

High Prevalence of Occult Left Ventricular Diastolic Dysfunction Detected by Exercise Stress Test in Systemic Sclerosis

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Research Article

Keywords: pulmonary hypertension, systemic sclerosis, left ventricular diastolic dysfunction, exercise test

Posted Date: September 22nd, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-899443/v1>

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Abstract

Despite the poor prognosis of systemic sclerosis (SSc) due to the co-occurrence of left ventricular diastolic dysfunction (LVDD), detection for the occult LVDD has not been sufficiently investigated. The aim of this study was to reveal the prevalence and determinants of occult LVDD in patients with SSc by exercise stress test. Forty-five SSc patients (age, 63 ± 13 years; men/women, 6/39) with normal pulmonary artery pressure and pulmonary artery wedge pressure (PAWP) at rest underwent symptom-limited exercise test with right heart catheterization using a supine cycle ergometer and evaluated hemodynamic parameters at rest, leg raise and during exercise. Occult LVDD defined PAWP ≥ 25 mmHg during exercise was seen in 13 patients (29%). Higher PAWP, lower pulmonary vascular resistance and diastolic pulmonary pressure gradient, larger left atrium at rest, and high PAWP during leg raise (15 ± 4 vs 10 ± 4 mmHg, $p < 0.001$) were significantly higher in the occult LVDD group. The area under the ROC curve for PAWP after leg raise was largest at 0.83 (95% CI: 0.70–0.95, $p = 0.001$). About one-third of SSc patients with normal hemodynamics at rest showed occult LVDD. A higher PAWP after leg raise could be useful for detecting occult LVDD.

Introduction

Pulmonary hypertension (PH) is recognised as a critical complication that occurs in approximately 7–12% of the patients with systemic sclerosis (SSc)^{1–3}. This may be caused by pre-capillary microvascular narrowing in pulmonary arterial hypertension (PAH), interstitial lung disease (ILD), veno-occlusive disease, post-capillary pulmonary hypertension due to left heart disease, or combinations of these abnormalities⁴. PH patients with SSc have a threefold higher risk of death and poorer response to therapy than those with idiopathic PAH^{5,6}. The poor prognosis of PH in patients with SSc partly results from overt left ventricular diastolic dysfunction (LVDD)^{7,8}, which is frequently associated with myocardial fibrosis^{9, 10}. PAH-specific vasodilator drugs may have deleterious effects or may be ineffective if administered to patients with LVDD. Thus, accurate differentiation between pre-capillary and post-capillary PH is essential for risk stratification and appropriate selection of treatment.

Differentiation between pre-capillary and post-capillary PH is based on a pulmonary arterial wedge pressure (PAWP) > 15 mmHg as the current criterion for diagnosing PH due to LVDD¹¹. Some patients with LVDD may have normal resting PAWP, but an abnormal increase in PAWP in response to fluid loading. In one study, several PAH patients were reclassified as occult post-capillary PH after fluid loading, which was indicative of the difficulty of differentiating PH etiology in SSc patients¹².

The exercise stress test has been reported to facilitate early detection of PH, allowing early intervention and the opportunity to improve outcomes^{13,14–15}. Recently, elevated PAWP during exercise, or exercise-induced post-capillary PH, was recognised as an indicator of early heart failure with preserved ejection fraction (HFpEF)¹⁶, and exercise stress in the early detection of LVDD has received much attention. In SSc patients with normal resting hemodynamics, an inordinate increase in pulmonary artery pressure (PAP)

during exercise is thought to be an early sign of pulmonary vasculopathy, as well as post-capillary pulmonary hypertension (i.e., LVDD)¹⁷. Furthermore, therapeutic interventions for patients with resting mean PAP of 21–24 mmHg, or so-called borderline PH, were recently established, and the importance of early differentiation between pre-capillary and post-capillary PH was emphasized. Therefore, we investigated the prevalence of occult LVDD in SSc via the exercise stress test with normal hemodynamics at rest. We also examined the factors predicting PAWP elevation during exercise among the resting hemodynamic parameters (at rest and during leg raise) without specialised equipment.

Results

Baseline characteristics

The patient flow chart is shown in Figure 1. Among the 50 patients who underwent exercise testing, five were excluded due to a high mean PAP. Eventually, 45 patients (age, 63 ± 13 years; men/women, 6/39) were analysed. Of these, 13 (29%) showed occult LVDD. The distributions of the PAWP at rest by group are shown in Figure 2. Resting PAWP in most occult LVDD patients was the upper limit of the normal range.

The baseline characteristics of the study groups classified by the presence or absence of occult LVDD are shown in Table 1. Parameters determined through RHC at rest were as follows: mPAP, 17 ± 4 mmHg; PAWP, 7 ± 3 mmHg; PVR, 2.3 ± 1.1 Wood units; and CO, 4.5 ± 1.4 L/min. There were no significant differences in sex, comorbidities, pulmonary function, mean PAP, CO, and 6-minute walk distance (6MWD) between the two groups. Age, brain natriuretic peptide (BNP) value, and PAWP (10 ± 3 vs 7 ± 3 mmHg, $p < 0.001$) were significantly higher in the occult LVDD group. PVR (1.7 ± 0.8 vs 2.5 ± 1.1 , $p = 0.020$) and DPG (-2 ± 2 vs 1 ± 4 , $p = 0.004$) were significantly lower in the occult LVDD group than in the non-LVDD group.

Hemodynamic parameters during exercise

Cardiopulmonary exercise testing with RHC findings at rest (after leg raise), AT, and peak exercise are shown in Table 2. Despite the PAWP level at rest within normal limits in both groups, its level in leg raise was significantly higher in the occult LVDD group than in the other group (15 ± 4 vs 10 ± 4 mmHg, $p < 0.001$). The relationships of PAWP with CO in each group are shown in Figure 3. The mean PAWP in the occult LVDD group during exercise was higher (AT: 25 ± 5 vs 16 ± 5 mmHg, $p < 0.001$; peak: 28 ± 4 vs 16 ± 5 mmHg, $p < 0.001$), compared to PAWP in the non-LVDD group. CO during exercise was not significantly different between the two groups. CO at peak exercise and peak VO_2 in our study patients were 9.9 ± 4.9 L/min and 14.3 ± 8.8 mL/min/kg, respectively, indicating that their exercise capacities were low.

Echocardiographic parameters

The echocardiographic parameters between each group are shown in Table 3. There were no significant differences between the two groups in E/e' and E/A . LV mass index (112 ± 45 vs 90 ± 21 g/m², $p=0.043$), LAD (39 ± 7 vs 33 ± 5 mm, $p=0.005$), and LAVi (53 ± 20 vs 39 ± 13 mL/m², $p=0.033$) in the occult LVDD group were significantly greater than in the non-LVDD group.

Detection of occult LVDD

Among the resting hemodynamic parameters, the ROC curve revealed that PAWP at leg raise (AUC = 0.83 [95% confidence interval (CI): 0.70–0.95], $p=0.001$) and PAWP in the resting state (AUC 0.82 [95% CI: 0.69–0.95], $p=0.001$) may be useful in detecting occult LVDD (Figure 4), followed by DPG at rest (AUC = 0.74 [95% CI: 0.60–0.89], $p=0.011$) and PVR at rest (AUC 0.73 [95% CI 0.57–0.89], $p=0.019$). A PAWP at leg raise > 11 mmHg had 100% sensitivity and 56% specificity in predicting increased PAWP ≥ 25 mmHg by exercise.

Discussion

In this study, one-third of the SSc patients with normal hemodynamics at rest showed occult LVDD via exercise test. Higher PAWP after leg raise was a useful parameter for the detection of occult LVDD in these patients.

PH is recognised as a critical complication which worsens prognosis in patients with SSc. This prognosis is mainly linked to cardiovascular damage²². Currently, there are no established therapeutic interventions for improving SSc prognosis. Although the clinical course and mortality in PAH have improved due to progresses in PAH-specific therapy, SSc-PH outcomes have not improved²³. SSc-PH is not only caused by vasculopathy, but also causes diverse and sometimes overlapping mechanisms, including extensive vasculopathy, inflammation, autoimmunity, and widespread fibrosis^{4,10}. SSc-PH can, therefore, be explained by pulmonary arterial vasculopathy (group 1), pulmonary fibrosis (group 3), heart involvement (group 2), and PVOD-like lesions (group 1). SSc has the pathological hallmark of myocardial fibrosis and has been reported in 50–80% of necropsy cases²⁴. Mechanistically, it appears that disease-related loss-of-function of small coronary arteries and arterioles leads to ischaemia and reperfusion injury, driving cardiac fibrotic tissue formation²⁵. Myocardial delayed contrast enhancement revealed myocardial fibrosis associated with LVDD, and approximately 21% of SSc patients had abnormal MRI images²⁶. Furthermore, LV dysfunction gradually progresses to pulmonary arteriopathy and RV dysfunction^{4,27}. In a previous study, at baseline, 17% of patients with SSc were diagnosed with overt LVDD evaluated by echocardiography at rest and associated with high mortality⁷. Concomitant pulmonary vascular disease and LVDD likely contribute to poor survival in patients with SSc-PH⁸. In cases of LV dysfunction, aggressive pulmonary vasodilator therapy by preload increase is somewhat counterproductive. Accurate differentiation between pre-capillary and post-capillary PH is important.

SSc patients without obvious PH at baseline develop PH at 0.75 cases per 100 patients/year²⁸. The clinical importance of pulmonary hemodynamics during exercise has been recognised in the early

detection of PH^{15,29-31}. In SSc patients, a previous study showed that exercise PH was associated with increased mortality compared to that of normal exercise hemodynamics^{32,33}. In SSc, it has been noted that borderline PH (21– 24 mmHg of mean PAP) has a high likelihood of developing into overt PH^{34,35}; hence, attention has focussed on early interventions for managing borderline PH, and lowering the criteria has been advocated³⁶. Exercise PH may be useful in predicting the future development of patients with borderline PH. Some patients with LVDD may have normal resting PAWP but show an abnormal increase in PAWP in response to fluid loading. PAWP 15 mmHg has been used, with high sensitivity, to distinguish between patients between pre-capillary and post-capillary PH; however, normal PAWP, especially between 12 and 15 mmHg, does not rule out the presence of LVDD¹⁸. Volume or exercise challenge during RHC may be useful to unmask the presence of LVDD. Fox et al. reported that several PAH patients were reclassified as having occult post-capillary PH after fluid loading, which was indicative of the difficulty of differentiation in patients with SSc¹². It is known that PAWP in patients with SSc is more likely to be elevated than that of controls and other types of PH in fluid loading, and it is likely that occult LVDD is more common³⁷.

Patients with dyspnoea and seemingly normal hemodynamics (euvolemic, normal BNP, and normal cardiac filling pressures) have elevated PAWP during exercise, suggesting early stage of HFpEF due to LVDD¹⁶. Exercise tests may distinguish between exercise-induced pre-capillary PH and post-capillary PH.

It has been reported that 32% of SSc patients with normal resting hemodynamics and increased estimated pulmonary pressure on an exercise echocardiogram (> 40 mmHg) showed occult LVDD defined as increasing PAWP > 20 mmHg at exercise RHC with 1-pound weights³⁸. Stamm et al. showed that about 12% of SSc patients without resting PH were classified under exercise post-capillary PH³². With an exercise PAWP \geq 20 mmHg, 12 of 17 patients were reported having exercise-induced LVDD¹⁷. They also reported that LA dilatation might indicate occult LVDD. Our study revealed that the prevalence of occult LVDD was about one-third of SSc patients, with an exercise PAWP \geq 25 mmHg. LA dilatation in patients with occult LVDD was also observed in our study.

Hemodynamic measurements during exercise are useful for detecting early stage LVDD, but some procedural problems of examination time, invasiveness, and ergometer equipment can occur.

Fluid challenge has been reported useful in differentiating post-capillary PH^{12,39}. Among HFpEF patients with normal hemodynamics at rest, a PAWP > 15 mmHg during leg raise can indicate a PAWP \geq 25 mmHg during exercise with 91% probability⁴⁰. These reports show that increased preload could detect left heart dysfunction. We defined occult LVDD as \geq 25 mmHg in the supine position during exercise and showed that PAWP during leg raise was significantly higher in the occult LVDD group. In SSc patients, PAWP > 11 mmHg at leg raise may be easier for distinguishing occult LVDD than previous provocation examinations. Hemodynamic measurement with leg raise is quick, can distinguish occult LVDD easily, and may be useful for early therapeutic intervention. In our study, exercise-induced PAWP elevation was common in patients with upper limit of normal PAWP at rest. This is also consistent with the past recommendation¹⁸.

Fluid challenge is an easy manoeuvre that can be performed in any catheterization laboratory without specialised equipment. Leg raise might be even easier and safer than the fluid challenge.

This study had several limitations. Our study was a retrospective, single-centre, and non-randomized trial. Our study included a limited number of cases from a single institution, and the study population did not include overt LVDD. Although we evaluated patients with normal hemodynamics at rest, BNP levels were high in both groups, and 6MWD and peak VO_2 showed low exercise capacity, which was different from that of healthy subjects.

Age is an important confounder of the pulmonary vascular response and PAWP during exercise.

In conclusion, a high prevalence of occult LVDD was demonstrated via RHC with exercise test in SSc with normal hemodynamics at rest. The evaluation of PAWP with leg raise is easy and useful for detecting occult LVDD.

Methods

Study participants

Consecutive patients with SSc who exhibited dyspnea during exertion and suspected PH underwent cardiopulmonary exercise testing (CPX) with right heart catheterization (RHC) at our hospital between June 2013 and February 2020 were eligible for inclusion in the study. Patients with a high mean PAP (≥ 25 mmHg) and PAWP elevations (> 15 mmHg) at rest were excluded (Figure 1).

This study was approved by the Committee for Clinical Studies and Ethics of Kyorin University School of Medicine. The purposes and risks of the study were explained to the patients, who provided informed consent prior to participating. All methods were performed in accordance with the relevant guidelines and regulations.

Right heart catheterization and cardiopulmonary exercise testing

RHC was performed with a 6-F double-lumen, balloon-tipped, flow-directed Swan–Ganz catheter (Harmac Medical Products, Inc., Buffalo, NY, USA) via a transjugular approach. Baseline hemodynamic data were recorded, the zero-reference level (mid-chest) was adjusted at the start of pressure measurement, and the PAWP was obtained as the mean value of the arterial trace during occlusion. Measurements were obtained at the end of normal expirations with patients in the supine flat position to assess the right chamber, pulmonary artery pressure (mean PAP, systolic PAP, and diastolic PAP), and PAWP¹⁸.

An incremental symptom-limited exercise test was performed in the supine position, with an electromagnetically braked cycle ergometer (Nuclear Imaging Table with Angio Ergometer; Lode B.V.; Groningen, Netherlands) according to the ramp protocol. During cycling, the legs were elevated to approximately 30 degrees. After the parameters were stabilised, the test consisted of a 3-min rest,

followed by 3 min of warmup at an ergometer setting of 10 W (60 rpm), and, finally, testing with a 1-W increase in exercise load every 6 s (totalling 10 W/min).

During the exercise, oxygen consumption (VO_2), carbon dioxide output (VCO_2), and minute ventilation (VE) were measured with a metabolic cart (Cpex-1; Inter Reha Corp., Tokyo, Japan). Prior to calculating the parameters with respiratory gas analysis, an eight-point moving average of the breath-by-breath data was obtained. Peak VO_2 was defined as the average value obtained during the last 30 seconds of exercise. The anaerobic threshold (AT) point was determined using the V-slope method, along with the following conventional criteria: VE/ VO_2 increases after decreasing or registering as flat, whereas VE/ VCO_2 remains constant or decreases¹⁹. The VE vs VCO_2 slope was calculated from the start of incremental exercise to the respiratory compensation point using a least-squares linear regression²⁰.

Heart rate, arterial blood pressure directly recorded in the radial artery, and electrocardiogram were monitored continuously during the test. PAP and PAWP in the RHC were measured every minute. We used the averaged mean PAP and mean PAWP during several-second periods rather than end-expiratory measurements during exercise.

Oxygen (O_2) saturation in arterial blood (SaO_2) in the radial artery and O_2 saturation in the pulmonary artery (SvO_2) were measured at rest, AT, and peak exercise. Cardiac output (CO) was determined by the Fick method using the formula: $\text{CO (L/min)} = \text{VO}_2 / \{1.34 \times \text{hemoglobin} \times (\text{SaO}_2 - \text{SvO}_2)\}$. The cardiac index (L/min/m^2) was determined as follows: $\text{CO/body surface area (BSA)}$. Pulmonary vascular resistance (PVR), transpulmonary pressure gradient (TPG), and diastolic pulmonary pressure gradient (DPG) were calculated as: $\text{PVR (Wood units)} = (\text{mPAP} - \text{PAWP}) / \text{CO}$, $\text{TPG} = \text{mPAP} - \text{PAWP}$, and $\text{DPG} = \text{diastolic PAP} - \text{PAWP}$. All measurements during exercise testing were performed without supplemental oxygen.

We defined SSc with LVDD as PAWP increased during the RHC exercise test and divided the patients on this basis into two groups: occult LVDD group ($\text{PAWP} \geq 25 \text{ mmHg}$) and non-LVDD group ($\text{PAWP} < 25 \text{ mmHg}$).

The 6-minute walk test (6MWT) was performed according to American Thoracic Society guidelines without supplemental O_2 a day before RHC.

Echocardiography

A transthoracic Doppler echocardiogram at the resting state was obtained and stored digitally on an Artida (Toshiba, Tokyo, Japan) or EPIQ (Philips Healthcare, Cambridge, MA USA) ultrasound system within 3 months of the RHC. Each patient was given a unique identification number to ensure that the analysis of images could be performed blinded to all invasive data and patient characteristics. The frame rate was maintained at a minimum rate of 60 frames per second. For Doppler recordings, the average of 3 to 5 consecutive beats was measured using a horizontal sweep of 75 to 100 cm/s.

Left ventricular (LV) dimensions and left atrial diameter (LAD) were measured from the lv. The LV mass was calculated and indexed to BSA. Left ventricular ejection fraction (LVEF) was calculated using Simpson's biplane method from the apical 4- and 2-chamber views.

The left atrium (LA) maximal and LA minimal volumes were estimated from the apical 4- and 2-chamber views using biplane planimetry. LA maximal volume was measured from the frame just before the mitral valve opening, and LA volume index (LAVi) was indexed for BSA.

Mitral inflow was assessed in the apical 4-chamber view with the pulsed-wave Doppler sample volume placed at the tips of the mitral valve leaflets during diastole; the early (E) and late (A) peak diastolic velocities of the mitral inflow and the E wave deceleration time were thus measured. Mitral annular motion was assessed using pulsed-wave tissue Doppler with the sample volume placed in the septal (e' septal) and lateral mitral annulus (e' lateral). The E/e ratio was calculated.

The right ventricular (RV) systolic function was assessed by measuring the tricuspid annular plane systolic excursion (TAPSE). The RV end-diastolic area (RVEDarea) and end-systolic area (RVESarea) were assessed by manual planimetry in the apical 4-chamber view, and the RV fractional area change (RVFAC) was derived using the formula: $RVFAC = [(RVEDarea - RVESarea) / RVEDarea] \times 100^{21}$.

Statistical analysis

Continuous variables are expressed as mean \pm standard deviation (SD) or median with interquartile ranges (Q1–Q3) as appropriate. Categorical variables are expressed as numbers and percentages. Group comparisons were made using Student's t-test or Mann-Whitney U test, as appropriate, for continuous variables and χ^2 statistics or Fisher's exact test, as appropriate, for categorical variables. Receiver operating characteristic (ROC) curves among resting hemodynamic parameters were drawn, and the area under the curve (AUC) was calculated. The cut-off value that resulted in the highest product sensitivity and specificity was considered the best for the detection of exercise PAWP elevation. Statistical comparisons were considered significant at $p < 0.05$. All analyses were performed using SPSS statistical software (version 26.0; IBM Corp., Armonk, NY, USA).

Declarations

Acknowledgements

We would like to thank Editage (www.editage.com) for English language editing.

Author contributions

A.G. and T.M. designed the study, analysed the data, and wrote the manuscript. T.K., K.S., T.S., and K.S. reviewed the data and edited the manuscript. S.T., H.K., and T.I. performed the exercise tests.

Funding

This work was supported by no specific grant from any funding agency.

Declaration of interest

The authors have no potential conflict of interest related to any company or organization whose products or services are discussed in this article.

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Tables

Table 1: Baseline Characteristics of the Study Patients

	Occult-LVDD (n=13)	Non-LVDD (n=32)	P value
Age, years	68 ± 9	60 ± 14	0.023
Sex, male/female	2/11	4/28	0.567
BW, kg	55 ± 7	55 ± 12	0.892
Duration from diagnosis, (years)	4 (2–8)	8 (3–14)	0.179
6-minute walk distance, (m)	409 (380–473)	358 (280-474)	0.280
<i>Co-morbidities</i>			
Hypertension, n, (%)	7, (54)	12, (38)	0.341
Hyperlipidaemia, n, (%)	3, (23)	4, (13)	0.394
Diabetes mellitus, n, (%)	2, (15)	2, (6)	0.567
Atrial fibrillation, n, (%)	2, (15)	1, (3)	0.196
Interstitial lung disease, n, (%)	2, (15)	9, (28)	0.311
<i>Blood analysis</i>			
BNP, pg/dL	65 (41–161)	28 (17–70)	0.008
Hemoglobin, g/dL	11.6 ± 1.8	12.8 ± 1.3	0.016
Autoantibodies (n=39)			
Anti-nuclear +, n, (%)	9, (75)	24, (83)	0.523
Anti-centromere +, n, (%)	8, (67)	13, (45)	0.440
Anti-SCL70 +, n, (%)	1, (8)	4, (14)	0.961
<i>Pulmonary function (n=37)</i>			
FEV1 % predicted	87 ± 19	83 ± 17	0.561
FVC % predicted	91 ± 23	89 ± 20	0.765
DLCO % predicted	63 ± 24	60 ± 18	0.678
DLCO/VA % predicted	75 ± 29	69 ± 23	0.517
%FVC/%DLCO	1.7 ± 1.1	1.6 ± 0.6	0.741
<i>Hemodynamic parameter (flat position)</i>			
Mean RAP, mmHg	4 ± 2	3 ± 2	0.076
Systolic PAP, mmHg	30 ± 6	31 ± 7	0.646

Diastolic PAP, mmHg	8 ± 3	8 ± 4	0.898
Mean PAP, mmHg	18 ± 4	17 ± 4	0.618
PAWP, mmHg	10 ± 3	7 ± 3	< 0.001
TPG, mmHg	8 ± 4	11 ± 4	0.045
DPG, mmHg	-2 ± 2	1 ± 4	0.004
SaO ₂ , %	95 ± 2	96 ± 2	0.317
SvO ₂ , %	72 ± 4	73 ± 6	0.448
Cardiac output, L/min	4.8 ± 1.1	4.5 ± 1.5	0.479
PVR, Wood units	1.7 ± 0.8	2.5 ± 1.1	0.020

Values are reported as means ± standard deviation (SD), or medians (25th, 75th interquartile ranges), where appropriate.

BW, body weight; DPG, diastolic pulmonary pressure gradient; LVDD, left ventricular diastolic dysfunction; RAP, right atrium pressure; PAP, pulmonary artery pressure; PAWP, pulmonary artery wedge pressure; PVR, pulmonary vascular resistance; SaO₂, O₂ saturation in arterial blood; SvO₂, O₂ saturation in the pulmonary artery; TPG, transpulmonary pressure gradient; %FEV1: forced expiratory volume in 1 s %predicted, %FVC: forced vital capacity %predicted, %DLCO: diffusing capacity of the lung for carbon monoxide %predicted; DLCO/VA % predicted: diffusing capacity divided by the alveolar volume.

Table 2. Haemodynamic Parameters at rest (after leg raise), anaerobic threshold, and peak exercise

	Occult-LVDD (n=13)	Non-LVDD (n=32)	P value
<i>Rest after leg raise</i>			
HR, bpm	69 ± 10	74 ± 14	0.251
Systolic PAP, mmHg	40 ± 9	34 ± 8	0.027
Diastolic PAP, mmHg	13 ± 5	9 ± 4	0.012
Mean PAP, mmHg	24 ± 6	21 ± 5	0.121
PAWP, mmHg	15 ± 4	10 ± 4	< 0.001
ΔPAWP (pre-leg raise), mmHg	6 ± 2	3 ± 4	< 0.001
Cardiac output, L/min	5.2 ± 1.2	5.4 ± 3.5	0.882
PVR, Wood units	1.7 ± 0.8	2.5 ± 1.3	0.014
SaO ₂ , %	96 ± 1	96 ± 3	0.801
SvO ₂ , %	70 ± 4	71 ± 6	0.473
VO ₂ , mL/min	211 ± 49	204 ± 70	0.764
VCO ₂ , mL/min	173 ± 43	173 ± 57	0.997
R	0.81 ± 0.06	0.84 ± 0.07	0.148
VE, L/min	8.3 ± 2.7	8.1 ± 2.6	0.850
VE/VO ₂	39.9 ± 10.2	42.2 ± 11.3	0.537
VE/VCO ₂	49.2 ± 10.8	49.9 ± 11.4	0.852
<i>Anaerobic Threshold</i>			
Work Rate, Watts	28 ± 19	29 ± 22	0.837
HR, bpm	97 ± 17	104 ± 21	0.357
Systolic PAP, mmHg	56 ± 11	54 ± 12	0.478
Diastolic PAP, mmHg	17 ± 5	15 ± 5	0.189
Mean PAP, mmHg	37 ± 7	33 ± 8	0.199
PAWP, mmHg	25 ± 5	16 ± 5	< 0.001
Cardiac output, L/min	7.7 ± 1.9	8.6 ± 4.1	0.372
PVR, Wood units	1.6 ± 0.8	2.4 ± 1.2	0.016

SaO ₂ , %	97 ± 3	95 ± 4	0.371
SvO ₂ , %	52 ± 4	54 ± 7	0.277
VO ₂ , mL/min	528 ± 153	598 ± 332	0.493
VCO ₂ , mL/min	502 ± 142	358 ± 323)	0.552
R	0.98 ± 0.14	0.98 ± 0.14	0.971
VE, L/min	20.3 ± 6.6	20.1 ± 8.4	0.935
VE/VO ₂	40.9 ± 16.3	39.9 ± 12.5	0.838
VE/VCO ₂	42.8 ± 12.6	42.1 ± 11.4	0.846
Peak			
Work Rate, Watts	54 ± 24	60 ± 32	0.585
HR, bpm	108 ± 23	117 ± 26	0.318
Systolic PAP, mmHg	63 ± 9	58 ± 13	0.189
Diastolic PAP, mmHg	17 ± 7	17 ± 7	0.835
Mean PAP, mmHg	41 ± 7	36 ± 9	0.068
PAWP, mmHg	28 ± 4	16 ± 5	< 0.001
Cardiac output, L/min	8.8 ± 1.9	10.3 ± 5.7	0.359
PVR, Wood units	1.6 ± 0.7	2.2 ± 1.2	0.086
SaO ₂ , %	96 ± 4	95 ± 5	0.463
SvO ₂ , %	48 ± 8	49 ± 8	0.637
VO ₂ , mL/min	654 ± 205	823 ± 613	0.340
VCO ₂ , mL/min	716 ± 232	924 ± 773	0.349
R	1.10 ± 0.16	1.09 ± 0.15	0.779
VE, L/min	31.0 ± 9.7	33.4 ± 19.4	0.671
VE/VO ₂	49.4 ± 18.6	44.7 ± 12.6	0.328
VE/VCO ₂	44.8 ± 12.3	41.0 ± 10.7	0.305
Peak VO ₂ , mL/kg/min	12.4 ± 3.9	15.0 ± 10.2	0.365
VE vs. VCO ₂ slope	38.2 ± 14.4	38.2 ± 21.6	0.997

Values are reported as mean \pm standard deviation (SD).

BP, blood pressure; HR, heart rate; LVDD, left ventricular diastolic dysfunction; PAP, pulmonary artery pressure; PAWP, pulmonary artery wedge pressure; PVR, pulmonary vascular resistance; SaO₂, O₂ saturation in arterial blood; SvO₂, O₂ saturation in the pulmonary artery; VO₂, oxygen consumption; VCO₂, carbon dioxide output; R, respiratory exchange ratio; VE, minute ventilation.

Table 3. Echocardiographic Parameters

	Occult-LVDD (n=13)	Non-LVDD (n=32)	P value
LVEF, %	69 \pm 6	65 \pm 5	0.018
LV mass index, g/m ²	112 \pm 45	90 \pm 21	0.043
LAD, mm	39 \pm 7	33 \pm 5	0.005
LAVi, mL/m ²	53 \pm 20	39 \pm 13	0.033
E, cm/s	74.2 \pm 24.3	67.1 \pm 17.0	0.088
A, cm/s	87.4 \pm 19.7	72.6 \pm 16.3	0.016
E/A	0.9 \pm 0.2	1.0 \pm 0.3	0.367
DcT, cm/s	193 \pm 47	206 \pm 47	0.419
E' septal, cm/s	6.9 \pm 2.1	6.9 \pm 2.5	0.965
E/e' septal, cm/s	12.1 \pm 3.9	10.7 \pm 3.9	0.282
E' lateral, cm/s	8.3 \pm 1.8	9.0 \pm 2.3	0.376
E/e' lateral, cm/s	9.3 \pm 3.0	7.8 \pm 2.3	0.076
TAPSE, mm	24 \pm 4	22 \pm 3	0.165
RV FAC, %	42 \pm 9	40 \pm 8	0.085

Values are reported as mean \pm standard deviation (SD).

DcT, deceleration time; LAD, left atrial diameter; LAVi, left atrium volume index; LVDD, left ventricular diastolic dysfunction; LVEF, left ventricular ejection fraction; LV mass index, left ventricular mass index; RV FAC, right ventricular fractional area change; TAPSE, tricuspid annular plane systolic excursion.

Figures

Figure 1

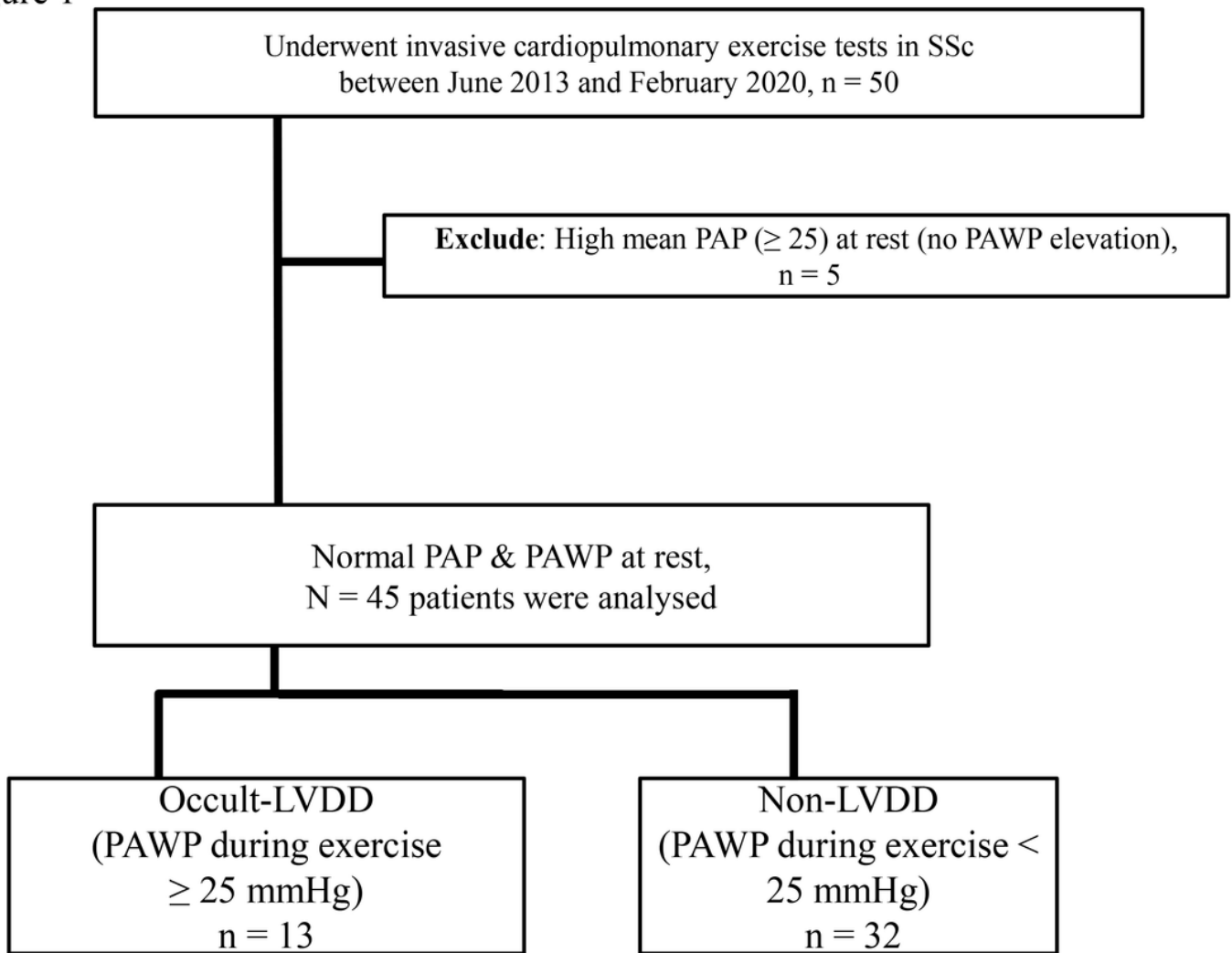


Figure 1

Flow chart of patients with SSc who underwent cardiopulmonary exercise testing with right heart catheterization LVDD, left ventricular diastolic dysfunction; PAP, pulmonary artery pressure; PAWP, pulmonary artery wedge pressure; PH, pulmonary hypertension; SSc, systemic sclerosis

Figure 2

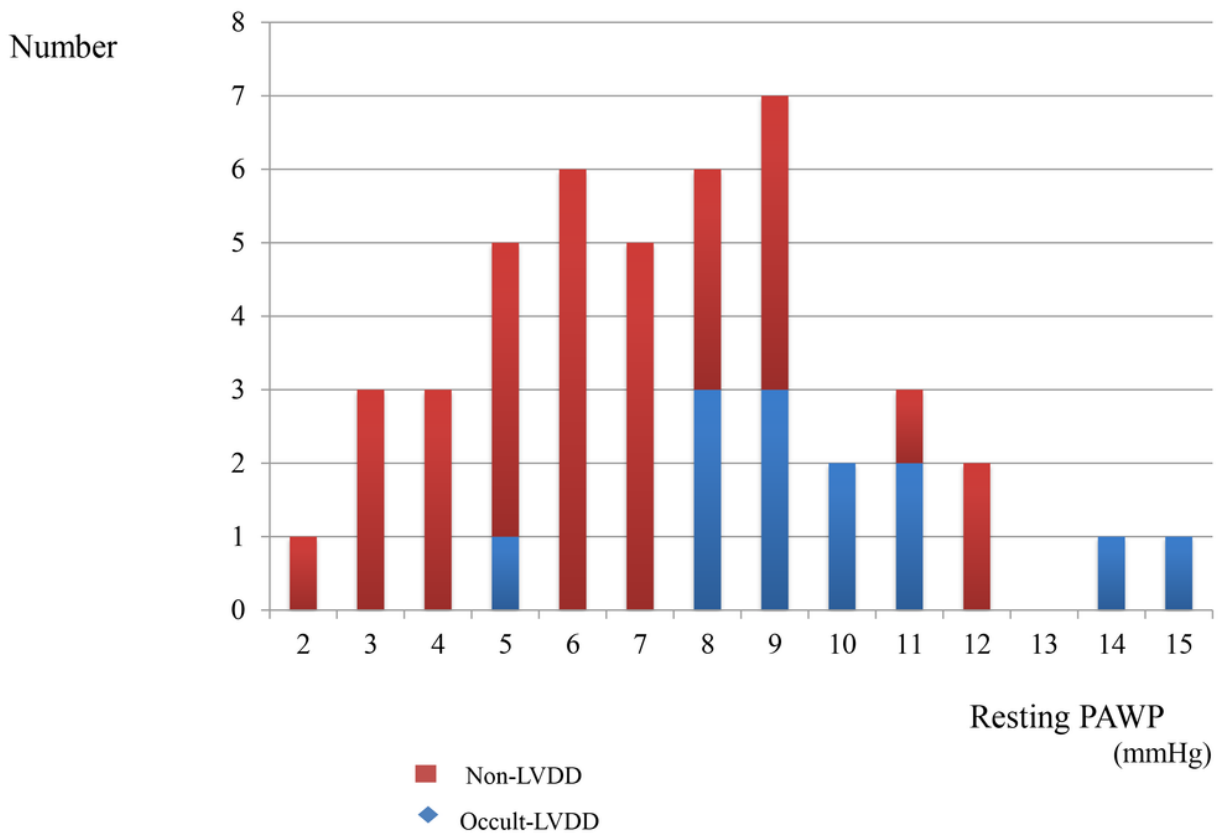


Figure 2

Distributions of the resting PAWP and exercise PAWP elevation LVDD, left ventricular diastolic dysfunction; PAWP, pulmonary artery wedge pressure

Figure 3

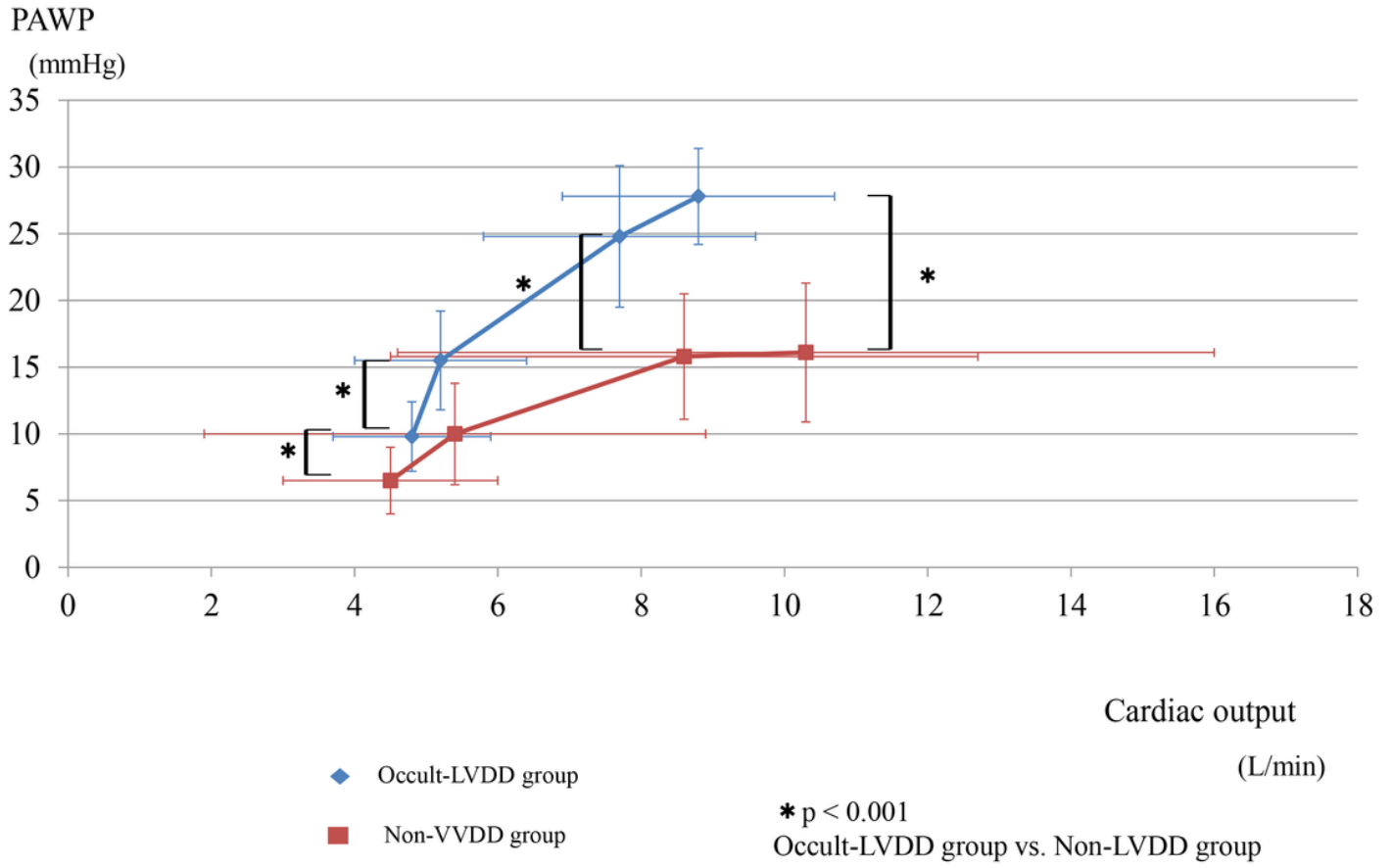


Figure 3

Relationships of the cardiac output to PAWP LVDD, left ventricular diastolic dysfunction; PAWP, pulmonary artery wedge pressure

Figure 4

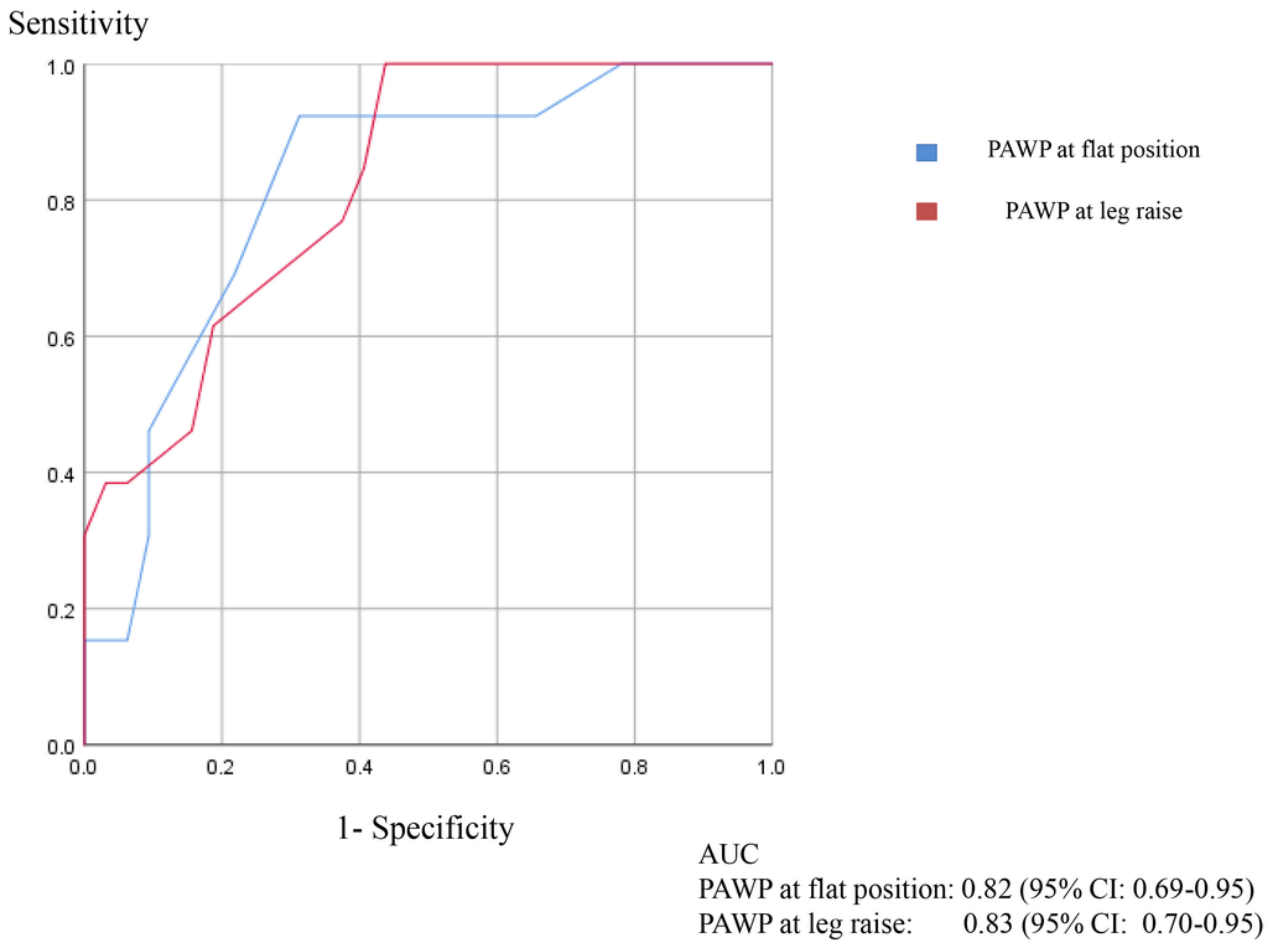


Figure 4

Receiver operating characteristic curves of PAWP at flat position and PAWP at leg raise AUC, area under the curve; CI, confidence interval; PAWP, pulmonary artery wedge pressure