Exercise capacity and cardiac reserve in children and adolescents with corrected pulmonary atresia with intact ventricular septum after univentricular palliation and biventricular repair

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Objective: Management of pulmonary atresia with intact ventricular septum is challenging and depends on the severity of right ventricular hypoplasia. Clinical outcomes of biventricular repair seem favorable to univentricular palliation, but data on superiority of biventricular repair regarding exercise capacity are conflicting. We investigated the response to physical and pharmacologic stress in patients with surgically corrected pulmonary atresia with intact ventricular septum.

Methods: Sixteen patients (7 patients after univentricular palliation, age 11.8 ± 2.6 years; 7 patients after biventricular repair, age 12.9 ± 2.7 years; and 2 patients after 1.5 ventricular repair, age 12 and 19 years) underwent cardiopulmonary exercise test, dobutamine stress magnetic resonance imaging, and delayed contrast-enhanced magnetic resonance imaging.

Results: The univentricular group showed impaired exercise capacity in contrast with normal exercise capacity in the biventricular group. Left ventricular ejection fraction increased in both groups. With dobutamine, left ventricular stroke volume increased only in the biventricular group ($+11.3 \pm 5.0$ mL, $P < .001$) and not in the univentricular group (-0.04 ± 3.6 mL, $P = .9$). Heart rate increase was inadequate in the univentricular group. Maximum oxygen consumption and oxygen pulse were strongly correlated with left ventricular stroke volume during stress but not at rest. The results of the 2 patients after 1.5 ventricular repair were comparable to those of the univentricular group. No myocardial fibrosis was detected.

Conclusions: Impaired exercise capacity in children and adolescents with pulmonary atresia with intact ventricular septum after univentricular palliation is related to decreased cardiac reserve and inadequate chronotropic response. Young patients with pulmonary atresia with intact ventricular septum after biventricular repair show normal exercise capacity and cardiac reserve. (J Thorac Cardiovasc Surg 2012;143:569-75)

Pulmonary atresia with intact ventricular septum (PAIVS) is a rare congenital cardiac anomaly constituting 1% to 3% of congenital heart disease (CHD). Surgical treatment of PAIVS is challenging, and treatment strategies differ among surgical centers. If the right ventricle (RV) and tricuspid valve (TV) grow adequately after initial palliation in the first years of life, biventricular repair may be considered.

Patients with a hypoplastic RV or TV may be considered for univentricular palliation (Fontan operation) or a so-called 1.5 ventricular repair: patent right ventricular outflow tract (RVOT) with superior cavopulmonary anastomosis.^{1,2}

Theoretically, biventricular repair is superior to univentricular palliation because blood flow to the pulmonary arteries is actively sustained by the RV rather than passive as seen in the univentricular circulation. However, studies comparing long-term clinical outcomes of univentricular palliation and biventricular repair in patients with PAIVS are limited. Decreased exercise capacity after surgical repair of PAIVS has been demonstrated.^{3,4} The underlying mechanisms for impaired exercise tolerance after surgical repair of PAIVS, including biventricular repair, are unclear and may be caused by impaired left ventricle (LV) performance, coronary perfusion abnormalities, or RV hypoplasia.^{3,4} It is currently uncertain whether biventricular repair leads to superior exercise performance.

Comprehensive assessment of cardiac reserve may provide information on the mechanism of impaired exercise tolerance. Pharmacologic stress test facilitates noninvasive quantitative assessment of cardiac reserve.^{5,6} Dobutamine

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Abbreviations and Acronyms

AP	= aortopulmonary
CHD	= congenital heart disease
CO	= cardiac output
DCE	= delayed contrast enhancement
DS	= dobutamine stress
EDV	= end-diastolic volume
EF	= ejection fraction
ESV	= end-systolic volume
HR	= heart rate
IVS	= interventricular septum
LV	= left ventricle
MHR	= maximum heart rate
MRI	= magnetic resonance imaging
O ₂	= oxygen
PAIVS	= pulmonary atresia with intact ventricular septum
RER	= respiratory exchange ratio
RV	= right ventricle
RVOT	= right ventricular outflow tract
SV	= stroke volume
TV	= tricuspid valve
VO ₂ max	= maximum oxygen consumption

stress magnetic resonance imaging (DS-MRI) is an attractive imaging modality for assessment of cardiac reserve because of excellent endocardial visualization and the lack of radiation. Delayed contrast enhancement (DCE)-MRI using gadolinium-based contrast media is a technique that allows the direct visualization of myocardial fibrosis.⁷

The present study analyzed differences in exercise capacity in patients with surgically corrected PAIVS after univentricular palliation, 1.5 ventricular repair, and biventricular repair. The presence of myocardial fibrosis was assessed using DCE-MRI. Subsequently, LV response to pharmacologic stress was evaluated using DS-MRI, and the potential role of impaired LV stress-response in diminished exercise capacity was studied by correlating parameters of exercise performance to functional LV parameters at rest and during pharmacologic stress.

PATIENTS AND METHODS

The local medical ethics committee approved the study, and informed consent was obtained from all participants or parents before their enrollment. Patients with surgically corrected PAIVS, aged more than 8 years, followed up at our institutions, and with no contraindication for MRI examination were included in the study. Patients were recruited from the pediatric cardiology database of the Center for Congenital Heart Disease Amsterdam Leiden (www.CAHAL.nl) and the national database and DNA data bank of adult patients with a congenital heart disease (www.CONCOR.nl).⁸

The database identified 31 eligible patients with PAIVS after surgical repair. Eleven patients were not enrolled, 10 because of family refusal to participate and 1 because of pregnancy. After univentricular palliation for PAIVS, 7 patients were identified, and of 11 patients after biventricular repair, 7 age- and sex-matched patients after biventricular repair were selected for comparison. Furthermore, 2 patients after 1.5 ventricular repair of PAIVS were included in the study.

All patients underwent a symptom limited cardiopulmonary exercise test with MRI examination, including DCE-MRI and DS-MRI, and determination of maximum oxygen consumption (VO₂max).

Cardiopulmonary Exercise Test

A symptom-limited cardiopulmonary exercise test to assess maximal exercise capacity was performed, according to the guidelines of the American Thoracic Society,⁹ by means of graded exercise testing on a motor-driven treadmill (Jaeger, Würzburg, Germany) using a modified Bruce protocol with a continuous 12-lead electrocardiographic monitoring system. At baseline and during the exercise tests, heart rate (HR) was continuously measured and maximum heart rate (MHR) was reported. VO₂max was defined as the highest value of oxygen uptake measured twice during the last 15 seconds of exercise. Oxygen (O₂) pulse is an indirect index of combined cardiopulmonary oxygen transport, and thus stroke volume. O₂ pulse is measured by O₂ consumption per minute divided by HR. Exercise tests were considered valid if the patient reached the anaerobic threshold, defined as having a respiratory exchange ratio (RER) greater than 1.0. Measured cardiopulmonary exercise test parameters were compared with predicted normal values from Wasserman and coworkers,¹⁰ and impaired exercise tolerance was defined as VO₂ max lower than 85% of the predicted values.

Magnetic Resonance Imaging

MRI was performed using an open MRI 1.0 T MRI-scanner (Panorama; Philips Medical Systems, Best, The Netherlands). Long-axis and 2- and 4-chamber views and short-axis views consisting of 12 to 14 contiguous slices, covering the LV from the base of the heart to the apex, were acquired using a retrospective electrocardiogram-gated, steady-state, free-precession sequence during breath-holding at end expiration. Scan parameters were repetition time = 3.2–3.8 ms; echo time = 1.6–1.9 ms; flip angle = 50–70 degrees; slice thickness = 8 mm without slice gap; matrix = 160 × 256; and field of view = 350–400 mm. Temporal resolution was approximately 25 ms. Short-axis images were repeated at maximum dobutamine infusion to assess LV dimensions and function during pharmacologic stress.

Dobutamine Infusion

An intravenous line was inserted into the antecubital vein before the MRI procedure. Dobutamine was administered by a digital MRI compatible infusion pump. After the MRI acquisition at rest, dobutamine was infused in serial incremental doses of 5, 10, and 15 µg/kg/min in 3-minute stages. Infusions were performed under continuous monitoring with electrocardiogram and automated blood pressure measurements. The end point for termination of dobutamine infusion was reaching a target HR, 85% of age-predicted MHR (220 – age in years), or 15 µg/kg/min of dobutamine infusion.

Delayed Contrast-Enhanced Magnetic Resonance Imaging

Ten to 15 minutes after injection of a gadolinium-based contrast agent (Magnevist, Schering AG, Berlin, Germany; 0.2 mmol/kg), DCE images were acquired in the same orientation as the cine short-axis images using a segmented inversion-recovery gradient-echo pulse sequence: repetition time /echo time = 4.01/1.25 ms, flip angle = 15 degrees, matrix = 208 × 256 and a typical voxel size of 1.6 × 1.3 × 5.0 mm, inversion time (T₁) = 180–200 ms.

Magnetic Resonance Imaging Post-Processing

All images were analyzed on a workstation with an Intel Pentium 4 processor (Intel, Santa Clara, Calif). LV functions were analyzed with the software package MASS (Medis BV, Leiden, The Netherlands).

LV systolic function was assessed by drawing endocardial contours at end-diastole and end-systole in all sections of the cine short-axis data.¹¹ End-diastolic volume (EDV) and end-systolic volume (ESV) were obtained. Stroke volume (SV) was calculated by subtracting ESV from EDV. Ejection fraction (EF) was calculated by dividing SV by EDV $\times 100$. Cardiac output (CO) was calculated by multiplying SV by HR.

Two observers (S.R. and M.G. with 4 and 15 years of experience in cardiac MRI, respectively) agreed on the presence or absence of DCE in the LV and in the interventricular septum (IVS).

STATISTICAL ANALYSIS

The study patients were categorized into 2 groups based on the surgical repair of PAIVS: univentricular repair and biventricular repair. Between both PAIVS groups, age-matched results of cardiopulmonary exercise test, DCE-MRI, and DS-MRI were compared. The studies of 2 patients with 1.5 ventricular repair were not statistically analyzed. Differences between groups were evaluated using the Student *t* test or Mann–Whitney test for pairwise comparisons. Variables that were normally distributed are presented as mean and standard deviation, and variables with skewed distribution are presented as medians and range. The presence of normal distribution was tested using the Shapiro–Wilk test. All statistical testing and data analysis were performed with SPSS version 16 (SPSS Inc, Chicago, Ill). The correlations were assessed between maximal achieved LV-SV during DS-MRI and cardiac work indices during the exercise test. The Pearson correlation coefficient was calculated.

RESULTS

Patient Characteristics

Characteristics of the patients are shown in Table 1. All patients were in New York Heart Association class I or II and received no heart failure medication. All patients with univentricular palliation received aspirin.

At our institution, patients with PAIVS with a normal or moderately hypoplastic RV and a TV diameter *z* score of -2.0 or more are generally considered candidates for biventricular repair, and patients with TV diameter *z* scores less than -2.0 are considered candidates for univentricular palliation or 1.5 ventricular repair.

The neonatal TV diameter *z* scores, available in 13 patients, were -1.7 ± 0.3 in the biventricular group (6/7 patients) and -3.7 ± 0.6 in the univentricular palliation group and 1.5 ventricular repair group (7/9 patients).

All patients with univentricular palliation had an aortopulmonary (AP) shunt neonatally. Two patients (28%) had RV-dependent coronary circulation. One patient (14%) had attempted RV decompression in the neonatal period but was ultimately managed with univentricular repair because of inadequate RV growth. Two patients (28%) had Ebstein's

TABLE 1. Patients' characteristics and results of cardiopulmonary exercise test

	Univentricular palliation group (N = 7)	Biventricular repair group (N = 7)	P value
Age (y)	11.8 $\pm$ 2.6	12.9 $\pm$ 2.7	.6
NYHA functional class			
I	5 (72%)	6 (86%)	.2
II	2 (28%)	1 (14%)	.6
Previous AP shunt (n, %)	7 (100%)	6 (86%)	.8
Oxygen saturation %	92.6 $\pm$ 2.3	97.5 $\pm$ 1.0	<.001
RER	1.1 $\pm$ 0.1	1.1 $\pm$ 0.1	.2
Resting HR (beats/min)	87 $\pm$ 10	85 $\pm$ 11	.4
MHR (beats/min)	143 $\pm$ 13	186 $\pm$ 7	<.001
MHR (% of predicted)	73.5 $\pm$ 6.8	94.9 $\pm$ 5.6	<.001
VO ₂ max (mL/kg/min)	25.9 $\pm$ 6.3	45.4 $\pm$ 6.3	<.001
VO ₂ max (% of predicted)	55.7 $\pm$ 10.8	92.7 $\pm$ 6.7	<.001
O ₂ pulse (mL/beat)	6.7 $\pm$ 1.3	11.2 $\pm$ 2.6	.006
O ₂ pulse (% of predicted)	59.6 $\pm$ 11.6	100.2 $\pm$ 18.0	<.001
Work load (METs)	7.9 $\pm$ 1.9	12.4 $\pm$ 2.2	.002
Exercise test time (min)	10.1 $\pm$ 1.3	15.1 $\pm$ 0.6	.003

Values are (mean $\pm$ standard deviation). AP, Aortopulmonary; RER, respiratory exchange ratio; HR, heart rate; MHR, maximum heart rate; NYHA, New York Heart Association; METs, metabolic equivalents.

malformation of TV. All patients had completion of the univentricular repair at mean age of 3.1 ± 0.7 years. The Fontan circulation had been completed by means of a lateral tunnel technique in 2 patients (28%) and an extracardiac conduit in 5 patients (72%). A fenestration was performed in 4 patients (57%), which was closed later in 3 patients (43%).

In the biventricular repair group, all patients had a surgical RVOT reconstruction in the neonatal period. Six patients (86%) required AP shunts because of cyanosis and RV failure.

Age at complete surgical repair was 2.5 ± 0.5 years. At the time of complete repair, 3 patients (42%) had an interatrial communication in the form of an atrial septal defect. Surgical or catheter-directed closure of atrial septal defect was performed at a later stage in all of them.

All patients completed the cardiopulmonary exercise test, DCE-MRI, and DS-MRI with no adverse events. In particular, none of the patients had episodes of hypotension or sustained arrhythmia leading to early termination of any test. None of the participants experienced headache, chest pain, or palpitations, and no ST-T changes or premature ventricular complexes were recorded on the electrocardiogram.

Cardiopulmonary Exercise Test

All patients reached an RER greater than 1.0, which indicates that all patients reached the anaerobic threshold. The cardiopulmonary exercise parameters of both groups are summarized in Table 1.

The univentricular palliation group showed impaired exercise capacity, defined as VO₂max less than 85% of

TABLE 2. Results of dobutamine stress magnetic resonance imaging in univentricular palliation group versus biventricular repair group

	Univentricular palliation group			Biventricular repair group			P value of difference between groups	
	Rest	Stress	P value	Rest	Stress	P value	Rest	Stress
MHR (beats/min)	88 ± 18	128 ± 18	.01	75 ± 8	139 ± 8	.001	.8	.01
LV-EDV (mL/m ²)	71.4 ± 7.8	63.5 ± 10.8	.002	89.7 ± 10.3	88.2 ± 11.2	.3	.01	.01
LV-ESV (mL/m ²)	32.5 ± 5.8	25.6 ± 6.7	.000	42.4 ± 4.8	31.6 ± 5.9	.001	.07	.5
LV-SV (mL/m ²)	38.2 ± 7.2	38.2 ± 6.5	.9	47.4 ± 9.2	57 ± 6.9	.001	.08	<.001
LV-EF (%)	53.4 ± 7.3	60.57 ± 6.0	.003	54.8 ± 5.9	62.0 ± 4.0	.02	.2	.6
LV-CO (L)	3.8 ± 1.4	4.8 ± 1.6	.007	4.8 ± 1.0	7.8 ± 2.5	.009	.2	.02

Values are mean ± standard deviation. MHR, Maximum heart rate; LV-EDV, left ventricular end-diastolic volume; LV-ESV, left ventricular end-systolic volume; LV-SV, left ventricular stroke volume; LV-EF, left ventricular ejection fraction; LV-CO, left ventricular cardiac output.

predicted. In contrast, the biventricular repair group showed normal exercise capacity. O₂ pulse in response to physical exercise was significantly lower in the univentricular repair group (Table 1). During exercise testing, all patients remained in sinus rhythm. There was no significant difference between both groups in the resting HR. HR increase, in response to physical exercise, was significant in both groups. However, the biventricular repair group had a good chronotropic response (MHR >85% of predicted), whereas the univentricular palliation group had inadequate chronotropic response (MHR <85% of predicted) (Table 1).

Magnetic Resonance Imaging

MRI scans of good quality were obtained in all patients at rest and during dobutamine infusion. LV dimensions and function at rest are shown in Table 2 and Figure 1. None of the patients showed DCE in the LV or IVS. There were no differences in the functional indices (LV-SV, LV-EF, and CO) between both groups at rest. In the univentricular group, the LV-EDV at rest was within the normal range but smaller compared with the biventricular group.

During DS, HR significantly increased in both groups. However, the biventricular repair group had a statistically

significant better chronotropic response. LV-EF increased and LV-ESV decreased in both groups. However, during DS, patients with univentricular palliation showed abnormal decrease of LV-EDV compared with no change in patients with biventricular repair. This resulted in a significant increase in LV-SV in patients with biventricular repair, whereas LV-SV did not change in patients with univentricular palliation (+11.3 ± 5.0 mL and −0.04 ± 3.6 mL, respectively; $P = .004$). LV-CO increased in both groups, but LV-CO increase was significantly greater in the biventricular repair group compared with the univentricular palliation group.

VO₂max and O₂ pulse during maximum physical exercise were strongly related to LV-SV during peak dobutamine infusion ($r = 0.73$, $P = .003$, and $r = 0.79$, $P = .001$, respectively), whereas no correlation was observed with LV-SV at rest ($r = 0.05$, $P = .4$, and $r = 0.15$, $P = .1$, respectively) (Figure 2).

Patients With Pulmonary Atresia With Intact Ventricular Septum After 1.5 Ventricular Repair

Two female patients aged 12 and 19 years underwent 1.5 ventricular repair. Both patients had a surgical RVOT reconstruction and AP shunts in the neonatal period and had a superior cavopulmonary anastomosis at 2 years of age. Both patients reached RER greater than 1.0; however, both had impaired exercise capacity; VO₂max was 73% and 75% of predicted and O₂ pulse was 56% and 63% of predicted. However, both patients had a good chronotropic response; maximum HR was 95% and 87% of predicted.

During pharmacologic stress test, LV function resembled the reaction to DS that was observed in the univentricular group. LV-EDV decreased abnormally from 75 to 65 mL/m² and from 59 to 56 mL/m², respectively. LV-ESV response was normal and decreased from 38 to 26 mL/m² and from 25 to 20 mL/m², respectively; LV-SV remained unchanged before and after dobutamine, from 37 to 36 mL/m² in 1 patient and 35 mL/m² in 1 patient. LV-EF increased from 51% to 60% and from 58% to 64%. LV-CO increased from 4.0 to 5.7 L and from 2.5 to 4.2 L. None of the 2 patients showed DCE of the LV or IVS.

FIGURE 1. Changes of LV-EDV, LV-ESV, LV-SV, LV-EF, and LV-CO during maximum dobutamine infusion in patients after univentricular palliation (white bars) and biventricular repair (black bars). LV, Left ventricle; EDV, end-diastolic volume; ESV, end-systolic volume; SV, stroke volume; EF, ejection fraction; CO, cardiac output.

FIGURE 2. A, Correlation between change in LV-SV during maximum dobutamine infusion and VO_2max . B, Correlation between change in LV-SV during maximum dobutamine infusion and O_2 pulse. LV, Left ventricle; SV, stroke volume; O_2 , oxygen; VO_2max , maximum oxygen consumption.

DISCUSSION

The present study showed that children and adolescents with PAIVS after univentricular palliation have an impaired exercise capacity that is related to decreased cardiac reserve. Of note, in all children with PAIVS exercise capacity and cardiac reserve were found to be completely normal after biventricular repair.

Management of PAIVS is difficult, and surgical and interventional therapies are associated with significant mortality and morbidity. Different treatment options have to be considered, including biventricular repair, 1.5 ventricular repair, or Fontan-type operation. The major problem when planning a strategy for a definitive repair is the fact that RV function and growth are difficult to predict before the operation. Currently, follow-up data on cardiac function and exercise capacity in patients with PAIVS after different types of repair remain limited.

Our results demonstrate that the increase in both SV and HR in response to physical and pharmacologic stress was normal in the biventricular repair group. In contrast, the univentricular palliation group had an impaired exercise capacity because of the inability to increase SV and inadequate chronotropic response. The SV response to physical stress in patients with univentricular palliation, as measured by O_2 pulse, was inadequate, as well as the increase of HR. During pharmacologic stress using DS-MRI, we confirmed that LV-SV failed to increase and that the HR increase was inadequate in the univentricular palliation group. We showed a strong correlation between indices of LV-SV augmentation during physical stress and pharmacologic stress, but not with LV-SV at rest (Figure 2). In the absence of myocardial fibrosis, the inability to increase LV-SV despite a normal EF could be explained by unfavorable ventricular filling, evidenced by abnormally decreased LV-EDV in response to pharmacologic stress. This is the first study to investigate the mechanism of impaired exercise capacity in this group of patients.

Cardiopulmonary exercise test is a strong predictor of survival in patients with chronic heart failure, and decreased VO_2max is related to adverse long-term outcome.¹² Furthermore, poor exercise capacity has been used as

a predictor for identifying patients with CHD who are at risk for hospitalization or death.¹³ In patients with surgically corrected PAIVS, decreased exercise capacity has been reported, but controversy exists whether biventricular repair leads to superior exercise performance compared with univentricular palliation.⁴ Published data on assessment of exercise capacity in patients after surgical repair of PAIVS are limited. Few studies are available on exercise capacity assessment exclusively in this group of patients.^{3,4} Our results are in line with the results of Ekman-Joelsson and colleagues,³ who showed that patients with PAIVS after biventricular repair have a better exercise capacity compared with those after univentricular palliation. In contrast, Sanghavi and colleagues⁴ showed that exercise capacity varied widely within the 2 postoperative PAIVS groups and found no difference after univentricular palliation and after biventricular correction. Sanghavi and colleagues even question whether biventricular repair had been the optimal treatment option in some of the patients in their study cohort.⁴ The exact mechanism of impaired exercise capacity in patients with surgically corrected PAIVS is not clear. Although several factors have been suggested to influence exercise capacity, such as age at surgical repair, RV size at birth, TV abnormalities, presence of RV-dependent coronary circulation, and cardiac function parameters at rest, no correlations were found in earlier studies.^{3,4} Both previous studies showed inadequate chronotropic response in the univentricular palliation group. Univentricular palliation often involves surgery near sinus node, and sinus node dysfunction is a recognized complication of these procedures.¹⁴ However, as shown in our results, the magnitude of the difference in chronotropic response was insufficient to have a significant impact on the exercise capacity.

In the present study, the patients with PAIVS after the Fontan operation had similar results regarding the degree of impairment of exercise performance and reduction of VO_2max compared with large Fontan cohorts with a variety of underlying CHD.¹⁵

The importance of assessment of cardiac reserve is stressed by the observation that the most important predictor

for development of cardiac dysfunction is not a depressed cardiac function at rest, but an abnormal response to stress.^{5,16} The evaluation of cardiac reserve is of special interest in patients with CHD because it is an early predictor for cardiac dysfunction and assessment of cardiac reserve may reveal cardiac dysfunction, which is not present at rest.^{5,6,16,17} There are no previously published data on evaluation of cardiac reserve exclusively in surgically treated patients with PAIVS after biventricular repair or univentricular palliation. Previous studies evaluated cardiac reserve in patients after univentricular palliation with several underlying diagnoses by DS imaging. In general, impaired cardiac reserve was observed in patients after univentricular palliation. However, the clinical impact of impaired cardiac reserve has not been unveiled in this heterogeneous Fontan cohort.¹⁸⁻²⁰ Our results confirmed the impaired exercise capacity in patients with univentricular palliation by demonstrating a significant decrease in LV-EDV in response to pharmacologic stress, which indicates improper LV filling. The present study for the first time demonstrates that reduced exercise functional capacity is strongly related to cardiac reserve in a group of young patients with PAIVS after the Fontan operation. Possible explanations for improper LV filling are that loss of flow pulsatility augmentation in the univentricular circulation reduces the release of endothelium-derived nitric oxide, thereby attenuating the lowering of pulmonary vascular resistance induced by nitric oxide, leading to reduced preload.¹⁹⁻²² Moreover, specifically in patients with PAIVS, the presence of a high-pressure residual RV may have an adverse effect on ventricular–ventricular interaction, leading to further impairment of LV filling.^{23,24}

No LV or RV myocardial fibrosis was detected by DCE in this PAIVS cohort, including 2 patients who underwent the Fontan procedure with RV coronary-dependent circulation. These findings are in contrast with the study by Liang and colleagues,²⁵ who showed the presence of DCE in several patients with PAIVS after biventricular repair, perhaps because the majority of their patients received an RVOT patch. However, because the DCE acquisition parameters were not mentioned in this study, it is difficult to compare results. In another study by Ekman-Joelsson and colleagues,²⁶ perfusion defects were demonstrated in patients with PAIVS after the Fontan operation using myocardial perfusion scintigraphy. Perfusion defects were present in the septum and LV free wall and appeared to be related with ventriculo-coronary arterial connections and late age of univentricular palliation. They also demonstrated septal or LV hypokinesia or dyskinesia using echocardiography. These findings are clearly in contrast with those of our DS-MRI study, in which none of the patients were found to have segmental wall motion abnormalities at rest or during stress, and none had signs or symptoms of ischemia, indicating adequate coronary artery perfusion. This difference may be explained

by younger age at Fontan operation in the present study or by differences in patient selection.

The present study found normal results regarding cardiac reserve during pharmacologic stress and normal exercise capacity tests in the biventricular PAIVS group, which is encouraging. After birth, the majority of children in this cohort required an additional AP shunt and interatrial communication to maintain adequate pulmonary blood flow, indicating severe RV dysfunction in the first months of life. Our data indicate that cardiac function seems to recover and remains preserved in this biventricular group during midterm follow-up.

Data on the response to physical stress in patients after 1.5 ventricular repair is limited. Only 2 studies are available, and both studies showed that exercise capacity was impaired and correlated with impaired RV function in this group,^{27,28} similar to our 2 patients. In the present study, both patients showed abnormal response to pharmacologic stress with failure to increase LV-SV after 1.5 ventricular repair. More studies on patients with PAIVS after 1.5 ventricular repair are needed for better understanding of the 1.5 ventricular physiology.

Study Limitations

The present study included relatively few patients; however, significant differences were observed between the patients with PAIVS after univentricular or biventricular correction. Furthermore, the age at MRI examination and exercise test was relatively young. Long-term follow-up is needed to evaluate whether the observed differences between the different ways of PAIVS correction remain.

CONCLUSIONS

Impaired exercise capacity in children and adolescents with PAIVS after univentricular palliation is related to decreased cardiac reserve caused by impaired LV filling during stress and inadequate chronotropic response. In contrast, young patients with PAIVS after biventricular repair show normal exercise capacity and cardiac reserve. These findings support the superiority of biventricular correction of PAIVS over univentricular palliation during midterm follow-up.

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