RV systolic function was similar between the groups, the elevated RAP group had a higher tricuspid E/A, larger IVC diameter, and a lower IVC respiratory changes, resulting in the higher prevalence of high RAP estimated using the IVC findings. According to the SVC flow parameters, the elevated RAP group had a significantly lower SVC-S, higher SVC-D, and lower SVC-S/D than those in the normal RAP group.

Prediction of elevated RAP

Supplemental Figure 3 illustrates the comparison of invasive RAP among the patients classified by the ASE guidelines.[10] Although the RAP was significantly higher in patients classified as elevated RAP than those in other two grades; it was comparable in patients classified as normal or intermediate RAP. Guideline-pre-specified elevated RAP findings predicted an invasive RAP of >8 mmHg with 40% sensitivity, 97% specificity, 80% positive predictive value, 86% negative predictive value, and 86% accuracy.

As shown in **Figure 2A**, the SVC-S/D was inversely correlated with invasive RAP (r=−0.50, P<.001). Moreover, invasive RAP was an independent determinant of SVC-S/D even after adjustment for potential confounders, including atrial fibrillation, RV systolic function, right atrial size, and significant TR (β=−0.48, P<.001) (**Table 2**). An optimal cut-off value of 1.9 to identify the patients with an elevated RAP was identified by receiver operating characteristic analysis. This cut off value yielded a c-index for SVC-S/D of 0.84 (95% confidence interval [CI]: 0.76–0.93) and had 85% sensitivity, 74% specificity, 46% positive predictive value, 95% negative predictive value, and 77% accuracy (Figure 2B).

Incremental diagnostic value of SVC- S/D over the guideline-recommended RAP grading

When an SVC-S/D of <1.9 was used in 49 patients whose RAP was graded as indeterminate by the ASE guidelines, it could identify a subgroup of patients with elevated RAP with a sensitivity, specificity, positive predictive value, negative predictive value, and accuracy of 63%, 78%, 36%, 91%, and 76%, respectively. The SVC-S/D showed an incremental diagnostic value when combined with RAP grading (c-index=0.72, 95% CI: 0.58–0.84 for RAP grading only, and c-index=0.86, 95% CI: 0.75–0.92 for RAP grading plus SVC-S/D, P=.006) (**Figure 3**).

Validation cohort

Of 48 patients who met the inclusion criteria, measurement of the SVC-S/D was feasible in 43 patients (90%). Among the 43 patients, one-third of the patients presented with NYHA functional class III, and no patients presented with NYHA functional class IV. The mean RAP was 5.7±3.3 mmHg (range 1–14

mmHg) and 8 patients (19%) showed elevated RAP. As shown in **Supplemental Figure 4**, the SVC-S/D ratio was inversely correlated with invasive RAP (r=−0.60, P<.001). When the SVC-S/D <1.9 performance for RAP elevation identification was tested in the validation cohort, it could identify a subgroup of patients with elevated RAP with a sensitivity, specificity, positive predictive value, negative predictive value, and accuracy of 100%, 66%, 40%, 100%, and 72%, respectively. Additionally, when the SVC-S/D was added to the RAP grading, the diagnostic value was significantly improved (**Supplemental Figure 5**).

Relationship between the SVC-S/D from the subcostal window and invasive RAP, in comparison with the right supraclavicular window

The association between SVC-S/D from both windows and invasive RAP was compared in 59 of Protocol 2 participants. Representative images of SVC flow and corresponding RAP waveforms are shown in **Figure 4.** As shown in **Figure 5**, the invasive RAP was more strongly correlated with SVC-S/D evaluated from the subcostal window than that evaluated from the supraclavicular window (r=−0.64, P<.001 vs. r=−0.28, P=.029; P<.001 by Meng's test).

DISCUSSION

Our findings can be summarized as follows: (i) the measurement of SVC flow velocities from the subcostal window was feasible, (ii) the effect of position change on the SVC-S/D ratio was less significant in the subcostal approach than in the supraclavicular approach, (iii) SVC-S/D ratio from the

246 subcostal window was inversely correlated with invasive RAP, (iv) evaluating the SVC-S/D ratio from the
247 subcostal window improved the diagnostic accuracy for RAP elevation when combined with guideline-
248 recommended RAP grading, and (v) the SVC-S/D ratio from the subcostal window correlated better with
249 RAP than that from the supraclavicular window, which is known as a conventional approach for
250 evaluating SVC flow. To the best of our knowledge, this is the first study to investigate the clinical utility
251 of SVC flow evaluated from the subcostal window. Our findings strengthen the clinical relevance of SVC
252 Doppler velocimetry in patients with cardiovascular diseases.

253 ***Echocardiographic estimation of elevated RAP***

254 Sonographic measurement of the diameter and respiratory changes in the IVC is a commonly
255 used noninvasive method for the estimation of RAP, and the current ASE guidelines recommend the
256 algorithm for categorizing RAP[10]; however, several studies reported that the RAP estimated using this
257 algorithm does not always match the invasive RAP.[8,11] Evaluation of the restrictive right-sided diastolic
258 filling pattern, tricuspid E/e′ >6, and diastolic flow predominance in the hepatic veins are recommended in
259 the cases where RAP remains indeterminate.[10] However, the diagnostic accuracy of the tricuspid E/A and
260 E/e′ for elevated RAP was limited,[25,26] possibly due to differences in the physiologic mechanism of e′ or E
261 between the left and right hearts, that is, absence of correlation between tricuspid e′ and RV relaxation and
262 the poor correlation between tricuspid E-wave velocity and RAP event after controlling for RV
263 relaxation.[25] The hepatic vein systolic filling fraction is considered to reflect the changes in RAP during a

cardiac cycle similar to that of SVC-S/D,[10,22] but previous studies failed to demonstrate its predictive value for RAP.[25] This could be due to changes in hepatic vein flow associated with parenchymal fibrosis in patients with organic hepatic disorders.[28] Incorporation of these secondary indices to refine RAP estimates did not improve IVC measurement precision.[11,25] Therefore, further investigation is required for more reliable and feasible RAP estimation methods.

SVC flow velocity waveform and RAP

The SVC flow velocities reflect changes in RAP waveforms.[12-18] At low or normal RAP, the flow profile in the SVC is biphasic with a systolic dominance.[12-15] In cases of elevated RAP, the observed SVC flow profile is a diminished systolic flow velocity with a predominant diastolic forward flow.[13,15,18] The flow velocity of SVC is usually recorded from the supraclavicular approach; however, the ASE recently proposed using the subcostal window for SVC flow evaluation.[19] However, there is a paucity of data regarding the clinical utility of SVC flow evaluation from a subcostal window; its association with invasive RAP has not been validated. In the current study, we found that it was feasible to evaluate SVC flow from the subcostal window, which was associated with the invasive RAP. Notably, patients with an SVC-S/D <1.9 were observed to have an abnormally elevated RAP with acceptable accuracy. Based on its ability to enhance the diagnostic accuracy of RAP grading (**Figure 3 and Supplemental Figure 5**), subcostal SVC-S/D is a reliable marker for abnormal RAP, especially in patients with indeterminate RAP based on IVC parameters.

Superiority of the subcostal approach over the supraclavicular approach

We observed that the SVC flow velocities in healthy individuals were higher in the subcostal approach than in the supraclavicular approach, which indicated a better Doppler incident angle in the subcostal approach, because of the greater flexibility in probe position and scanning angles and evaluation in two mutually orthogonal planes. Additionally, in the subcostal approach, the SVC flow may be recorded after the confluence of the left innominate vein and the azygos vein, which is the only major tributary vein that drains into the SVC,[17] resulting in a larger amount of blood for evaluation. Interestingly, our data showed that SVC-S/D evaluation from the subcostal window correlated better with the invasive RAP than that from the supraclavicular window (**Figure 5**). This may be because the sampling position was closer to the right atrium in the subcostal approach than the supraclavicular approach. A previous study demonstrated that central venous pressure measured within the femoral vein, which is farther away from the right atrium, is less reliable.[29] Thus, we speculated that SVC flow recorded from the subcostal window, which is closer to the right atrial, could more accurately reflect the RAP waveforms (**Supplemental Figure 6**). Another explanation could be the better reproducibility of the SVC flow acquisition from the subcostal window compared to the right supraclavicular window as shown in the result of Protocol 1, probably because the sampling position is easily and adequately visualized in the subcostal view. Moreover, the effect of position change on the SVC flow velocities was less significant in the subcostal approach than in the supraclavicular approach (**Supplemental Table 1 and Supplemental Figure 2**).

Although we could not find any clear explanation, this might have a practical advantage of using subcostal SVC-S/D for RAP estimation in every clinical setting, for example, in Fowler's position in cases of acute decompensated heart failure showing orthopnea. Further studies are necessary to understand the pathophysiological mechanisms of the SVC flow in postural changes.

Clinical applications

Our findings showed that the use of SVC flow measurement from the subcostal window improved the diagnostic accuracy of the RAP grading recommended by the ASE guidelines. Incorporating these SVC flow measurements into routine echocardiographic evaluation requires minimal additional effort and time; sonographers can measure the IVC indices from the subcostal window, and subsequently, the SVC flow velocities can be measured by tilting the probe towards the head. Our data showed that the SVC flow had an excellent negative predictive value; hence, the use of SVC flow may be an alternative to IVC parameters for RAP estimation in individuals in whom the IVC appears enlarged despite low RAP.[1] In practice, SVC flow evaluation from the subcostal window may have additional diagnostic implications in patients with indeterminate RAP results based on IVC findings.

Study limitations

There are several limitations in this study. First, the sample size was small, especially for advanced heart failure patients showing high RAP (the number of patients with RAP greater than 10 mmHg was small: only 16 (16%) patients in the derivation cohort and 6 (14%) patients in the validation

318 cohort), thereby limiting the generalizability of the findings. Further study including a wider range of RAP
319 is needed. Second, cardiac catheterization and echocardiography were not performed simultaneously. In
320 the derivation cohort, no difference was found in the heart rate (69.2±11.1 vs. 68.3±10.7 beats/min,
321 p=0.261), systolic blood pressure (109.6±16.7 vs. 112.1±18.4 mmHg, p=0.176), diastolic blood pressure
322 (63.6±12.0 vs. 65.4±11.9 mmHg, p=0.144), and the body weight (57.4±11.1 vs. 57.3±11.0 kg, p=0.232)
323 between echocardiography and right-heart catheterization. Also, in the validation cohort, there were no
324 differences in the heart rate (67.7±9.3 vs. 67.5±10.3 beats/min, p=0.846), systolic blood pressure
325 (113.9±19.7 vs. 113.0±20.5 mmHg, p=0.744), diastolic blood pressure (64.9±13.5 vs. 64.1±13.4 mmHg,
326 p=0.728), and the body weight (58.5±15.5 vs. 58.4±15.4 kg, p=0.383) between echocardiography and
327 right-heart catheterization. However, the possibility of hemodynamic alteration might not be completely
328 excluded. Third, in patients with atrial fibrillation, the application of subcostal SVC flow for evaluating
329 RAP might be limited because feasibility was not high enough in such individuals (**Supplemental Table**
330 **2**). Moreover, atrial fibrillation was a strong independent determinant of the SVC-S/D ratio (**Table 2**). In
331 patients with atrial fibrillation, one needs to interpret our findings with caution, since it is based on a small
332 number of the patients. Fourth, because in the present study there were no patients who needed assistance
333 with ventilation such as BiPAP or mechanical ventilation via intubation, it remains unknown whether the
334 subcostal SVC flow could be applicable in such patients. Fifth, because the present study was conducted
335 in Asian subjects who had a relatively low body mass index (23 ± 3, 16 to 31 kg/m^2 in analyzed 98

patients from the derivation cohort; 23 ± 5, 14 to 34 kg/m^2 in analyzed 43 patients from the validation cohort), it might affect generalizability when applied to patients with larger body size. Further investigation involving a subset of patients with an elevated body mass index is necessary to validate the clinical utility of SVC flow evaluation from the subcostal window and compare its diagnostic accuracy with that from the supraclavicular window for RAP estimation.

CONCLUSIONS

Evaluation of SVC flow from the subcostal window could be useful to identify elevated RAP. Importantly, a combined index using IVC parameter measurements and SVC flow evaluation from the subcostal window may enable an accurate assessment of RAP. The SVC flow profile provides additional diagnostic insights into the quantification of RAP.

Acknowledgments: We greatly appreciate Sana Maedomari, BS, for cooperation with Protocol 1. We also acknowledge Ryosuke Fujisawa, MS, Miho Aiba, MS, Mio Shinkawa, BS, and Airi Onoda, BS, for their contributions in data collection. We thank Asuka Tanemura, BS, Dr. Yoji Tamaki, Dr. Hiroyuki Aoyagi in the echocardiography laboratory at Hokkaido University Hospital for supporting this project, and thank Taisei Mikami, MD, Ph.D., for advice on the discussion section. We would also like to thank Editage (www.editage.com) for English language editing.

Funding: This research did not receive any specific grant from funding agencies in the public,

commercial, or not-for-profit sectors.

Declarations of Interest: None

Author Contributions: MM, SK and KO designed the study. MM acquired the echocardiographic data. MM and SK drafted the manuscript. MM, MN, SY, HN, ST, YC, SI, KO, and MN collected the echocardiographic and demographic data. SK, KO, HI, MN, SY, HN, ST, YC, SI, KO, KK, MN, TN, and TA supported the statistical analysis and counseled about the discussion section. MM, SK, KO, HI, MN, SY, HN, and MN participated in the interpretation of the results regarding echocardiography. HI, ST, YC, SI, KO, KK, TN, and TA collected the catheterization data and contributed to the interpretation of the results. HI, KK, MN, TN, and TA advised on methodological consideration, provided guidance about main thesis, revised the manuscript critically for important intellectual content and finally approved submission of the manuscript. All authors have read and approved the final manuscript.

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FIGURE LEGENDS

Figure 1. Pulsed-wave Doppler measurements of SVC flow velocity waveform from the subcostal window

SVC flow velocity waveform was recorded from the subcostal long-axis view (A) or subcostal four-chamber view (B) with the angle of the transducer towards the head with the patients in a supine position. A 3- to 5-mm sample volume was placed approximately10 mm proximal to the junction of the RA and SVC. From the waveforms, the peak systolic and diastolic forward SVC flows (SVC-S and SVC-D, respectively) and SVC-S/D ratio were measured. IVC = inferior vena cava; SVC = superior vena cava; RA = right atrium; RV = right ventricle.

Figure 2. Correlation of SVC-S/D ratio with invasive RAP and receiver operating characteristic curve for the SVC-S/D ratio to detect RAP >8 mmHg in the derivation cohort

RAP = right atrial pressure; other abbreviations as in Figure 1.

Figure 3. Incremental diagnostic value of the SVC-S/D ratio to the RAP grading according to the guidelines for detecting elevated RAP in the derivation cohort

To test the incremental diagnostic ability of the SVC-S/D ratio to the established guidelines, two models

(model 1: RAP grading alone; model 2: model 1 plus SVC-S/D) were constructed and compared using receiver operating curve analysis. CI = confidence interval; other abbreviations as in Figures 1 and 2.

Figure 4. Examples of SVC flow from supraclavicular (*top*) and subcostal (*middle*) views, and corresponding RAP (*bottom*).

(A) A case of dilated cardiomyopathy showing normal RAP of 5 mmHg. The flow profile in the SVC is a systolic dominance (supraclavicular SVC-S/D: 2.35; subcostal SVC-S/D: 2.30). (B) A case of left-sided valvular heart disease showing elevated RAP of 11 mmHg. The flow profile in the SVC is a diastolic dominance (supraclavicular SVC-S/D: 0.71; subcostal SVC-S/D: 0.45). Abbreviations as in Figures 1 and 2.

Figure 5. Correlation of SVC-S/D ratio measured from the subcostal and right supraclavicular windows with invasive RAP

Abbreviations as in Figures 1 and 2.

SUPPLEMENTARY MATERIAL

Supplemental Figure 1. Derivation and validation study population flowchart in Protocol 2

Abbreviations as in Figures 1 and 2.

Supplemental Figure 2. A representative case showing different impacts of postural changes on SVC flow between the subcostal and supraclavicular windows

The supine SVC flow from the subcostal window (**A**), and the sitting SVC flow from the subcostal window (**B**). The supine SVC flow from the right supraclavicular window (**C**), and the sitting SVC flow from the right supraclavicular window (**D**). In the subcostal approach, although a significant increase in SVC-S and D in the sitting position was observed, S/D was not significantly affected by postural changes. In contrast, in the supraclavicular approach, the sitting position significantly increased the SVC-S and D, with a decreased S/D compared to that in the supine position. Abbreviations as in Figure 1.

Supplemental Figure 3. Comparison of mean RAP among the three RAP grades from the guidelines in the derivation cohort

Error bars show average and range of standard deviation. Abbreviations as in Figure 2.

Supplemental Figure 4. Correlation of SVC-S/D ratio with invasive RAP in the validation cohort

Abbreviations as in Figures 1 and 2.

Supplemental Figure 5. Incremental diagnostic value of the SVC-S/D ratio to the RAP grading according to the guidelines for detecting elevated RAP in the validation cohort

To confirm the incremental diagnostic ability of the SVC-S/D ratio to the established guidelines, two models (model 1: RAP grading alone; model 2: model 1 plus SVC-S/D) were constructed and compared using receiver operating curve analysis. Abbreviations as in Figures 1 to 3.

Supplemental Figure 6. A representative case showing different SVC flow velocity waveforms in the several sampling positions

A case of chronic thromboembolic pulmonary hypertension showing normal RAP of 2 mmHg. In this case, note that the absolute SVC flow velocities differ depending on sample volume location and that the S/D ratio increases as the sample volume is moved to the right atrium. In this case, the SVC flow waveform recorded at the sampling location closest to the right atrial most accurately reflected the RAP waveforms. Abbreviations as in Figures 1 and 2.

Table 1. Comparison of clinical, echocardiographic, and invasive data stratified by RAP of the derivation cohort

Variable	Total	RAP ≤8 mmHg	RAP >8 mmHg	*P*
Demographics				
Number, n (%)	98	78 (80)	20 (20)	N/A
Age, years	64 ± 15	65 ± 15	63 ± 15	.694
Male, n (%)	45 (46)	35 (45)	10 (50)	.803
Body mass index, kg/m^2	23 ± 3	22 ± 3	24 ± 3	.100
NYHA functional class III or IV, n (%)	34 (35)	24 (31)	10 (50)	.121
Systolic blood pressure, mmHg	110 ± 17	110 ± 16	107 ± 18	.409
Heart rate, beats/min	69 ± 11	69 ± 11	70 ± 11	.804
Atrial fibrillation	11 (11)	8 (10)	3 (15)	.691
Cardiac disease, n (%)				
Nonischemic dilated cardiomyopathy	29 (30)	25 (32)	4 (20)	.412
Valvular heart disease	20 (20)	16 (21)	4 (20)	.999
Precapillary pulmonary hypertension	20 (20)	19 (24)	1 (5)	.066
Ischemic heart disease	9 (9)	6 (8)	3 (15)	.383
Hypertrophic cardiomyopathy	8 (8)	5 (6)	3 (15)	.354

Others	12 (12)	7 (9)	5 (25)	.065
Laboratory data				
Hemoglobin, g/dL	12.7 ± 1.8	12.9 ± 1.9	11.9 ± 1.6	.041
Platelets, 10^4/μL	21.0 ± 5.4	21.0 ± 5.2	20.9 ± 6.1	.912
eGFR, mL/min/1.73 m^2	58.5 ± 25.4	60.6 ± 25.5	50.2 ± 24.9	.105
Creatinine, mg/dL	0.9 (0.7–1.2)	0.9 (0.7–1.1)	0.9 (0.7–1.8)	.328
Total bilirubin, mg/dL	0.8 (0.6–1.1)	0.8 (0.6–1.1)	0.8 (0.7–1.2)	.986
AST, IU/L	21.0 (18.0–27.0)	21.0 (17.0–27.0)	20.5 (19.0–23.8)	.761
ALT, IU/L	15.5 (11.0–21.0)	15.5 (11.8–22.3)	15.5 (11.0–19.0)	.708
Albumin, g/dL	3.9 ± 0.5	3.9 ± 0.5	4.0 ± 0.4	.577
Cholinesterase, U/L	269 ± 74	280 ± 67	229 ± 96	.007
BNP, pg/mL	100 (33–338)	91 (29–223)	540 (81–1361)	.006
Echocardiography				
Left heart structure and function				
Left ventricular end-diastolic volume, mL	99 (70–145)	99 (75–144)	100 (62–165)	.734
Left ventricular mass index, g/m^2	104 (83–135)	105 (83–135)	101 (66–134)	.588
Left ventricular ejection fraction, %	58 (34–68)	58 (34–68)	59 (30–70)	.982

Right heart structure and function				
RV basal diameter, mm	39 ± 7	38 ± 7	43 ± 8	.008
RV mid diameter, mm	29 ± 6	28 ± 6	33 ± 7	.006
RV end-diastolic area, cm^2	19 ± 6	18 ± 6	22 ± 6	.005
RV fractional area change, %	37 ± 11	37 ± 11	36 ± 12	.525
Tricuspid annular plane systolic excursion, mm	18 ± 5	18 ± 5	18 ± 6	.712
RV S′, cm/s	10.9 ± 3.0	11.1 ± 3.1	9.8 ± 2.2	.090
Tricuspid E/A	1.1 (0.8–1.4)	1.0 (0.8–1.3)	1.3 (1.0–2.1)	.027
Tricuspid E/e′	4.8 (3.8–6.4)	4.5 (3.6–6.5)	5.5 (4.3–6.4)	.109
Hepatic vein systolic filling fraction, %	61 ± 9	62 ± 8	58 ± 10	.098
SVC-S, cm/s	47.7 ± 18.1	50.6 ± 16.6	36.6 ± 23.2	.018
SVC-D, cm/s	25.4 ± 10.3	23.7 ± 8.2	31.9 ± 16.1	.038
SVC-S/D	2.1 ± 0.9	2.3 ± 0.9	1.2 ± 0.7	<.001
Right atrial maximum area, cm^2	19 ± 6	18 ± 6	23 ± 8	.007
IVC dimension, mm	15 ± 5	13 ± 4	19 ± 7	.002
IVC respiratory change, %	44 ± 15	46 ± 14	35 ± 17	.002
Judgment by guidelines, n (%)				

Elevated RAP (15 mmHg)	10 (10)	2 (2)	8 (40)	<.001
Indeterminate RAP (8 mmHg)	49 (50)	41 (53)	8 (40)	.453
Normal RAP (3 mmHg)	39 (40)	35 (45)	4 (20)	.071
Significant tricuspid regurgitation, n (%)	17 (17)	11 (14)	6 (30)	.107
Cardiac Catheterization				
Mean RAP, mmHg	6.0 ± 2.3	4.5 ± 2.0	11.9 ± 3.4	<.001
Pulmonary arterial wedge pressure, mmHg	11.8 ± 5.0	10.1 ± 4.3	18.6 ± 7.1	<.001
Mean pulmonary arterial pressure, mmHg	22.9 ± 9.3	21.7 ± 9.5	27.6 ± 8.8	.013
Pulmonary vascular resistance, Wood units	2.8 ± 2.4	2.8 ± 2.4	2.6 ± 2.6	.787
Cardiac index, L/min/m^2	2.6 ± 0.6	2.6 ± 0.6	2.4 ± 0.6	.169

Data are expressed as mean ± standard deviation if normally distributed, median (interquartile range) if not normally distributed, or n (%). *P* values are from the Student's *t*-test, Wilcoxon rank-sum test, or chi-square test.

RAP = mean right atrial pressure; NYHA = New York Heart Association; eGFR = estimated glomerular filtration rate; AST = alanine aminotransferase; ALT = aspartate aminotransferase; BNP = plasma brain natriuretic peptide; RV = right ventricular; RV S′ = RV systolic excursion velocity derived from pulsed tissue Doppler echocardiography; Tricuspid E/A = the ratio of early-diastolic

transtricuspid flow velocity to late-diastolic tricuspid flow velocity; Tricuspid E/e′ = the ratio of early-diastolic transtricuspid flow velocity to early-diastolic tricuspid annular velocity; Hepatic vein systolic filling fraction = hepatic vein peak systolic velocity divided by the sum of peak systolic and diastolic velocity; SVC-S = the peak systolic velocity of superior vena cava derived from subcostal view; SVC-D = the peak diastolic velocity of superior vena cava derived from subcostal view; IVC = Inferior vena cava.

Table 2. Results of linear regression analysis to assess the associations between the SVC-S/D ratio and invasive RAP after adjustment for several confounders in the derivation cohort

Variable	Univariable		Multivariable	
	β	*P* value	β	*P* value
Age, years	−0.045	0.659		
Body mass index, kg/m^2	−0.059	0.562		
Heart rate, beats/min	−0.034	0.738		
Atrial fibrillation	−0.542	<0.001	−0.445	<0.001
Precapillary pulmonary hypertension	0.158	0.121		
Left ventricular ejection fraction, %	0.154	0.130		
RV basal diameter, mm	−0.116	0.256		
Tricuspid annular plane systolic excursion, mm	0.276	0.008	0.148	0.081
RV fractional area change, %	−0.015	0.885		
Right atrial maximum area, cm^2	−0.327	0.001	0.163	0.104
Significant tricuspid regurgitation	−0.382	<0.001	−0.117	0.248
Mean pulmonary arterial pressure, mmHg	−0.059	0.564		
Mean RAP, mmHg	−0.495	<0.001	−0.476	<0.001

Abbreviations are the same as in Table 1. We found no evidence for collinearity problems in our model (variance inflation factor values <2).

Table 3. Comparison of clinical, echocardiographic, and invasive data stratified by RAP of the validation cohort

Variable	Total	RAP ≤8 mmHg	RAP >8 mmHg	*P*
Demographics				
Number, n (%)	43	35 (81)	8 (19)	N/A
Age, years	69 ± 18	70 ± 18	68 ± 20	.803
Male, n (%)	20 (47)	15 (43)	5 (63)	.440
Body mass index, kg/m^2	23 ± 5	23 ± 5	24 ± 4	.643
NYHA functional class III, n (%)	11 (28)	7 (22)	4 (50)	.172
Systolic blood pressure, mmHg	114 ± 20	116 ± 19	106 ± 22	.212
Heart rate, beats/min	68 ± 9	68 ± 10	68 ± 8	.992
Atrial fibrillation	3 (7)	2 (6)	1 (13)	.470
BNP, pg/mL	166 (54–299)	123 (34–275)	294 (181–545)	.024
Cardiac disease, n (%)				
Valvular heart disease	15 (35)	12 (34)	3 (38)	.999
Nonischemic dilated cardiomyopathy	13 (30)	11 (31)	2 (25)	.999
Precapillary pulmonary hypertension	7 (16)	6 (17)	1 (13)	.999
Ischemic heart disease	5 (12)	4 (11)	1 (13)	.999

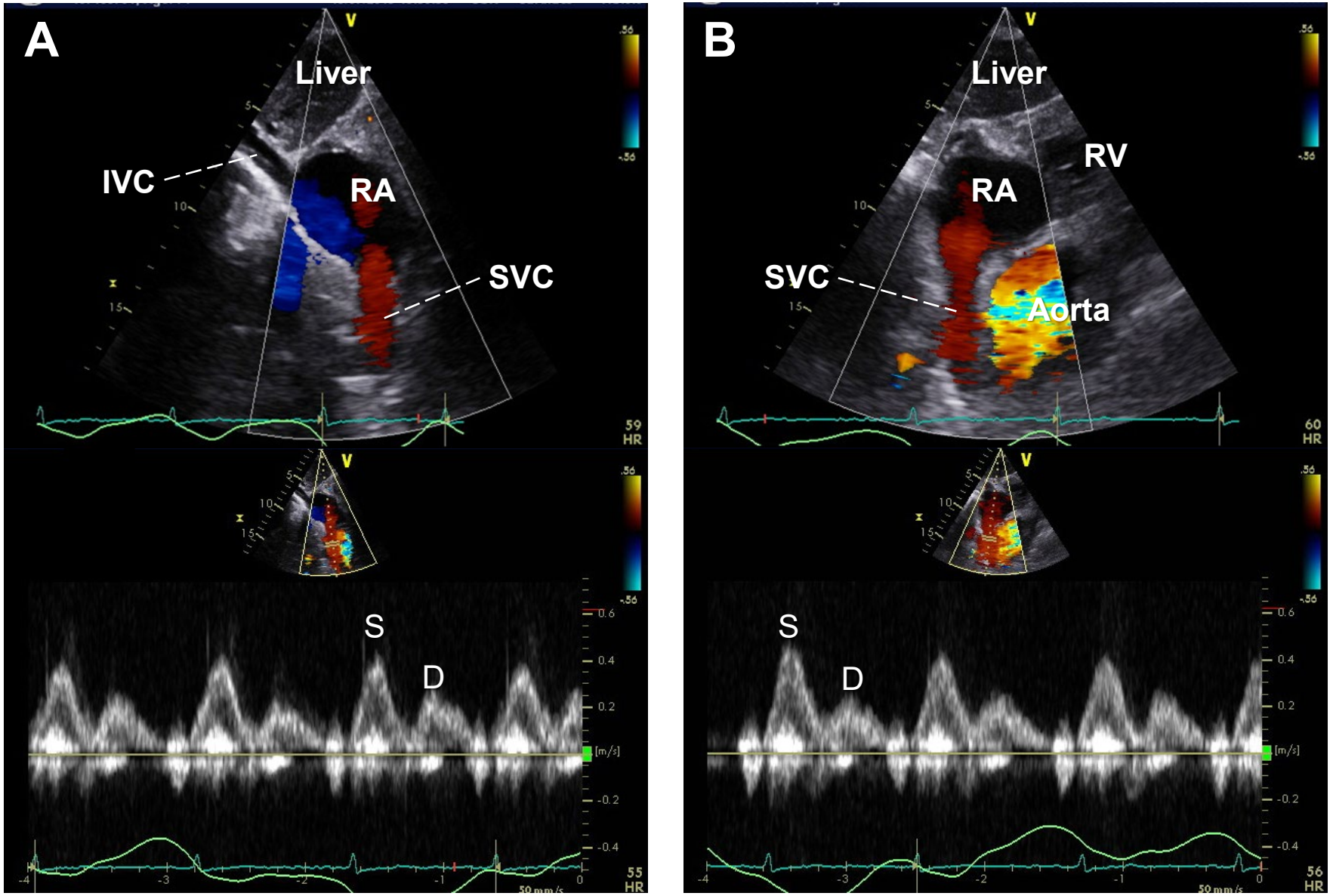
Others	3 (7)	2 (6)	1 (13)	.939
Right heart structure and function				
RV basal diameter, mm	41 ± 7	40 ± 6	43 ± 10	.328
RV fractional area change, %	39 ± 11	39 ± 11	35 ± 10	.299
SVC-S, cm/s	47.4 ± 21.0	52.5 ± 19.5	25.0 ± 9.9	<.001
SVC-D, cm/s	27.6 ± 12.4	26.3 ± 12.2	33.0 ± 12.4	.172
SVC-S/D	1.9 ± 0.9	2.2 ± 0.7	0.9 ± 0.5	<.001
IVC dimension, mm	15 ± 5	14 ± 4	20 ± 6	.048
IVC respiratory change, %	45 ± 16	48 ± 13	33 ± 20	.016
Judgment by guidelines, n (%)				
Elevated RAP (15 mmHg)	5 (12)	1 (3)	4 (50)	.003
Indeterminate RAP (8 mmHg)	20 (46)	18 (51)	2 (25)	.250
Normal RAP (3 mmHg)	18 (42)	16 (46)	2 (25)	.434
Significant tricuspid regurgitation, n (%)	16 (37)	10 (29)	6 (75)	.022
Cardiac Catheterization				
Mean RAP, mmHg	5.7 ± 3.3	4.5 ± 2.2	11.0 ± 2.0	<.001
Mean pulmonary arterial pressure, mmHg	21.4 ± 7.7	20.3 ± 7.1	26.6 ± 8.4	.034

Pulmonary vascular resistance, Wood units	2.5 ± 1.6	2.5 ± 1.6	2.7 ± 1.3	.762
Cardiac index, L/min/m^2	2.6 ± 0.6	2.7 ± 0.6	2.4 ± 0.7	.273

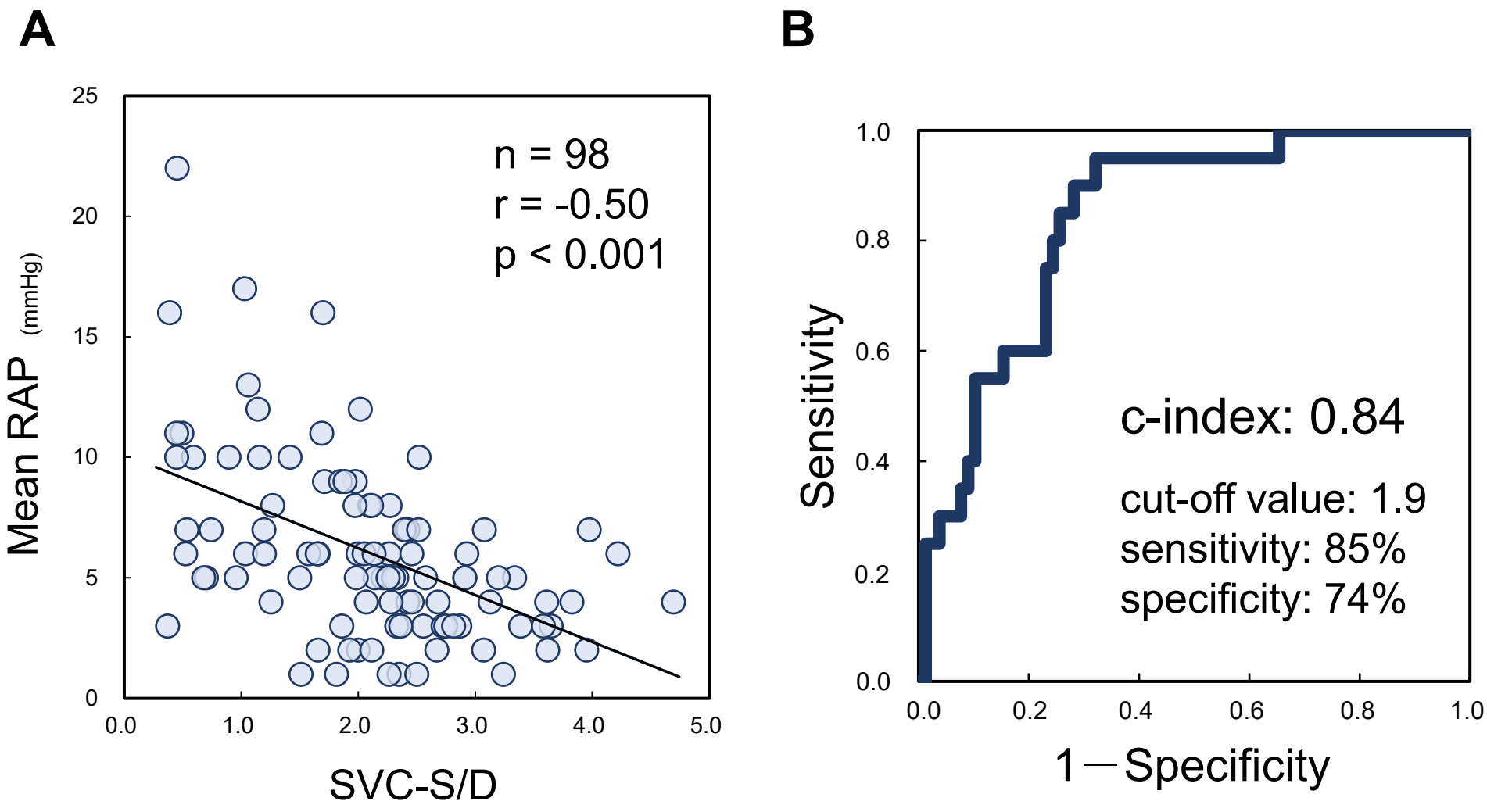
Data are expressed as mean ± standard deviation if normally distributed, median (interquartile range) if not normally distributed, or n (%). *P* values are from the Student's *t*-test, Wilcoxon rank-sum test, or chi-square test.

Abbreviations are the same as in Table 1.

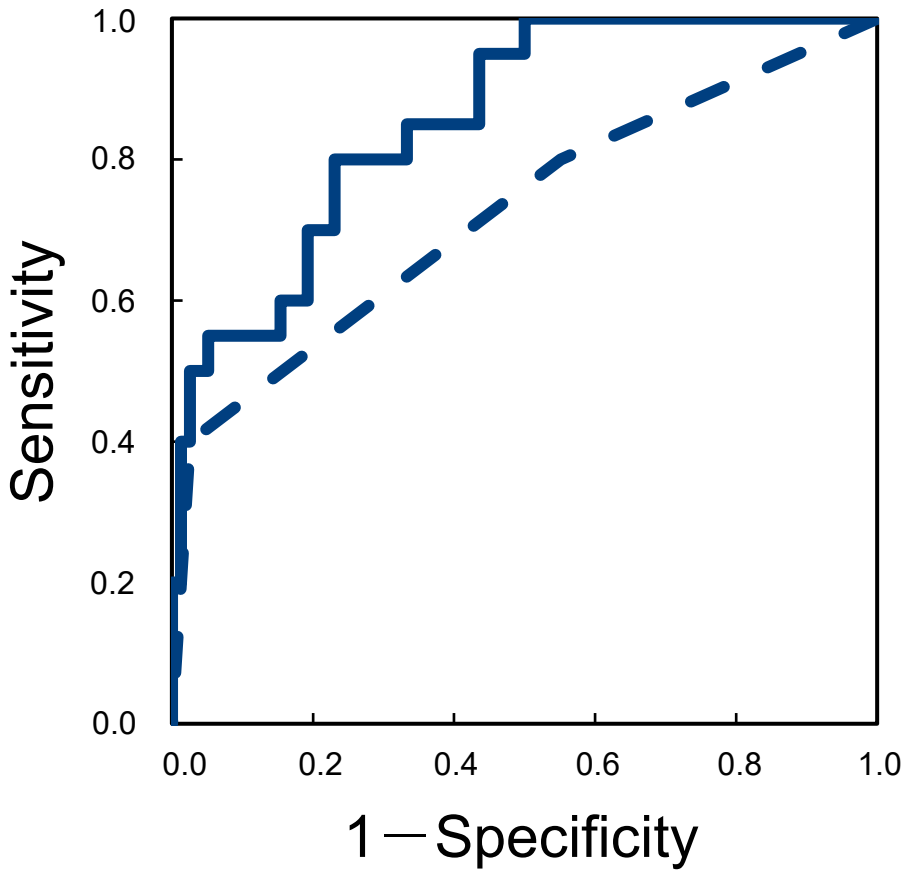
Fig 1



R1 Fig 2


A
Mean RAP (mmHg)
SVC-S/D
n = 98
r = -0.50
p < 0.001
0
5
10
15
20
25
0.0
1.0
2.0
3.0
4.0
5.0
B
Sensitivity
1－Specificity
c-index: 0.84
cut-off value: 1.9
sensitivity: 85%
specificity: 74%
0.0
0.2
0.4
0.6
0.8
1.0

R1 Fig 3



RAP grading + SVC-S/D

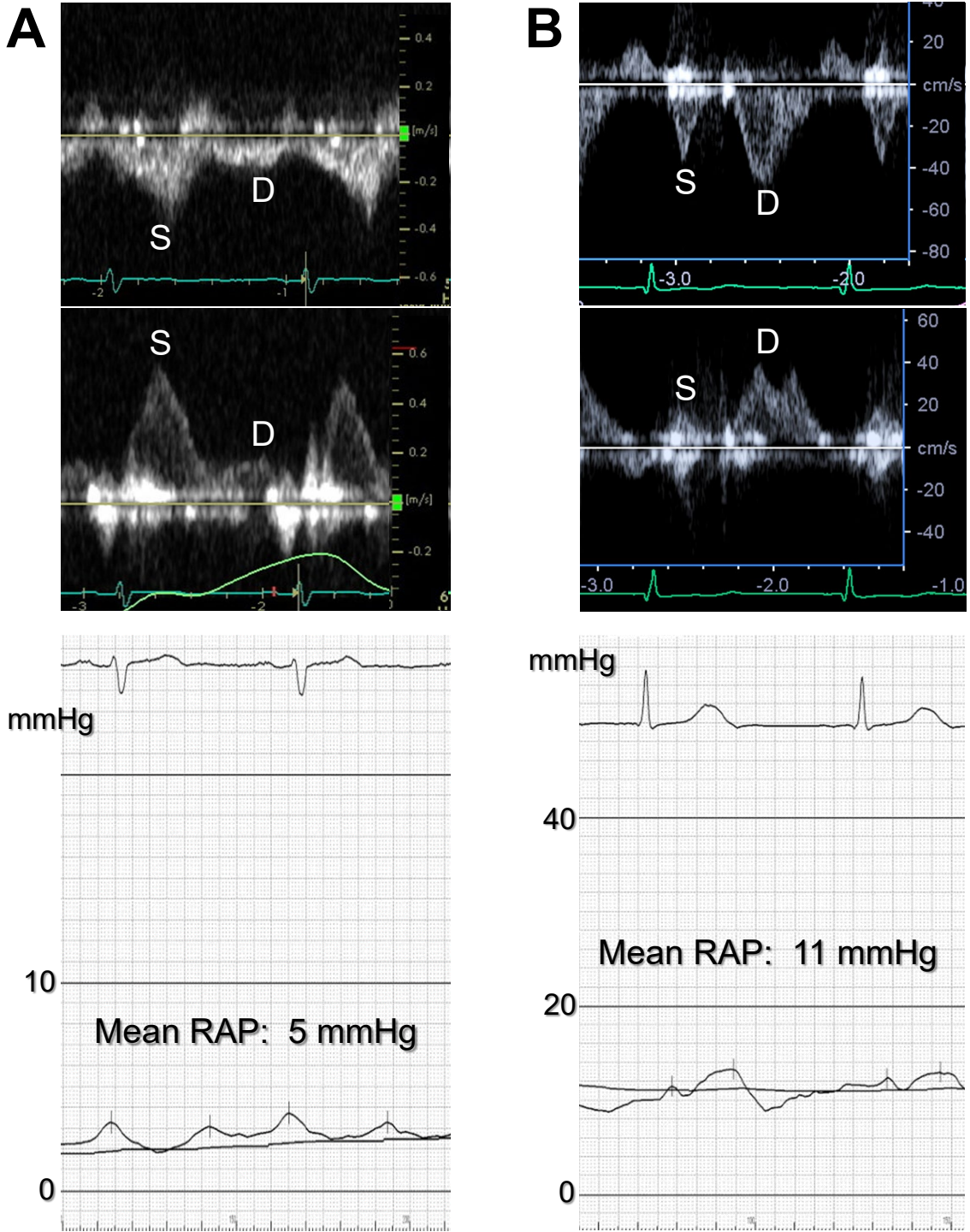
(c-index = 0.86; 95% CI: 0.75 to 0.92)

p = 0.006

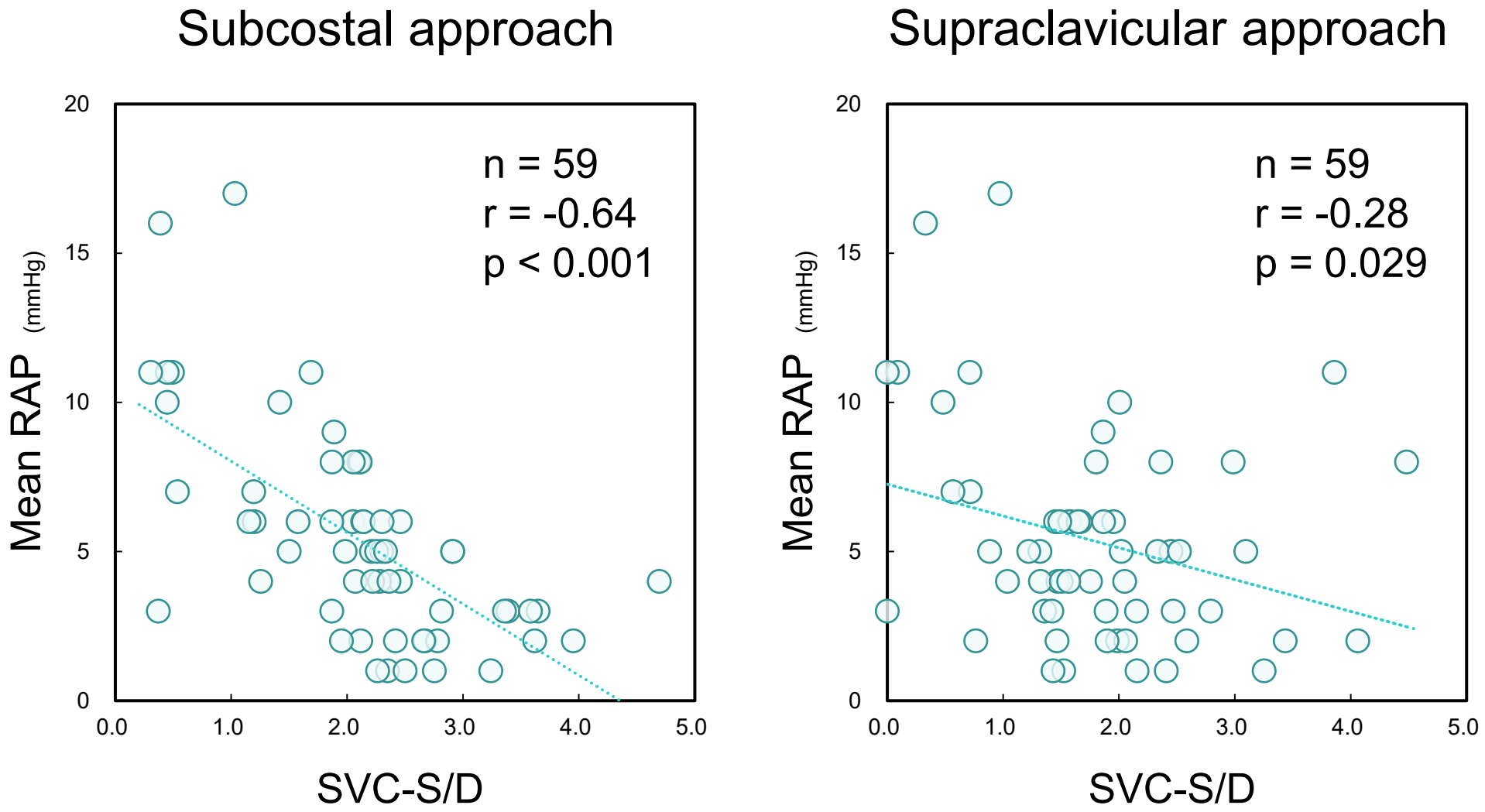
RAP grading

(c-index = 0.72; 95% CI: 0.58 to 0.84)

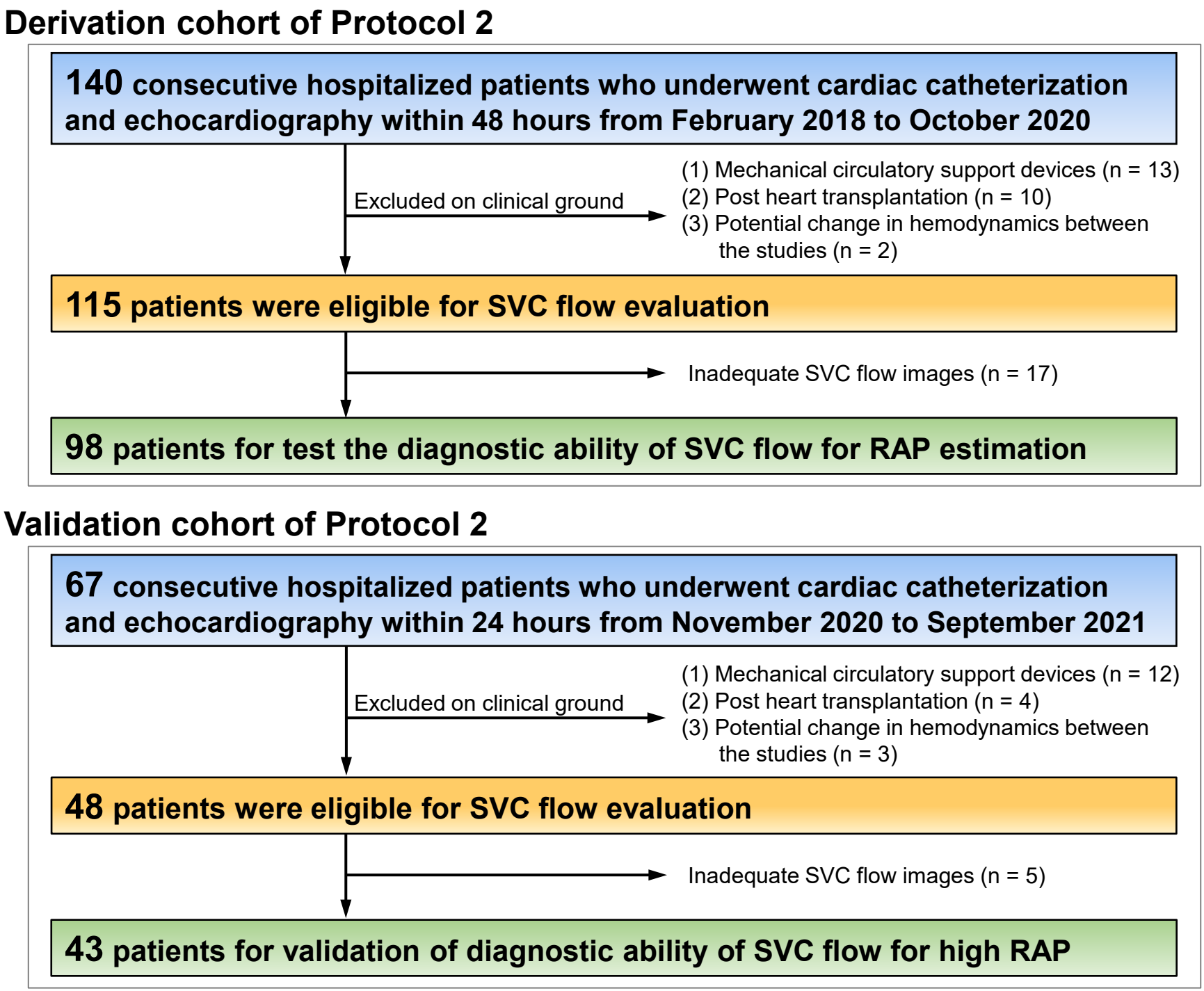
R1 Fig 4


A
B
S
D
S
D
S
D
S
D
mmHg
10
0
Mean RAP: 5 mmHg
mmHg
40
20
0
Mean RAP: 11 mmHg

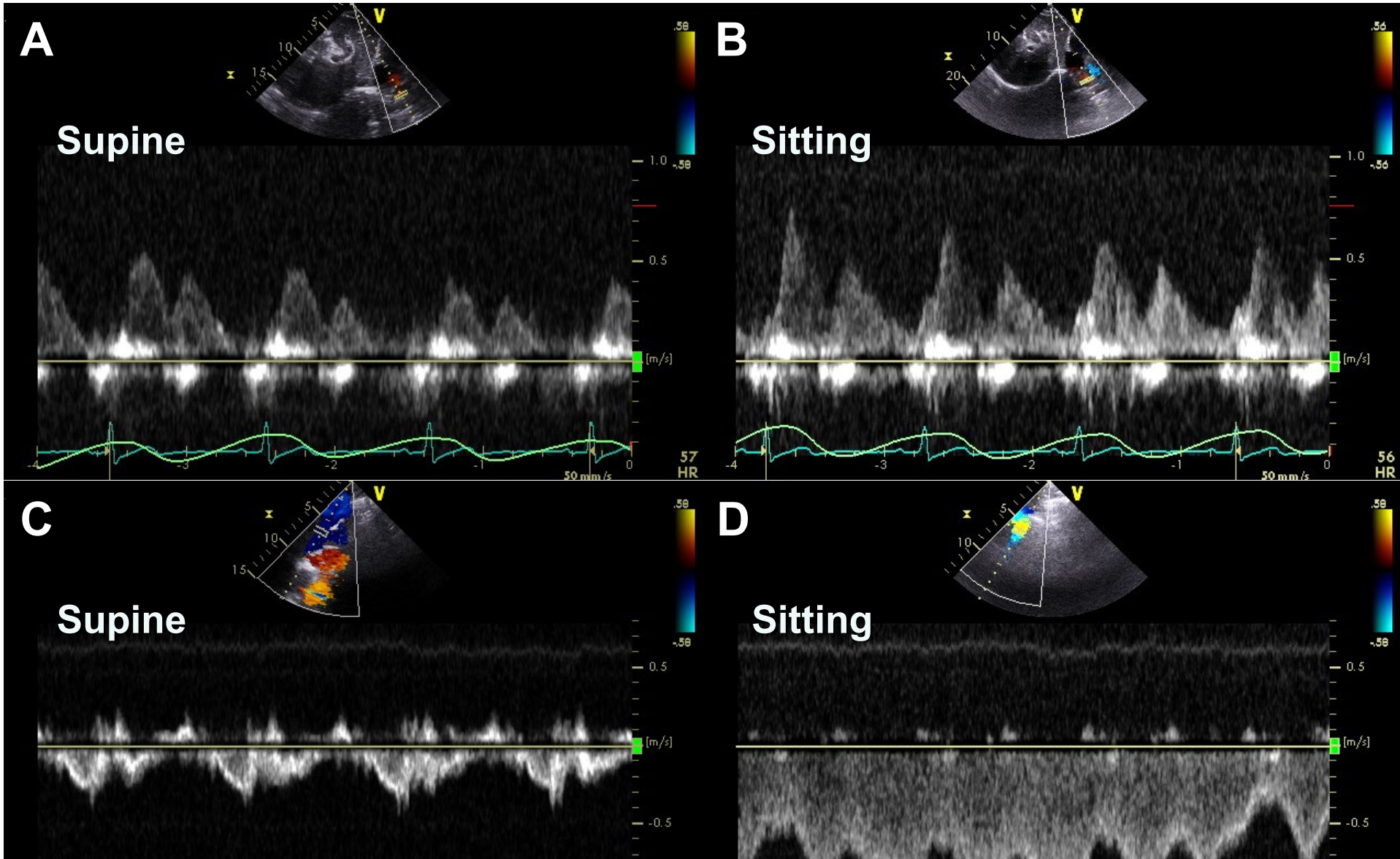
R2 Fig 5


Subcostal approach
n = 59
r = -0.64
p < 0.001
Mean RAP (mmHg)
SVC-S/D
0
5
10
15
20
0.0
1.0
2.0
3.0
4.0
5.0
Supraclavicular approach
n = 59
r = -0.28
p = 0.029
Mean RAP (mmHg)
SVC-S/D

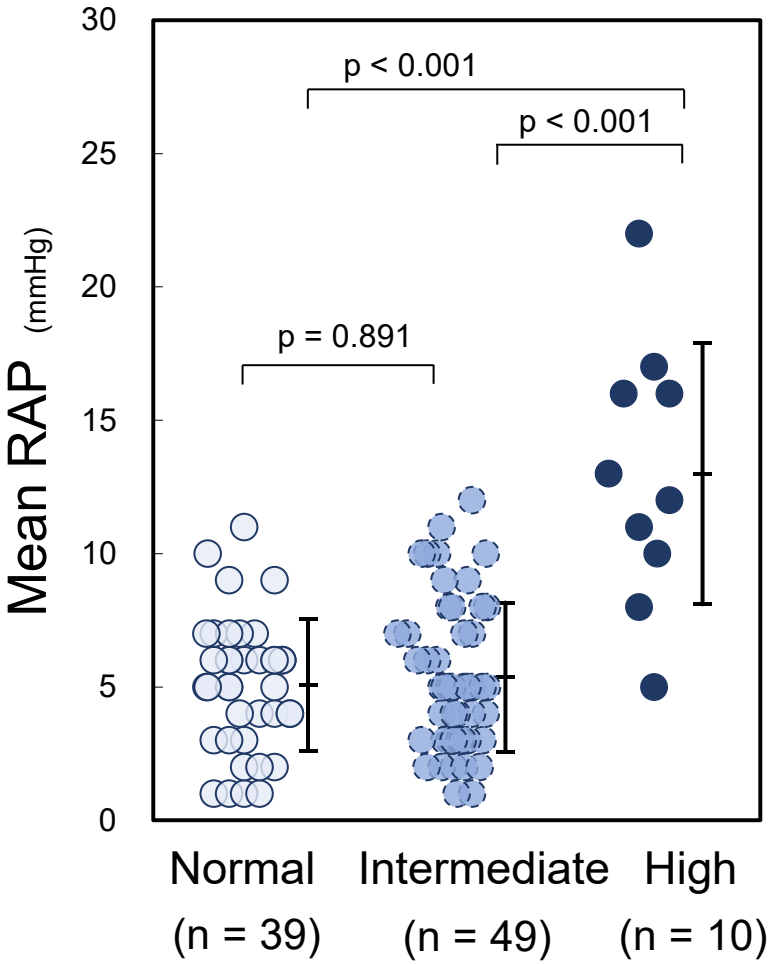
R1
Sup
Fig 1


Derivation cohort of Protocol 2
140 consecutive hospitalized patients who underwent cardiac catheterization and echocardiography within 48 hours from February 2018 to October 2020
Excluded on clinical ground
(1) Mechanical circulatory support devices (n = 13)
(2) Post heart transplantation (n = 10)
(3) Potential change in hemodynamics between the studies (n = 2)
115 patients were eligible for SVC flow evaluation
Inadequate SVC flow images (n = 17)
98 patients for test the diagnostic ability of SVC flow for RAP estimation
Validation cohort of Protocol 2
67 consecutive hospitalized patients who underwent cardiac catheterization and echocardiography within 24 hours from November 2020 to September 2021
Excluded on clinical ground
(1) Mechanical circulatory support devices (n = 12)
(2) Post heart transplantation (n = 4)
(3) Potential change in hemodynamics between the studies (n = 3)
48 patients were eligible for SVC flow evaluation
Inadequate SVC flow images (n = 5)
43 patients for validation of diagnostic ability of SVC flow for high RAP

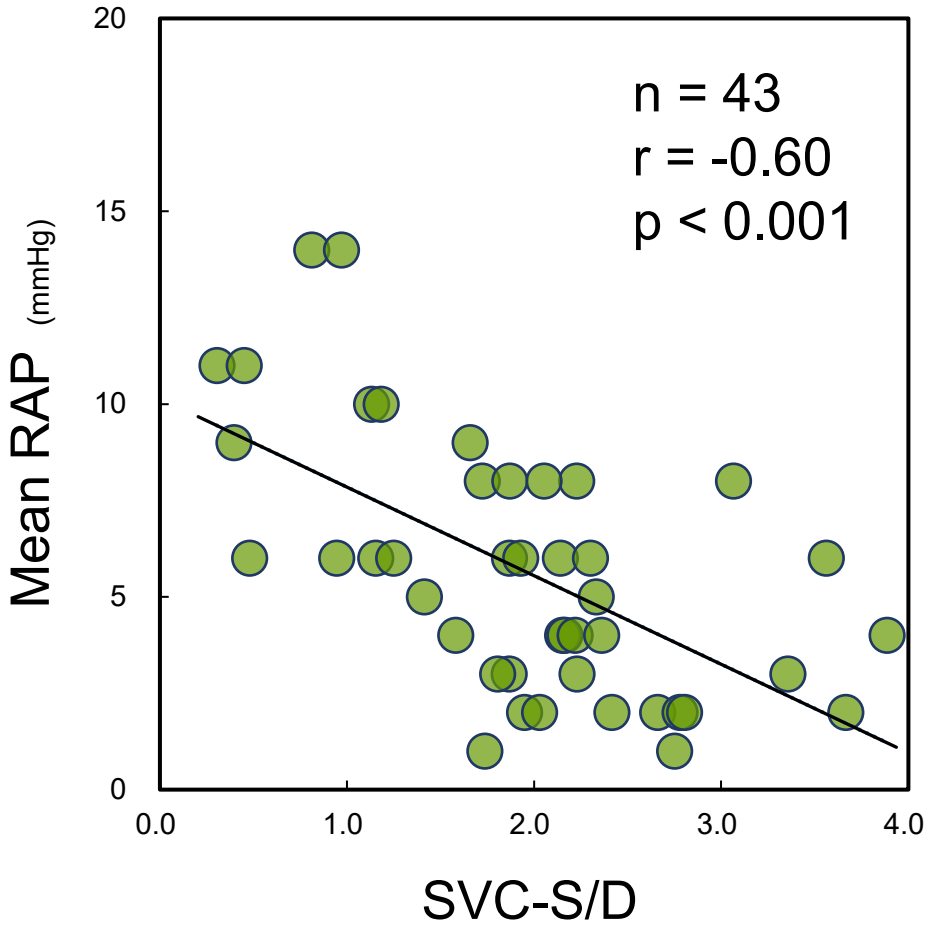
R2 Sup Fig 2



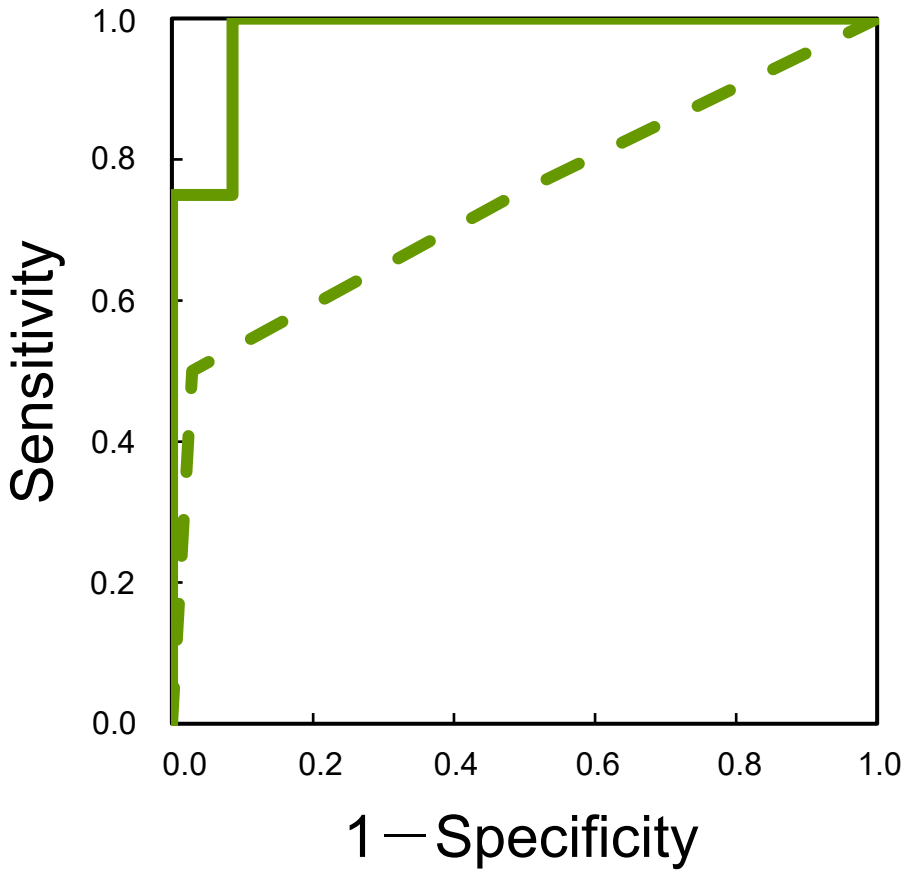
R1 Sup Fig 3


30
25
20
15
10
5
0
Mean RAP (mmHg)
p < 0.001
p < 0.001
p = 0.891
Normal
(n = 39)
Intermediate
(n = 49)
High
(n = 10)

R1 Sup Fig 4



R1 Sup Fig 5



RAP grading + SVC-S/D

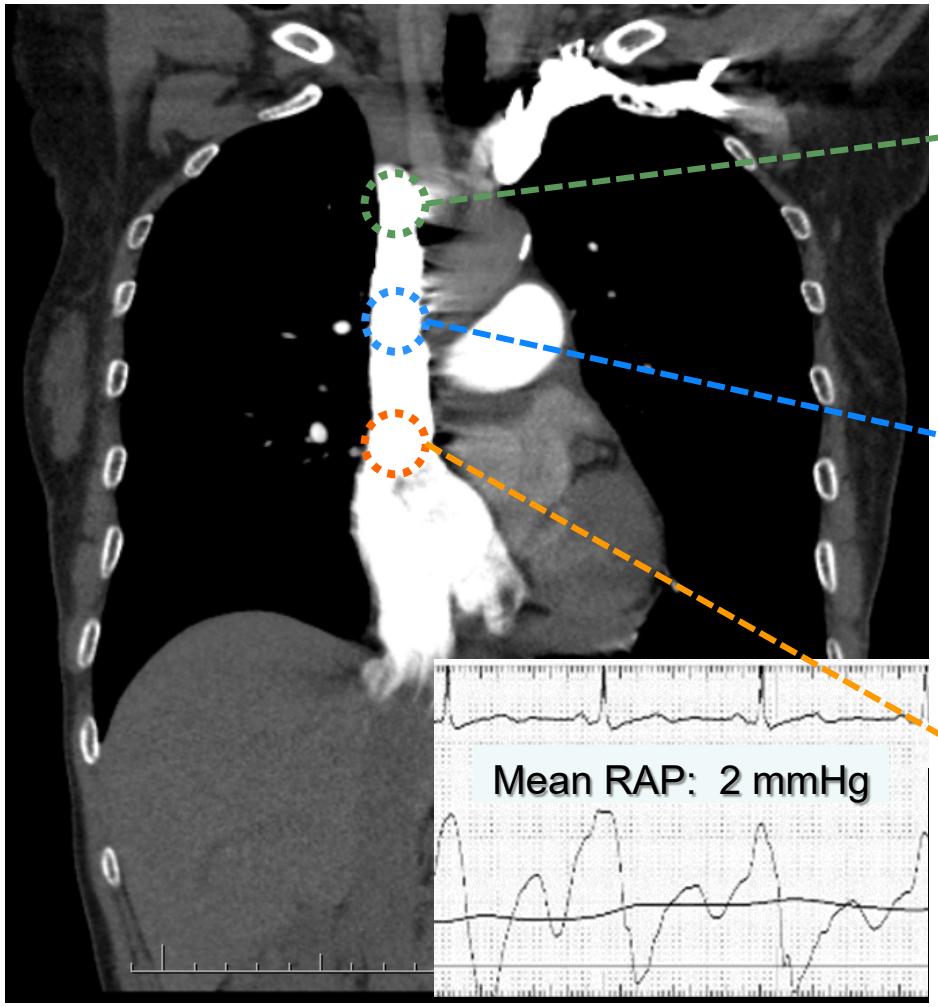
(c-index = 0.98; 95% CI: 0.89 to 0.99)

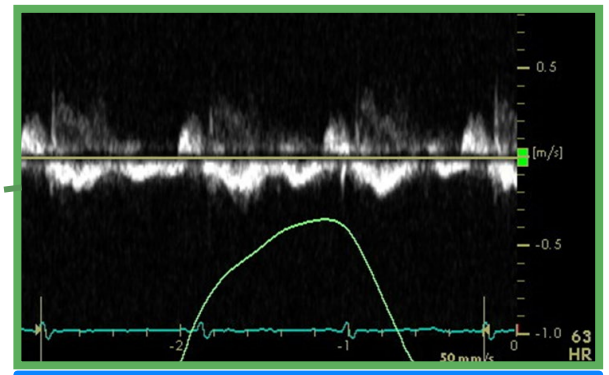
p = 0.033

RAP grading

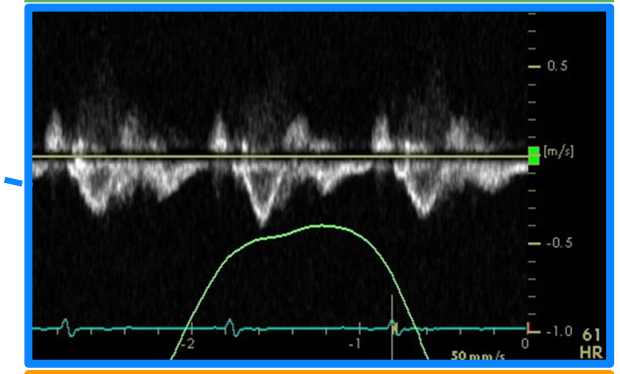
(c-index = 0.74; 95% CI: 0.47 to 0.90)

R2 Sup Fig 6

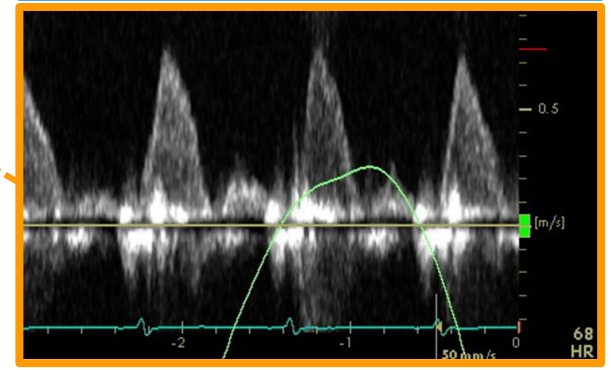




S/D: 1.2



S/D: 1.4



S/D: 4.0