ESC European Society of Cardiology

European Heart Journal – Cardiovascular Imaging (2017) **18**, 1145–1152
doi:10.1093/ehjci/jew176

Changes in blood volume shunting in patients with atrial septal defects: assessment of heart function with cardiovascular magnetic resonance during dobutamine stress

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Received 12 April 2016; accepted after revision 27 July 2016; online publish-ahead-of-print 1 September 2016

Background The purpose of this study was to determine the effect of stress on left-to-right shunting in patients with atrial septal defect (ASD) and to investigate if the degree of shunting, cardiac output (CO), and right ventricular (RV) volumes are related to exercise capacity.

Methods Twenty-six patients with a secundum ASD and 16 healthy volunteers were studied with rest/stress cardiac magnetic resonance using 20 μg/kg/min dobutamine and 0.25–0.75 mg atropine to quantify CO, pulmonary to systemic flow ratio (QP/QS), and left ventricular (LV) and RV volumes. Peak oxygen uptake (VO_2 *peak*) was determined on ergospirometry.

Results In patients with ASD the QP/QS decreased from 2.0 ± 0.2 at rest to 1.5 ± 0.1 ($P < 0.001$) during dobutamine stress ($n = 20$) and shunt volume per heartbeat decreased from 70 ± 9 to 38 ± 9 mL ($P < 0.001$). However, absolute shunt volume per minute was unchanged (5.1 ± 0.8 vs. 4.5 ± 1.0 L/min, $P = 0.32$) explained by a higher increase in systemic CO during stress (90 ± 11%) compared with pulmonary CO (43 ± 7%, $P < 0.001$). In ASD patients, VO_2 *peak* correlated with aortic CO during stress ($r = 0.77$) and QP/QS at rest ($r = -0.48$) but not during stress ($P = 0.09$). VO_2 *peak* did not correlate with RV volumes in patients.

Conclusion Pulmonary to systemic flow ratio and shunt volume per heartbeat decrease during stress in ASD patients. This may be explained by an enhanced LV diastolic function during stress and may have implications to detect disturbances in LV compliance in ASD patients. A high systemic CO during stress is a strong predictor of exercise capacity.

Introduction

Patients with atrial septal defects (ASDs) often have decreased exercise capacity, shortness of breath and palpitations.[1] ASD closure is recommended in all patients with left-to-right shunts larger than 1.5:1, dilation of the right atrium or ventricle and pulmonary vascular resistance <5 Wood units. Patients with paradoxical embolism should also be considered for intervention.[1] Pulmonary cardiac output (CO) (QP) divided by systemic CO (QS) is used to quantify the degree of left-to-right shunting (QP/QS). The magnitude of left-to-right shunting has been related to the size of the ASD[2] and the compliance of the ventricles.[3] However, the effect of exercise on left-to right shunting is less well known. Two previous invasive studies have found decreased pulmonary to systemic flow ratio during exercise but with different responses in absolute shunt volumes. Bay *et al.* showed increased absolute shunt volume during exercise[4]

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while Nielsen *et al.* found decreased shunt volume during exercise.[5] An invasive study using rapid atrial pacing showed increased aortic blood flow but not pulmonary blood flow in sedated children with ASD.[6] It is therefore not clear if and how the shunt volume changes with increased heart rate and systemic stroke volume (SV). Also, the mechanisms for these changes during stress are relatively unknown.

Quantification of left-to-right shunting in ASDs with cardiac magnetic resonance (CMR) is highly accurate.[7] Flow measurements with CMR have proved to be superior to invasive cardiac catheterization besides the advantages of CMR being non-invasive.[8,9] Dobutamine infusion can be used to simulate stress in the MR scanner and enables quantification of cardiac function during stress. Dobutamine increases heart rate through stimulation of β-1 receptors and SV through α-1 stimulation with the net result of increased CO.[10]

Exercise capacity is often used as a marker of the impact of the ASD because it is quantitative and less prone to bias compared with reported symptoms. Several studies have found improved exercise capacity after surgical or transcatheter closure of the ASD,[11–16] even though impaired results have also been described in a subset of patients.[16] The relationship between exercise capacity and the size of the defect or the degree of shunting (QP/QS) is not straightforward. In this study, we hypothesized that exercise capacity in patients with ASD has a stronger relationship to QP/QS during stress compared with rest.

The purpose of the study was therefore to (i) determine if left-to-right shunting changes during stress, (ii) investigate the mechanisms for these changes and (iii) determine if the pulmonary to systemic flow ratio (QP/QS), systemic and pulmonary flow and RV volumes during stress are related to exercise capacity in ASD patients.

Methods

Study population

The study was approved by the Regional ethics committee in Lund, Sweden. Written informed consent was obtained by patients and controls. In total, 26 patients with a secundum ASD were included, 18 patients (13 females) with a large ASD and indication for transcatheter closure of the defect, and 8 patients (3 females) with a small ASD not eligible for transcatheter closure. In addition, 16 healthy controls (3 females) were included. Patients with uncontrolled atrial fibrillation were excluded. Detailed information on methodology, i.e. CMR sequence parameters, can be found in the Supplementary data online, Appendix.

Cardiovascular magnetic resonance imaging

CMR was performed at rest and during dobutamine stress. An intravenous infusion of 10 μg/kg/min of dobutamine for 3 min followed by 20 μg/kg/min dobutamine was administered and 0.25–0.75 mg atropine was added to reach a target of 70% of age-predicted maximal heart rate determined as 220 minus the patient's age. Cine imaging in the left ventricular (LV) short-axis and long-axis views and phase contrast flow velocity mapping in the aorta and pulmonary trunk was performed at rest, at an infusion rate of 10 μg/kg/min of dobutamine and when target heart rate was reached.

Image analysis

All image analysis was performed using Segment, v1.9 (http://segment.heiberg.se).[17] Left and right ventricular (RV) volumes and SVs were obtained at rest and at max heart rate by delineating the endocardial borders of both ventricles in all slices in end-diastole (ED) and end-systole (ES). Flow images were used to calculate CO in the aorta and pulmonary trunk as well as the QP/QS as earlier described and validated.[7]

Ergospirometry

Peak oxygen uptake (VO_2 *peak*) was determined using an exercise test with continuous gas analysis. VO_2 *peak* per cent of predicted value was calculated according to the Hansen/Wasserman equation.[18]

Catheterization and transoesophageal echocardiography

Eighteen patients underwent cardiac catheterization under conscious sedation ($n = 16$) or general anaesthesia ($n = 2$) and ASD diameters were measured in two planes using transoesophageal echocardiography. Invasive pressure recordings were obtained in 17 patients using 5F MPA catheter in the right and left atrium, right ventricle, and pulmonary trunk.

Statistical analysis

Statistical analysis was performed using Graphpad Prism v 6.0. Continuous variables are reported as means ± SEM. Pearson's correlation was used to examine the relationship between VO_2 *peak*, and systemic and pulmonary CO, QP/QS, and ASD size. Mann–Whitney and Wilcoxon tests were used to test if results differed (*Table 2*). Results with a *P*-value of <0.05 were considered statistically significant.

Results

Patient characteristics

Two patients did not undergo dobutamine stress due to technical reasons and one patient did not reach target heart rate. Three patients were excluded from the flow measurements due to background phase errors, leaving 20 patients for analysis at both rest and stress. Characteristics for the 20 patients and 16 controls are presented in *Table 1*. Results from CMR including ventricular

Table 1 Subject characteristics of the ASD patients and controls that underwent CMR both at rest and during dobutamine stress

	ASD patients $n = 20$	Healthy controls $n = 16$
Mean age and range	47 ± 4 (24–81)*	35 ± 3 (21–62)
Females, *n* (%)	15 (75)	3 (19)
BSA, mean and range (m^2)	1.8 ± 0.0 (1.5–2.4)	1.9 ± 0.0 (1.7–2.3)
VO_2 *peak* (mL/kg/min)	27.6 ± 9.0***	46.0 ± 2.0
VO_2 *peak* per cent of predicted value (%)	103 ± 6**	130 ± 6
PAP, mean and range (mmHg, $n = 17$)	20 ± 1 (14–31)	
LAP, mean and range (mmHg, $n = 17$)	7 ± 1 (2–14)	

Continuous variables are presented as mean ± SEM.
BSA, body surface area; VO_2 *peak*, peak oxygen uptake; PAP, pulmonary artery pressure; LAP, left atrial pressure.
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

Table 2 Results at rest and during dobutamine stress

	ASD patients, rest ($n = 20$)	ASD patients, dobutamine ($n = 20$)	Controls, rest ($n = 16$)	Controls, dobutamine ($n = 16$)
HR (bpm)	$71 \pm 3^{***}$	122 ± 3	$67 \pm 3^{***}$	127 ± 3
Systolic blood pressure (mmHg)	$120 \pm 5^{***}$	147 ± 5	$122 \pm 3^{***}$	158 ± 5
Diastolic blood pressure (mmHg)	$72 \pm 3^{*}$	81 ± 3	$74 \pm 2^{***}$	87 ± 3
LVEDVI (mL/m^2)	$88 \pm 4^{***++}$	$80 \pm 4^{+}$	$108 \pm 4^{**}$	96 ± 4
LVESVI (mL/m^2)	$39 \pm 3^{***+}$	27 ± 2	$50 \pm 2^{***}$	31 ± 2
LVSVI (mL/m^2)	$50 \pm 2^{++}$	$53 \pm 2^{++}$	$58 \pm 3^{**}$	65 ± 3
LVEF (%)	$57 \pm 2^{***}$	68 ± 2	$54 \pm 2^{***}$	68 ± 1
RVEDVI (mL/m^2)	$164 \pm 13^{***+++}$	$123 \pm 10^{++}$	$109 \pm 4^{***}$	92 ± 4
RVESVI (mL/m^2)	$77 \pm 7^{***+++}$	$44 \pm 5^{+++}$	$50 \pm 3^{***}$	28 ± 1
RVSVI (mL/m^2)	$87 \pm 7^{+++}$	$79 \pm 6^{+}$	59 ± 2	64 ± 3
RVEF (%)	$53 \pm 1^{***}$	$65 \pm 2^{++}$	$56 \pm 1^{***}$	70 ± 1
Systemic CI (L/min/m^2)	$2.9 \pm 0.1^{***++}$	5.4 ± 0.3	$3.6 \pm 0.2^{***}$	6.1 ± 0.3
Pulmonary CI (L/min/m^2)	$5.7 \pm 0.5^{***+++}$	$7.9 \pm 0.5^{++}$	$3.6 \pm 0.2^{***}$	5.9 ± 0.3
Shunt per heartbeat (mL)	$70 \pm 9^{***}$	38 ± 9		
Absolute shunt volume (L/min)	5.1 ± 0.8	4.5 ± 1.0		
QP/QS	$2.04 \pm 0.17^{***+++}$	$1.54 \pm 0.13^{+++}$	1.02 ± 0.02	0.97 ± 0.02

HR, heart rate; LVEDVI, left ventricular end-diastolic volume indexed to body surface area (BSA); LVESVI, left ventricular end-systolic volume indexed to BSA; LVSVI, left ventricular stroke volume indexed to BSA; LVEF, left ventricular ejection fraction; RVEDVI, right ventricular end-diastolic volume indexed to BSA; RVESVI, right ventricular end-systolic volume indexed to BSA; RVSVI, right ventricular stroke volume indexed to BSA; RVEF, right ventricular ejection fraction; QP/QS, pulmonary to systemic flow ratio.
Continuous variables are presented as mean ± SEM.
Comparing subjects at rest to subjects during dobutamine stress, $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.
Comparing patients to controls, either at rest or during dobutamine stress, $^{+}P < 0.05$, $^{++}P < 0.01$, $^{+++}P < 0.001$.

volumes, systemic and pulmonary output, and QP/QS are presented in *Table 2*.

Haemodynamic changes during dobutamine stress

Typical aortic and pulmonary flow curves at rest and during dobutamine are shown in *Figure 1*. Systemic and pulmonary CI at rest and during dobutamine stress is shown in *Figure 2*. Dobutamine stress increased heart rate in both patients (76% increase) and healthy subjects (94%). In patients, left ventricular stroke volume (LVSV) had a non-significant increase of 7% during stress, and RV stroke volume (RVSV) had a non-significant decrease of 6%, leading to a decreased shunting volume per heartbeat by 28% during stress ($P < 0.001$), *Table 2*. This resulted in an increase in systemic CO during stress by 90 ± 11% and a concomitant lower increase in pulmonary CO, 43 ± 7% compared with rest ($P < 0.001$ for both), *Figure 3*. Thus, the pulmonary to systemic flow ratio was lower during stress (1.5 ± 0.1) compared with rest (2.0 ± 0.2, $P < 0.001$). However, there was no difference in the mean absolute left-to-right shunt flow at rest and during stress per minute (5.1 ± 0.8 vs. 4.5 ± 1.0 L/min, $P = 0.32$). Absolute shunt flow decreased in 12 patients, increased in 7 patients, and was unchanged in one patient during dobutamine stress. Only 2 patients out of 20 had increased shunting volume per heartbeat. There were no significant differences between patients with decreased and increased shunt flow in terms of indexed RV or LV volumes, indexed ASD size, shunt volume at rest, right atrial pressure (RAP), LAP or PAP, VO_2 *peak or* VO_2% of predicted value. Mean ASD diameter was 15.3 ± 1.3 mm and mean cross-sectional area indexed to BSA was 1.0 ± 0.2 cm^2/m^2. The latter did neither correlate to absolute shunt flow (L/min/BSA) at rest ($r = 0.47$, $P = 0.07$) nor during dobutamine stress ($r = 0.44$, $P = 0.09$), *Figure 4A*. However, ASD size correlated to QP/QS and shunting volume per heartbeat (mL/BSA) both at rest ($r = 0.75$, $P < 0.001$ and $r = 0.70$, $P < 0.01$, respectively) and during dobutamine stress ($r = 0.50$, $P < 0.05$ and $r = 0.60$, $P < 0.05$, respectively), *Figure 4B* and *C*. Also, there was an inverse correlation between indexed ASD size and systemic CI at rest ($r = -0.50$, $P < 0.05$) but no correlation during dobutamine stress ($P = 0.38$). Of note, there was no correlation between indexed ASD size and pulmonary CI at rest ($P = 0.21$) or during stress ($P = 0.25$). The change in absolute shunting volume per heartbeat from rest to dobutamine stress did not differ in patients with restrictive ASD defined as <0.9 cm^2/m^2 (44 ± 12%) compared with patients with larger ASD sizes (44 ± 11%, $P = 0.99$).

Pressure measurements

The mean pulmonary artery pressure (PAP) measured invasively during cardiac catheterization was 20 ± 1 mmHg (range 14–31), left atrial pressure (LAP) was 7 ± 1 mmHg, and right atrial pressure (RAP) was 5 ± 1 mmHg. There was no correlation between PAP, LAP or RAP and absolute shunt flow or QP/QS at rest or during dobutamine stress ($P =$ ns.). There was no correlation between absolute shunt flow and pressure recordings in either patients with restrictive or non-restrictive ASD.

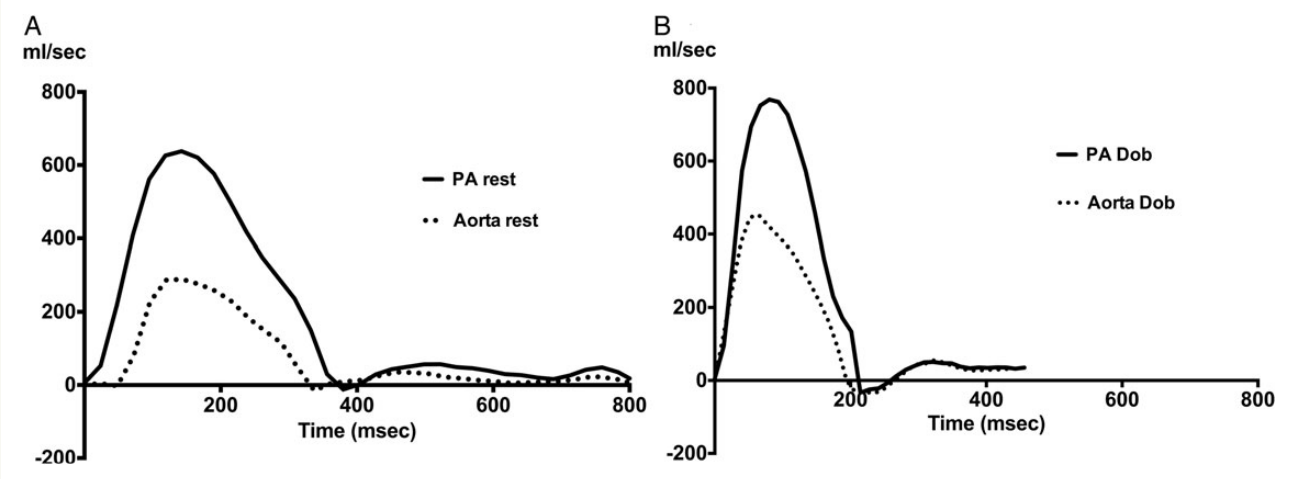

Figure 1 Flow data in the pulmonary artery (PA) (solid line) and aorta (dotted line) at rest with QP/QS 2.6 (*A*) and during dobutamine stress with QP/QS 1.6 (*B*) in a patient with ASD. During dobutamine the time for systole decreases but even more so the time for diastole. The decrease in difference between the PA and aorta in ejected stroke volume from rest to dobutamine can be visually appreciated from the flow curves. This translates into decreased absolute shunting volume per heartbeat.

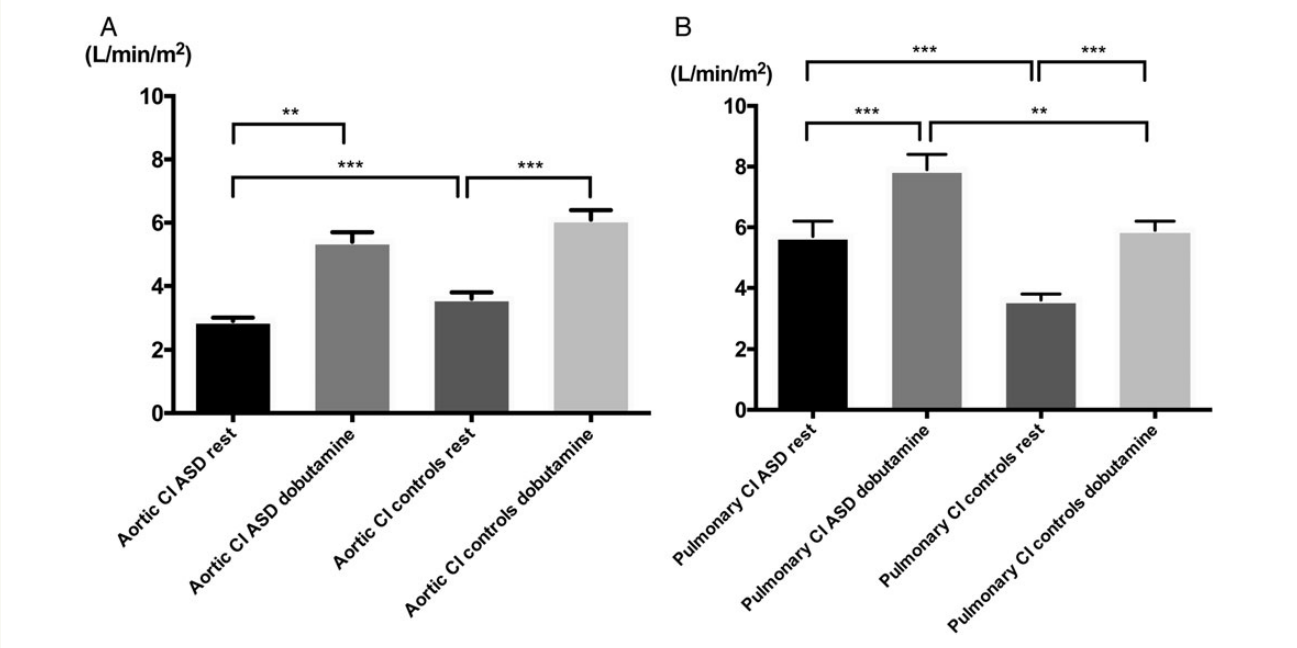

Figure 2 Aortic (*A*) and pulmonary (*B*) cardiac index in ASD patients and controls at rest and during dobutamine stress.

Relations to exercise capacity

There was a moderate correlation between VO_2 *peak* and aortic and pulmonary CO during dobutamine stress in controls, *Figure 5A*. In contrast, VO_2 *peak* in patients did not correlate with pulmonary CO during dobutamine stress ($r = 0.25$, $P = 0.29$), but there was a strong correlation with aortic CO ($r = 0.77$, $P < 0.001$) (*Figure 5B*). There was an inverse correlation between VO_2 *peak* and QP/QS at rest ($r = -0.48$, $P < 0.05$) but not during dobutamine stress in ASD patients ($r = -0.39$, $P = 0.09$), *Figure 5C*. VO_2 *peak* correlated with RV end-diastolic and end-systolic volume during stress in controls ($P < 0.001$ and $P < 0.01$, respectively) but not in patients ($r = 0.14$, $P = 0.59$ and $r = 0.14$, $P = 0.58$, respectively). There was no correlation between VO_2 *peak* and LAP or PAP at rest ($P = 0.63$ and $P = 0.41$, respectively). There was no correlation between absolute shunt flow and exercise capacity in either patients with restrictive or non-restrictive ASD.

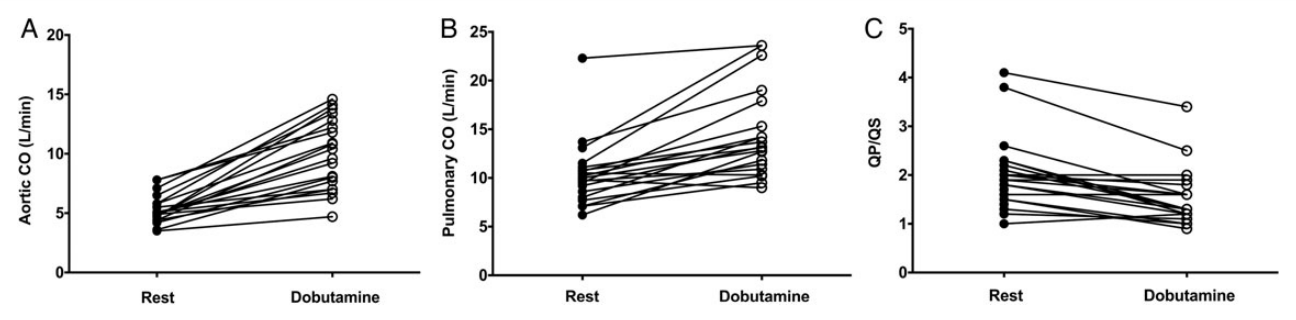

Figure 3 Aortic cardiac output (*A*), pulmonary cardiac output (*B*), and pulmonary to systemic flow ratio (QP/QS) (*C*) at rest and during dobutamine stress in 20 patients with ASD.

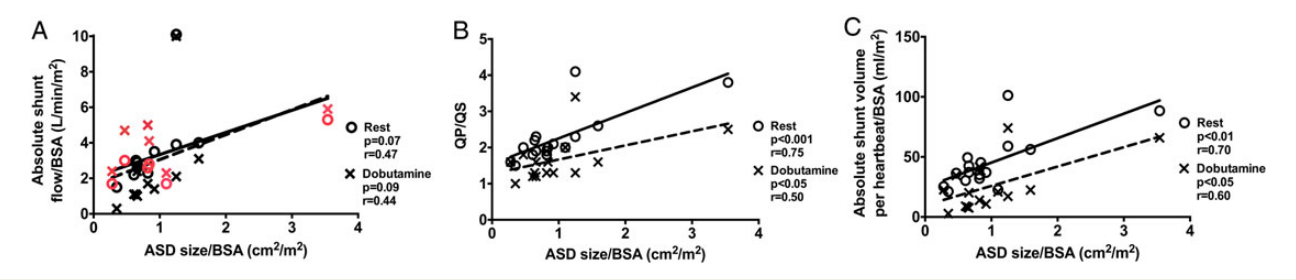

Figure 4 Linear regression analysis between the cross-sectional area of the ASD indexed to body surface area (BSA), and (*A*) absolute shunt flow indexed to BSA at rest (open circles) and during dobutamine stress (crosses), (*B*) pulmonary to systemic flow ratio (QP/QS) at rest (open circles) and during dobutamine stress (crosses), and (*C*) shunt volume per heartbeat indexed to BSA at rest (open circles) and during dobutamine stress (crosses) in 16 patients who had both transoesophageal echocardiography and dobutamine stress CMR flow results. The degree of shunting (QP/QS) was strongly related to indexed ASD size at rest ($Y = 0.70X + 1.55$) and to a lesser degree during dobutamine stress ($Y = 0.39X + 1.28$). The degree of shunting decreased during dobutamine stress for all ASD sizes. Black colour in *Figure 4A* represents patients with decreased shunt flow during stress and red colour represents patients with increased shunt volume during stress.

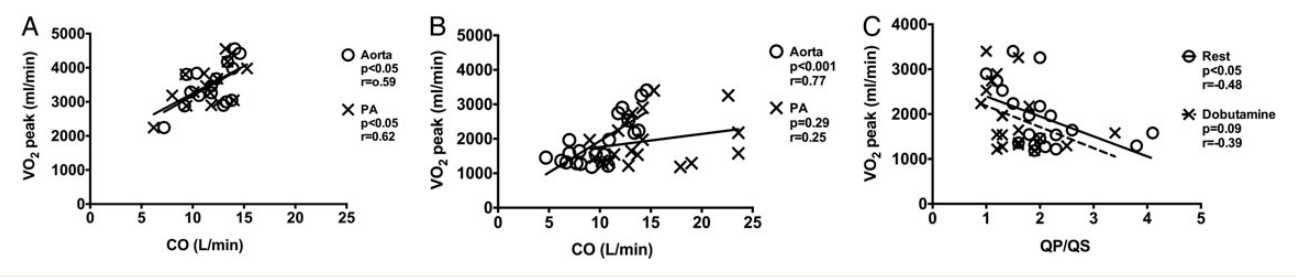

Figure 5 (*A* and *B*) Linear regression analysis between peak oxygen uptake on ergospirometry (VO_2 *peak*) and systemic (Aorta, open circles) or pulmonary (PA, crosses) cardiac output during dobutamine stress in healthy controls (*A*) and patients with ASD (*B*). Systemic cardiac output during dobutamine was related to exercise capacity in patients whereas pulmonary cardiac output was not (Aorta; $y = 183.1x + 107.9$). *Figure 5C*: Linear regression analysis between QP/QS and VO_2 *peak* showed an inverse correlation both at rest (open circles) and during dobutamine stress (crosses).

Discussion

This study has demonstrated that the pulmonary to systemic flow ratio (QP/QS) decreases during stress due to a higher increase in systemic compared with pulmonary CO. Thus, flow across the septal defect does not increase in relation to increased systemic flow. Even though the mean absolute shunt volume per minute did not change between rest and dobutamine stress, results differed

between individual patients. In the majority of the patients, the shunt volume per minute decreased, but in a large minority, the shunt volume per minute increased. Interestingly, the absolute shunting volume with each heartbeat decreased during stress. Thus, with increased heart rate and shorter diastole, less volume is shunted from left to right with each heartbeat. The size of the ASD indexed to BSA was strongly related to QP/QS at rest but to a lesser degree during stress. Independently of the ASD size the QP/QS was unchanged or decreased in all patients during stress. This indicates that with increased flow, the ASD size *per se* has less impact on left-to-right shunting. More likely, the degree of shunting during stress is determined by the relationship between diastolic compliance of the LV and RV. The normal relationship between peak oxygen uptake and CO in both the systemic and pulmonary circulation during stress is disrupted in ASD patients, where peak oxygen uptake has a strong correlation with systemic CO at rest and during stress, but no correlation with pulmonary CO or RV volumes.

Physiological explanations for changes in shunting during exercise

With increased heart rate and flow during dobutamine stress, we found a relatively larger increase in CO from the left than the right ventricle compared with rest. Thus, during stress the increase in transmitral flow per heartbeat is larger than the increase in the left-to-right flow through the ASD. This was seen in all but two patients during stress. Possible explanations for the decrease in shunting fraction and differences in response with respect to shunting volume include: (i) the ASD becomes more restrictive with increased flow, limiting the left-to-right shunt; (ii) the LV diastolic pressure gradient decreases with stress due to increased LV compliance; (iii) decreased RV compliance during stress; (iv) the diastolic movement of the ventricular septum towards the left ventricle decreases during stress and therefore does not impair LV filling; (v) the recruitment of pulmonary vasculature has been maximized at rest and further increase in pulmonary flow leads to increased pulmonary pressure; and (vi) the kinetic energy of left atrial blood increases during stress, driving the flow towards the left ventricle.

(i) A small sized ASD is often described as restrictive to the shunting volume, but this is affected by body surface area and CO. The correlation coefficients between ASD size and QP/QS at rest varies between studies[2,19,20] and studies on the correlation between ASD size and shunt ratio during stress are lacking. An ASD of 10 mm in diameter may be non-restrictive at rest but restrictive during exercise with increased flow. Our study showed decreased QP/QS in all patients at stress, independent of ASD size. There was no relation between the ASD size and whether the absolute shunting volume increased or decreased during stress. Thus, in our study, the decrease of shunting fraction does not seem to be explained by restrictive ASD.

(ii) With improved LV compliance, more blood will be drawn into the left ventricle in diastole, thus limiting the shunting volume and shunting fraction. The left-to-right shunting occurs predominantly in late systole and early diastole as well as during atrial contraction.[3] In healthy subjects, the pulmonary capillary wedge pressure, representing LAP, increases with exercise[21] and LV end-diastolic pressure increases or is unchanged between rest and supine exercise.[22,23] However, the nadir of diastolic pressure is lower during exercise than at rest due to enhanced LV relaxation and elastic recoil.[22] This leads to increased atrioventricular pressure gradient and enhanced flow across the mitral valve during exercise.[22]

(iii) A decreased RV compliance during stress would also cause decreased shunting in the same way increased LV compliance during stress would lower QP/QS. There is limited data on RV diastolic function during stress in ASD patients. Further studies will have to elucidate the differences in diastolic function of the LV and RV in ASD patients and investigate if the decrease in shunting flow during stress is a marker of bi-ventricular compliance.

(iv) The filling of the left ventricle in patients with ASD is not only affected by the left-to-right shunting across the ASD but also from the volume overload of the right ventricle. The normal septal movement is disrupted in patients with right volume overload with systolic movement to the right side of the heart.[23] This leads to a diastolic movement towards the left and bulging of the interventricular septum into the left ventricle in diastole. This may cause impaired filling of the left ventricle and decreased SV. There may be changes in septal motion during stress in these patients that can affect LV filling and limit ASD shunting, but this remains to be studied.

(v) It has been shown that systolic pulmonary artery pressure increases during exercise in adult patients with ASD but not in controls.[24] This affects systemic CO and exercise tolerance in ASD patients.[24] The mechanism for increased pulmonary artery pressure may be that total pulmonary vascular capacity is already used at maximum level at rest and further increases in pulmonary blood flow will thus increase the pressure. However, increased pulmonary artery pressure would only result in lower ASD shunting if RV filling pressure increased concurrently.

(vi) Atrial kinetic energy contributes to ventricular filling due to the inertia of the rotating blood generated by systolic contraction and the position of the veins.[25] This 'flywheel' mechanism is probably of minor importance at rest but during stress the kinetic energy plays a larger part in heart pumping.[26] Thus, the increase in kinetic energy may contribute to increased transmitral flow during stress in ASD patients.

In summary, the most likely explanation for the decreased shunting fraction during dobutamine stress is improved compliance of the LV and less pronounced bulging of the ventricular septum towards the LV in diastole.

ASD and exercise capacity

In contrast to our hypothesis, exercise capacity was not significantly related to shunting during stress. Furthermore, pulmonary flow and RV volumes during stress were not related to exercise capacity. The strongest relationship was found between exercise capacity and systemic flow during stress. This is probably explained by the fact that the body is dependent on a high systemic outflow to perform exercise. Whether this happens during a high or low degree of shunting does not seem to be relevant to the exercising body, as long as systemic CO is delivered at an appropriate rate. These findings support the current guidelines where athletes with ASD and no pulmonary artery hypertension (PAH) are allowed to participate in all sports.[27] The increase in SV and heart rate seen during stress can be compared with the haemodynamic changes seen during pregnancy. Our findings thus suggest that shunt size during pregnancy in women

with ASD and no PAH does not increase and the haemodynamic changes should be well tolerated in pregnant ASD patients.[28]

Stress studies may help in the assessment of patients who do not fully meet the criteria for ASD closure. Further studies on the outcome of ASD closure are needed to assess the clinical benefit of stress studies.

Previous studies, that have evaluated the exercise capacity of patients with ASD, often show significantly impaired VO_2 *peak* or VO_2 *peak* % of predicted values.[14,29–32] In these studies, VO_2 *peak* was reported between 13.1 and 23.5 mL/min/kg and VO_2 *peak* % of predicted values ranging from 50 to 91%. The patients in our study had peak oxygen consumption of 27.6 mL/min/kg or 103% of predicted value, which implies that our group of patients were relatively fit compared with cohorts in previous studies. Ten patients had a shunt of less than 2:1 and 8 patients had moderate-sized shunts between 2:1 and 3:1.

Limitations

Subjects were stressed to 70% and not 100% of age-predicted maximum heart rate because of problems to obtain good image quality at high heart rates. Thus, we do not have CMR data on volumes and flows at heart rates comparable with the ones at peak oxygen uptake on ergospirometry. New developments in CMR have enabled the improved imaging of ventricular function at high heart rates and these techniques can be used in future studies.

Dobutamine stress was used as a surrogate to supine exercise, but whether the two methods are comparable regarding the response of LV and RV flow and pressure is not entirely clear. However, one study using dobutamine stress found a decrease in both LV mean and end-diastolic pressure.[33] Both physical exercise and dobutamine infusion cause increased heart rate and β-adrenergic stimulation, with enhanced LV relaxation. Also, a previous CMR study showed similar results using dobutamine infusion and physical exercise on SV, CO, and ejection fraction.[34] Our results in controls with decreased LV and RV volumes during dobutamine stress and increased SVs, although not significant for the RV, are similar to our previous findings using supine moderate exercise in the CMR scanner.[35]

Conclusion

Pulmonary to systemic flow ratio and shunt volume per heartbeat decrease during stress in ASD patients. This may be explained by an enhanced LV diastolic function during stress and may have implications to detect disturbances in LV compliance in ASD patients. A high systemic CO during stress is a strong predictor of exercise capacity.

Supplementary data

Supplementary data are available at *European Heart Journal – Cardiovascular Imaging* online.

Conflict of interest: None declared.

Funding

Swedish Heart-Lung Foundation. Lund University, Skåne University Hospital. The Swedish Medical Society.

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IMAGE FOCUS

doi:10.1093/ehjci/jex168
Online publish-ahead-of-print 30 June 2017

Non-invasive management of post-partum spontaneous left main coronary artery dissection using cardiac computed tomography angiography

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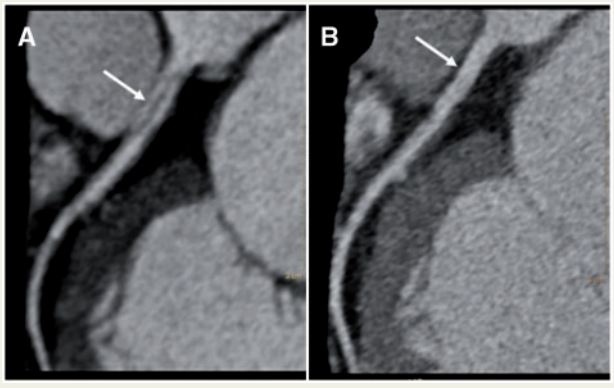

A 34-year-old primigravida had chest pain and dyspnoea 2 h after an urgent cesarean section and a twin delivery. The indication for surgery was premature rupture of membranes at 32 weeks of gestation. Electrocardiogram (ECG) during chest pain showed 2-mm ST-depression in anterior leads and the Troponin T level increased to 174 ng/L (normal <13). The chest pain and ECG changes spontaneously resolved, and an echocardiogram performed later was normal. A clinical diagnosis of non-ST-elevation myocardial infarction with probable spontaneous coronary artery dissection (SCAD) was made and the patient was treated with aspirin, clopidogrel, and bisoprolol. Since the patient was stable, invasive coronary angiography was deferred and a cardiac computed tomography angiography (CCTA) was performed the following day, confirming the diagnosis of SCAD involving the left main (LM) and left anterior descending coronary arteries (*A*). The patient remained stable and repeat CCTA a week later was normal (*B*). Six-months follow-up was uneventful and an exercise test performed 2-months post-discharge was normal.

Invasive coronary angiography and revascularization are generally recommended for patients with suspected post-partum SCAD, especially with LM involvement. This approach, however, is associated with increased risk of intimal tears, spiral dissections, and occlusion of the friable coronary arteries. Spontaneous coronary artery dissection is a rare condition which has been associated with the elevated oestrogen and progesterone and stress during pregnancy and delivery, but randomized studies to guide management are unavailable. This case illustrates the usefulness of CCTA for the diagnosis of SCAD, allowing for conservative management of stable patients, even with LM involvement.