Impact of Baseline Hemodynamics on the Effects of a

Transcatheter Interatrial Shunt Device in Heart Failure with Preserved Ejection Fraction

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ABSTRACT

Background:

InterAtrial Shunt Device (IASD) effects have been described in patients with heart failure (HF) and ejection fractions (EFs) ≥40%. However, baseline characteristics that correlate with greatest hemodynamic effects are unknown. Based on fundamental principles we hypothesized that larger pressure gradients between left and right atria would yield greater shunt flow and greater hemodynamic effects.

Methods and Results:

REDUCE LAP-HF was a multicenter study that investigated IASD safety and performance. 64 patients with EF≥40% underwent device implantation followed by hemodynamic assessments at rest and exercise, including pulmonary capillary wedge pressure (PCWP, surrogate for LA pressure) and central venous pressure (CVP). At 6 months, IASD resulted in an average Qp:Qs of 1.27 and increased exercise tolerance. The PCWP-CVP gradient (i.e., the driving pressure for shunt flow) decreased at peak exercise from 16.8±6.9 to 11.4±5.5 mmHg, because of increased CVP (17.5±5.4 to 20.3±7.9 mmHg, p=0.04) and decreased PCWP (34.1±7.6 to 31.6±8.0 mmHg, p=0.025). Baseline PCWP-CVP gradient during exercise correlated with changes of both PCWP-CVP and PCWP: $\Delta(\text{PCWP-CVP})=10.0-0.89\cdot(\text{PCWP-CVP})_{\text{baseline}}$ ($r^2=0.56$) and $\Delta\text{PCWP}=7.54-0.60\cdot(\text{PCWP-CVP})_{\text{baseline}}$ (p=0.001). Hemodynamics of patients with EF≥50% and those with EF<50% responded similarly to IASD.

Conclusion:

In HF patients with EF≥40%, IASD significantly reduced PCWP and PCWP–CVP at peak exercise. Patients with higher baseline PCWP-CVP gradient had greater reductions in both parameters at

follow-up. Results were sustained through 12 months and were independent of whether EF was ≥50% or between 40-49%. Additional studies will help further define the baseline hemodynamic predictors of exercise, hemodynamic and clinical efficacy of the IASD.

Clinical Trial Registration Information:

NCT01913613 **https://clinicaltrials.gov/ct2/show/NCT01913613**

COMMENTARY

What is new?

Interatrial shunts devices (IASD) have been shown to reduce work-normalized pulmonary capillary wedge pressure during exercise and are being further investigated as a therapy for patients with heart failure and preserved ejection fraction. However, baseline factors that correlate with greatest reductions of PCWP are not known. We show that the greater the difference between pulmonary capillary wedge pressure and central venous pressure (PCWP-CVP, which is the driving force for flow through the shunt) the greater is the reduction on this pressure gradient and the greater the reduction of PCWP at peak exercise.

What are the clinical implications?

IASDs have already received Conformité Européene (CE) marking in the European Union and are being investigated in the United States. The current results may help guide clinicians on how to evaluate and identify pateints who are most likely to benefit, at least in terms of reductions of PCWP. Additional work is ongoing to determine if reductions of PCWP correlate with clinical outcomes.

INTRODUCTION

Heart failure (HF) with preserved (HFpEF) accounts for more than half of all cases of HF with a prevalence that continues to increase.[1] This rising burden has been accompanied by disappointing therapeutic results as effective treatment options remain elusive.[2] As the exploration of alternative management options continues, increasing emphasis has been placed on the multitude of HFpEF phenotypes and the wide range of mechanisms that contribute to the common spectrum of signs and symptoms.[3]

However, regardless of etiology, HFpEF patients all demonstrate excessive increases in left atrial pressures in particular during exercise which contributes to effort intolerance and portends a worse prognosis.[4-8] The understanding of the mechanisms underlying such hemodynamic changes has evolved from the now outdated singular concept of diastolic dysfunction to include abnormalities in blood volume regulation, increased pericardial restraint and increased sensitivity of blood volume distribution to acute neuro-hormonal stimulation during exercise[3, 9-14] and volume loading.[6, 15, 16] While many gaps in understanding remain, these studies have led to the concept that exercise-induced increase of left atrial pressure is a viable therapeutic target for these patients.[17-21]

We recently introduced a device-based therapeutic strategy that establishes an interatrial communication to allow left-to-right shunting and reduce left atrial pressure.[17, 22-27] Fundamentally, an interatrial shunt will reduce the pressure gradient between the left and right atria. In the setting of heart failure, where left atrial pressure (for which pulmonary capillary wedge pressure [PCWP] serves as a surrogate) is elevated above right atrial pressure (and its equivalent, central venous pressure [CVP]) a left-to-right shunt is expected and has been

demonstrated in our initial clinical studies with the InterAtrial Shunt Device (IASD) including a randomized controlled trial.[23, 24, 27] However, the baseline characteristics that are associated with better hemodynamic and clinical outcomes have not been identified. Basic principles and theories of shunt hemodynamics[17] suggest that at a given diameter, shunt flow and the ability to reduce left atrial pressure is driven by the pre-existing pressure gradient between atria, which is indexed by the difference between PCWP and CVP. Accordingly, the purpose of the present study was to better define changes in PCWP, CVP and their difference in response to exercise and test whether the PCWP-CVP gradient correlates with hemodynamic response to IASD.

Methods

The data and study materials from this study will not be made available to other researchers.

Study design and subjects

The REDUCE LAP-HF study was a multicenter, prospective, open-label, single-arm study designed to investigate the safety and performance of a transcatheter, transvenous InterAtrial Shunt Device (IASD system II, Corvia Medical Inc, Tewksbury, MA, USA). The study design has been previously described in detail.[22] The data, analytic methods, and study materials will be made available to other researchers for purposes of reproducing the results or replicating the procedure.

Patients with heart failure and EF ≥40% (assessed by the clinical site) were eligible for study inclusion if they were adults (aged >40 years) with evidence of chronic symptomatic heart failure [New York Heart Association (NYHA) functional class II–IV] and increased PCWP (>15 mmHg at

rest, or >25 mm Hg during supine bicycle exercise) measured during right heart catheterization (RHC). Patients were excluded for substantial right ventricular dysfunction indexed by elevated central venous pressure (CVP > 14 mmHg) or tricuspid annular plane systolic excursion below 14 mm; as well as for recent (<3 months) myocardial infarction, coronary artery bypass graft, or percutaneous coronary intervention; non-ambulatory NYHA IV heart failure; infiltrative or obstructive hypertrophic cardiomyopathy; moderate or greater aortic stenosis or mitral regurgitation; and severe renal dysfunction. The study protocol was approved by the ethics and instutional review committees at each institution and country-specific competent authorities and all patients gave informed consent. The study from which the data are derived is registered with ClinicalTrials.gov, identifier number NCT01913613.

The EF inclusion criterion for HFpEF was consistent with prior studies (see for example[28]). However, subsequent to the start of the present study, new guidelines were published that defined HFpEF as EF≥50% and HFmrEF (heart failure with mid-range EF) as EF 40-49%. As detailed below, the impact of EF range on the results were examined.

Procedures

All patients underwent RHC with assessment of cardiac output and central hemodynamics [right atrial pressure (RAP), pulmonary artery pressure (PAP), and PCWP] at rest and during supine ergometry at the following time points: baseline, 6 months, and optionally at 12 months after device implantation. Right heart catheterization was performed from either an antecubital or internal jugular vein with a 7F or 8F sheath. Cardiac output was determined by thermodilution (at rest and during exercise) made at least in triplicate, and by Fick method at rest only; for the latter, oxygen consumption was assumed to be related to gender, age and heart rate according

to previously validated equation and calculated at the hemodynamic core lab to ensure consistency of calculation.[29] Following baseline resting hemodynamic measurements, measurements were taken 5 minutes after raising legs into the bicycle pedals and then during symptom-limited supine bicycle exercise starting at 20 watts (W) with 20W increments every 3 min until the patient achieved maximum effort (defined by symptom limiting dyspnea or fatigue). Resting blood samples were collected from the pulmonary artery and superior and inferior vena cavae at baseline and at follow-up to measure oxygen saturation for assessment of left-to-right shunting as indexed by the pulmonary-to-systemic blood flow ratio (Qp:Qs). For calculation of Qp:Qs, we assumed that mixed venous oxygen saturation (SMV) was determined by $SMV=(3\cdot S_{SVC}+S_{IVC})/4$ where S_{SVC} and S_{IVC} were blood oxygen saturations in the superior and inferior vena cavae, respectively. Qp:Qs was then calculated as $(S_A-S_{MV}) / (S_A-S_{PA})$ where S_A is the oxygen saturation of arterial blood S_{PA} is oxygen saturation of pulmonary arterial blood.

Device insertion was done within 45 days of screening evaluations. Implantation was performed percutaneously via the femoral vein on a separate occasion following hemodynamic qualification. Standard trans-septal puncture of the interatrial septum was performed using the operator's preferred technique, using fluoroscopy and transesophageal or intracardiac echocardiography, and the implant was inserted and positioned using an over-the-wire technique. The IASD had an internal diameter of 8 mm.

Outcomes

The primary objective of this study was to assess exercise-induced hemodynamic changes 6 and 12 months after device implantation. The hemodynamic endpoints measured were Qp:Qs, cardiac output, CVP, PAPs, PCWP, pulmonary vascular resistance (PVR) and aortic pressures.

Resting forward cardiac output was assessed by indirect Fick method using the estimated MVS (as quantified above). Hemodynamic tracings were analyzed at an independent core laboratory (PVLoops LLC, NY, USA).

Analyses

Hemodynamic tracings at each stage of exercise were printed, scanned and sent to a core lab for independent quantification of pressures at rest and at each stage of exercise. Baseline and follow-up tests were read independently of each other in order to reduce bias.

Normally distributed data are presented as mean (SD) and non-parametric data as median (IQR). We used a paired *t* test or Wilcoxon matched pair sign-rank test as appropriate to compare follow-up data versus baseline data. Linear regression analysis was applied to data at peak exercise and compared to baseline data by analysis of covariance (ANCOVA). The null hypothesis was rejected at $p<0{\cdot}05$.

Since the primary driver of flow through an IASD the pressure gradient between RA and LA, we examined the baseline PCWP-CVP difference and how it changed in response to the presence of the IASD. Secondly, to understand the determinants of changes in the PCWP-CVP gradient, we examined plots of CVP vs PCWP to better elucidate the simultaneous impact of exercise on right and left-sided hemodynamics before and after IASD implant. As in prior studies [30, 31] we divided the PCWP-CVP diagram into 5 quadrants (or zones) at rest and during exercise corresponding with different states of left- and right-sided congestion: a normal zone with normal CVP and PCWPs; a zone of primary left-sided congestion with elevated PCWP and normal CVP; a zone of primary right-sided congestion with elevated CVP and normal PCWP; a zone with right- and left-

sided congestion with elevated CVP and PCWP; and a state of relative hypovolemia with both CVP and PCWP below the normal lower limits (detailed further below). Based on recently published resting and exercise data,[8, 32, 33] normal upper limits for CVP and PCWP at rest were set at 10 and 15 mmHg, respectively. Normal upper limits for CVP and PCWP during exercise were set at 16 and 26 mmHg, respectively. Finally, to assess the IASD operating characteristics, we explored hemodynamic factors that correlated with reductions of the PCWP-CVP gradient and reductions of PCWP at rest and during exercise.

The data, analytic methods, and study materials will not be made available to other researchers for purposes of reproducing the results or replicating the procedure.

Results

Sixty-four patients underwent implantation of the IASD system. The demographics have been detailed previously [23, 24] and are summarized briefly in Table 1, in which demographics are also compared between patients with EF ≥50% and patients with EF < 50%. There were no significant differences in clinical characteristics between these two subgroups (additional details below) except for a greater proportion of NYHA III patients in the EF<50% group (36% versus 72%).

The group-averaged resting and peak exercise hemodynamic parameters at baseline and 6 months post-IASD are summarized in Table 2. Most of these data have been described previously.[23] In brief, the key hemodynamic effects of IASD under resting conditions included a Qp:Qs (calculated from vena caval and pulmonary artery oxygen saturations) of 1.27±0.24 which resulted in increased resting cardiac output measured by thermodilution (indicative of flow

through the pulmonary circulation) and no change in resting cardiac output assessed by indirect Fick method (indicative of flow to the systemic circulation). There was a small increase in resting CVP and a small decrease in resting PCWP. In the majority of patients, the PCWP-CVP pressure difference decreased from baseline to 6 months following the IASD implant (Fig. 1A; note that in this and subsequent figures, the red symbols represent data from patients with EF≥50% while black symbols represent patients with EF<50%). However, there was noticeable variability and the pressure gradient increased in some patients.

Peak exercise tolerance increased 6 months following IASD from 42.5±18.3 at baseline to 49.0±20.3 Watts at 6 months ($p=0.002$). Work- and weight-normalized PCWP (PCWP/(Watts/Kg)) decreased significantly from 89.1±53.5 at baseline to 70.5±42.8 at 6 months post-IASD ($p<0.001$). As was the case at rest, the CVP at peak exercise increased while PCWP decreased. Also, as was the case at rest, the PCWP-CVP pressure difference at peak exercise decreased 6 months following IASD implant, and there was significant variability (Fig. 1B).

CVP-PCWP relationships at rest and exercise

A further understanding of the impact of the IASD was revealed upon examining the relationship between CVP and PCWP in individual patients as illustrated in Fig. 2A and as summarized in Table 3. At baseline in the resting state, 37% of patients fell in the normal zone with PCWP and CVP within normal limits. 27% of patients were in the zone with ↑PCWP and normal CVP, and 34% in the ↑PCWP/↑CVP zone. Six months following IASD, resting CVP and PCWP were more closely correlated to each other than at baseline (Fig. 2B); the percent of patients in the normal zone

was similar to baseline but there was a lower percentage of patients in the ↑PCWP quadrant and an increased percentage in the ↑PCWP/↑CVP quadrant (Fig. 2B, Table 3).

During exercise at baseline, and accounting for exercise-appropriate normal upper limits, 8% of patients fell in the normal hemodynamic quadrant, 33% were in the ↑PCWP quadrant, and 59% were in the combined ↑PCWP/↑CVP quadrant (Fig. 2C, Table 3). At 6-months following IASD implant, there was a greater percentage of patients in the normal quadrant, fewer in the ↑PCWP quadrant and similar numbers in the ↑CVP and ↑PCWP/↑CVP quadrants (Fig. 2D, Table 3). Linear regression analysis applied to the data at peak exercise showed that the PCWP-CVP relationship was shifted downward by ~4.7 mmHg at 6 months compared to baseline by ANCOVA which yielded the following regression coefficients: PCWP = 20.9(1.7) - 4.7(1.1)·Treatment + 0.76(0.08)·CVP (values in parenthases are standard errors of respective coefficients), where Treatment is a dummy variable that equals 0 for data obtained at baseline (prior to IASD) and 1 for data obtained at 6 months following IASD ($p<0.0001$ for all coefficients). In contrast, there was no impact of treatment on the slope of this relationship ($p=0.65$).

Exercise-induced increases in PCWP were greater than concomitant increases in CVP; this is important since it suggests that the pressure gradient driving left-to-right flow increases during exercise and that the IASD-mediated reductions in PCWP will be greater during exercise. There was a weak correlation between the increase of PCWP from rest to peak exercise (ΔPCWP) and the increase of CVP from rest to peak exercise (ΔCVP): ΔPCWP = 13.7(1.8)+0.38(0.19)·ΔCVP ($p=0.05$, $r2=0.065$. Six months following IASD these two parameters became more tightly correlated, presumably because of the communication between right and left atria: ΔPCWP = 11.0(1.0) + 0.45(0.09)·ΔCVP.

Hemodynamic correlations with IASD induced reductions in left-to-right pressure gradient

The driving force for flow though the IASD is the pressure gradient between the LA and RA which is estimated by the difference between PCWP and CVP. We therefore hypothesized that a greater baseline PCWP-CVP difference should be associated with greater shunting and a greater reduction of this gradient. Notably, there were no statistically significant correlations between baseline values of hemodynamics at rest and changes in PCWP-CVP or changes in PCWP from data measured. However, at peak exercise where PCWP-CVP differences were greater, there was an inverse relationship between baseline peak exercise PCWP-CVP pressure gradient and the change of this gradient from baseline to 6 months (Δ(PCWP-CVP), Fig. 3A): $\Delta(\text{PCWP-CVP}) = 10.0(1.9) - 0.89(0.11)\cdot(\text{PCWP-CVP})_{\text{baseline}}$ (r^2=0.56, p<0.001). Δ(PCWP-CVP) at peak exercise was also inversely correlated with baseline peak exercise PCWP (Fig. 3B): $\Delta(\text{PCWP-CVP}) = 11.1(4.4) - 0.46(0.13)\cdot\text{PCWP}_{\text{baseline}}$ (r^2=0.18, p<0.001). Finally, Δ(PCWP-CVP) at peak exercise was inversely correlated to Qp:Qs measured 6 months following IASD implant (Fig. 3C): $\Delta(\text{PCWP-CVP}) = 10.9(5.3) - 11.9(4.1)\cdot\text{Qp:Qs}$ (p=0.005, r^2 = 0.13). Thus, the greater the Qp:Qs, the greater the reduction of the PCWP-CVP pressure gradient.

Importantly, the reduction of peak exercise PCWP at 6 months compared to baseline (ΔPCWP) was also correlated with the baseline peak exercise PCWP-CVP pressure gradient (Fig. 4): $\Delta\text{PCWP} = 7.54(2.5) - 0.60(0.14)\cdot(\text{PCWP-CVP})$ (p=0.001, r^2=0.23). Thus, the greater the driving pressure for shunt flow, the greater the reduction in peak exercise PCWP at 6 months.

Correlations between hemodynamics and exercise tolerance

While neither baseline hemodynamic nor clinical characteristics correlated with changes in the amount of exercise performed, there was a significant correlation between the change in PCWP and the change in work- and weight-normalized peak PCWP [i.e., PCWP/(Watts/kg)]: Δ[PCWP/(Watts/kg]=-15.7(4.7) + 1.5(0.6)·ΔPCWP (p=0.01).

HFpEF versus HFmrEF

As noted above, using an ejection fraction of ≥50% to define patients with HFpEF and <50% to define HFmrEF, there were no significant differences in baseline characteristics noted in Table 1. In addition, there were no differences in most of the baseline hemodynamic parameters (including CO, pulmonary vascular resistance and blood pressure or any resting hemodynamic parameters). However, at peak exercise, compared with the HFpEF group, CVP (18.8±5.1 vs 15.15.2, p=0.011) and PCWP (35.6±7.9 vs 31.3±6.3, p=0.029) were higher in the HFmrEF group. Nevertheless, the PCWP-CVP gradient did not differ between groups (16.9±6.8 mmHg for HFmrEF vs 16.6±7.1 mmHg for HFpEF, p=0.76). At 6 months follow up, the PCWP-CVP difference decreased to 11.8±4.2 for HFmrEF and 11.0±6.5 for HFpEF (p=ns). Regarding exercise tolerance, work- and weight-normalized PCWP values at baseline were 92.2±57.7 and 87.2±49.2 (mmHg/Watt/kg) and these decreased to 73.8±44.7 and 69.0±39.0 in HFmrEF and HFpEF, respectively (p=ns for differences between HFpEF and HFmrEF groups). Thus, while there were differences in baseline demographics and hemodynamics between patients segregated by EF, there were no differences in any of the hemodynamic and exercise responses to IASD. Similarity

of responses to IASD in these two groups is appreciated visually in Figs. 1, 3 and 4, where data from patients of the two groups are shown with different colored symbols.

Hemodynamics at 12-month follow-up

Eighteen (18) patients underwent a protocol-specified optional repeat exercise hemodynamic evaluation at 12 months post IASD implantation. Results, summarized in Table 4, show that the impact on hemodynamics and exercise tolerance observed at 6 months were sustained at 12 months. However, even with the smaller number of patients the decrease in work- and weight-normalized PCWP was statistically significant.

Effect of changes of diuretic therapy

It was previously reported that the median dose of orally administered furosemide at baseline was 40 mg per day (interquartile range 0-80).[23] Although the median dose did not change over the 6-month follow up period so that the median change was 0 mg/day, diuretic doses were increased in 11 patients that resulted in an interquartile range from 0 to 15 mg/day. When analyzed separately, patients in whom diuretic dose either remained the same or was decreased experienced an average 4 mmHg reduction in PCWP-CVP compared to an average 5 mmHg reduction in the patients whose diuretic dose was increased (p=0.55). Thus, changes in diuretic dose did not impact the main findings described above.

Discussion

This study examined the detailed effects of an interatrial shunt on resting and exercise hemodynamics in patients with a range of EFs spanning current definitions of HFpEF and HFmrEF. The analysis expanded the high level hemodynamic results presented in prior publications.[23, 24] Fundamentally, what an IASD can do is to reduce the difference between PCWP and CVP by allowing blood to flow from LA to RA; in principle, the reduced pressure gradient results from both a decrease of PCWP and an increase of CVP. Accordingly, the focus of the present study was on understanding the hemodynamic determinants of IASD-mediated reductions of PCWP-CVP gradient, CVP and PCWP.

First, the PCWP-CVP gradient under resting conditions is relatively small. Consequently, at 6 months after IASD implantation, there was a relatively small, though statistically significant reduction of the resting PCWP-CVP gradient, an increase in CVP but no reduction of PCWP. However, resting values of CVP and PCWP were more closely correlated to each other after IASD implantation compared to baseline. Importantly, baseline resting data did not correlate with hemodynamic effects of IASD at rest noted at 6 months. At baseline (prior to IASD implantation) while elevations of CVP were quite significant during exercise, increases of PCWP were greater, so that the PCWP-CVP pressure difference increased dramatically during exercise. Consequently, the impact of the IASD on the PCWP-CVP gradient, PCWP and CVP were quantitatively larger during exercise than at rest. As expected from theory[17] the greater the PCWP-CVP difference, the greater the hemodynamic effects of IASD, on reducing both the PCWP-CVP gradient and on PCWP itself. Also consistent with theory, the greater the Qp:Qs, the greater the reduction of the PCWP-CVP difference.

The impact of IASD on PCWP at peak exercise needs to be considered within the context the change in exercise performance. Peak exercise tolerance is limited when PCWP rises with exercise beyond a threshold. The IASD does not change that threshold level. Thus, a tight correlation between changes in PCWP and changes in exercise tolerance is not expected. Instead, PCWP may approach a similar threshold at peak exercise following IASD. This was indeed the case: there were both reductions of PCWP and increases in average Watts. It is for this reason that we turn to the work- and weight-normalized PCWP (PCWP/(Watts/kg)) to assess the impact of IASD on exercise performance. Lower values of this parameter have been associated with improved clinical outcomes in patient with HFpEF.[7, 34]

While baseline characteristics and hemodynamics differed between patients with EF≥50% and those with EF<50%, the impact of the IASD on hemodynamics and exercise were indistinguishable between the two groups, a finding what is also supported by theory (i.e., that the IASD lowers PCWP by decompressing the overloaded left atrium, a pathophysiologic finding that is common in HFpEF and HFmrEF).

Finally, all effects noted at 6 months were sustained through the 12 month follow up visit in the subset of patients who agreed to undergo optional repeat evaluation.

The findings noted above have implications for the inclusion and exclusion criteria for selecting patients most likely to respond, at least hemodynamically, to IASD. First, hemodynamic effects of IASD are not predicted by any parameter measured at rest; one must stress the cardiovascular system with exercise to identify hemodynamic derangements that identify favorable responders. This mirrors the diagnostic evaluation of HFpEF, where exercise assessment is necessary to identify hemodynamic perturbations that are often not apparent

from assessments at steady state where cardiovascular reserve is not stressed.[4, 6, 8] Second, during exercise, patients with larger differences in PCWP and CVP are more likely to exhibit reductions of PCWP. Finally, EF did not influence the hemodynamic effects over the range explored.

Two other observations deserve further discussion. First, as expected and reported previously, the presence of the shunt decreased PCWP at the expense of an increase in CVP both at rest and during exercise. Since exercise is episodic, the increase of CVP during exercise may not be associated with any clinical effects. CVP did not increase further between 6 and 12 months. The consequences of a rise of CVP during rest (which was on average 1.6 mmHg) on end organ function (e.g., renal, hepatic, etc) should be followed in long term studies. Secondly, there was no impact of IASD presence on pulmonary artery pressures or PVR, despite the increased flow through the pulmonary arteries. This suggests that there is no detrimental effect of the increased flow on the pulmonary vasculature and its ability to dilate in the face of increased flow through 12 months of follow up.

Several recent studies have highlighted the importance of understanding exercise hemodynamics in patients with HFpEF for guiding both the diagnosis and therapeutic developments.[2, 4-6, 16, 19-21, 35] Hemodynamics in many of these patients are relatively normal at rest (as in our study), but become rapidly abnormal upon initiation of mild exercise.[4-6, 13, 16, 20, 21, 35] The mechanisms underlying exercise intolerance in these patients is debated,[3, 13, 36] with many potential contributing factors. In addition to elevations of PCWP and limited capability to increase in stroke volume identified in many of the studies noted above, significant attention has also been placed on chronotropic incompetence.[37] However, all of these factors are inherently interrelated. Our

results obtained at baseline (prior to IASD implant) are in excellent quantitative agreement with all prior studies in that we observed marked increases in group averaged mean PCWP pressures, limited relative increases of peak exercise cardiac output to ~9 L/min [8, 35] (less than reported for age-matched normal subjects[33]) and low peak heart rates.

As in our study, marked elevations of CVP have been observed during exercise in prior studies noted above but the implications have not been discussed in detail.[38] This observation may hold additional clues as to the mechanisms of disease. On an individual patient basis, exercise-induced changes in CVP were substantially greater than reported previously in age matched normal subjects.[33] One recently proposed potential explanation for such CVP elevations is that patients with HFpEF and HFmrEF have impaired RV contractile reserve (i.e., inability to increase stroke volume) during exercise in addition to limited LV contractile reserve.[8] However, a an argument against this hypothesis is the fact that both pulmonary and systemic arterial pressures rise substantially during exercise, and more so than in normal subjects, which would not be possible if contractility of either ventricle were impaired or limited. For example, Santos observed increases in mean PAP to 41 mmHg in HFpEF patients (similar to our observed 45 mmHg) in comparison to a rise to only 30 mmHg in an age and gender matched control group.[33] Similar observations were made by Borlaug et al who reported an increase of mean PAP to 48 mmHg.[8] The increase in pressure in the face of limited increases in stroke volume suggests abnormal ventricular-vascular coupling,[8] rather than impaired contractile reserve. Another potential contributing mechanism may be exercise-induced, catecholamine-mediated splanchnic veno-constriction which redistributes blood from the peripheral splanchnic to the central circulation. An older hypothesis regarding the role of veno-constriction in the generation of elevated PCWP

and CVP in heart failure (regardless of ejection fraction)[39] has been recently revived, but not proven.[14] In support of such concept, a recent study demonstrated that in response to a rapidly infused bolus of saline, PCWP, mean PAP and right atrial pressures increase more significantly in HFpEF patients than in controls.[15] Although it has been suggested that such changes are indicative of intrinsic ventricular diastolic dysfunction, marked changes in filling pressure due to blood volume shifts can occur in the presence of normal intrinsic diastolic properties.[40] This is relevant to the current data since increases in venous return occurring during exercise due to neurohormonal-mediated veno-constriction would be far greater than those associated with the experimental infusion of saline noted above. Finally, most recently, it has been suggested that increased pericardial constraint may also contribute to this phenomenon, an effect that appears to be more pronounced among obese HFpEF patients.[16, 40] Pericardial constraint is sure to exacerbate changes in filling pressures induced by increased venous return.

Limitations

The main limitation of the present study is the lack of a parallel control group. Although the findings and conclusions of the present study are based on blinded assessment by a single core laboratory reader, non-IASD related changes in patient hemodynamic status over the follow up period cannot be excluded. This may include changes in compliance with diet and medical therapies; however, as noted in our analysis, changes in diuretic therapy from baseline to 6 months did not account for the observed hemodynamic predictors of IASD efficacy. The magnitude of shunting was not assessed during exercise, which would have provided additional insight and is worth examining in future studies.

Conclusions

In this heart failure patient population with EF>40%, both PCWP and CVP increased substantially during exercise, though the increases in PCWP were generally greater than those in CVP. Following IASD implantation with an average Qp:Qs of 1.27, PCWP and CVP became more strongly correlated with each other, a consequence of the hemodynamic communication with left to right flow between the atria. The IASD significantly reduced the PCWP–CVP pressure gradient at rest and at peak exercise, a result of small increases in CVP and larger decreases in PCWP. Work- and wight-normalized PCWP decreased significantly following the IASD. There was variability in hemodynamic responses to IASD among patients but, overall, there was a direct relationship between the peak exercise PCWP-CVP pressure gradient (i.e. the driving force for left-to-right flow) and the reduction of peak exercise PCWP observed at 6 months. These findings may have implications for selection of patients most likely to exhibit a chronic beneficial hemodynamic response to IASD implantation. As expected, the greater the Qp:Qs, the greater the reduction in PCWP-CVP gradient. Further investigations into the variability of Qp:Qs across the population is also important. Findings were the same in the HFmrEF and HFpEF subpopulations.

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Figure Legends

Figure 1. Difference between PCWP and CVP (an index of the estimated left-to-right atrial pressure gradient) at baseline and at 6 months, at rest (panel A) and at peak exercise (panel B). Most data points fall below the line of identity, indicating that the gradient is reduced at 6 months compared to baseline. Data from patients with ejection fraction ≥50 shown in red; data from patients with ejection fraction <50% shown in black.

Figure 2. Relationship between central venous pressure (CVP) and pulmonary capillary wedge pressure (PCWP) in individual patients at rest (panels A and C) and at peak exercise (panels B and D). Justification of values used for upper limits of normal for CVP and PCWP, which define the "normal" quadrant at rest and during exercise is provided in the text. Data are shown at baseline (panels A and B) and 6 months following InterAtrial Shunt Device (IASD, panels C and D). The PCWP-CVP diagram is divided into 5 quadrants (or zones) at rest and during exercise corresponding with different states of left- and right-sided congestion: a normal zone with normal CVP and PCWPs (green); a zone of primary left-sided congestion with elevated PCWP and normal CVP (pink); a zone of primary right-sided congestion with elevated CVP and normal PCWP (pink); a zone with right- and left-sided congestion with elevated CVP and PCWP (purple); and a state of relative hypovolemia with both CVP and PCWP below the normal lower limits (gray).

Figure 3. Baseline hemodynamic characteristics associated with an IASD-mediated reduction in the PCWP-CVP gradient at peak exercise include the baseline value of PCWP-CVP (panel A), PCWP itself (panel B) and the degree of shunting as quantified by the Qp:Qs (panel C). Data

from patients with ejection fraction ≥50 shown in red; data from patients with ejection fraction <50% shown in black.

Figure 4. The interatrial shunt-mediated reduction of pulmonary capillary wedge pressure (PCWP) at peak exercise was correlated with the baseline difference between PCWP and central venous pressure (CVP). The baseline value of the PCWP-CVP gradient is the force that drives flow through the shunt and reduces both the gradient and the value of PCWP itself. Data from patients with ejection fraction ≥50 shown in red; data from patients with ejection fraction <50% shown in black.

Table 1. Patient Characteristics

	All Patients	EF≥50%	EF<50%	p
	n=64	n=23	n=41	
Variable	Mean ± SD or %	Mean ± SD or %	Mean ± SD or %	
Age, years	69±8	69.7±7.7	69.4±8.8	0.90
Gender, (M/F)	42/22	15/8	27/14	0.75
NYHA Class (II/III)	27/73	9/14	9/32	0.01
BMI, kg/m2	33±6	32±4	33±7	0.35
Co-Morbidities				
Diabetes (%)	34	35	34	0.95
Hypertension (%)	81	80	81	1.00
Atrial fibrillation (%)	61	50	68	0.17
CAD (%)	23	20	24	1.00
MLWHFQ	49±20	46±18	51±20	0.32
Six Minute Walk Test (m)	309±108	335±111	294±106	0.16
Echocardiography (Core Lab)				
LV end diastolic volume index (ml/m2)	68±13	62±16	71±13	0.01
LVEF (%)	47±7	55±4	43±5	<0.001
LV mass index (g/m2)	119±36	117±39	120±35	0.81
LA volume index (ml/m2)	34±17	30±9	38±20	0.18
RV diastolic volume index (ml/m2)	22±9	21±8	23±9	0.24
RA volume index (ml/m2)	35±17	31±16	37±18	0.24
E/A ratio	1.3±0.8	1.2±0.6	1.4±0.9	0.37
E/e' ratio	13.9±5.9	13.7±4.3	14.0±6.7	0.88
TAPSE (mm)	20±4	21±3	20±5	0.37
NT-Pro BNP (pg/mL, median, IQR)	377 (222-925)	287 (100, 460)	572 (257, 1208)	0.09

Abbreviations: M/F, male/female; NYHA, New York Heart Association functional class; BMI, body mass index; CAD, coronary artery disease; MLWHFQ, Minnesota Living with Heart Failure Questionnaire; LV, left ventricular; LA, left atrium; RV, right ventricle; RA, right atrium; E/e' ratio is the average of septal and lateral annuli motion; TAPSE, tricuspid annular plane systolic excursion.

Table 2. Average (±SD) resting and exercise hemodynamic results from the 64 patients who underwent evaluation at baseline and 6 months (superscripted numbers are p values versus respective baseline values).

	At Rest		Peak Exercise	
	Baseline	6 Months	Baseline	6 Months
Qp:Qs	1.06 ± 0.32	1.27 ± 0.24 $^{<0.001}$	na ± na	na ± na
Peak Watts	na ± na	na ± na	42.5 ± 18.3	49.0 ± 20.3 $^{0.002}$
PA O_2sat (%)	68.9 ± 6.0	75.0 ± 4.5 $^{<0.001}$	46.9 ± 14.8	55.7 ± 12.5 $^{<0.001}$
HR (bpm)	68 ± 14	70 ± 12	95 ± 18	100 ± 20 $^{0.019}$
CO (TD, L/min))	5.5 ± 1.6	6.7 ± 1.5 $^{<0.001}$	8.7 ± 2.6	10.2 ± 2.7 $^{<0.001}$
CO (Fick, L/min)	4.6 ± 1.2	4.8 ± 1.3	na ± na	na ± na
CVP (mmHg)	9.0 ± 3.7	10.6 ± 5.1 $^{0.027}$	17.5 ± 5.4	20.3 ± 7.9 $^{0.041}$
PAS (mmHg)	37 ± 11	38 ± 10	66 ± 14	67 ± 14
PAD (mmHg)	17 ± 5	17 ± 5	33 ± 8	32 ± 8
PAM (mmHg)	24 ± 7	24 ± 6	43 ± 9	43 ± 9
PCWP (mmHg)	17.4 ± 5.2	16.5 ± 6.7	34.1 ± 7.6	31.6 ± 8.0 $^{0.025}$
PCWP-CVP (mmHg)	8.3 ± 4.1	6.1 ± 2.7 $^{<0.001}$	16.8 ± 6.9	11.4 ± 5.5 $^{<0.001}$
PVR (mmHg/(L/min))	1.3 ± 0.7	1.2 ± 0.5	1.2 ± 0.7	1.1 ± 0.6
AoS (mmHg)	143 ± 23	143 ± 21	170 ± 28	180 ± 30 $^{0.005}$
AoD (mmHg)	72 ± 13	74 ± 10	88 ± 19	95 ± 23 $^{0.02}$
AoM (mmHg)	96 ± 14	97 ± 12	114 ± 20	122 ± 21 $^{0.003}$
PCWP/(Watts/Kg)	na ± na	na ± na	89.1 ± 53.5	70.5 ± 42.8 $^{<0.001}$

Abbreviations are as follows. Qp:Qs, the ratio of flows through the pulmonary and systemic circulations; PA, pulmonary artery; HR, heart rate; CO, cardiac output; TD, thermodilution; CVP, central venous pressure; PAS, PAD and PAM, pulmonary artery systolic, diastolic and mean pressures, respectively; PCWP, pulmonary capillary wedge pressure; PVR, pulmonary vascular resistance ; AoS, AoD and AoM, aortic systolic, diastolic and mean pressures, respectively. Values without p values are not significantly different.

Table 3. Percent distribution of patients over the 4 Filling Pressure Quadrants at baseline and 6 months, at rest and at peak exercise.

		Filling Pressure Quadrant*			
		Normal	Elevated PCWP	Elevated CVP	Elevated CVP and PCWP
Resting	Baseline	37	27	2	34
	6 Months	37	14	3	46
Peak Exercise	Baseline	8	33	0	59
	6 Months	17	22	3	58

*All numbers are percentages

Table 4. Resting and exercise hemodynamic results in 18 patients who underwent protocol-specified evaluations at baseline, 6 month and protocol-specified optional evaluation at 12 months (superscripted numbers are p values versus baseline)

n=18	At Rest			Peak Exercise		
	Baseline	6 Months	12 Months	Baseline	6 Months	12 Months
Qp:Qs	1.09 ± 0.39	1.21 ± 0.2	1.30 ± 0.25			
Ex Duration (min)				8.2 ± 3.4	9.7 ± 3.18 $^{0.03}$	10.4 ± 4.24 $^{0.05}$
Peak Watts				47.8 ± 18.3	57.8 ± 18.0 $^{0.02}$	55.0 ± 15.5 $^{0.01}$
PA O2sat (%)	69 ± 7.4	75.0 ± 3.6 $^{0.003}$	74.4 ± 2.78 $^{0.02}$	44.6 ± 15.2	51.7 ± 11.43 $^{0.01}$	56.7 ± 17.9 $^{0.02}$
CO (TD, L/min)	5.2 ± 1.2	6.3 ± 1.4 $^{<0.001}$	6.8 ± 1.8 $^{0.003}$	8.7 ± 2.4	10.1 ± 2.3 $^{0.01}$	11.4 ± 2.9 $^{0.002}$
CO (Fick L/min))	4.8 ± 1.4	5.1 ± 1.3	5.6 ± 1.6 $^{0.05}$			
CVP (mmHg)	8.4 ± 3.5	10.6 ± 5.9	10.4 ± 3.5 $^{0.02}$	17.7 ± 6.2	20.9 ± 8.8	21.4 ± 8.3 $^{0.02}$
PAM (mmHg)	25 ± 8	23 ± 7	26 ± 8	45 ± 11	45 ± 11	45 ± 13
PCWP (mmHg)	18.8 ± 6.1	16.4 ± 7.5	17.4 ± 6.0	36.3 ± 8.5	33.4 ± 9.1	33.2 ± 10.4
PCWP-CVP	10.4 ± 4.7	5.8 ± 2.4	7.0 ± 3.6	19.3 ± 7.1	12.5 ± 4.8	11.8 ± 6.4
PVR ((mmHg/L/min)	1.3 ± 0.7	1.2 ± 0.6	1.3 ± 0.5	1.1 ± 0.9	1.1 ± 0.5	1.2 ± 0.7
AoS (mmHg)	153 ± 21.8	147 ± 21.06	146.6 ± 18.89	165 ± 36	166 ± 37.2	178 ± 25.9
AoD (mmHg)	75 ± 12	79 ± 8	79 ± 9.2	82 ± 22	89 ± 13.9	91 ± 14.4
AoM (mmHg)	101 ± 13	101 ± 10	101 ± 10.2	110 ± 25	114 ± 13.2	120 ± 12.9
PCWP/(Watts/Kg)				84.29 ± 49.47	59.7 ± 34.61 $^{0.02}$	62.2 ± 34.43 $^{<0.001}$

FIGURE 1

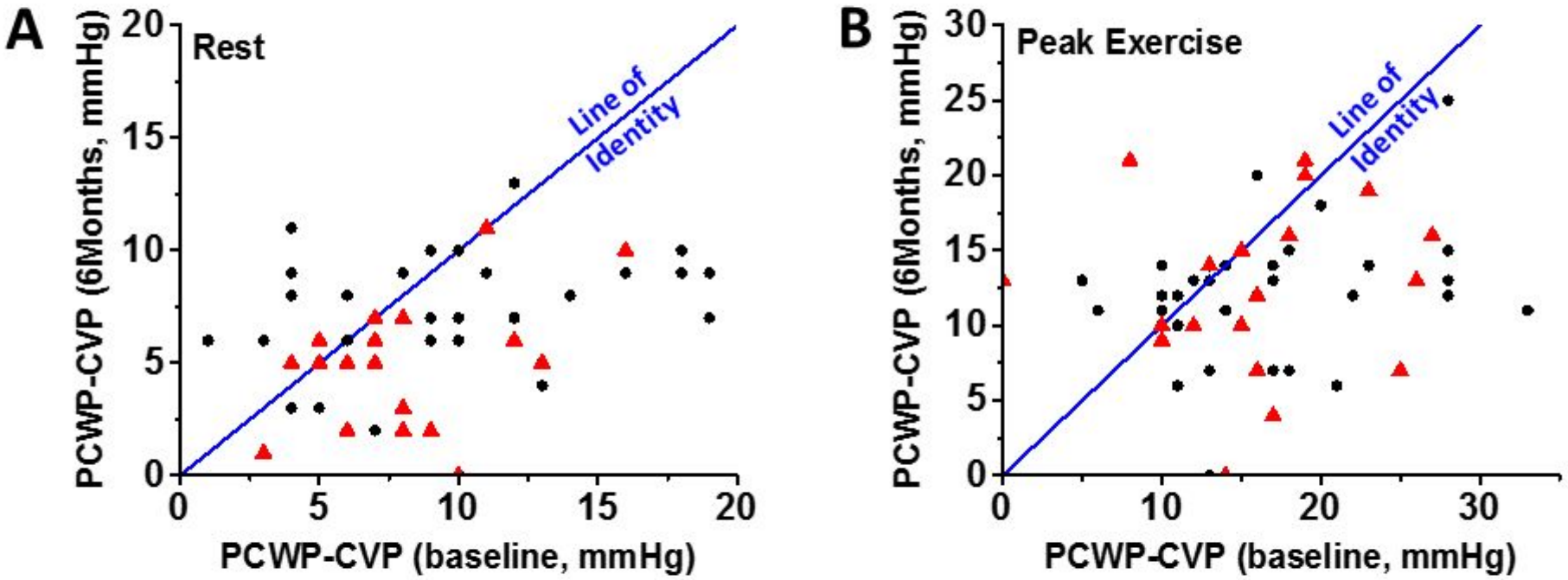

A
Rest
Line of Identity
PCWP-CVP (6Months, mmHg)
PCWP-CVP (baseline, mmHg)
0
5
10
15
20
B
Peak Exercise
Line of Identity
PCWP-CVP (6Months, mmHg)
PCWP-CVP (baseline, mmHg)
0
5
10
15
20
25
30

FIGURE 2

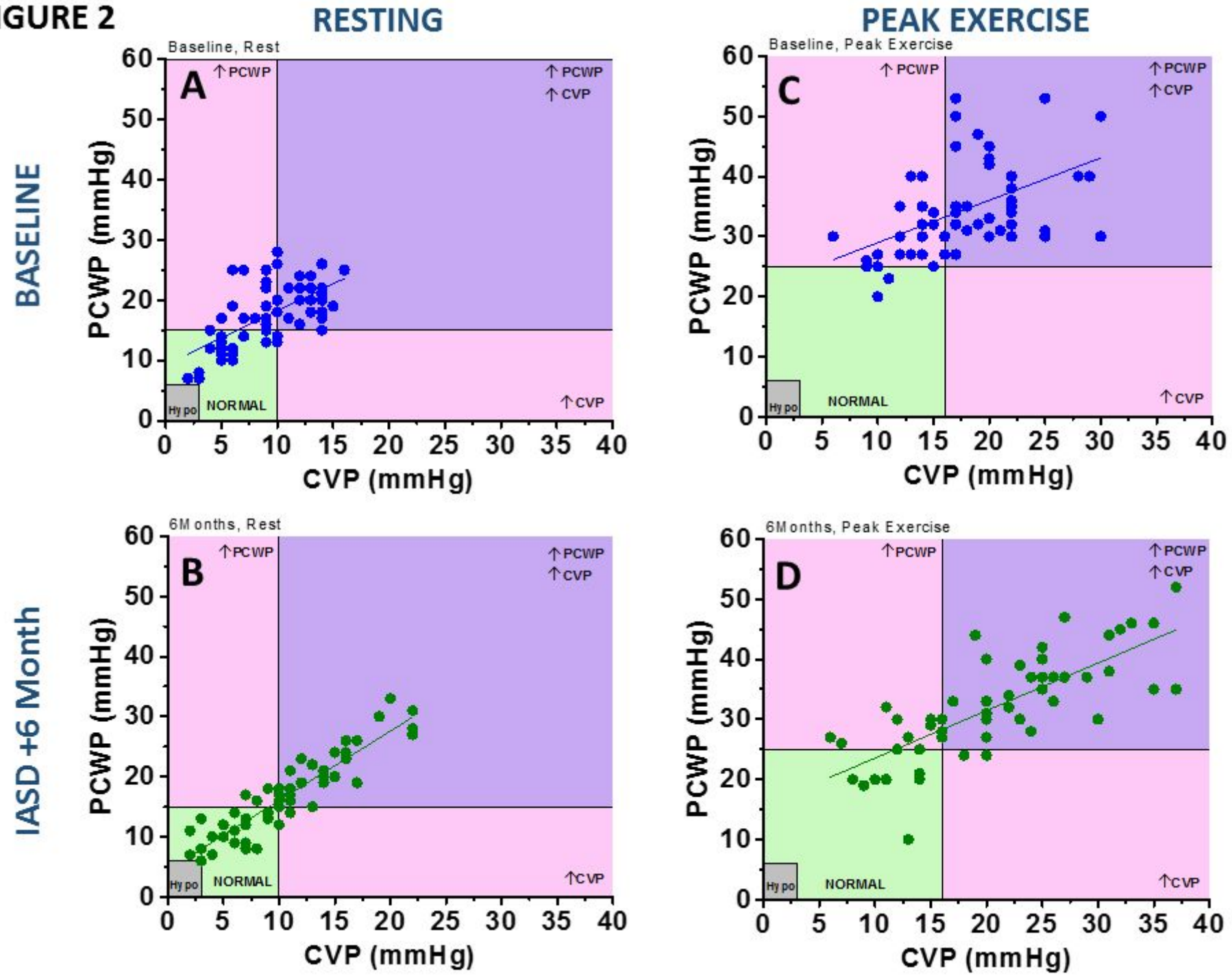

RESTING
PEAK EXERCISE
BASELINE
IASD +6 Month
Baseline, Rest
6Months, Rest
Baseline, Peak Exercise
6Months, Peak Exercise
A
B
C
D
↑PCWP
↑PCWP
↑CVP
↑CVP
Hy po
NORMAL
PCWP (mmHg)
CVP (mmHg)
0
5
10
15
20
25
30
35
40
50
60

FIGURE 3

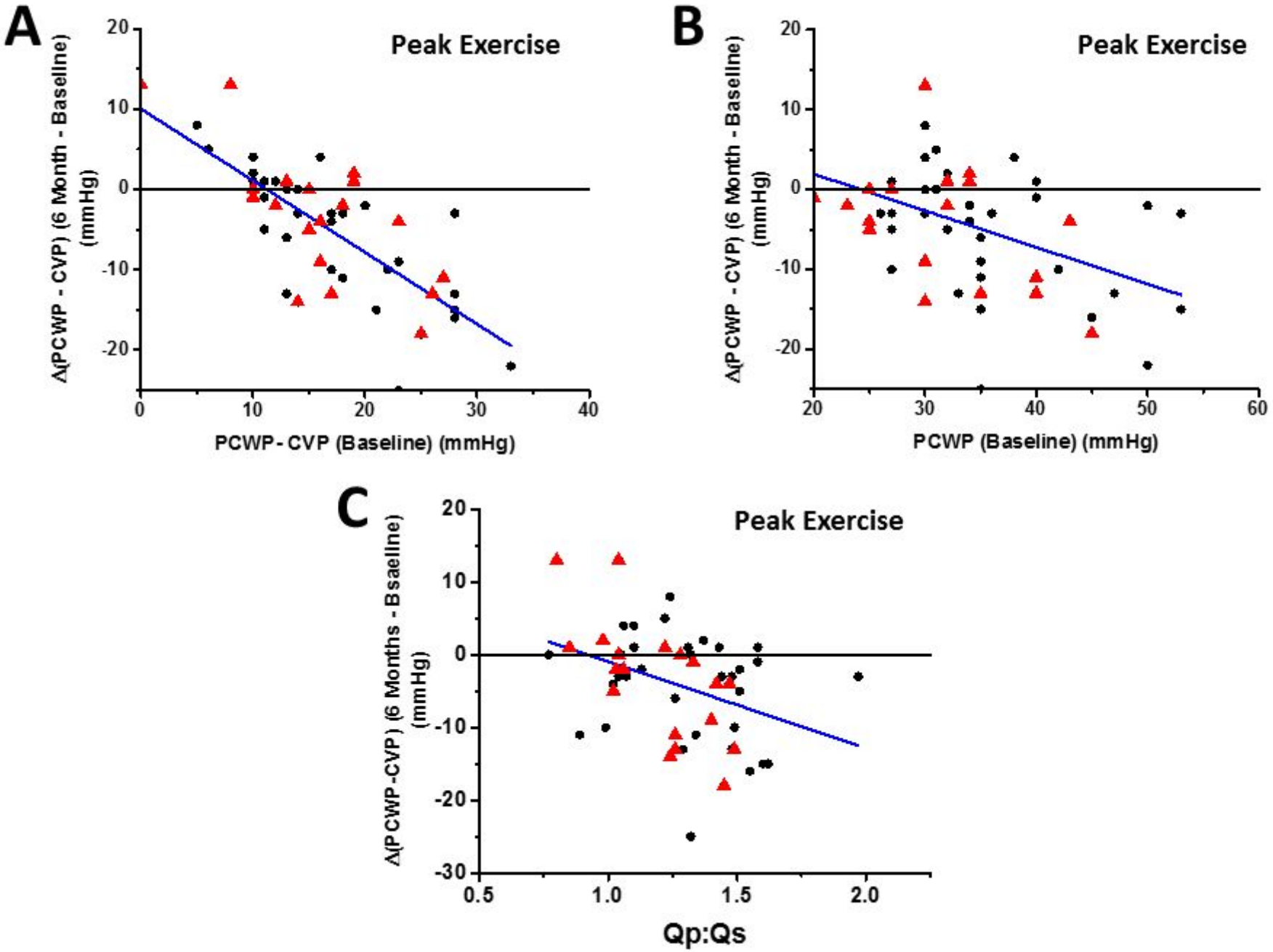
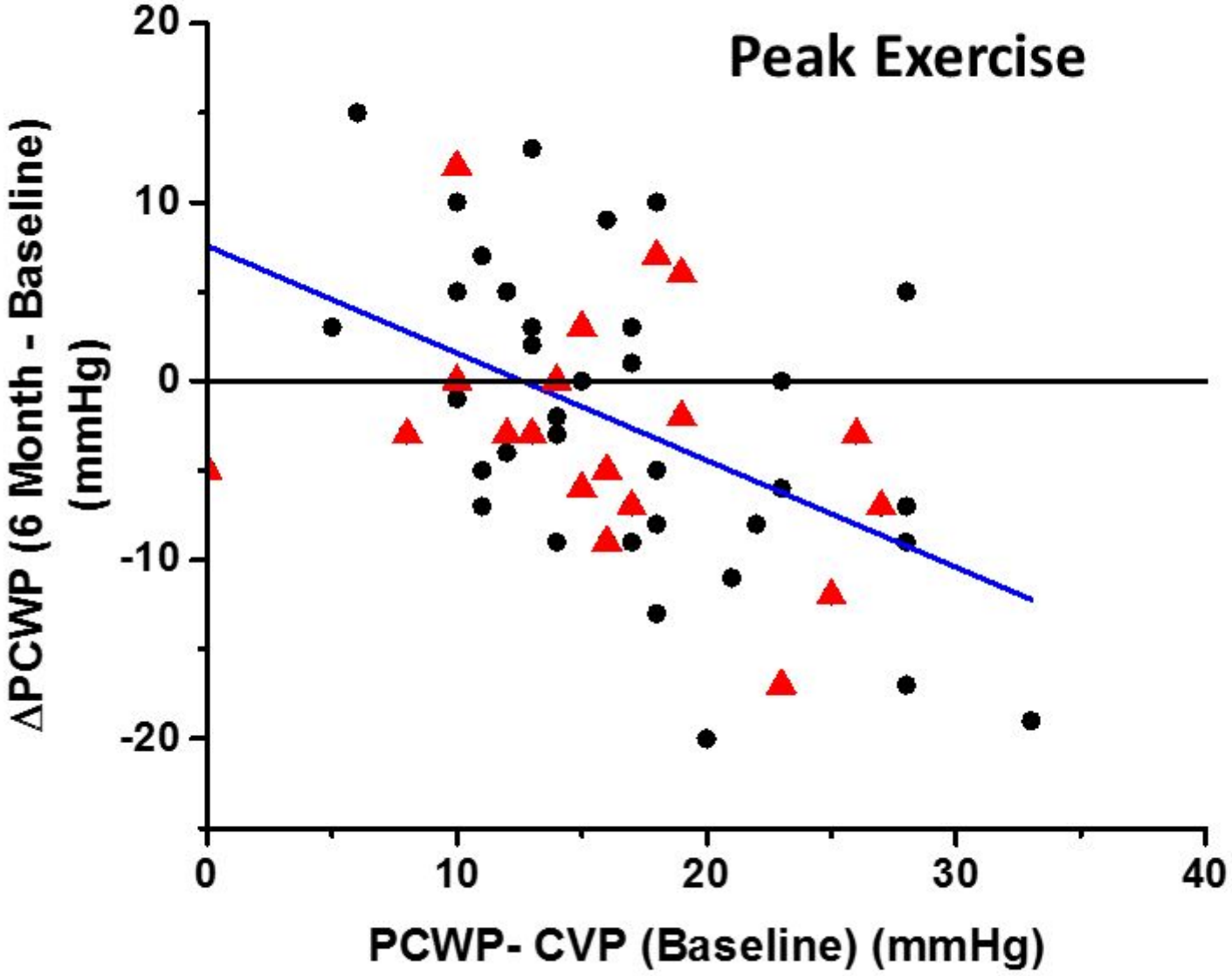

A
Peak Exercise
Δ(PCWP - CVP) (6 Month - Baseline) (mmHg)
PCWP - CVP (Baseline) (mmHg)
B
Peak Exercise
Δ(PCWP - CVP) (6 Month - Baseline) (mmHg)
PCWP (Baseline) (mmHg)
C
Peak Exercise
Δ(PCWP-CVP) (6 Months - Bsaelne) (mmHg)
Qp:Qs

FIGURE 4


Peak Exercise
ΔPCWP (6 Month - Baseline) (mmHg)
20
10
0
-10
-20
0
10
20
30
40
PCWP- CVP (Baseline) (mmHg)