Clinical Investigation

Clinical Evaluation of Exercise Capacity in Adults with Systemic Right Ventricle

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The right ventricle provides systemic circulation in individuals with congenitally corrected transposition of the great arteries (CCTGA) and in those with complete transposition who have had an atrial switch repair (DTGA). The aim of this study was to evaluate how the systemic right ventricle adapts to increased workload and oxygen demand during exercise.

From November 2005 through December 2015, 3,358 adult patients with congenital heart disease were treated at our institution; we identified 48 (26 females, 22 males; median age, 25.4 ± 8.1 yr) who met the study criteria; 37 had DTGA and atrial switch repair, and 11 had CCTGA. We studied their echocardiographic and cardiopulmonary exercise test results. A control group consisted of 29 healthy sex- and age-matched volunteers.

On exercise testing, oxygen uptake at anaerobic threshold, peak oxygen uptake, peak heart rate, and percentage of maximal heart rate were significantly lower in the group with systemic right ventricle than in the control group (all P *<0.001); in contrast, the peak ventilatory equivalent for carbon dioxide was higher in the study group (*P*=0.013). Impaired systemic right ventricular function reduced peak oxygen uptake. The peak heart rate was lower in the CCTGA group than in the DTGA group.*

Our results indicate that reduced exercise capacity is related to impaired systemic right ventricular function, severe tricuspid valve regurgitation, and chronotropic incompetence. There was no correlation between cardiopulmonary exercise test results and time after surgery. Chronotropic efficiency is lower in individuals with CCTGA than in those with DTGA. ***(Tex Heart Inst J 2019;46(1):14-20)***

The right ventricle (RV) is a thin-walled, crescent-shaped structure designed to support low-pressure pulmonary circulation. However, in individuals with congenitally corrected transposition of the great arteries (CCTGA) or in those with dextro-type transposition of the great arteries (DTGA) after atrial switch repair (a Senning or Mustard procedure), the RV must support high-pressure systemic circulation. In CCTGA, a double atrioventricular (AV) and ventriculoarterial mismatch exists. In DTGA, the anatomic correction in atrial switch repair leaves the aorta connected to the RV. These physiologic adaptations lead to increased RV end-diastolic volume, decreased ejection fraction at rest, and loss of contractile reserve during exercise, which cause marked tricuspid valve (TV) regurgitation. Patients with reduced systemic RV (SRV) function have a low exercise capacity. Increases in cardiac output depend on increases in stroke volume and heart rate. Winter and associates[1] found that the adaptive mechanisms to achieve this differed between a group of patients with CCTGA and one with DTGA. The CCTGA group had increased stroke volume and heart rate; in contrast, only heart rate increased in the DTGA group. Augmented cardiac output during exercise is related to an increase in peak oxygen uptake (peak Vo_2), and this is an important prognostic factor for determining life expectancy and quality of life in patients with SRV. Therefore, we analyzed cardiopulmonary exercise test (CPET) results from adults who had CCTGA or DGTA, to further identify which factors affect exercise capacity in these populations.

Patients and Methods

To determine how effectively the RV adapts to systemic circulation, we performed a retrospective study of adults with transposition of the great arteries (CCTGA or atrially switched DTGA) who had been treated at the Cardiological Outpatient Clinic

of the John Paul II Hospital in Krakow. The study was performed in accordance with the Helsinki Declaration and with the guidelines set by our institutional ethics committee.

Study Design

We conducted a chart review of 3,358 adult patients with congenital heart disease who were treated at our institution from November 2005 through December 2015. Patients were included in the study if they had DTGA or CTGA, were ≥18 years of age, and had been clinically stable for at least 3 months before undergoing CPET. Patients were excluded if they had severe valvular heart disease, a prior acute vascular event, acute inflammatory illness, neoplastic disease, or diabetes mellitus, or were pregnant. Finally, patients were excluded if they had single-ventricle circulation after Fontan operation.

A total of 3,292 patients were excluded on initial review; 28 of them had single-ventricle circulation after Fontan operation. Of the 66 remaining candidates who had SRV, 18 were excluded for these reasons: 2 had severe pulmonary stenosis, 1 had a substantial ventricular septal defect, 5 had severe left ventricular outflow tract obstruction, and 10 had no CPET results.

Thus, 48 patients met the inclusion criteria: 37 patients with DTGA who had undergone a Senning operation and 11 with CCTGA.

To determine how well SRV function compares with normal left ventricular function, we compared CPET results from the 48 patients who had SRV with those of 29 healthy sex- and age-matched volunteers. Then, to evaluate differences in RV function and exercise capacity in the presence of natural correction of transposition of the great arteries and atrial switch anatomy, we compared CPET results in the CCTGA patients with those in the DTGA patients.

Clinical Analysis

Clinical data gathered included age, body mass index, body surface area, exercise capacity in relation to New York Heart Association (NYHA) functional class, time since surgery (for the DTGA patients), and the presence of a pacemaker.

Transthoracic Echocardiographic Evaluation

Right systolic function was evaluated in the patients with SRV by measuring fractional area change (FAC), tissue-Doppler–derived tricuspid lateral annular systolic velocity (S' wave), and tricuspid annular plane systolic excursion (TAPSE). All calculations were made with use of a Vivid® 7 cardiovascular ultrasound system (GE Healthcare). Fractional area change—the difference in RV area from end-diastole to end-systole—was calculated by manually tracing the contour of the RV in the apical 4-chamber view at each point. The TAPSE was estimated by measuring the extent of systolic motion of the TV ring toward the apex on M-mode echocardiography.

Using the American Society of Echocardiography guidelines,[2,3] we defined RV dysfunction as FAC <35%, tissue-Doppler S' wave velocity <9.5 cm/s, and TAPSE <17 mm.

Tricuspid valve regurgitation, evaluated by color-Doppler echocardiography, was classified as mild-to-moderate or severe. We did not evaluate magnetic resonance images, but previous research has shown that the results are comparable to those of echocardiography for evaluating RV function.[4]

Cardiopulmonary Exercise Testing

Exercise tolerance was evaluated by CPET. Oxygen uptake (V_{O_2}), carbon dioxide production (V_{CO_2}), and minute ventilation (VE) were measured at rest and at peak exercise with use of a computerized analyzer. Peak V_{O_2}/kg (determined by the highest value of workload), peak heart rate, and percentage of maximal heart rate were also measured. The ventilatory anaerobic threshold was calculated by means of the V-slope method.[5] The ventilatory equivalent for carbon dioxide (VE/V_{CO_2}) was calculated as the amount of ventilation needed to eliminate a given amount of CO_2. The respiratory exchange ratio (RER) was calculated by dividing V_{O_2} by V_{CO_2}.[6]

Statistical Analysis

Continuous data were presented as mean ± SD when the data distributions were symmetric. Discrete data were presented as number and percentage. Continuous data in 2 different populations were compared by *t* test when the distributions of characteristics were consistent with the normal distribution and when there was homogeneity of variance. The Mann-Whitney test was used when there was no normality, and the Welch *t* test was used when there was no homogeneity of variance. The Shapiro-Wilk test was used to evaluate the compliance of the distribution with the normal distribution, and the Levene test was used to determine the equality of variances. Correlation between 2 continuous characteristics was determined by using the Pearson correlation coefficient or the nonparametric Spearman rank correlation coefficient. The correlation of 2 categorized characteristics was determined by means of the χ^2 or Fisher exact test when the expected values were too low (<5 in at least one cell of a contingency table). The age difference between the DTGA and CCTGA groups was leveled in statistical analysis. A P value ≤0.05 was considered statistically significant. Statistica™ version 10.0.1011.7 (Tibco Software Inc.) was used to analyze the data.

Results

We identified 48 patients with SRV who met the study criteria: 37 (77%) had DTGA and had undergone an

atrial switch operation, and 11 (23%) had CCTGA. The patients' median age was 25.4 ± 8.1 years; body mass index, 22.6 ± 3.4 kg/m^2; and body surface area, 1.75 ± 0.19 m^2. The CCTGA patients were older than the DTGA patients (P <0.001) (Table I). Other findings included a hemodynamically insignificant VSD in 6 patients (10.4%), and 3 (6.2%) had left ventricular outflow tract obstruction with maximal gradients below 35 mmHg. All but one of the DTGA patients had undergone a Rashkind procedure before the Senning operation; the median age at the time of the atrial switch operation was 7 months (range, 1–48 mo). One patient had undergone percutaneous angioplasty of a narrowed pulmonary baffle at 5 years of age. No baffle leaks were seen on the patients' echocardiograms.

Of the 37 DTGA patients, 4 (10.8%) had a permanent cardiac pacemaker to treat total AV block, and 2 (5.4%) had an implantable cardioverter-defibrillator for secondary prevention of sudden cardiac death. Of the 11 CCTGA patients, 5 (45.5%) had total AV block, and 4 (36.4%) had an implanted cardiac pacemaker; none had undergone cardiac surgery.

Echocardiographic Findings

The echocardiographic results showed that severe TV regurgitation was more frequent in the CCTGA patients than in the DTGA patients (P=0.004) (Table II). There were no significant differences between the groups in regard to RV dimensions or function (that is, FAC, S' velocity, and TAPSE), tricuspid ring diameter, or left ventricular dimensions or ejection fraction.

Cardiopulmonary Exercise Testing

The results of CPET in all 48 patients with SRV were compared with those in a control group of 29 patients (Table III). In the SRV group, the Vo_2/kg at anaerobic threshold (19.66 ± 5.8 vs 34.24 ± 11.14 mL/kg/min; P <0.001) and peak Vo_2/kg (26.43 ± 6.27 vs 48.01 ± 7.67 mL/kg/min; P <0.001) were significantly lower than that in the control group; in contrast, the SRV group had a significantly higher peak VE/Vco_2 (29.31 ± 4.69 vs 26.77 ± 3.21 mL/kg/min; P=0.013). The peak heart rate and the percentage of maximal heart rate were significantly reduced in the study group (both P <0.001).

TABLE I. Characteristics of the 48 Patients with Systemic Right Ventricle

Variable	**DTGA** (n=37)	**CCTGA** (n=11)	***P* Value**
Female	18 (48.6)	8 (72.7)	0.159
Male	19 (51.4)	3 (27.3)	—
Age (yr)	22.25 ± 3.61	35.64 ± 10.64	<0.001
Body mass index (kg/m^2)	22.41 ± 3.44	23.4 ± 3.97	0.436
Body surface area (m^2)	1.76 ± 0.21	1.74 ± 0.15	0.865
NYHA functional class			0.056
I	25 (67.6)	4 (36.4)	—
II	10 (27)	4 (36.4)	—
III	2 (5.4)	3 (27.3)	—
Time from surgery (yr)			
<20	9 (24.3)	—	—
20–25	21 (56.8)	—	—
>25	7 (18.9)	—	—
Preserved RV function	24 (64.9)	8 (72.7)	0.689
Trivial TV regurgitation	31 (83.8)	4 (36.4)	0.055
VSD	3 (8.1)	3 (27.3)	0.124
LVOTO	3 (8.1)	0	0.986
Total atrioventricular block	4 (10.8)	5 (45.5)	0.061
Bradyarrhythmia	2 (5.4)	3 (27.3)	0.037
Cardiac pacemaker	4 (10.8)	4 (36.4)	0.068
ICD	2 (5.4)	0	0.999

CCTGA = congenitally corrected transposition of the great arteries; DTGA = transposition of the great arteries after atrial switch repair; ICD = implantable cardioverter-defibrillator; LVOTO = left ventricular outflow tract obstruction; NYHA = New York Heart Association; RV = right ventricular: TV = tricuspid valve; VSD = ventricular septal defect

Data are presented as number and percentage or as mean ± SD. $P \leq 0.05$ was considered statistically significant.

TABLE II. Comparison of Echocardiographic Results between Patients with DTGA and CCTGA

Variable	**DTGA** (n=37)	**CCTGA** (n=11)	***P* Value**
LV EDD (mm)	55.67 ± 18.36	52.63 ± 8.46	0.792
LV ESD (mm)	27.11 ± 5.42	30.73 ± 5.04	0.057
LV ejection fraction	0.61 ± 0.05	0.62 ± 0.04	0.66
SRV EDD (mm)	69 ± 3.51	65.4 ± 9.58	0.098
SRV ESD (mm)	45.42 ± 9.33	45.9 ±11.89	0.892
SRV FAC (%)	43.42 ± 7.77	47 ± 9.24	0.216
SRV FAC <35%	13 (36.1)	3 (27.3)	0.669
S′ (cm/s)	10.31 ± 2.16	11.36 ± 3.04	0.205
TAPSE (mm)	17.58 ± 2.68	19.55 ± 4.11	0.069
Severe tricuspid valve regurgitation	6 (16.2)	7 (63.6)	0.004
Tricuspid ring diameter (mm)	35.78 ± 3.75	38.45 ± 4.39	0.783
Ventricular septal defect	3 (8.1)	3 (27.3)	0.124
Pulmonary valve stenosis	0	3 (27.3)	0.01

CCTGA = congenitally corrected transposition of the great arteries; DTGA = transposition of the great arteries after atrial switch repair; EDD = end-diastolic dimension; ESD = end-systolic dimension; FAC = fractional area change; LV = left ventricular; S′ = systolic wave velocity of the tricuspid valve annulus; SRV = systemic right ventricular; TAPSE = tricuspid annular plane systolic excursion

Data are presented as mean ± SD or as number and percentage. $P \leq 0.05$ was considered statistically significant.

TABLE III. Comparison of Exercise Test Results between All Patients with Systemic Right Ventricle and the Control Group

Variable	**SRV Group** (n=48)	**Control Group** (n=29)	***P* Value**
V_{O_2} at rest (L/min)	0.32 ± 0.11	0.36 ± 0.12	0.188
V_{O_2}/kg at rest (mL/kg/min)	4.94 ± 1.6	4.88 ± 1.5	0.902
V_{CO_2} at rest (L/min)	0.29 ± 0.1	0.32 ± 0.11	0.296
V_{O_2}/kg at AT (mL/kg/min)	19.66 ± 5.8	34.24 ± 11.14	<0.001
Peak heart rate (beats/min)	151.9 ± 28.46	185.97 ± 8.05	<0.001
Percentage of maximal heart rate	79.9 ± 14.18	97.76 ± 6.4	<0.001
Peak V_{O_2} (L/min)	1.77 ± 0.59	3.6 ± 0.92	<0.001
Peak V_{O_2}/kg (mL/kg/min)	26.43 ± 6.27	48.01 ± 7.67	<0.001
Peak V_{CO_2} (L/min)	1.92 ± 0.72	4.54 ± 3.4	<0.001
Peak RER	1.06 ± 0.11	1.1 ± 0.1	0.096
Peak VE/V_{CO_2} (mL/kg/min)	29.31 ± 4.69	26.77 ± 3.21	0.013
Peak breathing reserve (%)	68.41 ± 21.14	41.51 ± 17.69	<0.001

AT = anaerobic threshold; RER = respiratory exchange ratio; SRV = systemic right ventricle; V_{CO_2} = carbon dioxide production; VE/V_{CO_2} = ventilatory equivalent for CO_2; V_{O_2} = oxygen uptake

Data are presented as mean ± SD. $P \leq 0.05$ was considered statistically significant.

Because reduced RV function and severe TV regurgitation negatively affect exercise capacity, we compared CPET results from a subgroup of SRV patients with preserved RV function and trivial regurgitation (n=25) with those of the control group. The SRV patients had a significantly reduced V_{O_2}/kg at anaerobic threshold (20.03 ± 4.64 vs 34.24 ± 11.14 mL/kg/min; P <0.001) and peak V_{O_2}/kg (27.14 ± 4.36 vs 48.01 ± 7.67 mL/kg/min; P <0.001). The study group also had a significantly lower peak heart rate (158.76 ± 24.07 vs 185.97 ± 8.05 beats/min; P <0.001) and percentage of maximal heart rate (82.56% ± 12.05% vs 97.76% ± 6.4%, P <0.001) (Table IV).

Among all patients with SRV, our analysis showed no significant correlations between CPET results and age, body mass index, NYHA class, or time since surgery.

In a comparison of CPET results between the CCTGA and DTGA groups, however, peak heart rate (124.67 ± 35.04 vs 159.33 ± 21.57 beats/min; *P*=0.021) and percentage of maximal heart rate (67.56% ± 18.32% vs 83.27% ± 10.91%, *P*=0.03) were lower in the CCTGA group. In the CCTGA patients with pacemakers, heart rate increased above the stimulation threshold during exercise, and at peak exercise, native sinus rhythm resumed, but it was slower than that in the control group, and it was below 85% of the predicted value for age. A greater percentage of the CCTGA patients also had total AV block and bradyarrhythmia, which have an important negative impact on exercise capacity. Peak Vo_2/kg and the percentage of the predicted value for age were similar between the CCTGA and DTGA groups.

In comparison with the 32 patients (67%) who had preserved RV function, the 16 patients (33%) who had reduced RV function (that is, FAC <35%) had a lower peak Vo_2/kg (24.64 ± 7.86 vs 27.11 ± 4.76 mL/kg/min; *P*=0.603), peak heart rate (144.27 ± 32.44 vs 155.65 ± 26.04 beats/min; *P*=0.949), percentage of maximal heart rate (76.13% ± 15.97% vs 81.77% ± 13.12%; *P*=0.999), and RER (1.03 ± 0.11 vs 1.07 ± 0.1; *P*=0.521); in contrast, the peak VE/Vco_2 was higher (30.22 ± 4.96 vs 28.79 ± 4.62 mL/kg/min; *P*=0.677). A similar comparison was made between 13 patients (27%) with severe TV regurgitation and 35 (73%) with trivial TV regurgitation. The patients with severe regurgitation had a significantly lower peak heart rate (122 ± 28.19 vs 162.52 ± 19.95 beats/min; *P* <0.001) and percentage of maximal heart rate (65.64% ± 14.33% vs 84.97% ± 10.25%; *P* <0.001). In addition, their peak Vo_2/kg (24.55 ± 8.46 vs 27.14 ± 5.22 mL/kg/min; *P*=0.226) and peak RER (1.02 ± 0.12 vs 1.07 ± 0.1; *P*=0.137) were lower. Severe TV regurgitation was related to the RV enlargement and the dilation of the tricuspid ring (41.62 ± 1.71 vs 34.29 ± 2.52 mm; *P* <0.001).

Discussion

The most important finding of our study is that adults with SRV have reduced exercise capacity. Previously, peak Vo_2/kg had been positively related to the capability of increasing cardiac output, which is dependent on stroke volume and heart rate.[1] Peak heart rate and percentage of maximal heart rate during CPET were significantly lower in our patients with SRV than in healthy control subjects. Further analysis showed that peak heart rate and percentage of maximal heart rate were significantly lower in the patients with CCTGA than in those with DTGA. The inadequate heart response to exercise is an important factor in reduced exercise capacity and peak Vo_2/kg in patients with SRV. Fredriksen and colleagues,[7] who observed similar results in CCTGA patients, reported a correlation between chronotropic inability and abnormally low peak Vo_2 values. Winter and associates[1] found that patients with CCTGA were able to increase stroke volume and heart rate, but patients with DTGA had no increase in stroke volume.

On CPET, our DTGA and CCTGA groups had similar results for peak Vo_2/kg and the percentage of predicted value for age, even though the CCTGA patients

TABLE IV. Comparison of Exercise Test Results between Patients with Preserved Systemic Right Ventricular Function and Trivial Tricuspid Valve Regurgitation and the Control Group

Variable	**SRV Subgroup** (n=25)	**Control Group** (n=29)	***P* Value**
Vo_2 at rest (L/min)	0.33 ± 0.08	0.36 ± 0.12	0.338
Vo_2/kg at rest (mL/kg/min)	5.05 ± 1.04	4.88 ± 1.5	0.629
Vco_2 at rest (L/min)	0.3 ± 0.08	0.32 ± 0.11	0.717
Vo_2/kg at AT (mL/kg/min)	20.03 ± 4.64	34.24 ± 11.14	<0.001
Peak heart rate (beats/min)	158.76 ± 24.07	185.97 ± 8.05	<0.001
Percentage of maximal heart rate	82.56 ± 12.05	97.76 ± 6.4	<0.001
Peak Vo_2 (L/min)	1.82 ± 0.41	3.6 ± 0.92	<0.001
Peak Vo_2/kg (mL/kg/min)	27.14 ± 4.36	48.01 ± 7.67	<0.001
Peak Vco_2 (L/min)	1.94 ± 0.58	4.54 ± 3.4	<0.001
Peak RER	1.09 ± 0.1	1.1 ± 0.1	0.617
Peak VE/Vco_2 (mL/kg/min)	28.93 ± 4.7	26.77 ± 3.21	0.051
Peak breathing reserve (%)	66.96 ± 17.19	41.51 ± 17.69	<0.001

AT = anaerobic threshold; RER = respiratory exchange ratio; SRV = systemic right ventricle; Vco_2 = carbon dioxide production; VE/Vco_2 = ventilatory equivalent for CO_2; Vo_2 = oxygen uptake

Data are presented as mean ± SD. $P \leq 0.05$ was considered statistically significant.

had a lower peak heart rate. It may be assumed that the DTGA patients had a lower stroke volume. Stroke volume is related to SRV systolic function. Thus, RV failure is caused by chronic microvascular ischemia and high wall stress, which lead to diffuse myocardial fibrosis and ongoing functional decline.[8] Roest and colleagues,[9] who used cardiovascular magnetic resonance to analyze ventricular function at rest and during exercise, found that RV ejection fraction did not increase during exercise and that RV functional reserve decreased. This is caused by morphologic changes of the SRV over time. Some investigators[1,10] have proposed that myocardial fibrosis results from prolonged hypoxemia during infancy while patients await the atrial switch operation, and others[11] have thought that it may be caused by inadequate RV blood supply from the right coronary artery in the presence of hypertrophic SRV myocardium. These conditions are similar to the morphologic and hemodynamic changes of the RV in pulmonary artery hypertension in which afterload is also increased. Naeije and Manes[12] observed RV changes in patients with pulmonary artery hypertension. In the presence of high afterload, the RV adapts first by increasing contractility, after which right chamber dimensions increase, leading to hypertrophy and diastolic dysfunction due to myocardial fibrosis, and finally to systolic dysfunction and TV regurgitation.

The results of our study show that exercise capacity is related to SRV function. Exercise capacity during CPET was lower in patients with reduced RV ejection fraction than in those who had preserved RV function; however, these differences were not statistically significant. Myocardial dysfunction is not the only cause of diminished exercise capacity.[13] Patients with SRV who have undergone atrial switch surgery also have preload abnormalities, and such factors should be taken into account. After a Senning operation, patients may have hemodynamic abnormalities associated with pulmonary and systemic baffles. In our study, we observed no baffle narrowing. However, the presence of the atrial baffles—even those that are functioning properly—may decrease RV inflow.[14]

We also found that TV regurgitation had a negative effect on exercise capacity. During CPET, peak heart rate and percentage of maximal heart rate were significantly lower in patients with severe TV regurgitation than in those with no or trivial TV regurgitation. The patients with severe regurgitation also had lower levels of peak Vo_2/kg and peak RER, but these differences were not statistically significant. There are several potential mechanisms for TV regurgitation,[15] including congenital abnormalities of the TV, dysfunction of the SRV, right-to-left septal shift, increased retrograde transtricuspid pressure gradient, and iatrogenic causes. In our study, severe TV regurgitation was related to RV enlargement and dilation of the tricuspid ring. It is not clear whether SRV dysfunction or TV regurgitation occurs first. In one study,[16] patients who had undergone TV repair with an artificial ring had no significant increases in SRV ejection fraction. On the other hand, the modification to arterial switch and RV to low-pressure circulation reduced TV regurgitation.[16]

Study Limitations

Our study had several limitations. The number of patients was small, so the conclusions drawn from the statistical analysis should be read with caution; nevertheless, our patient population was representative of that in clinical practice. Another limitation is the retrospective nature of the study, which meant that we had to rely on the data that had been collected. In addition, the observed population was not uniform; some patients had concomitant heart disease (such as trivial pulmonary stenosis or mild VSD), which may have affected our results. Moreover, we did not account for anemia, respiratory system diseases, or thyroid abnormalities, all of which can affect CPET results. A larger series of patients and longer follow-up times are needed.

Conclusions

Adult patients with SRV have reduced exercise capacity, related to impaired SRV function, severe TV regurgitation, and chronotropic incompetence. Exercise intolerance occurs as a result of a lowered oxygen uptake and increased ventilatory response. Patients with CCTGA have lower chronotropic efficiency than do patients after atrial switch repair. These patients need regular follow-up monitoring at specialist centers for adult patients with congenital heart diseases.

References

1. Winter MM, van der Plas MN, Bouma BJ, Groenink M, Bresser P, Mulder BJ. Mechanisms for cardiac output augmentation in patients with a systemic right ventricle. Int J Cardiol 2010;143(2):141-6.
2. Rudski LG, Lai WW, Afilalo J, Hua L, Handschumacher MD, Chandrasekaran K, et al. Guidelines for the echocardiographic assessment of the right heart in adults: a report from the American Society of Echocardiography endorsed by the European Association of Echocardiography, a registered branch of the European Society of Cardiology, and the Canadian Society of Echocardiography. J Am Soc Echocardiogr 2010;23(7):685-713.
3. Lang RM, Badano LP, Mor-Avi V, Afilalo J, Armstrong A, Ernande L, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. Eur Heart J Cardiovasc Imaging 2015;16(3):233-70.
4. Iriart X, Horovitz A, van Geldorp IE, Barnetche T, Lederlin M, De Guillebon M, et al. The role of echocardiography in the assessment of right ventricular systolic function in patients with transposition of the great arteries and atrial redirection. Arch Cardiovasc Dis 2012;105(8-9):432-41.
5. Takken T, Blank AC, Hulzebos EH, van Brussel M, Groen WG, Helders PJ. Cardiopulmonary exercise testing in con-

genital heart disease: (contra)indications and interpretation. Neth Heart J 2009;17(10):385-92.
6. Tomkiewicz-Pajak L, Podolec P, Drabik L, Pajak J, Kolcz J, Plazak W. Single ventricle function and exercise tolerance in adult patients after Fontan operation. Acta Cardiol 2014;69 (2):155-60.
7. Fredriksen PM, Chen A, Veldtman G, Hechter S, Therrien J, Webb G. Exercise capacity in adult patients with congenitally corrected transposition of the great arteries. Heart 2001;85 (2):191-5.
8. Waterhouse BR, Bera KD. Why right is never left: the systemic right ventricle in transposition of the great arteries. J Physiol 2015;593(23):5039-41.
9. Roest AA, Lamb HJ, van der Wall EE, Vliegen HW, van den Aardweg JG, Kunz P, et al. Cardiovascular response to physical exercise in adult patients after atrial correction for transposition of the great arteries assessed with magnetic resonance imaging. Heart 2004;90(6):678-84.
10. Plymen CM, Sado DM, Taylor AM, Bolger AP, Lambiase PD, Hughes M, Moon JC. Diffuse myocardial fibrosis in the systemic right ventricle of patients late after Mustard or Senning surgery: an equilibrium contrast cardiovascular magnetic resonance study. Eur Heart J Cardiovasc Imaging 2013;14 (10):963-8.
11. Hornung TS, Bernard EJ, Jaeggi ET, Howman-Giles RB, Celermajer DS, Hawker RE. Myocardial perfusion defects and associated systemic ventricular dysfunction in congenitally corrected transposition of the great arteries. Heart 1998;80 (4):322-6.
12. Naeije R, Manes A. The right ventricle in pulmonary arterial hypertension. Eur Respir Rev 2014;23(134):476-87.
13. Davlouros PA, Niwa K, Webb G, Gatzoulis MA. The right ventricle in congenital heart disease. Heart 2006;92 Suppl 1:i27-38.
14. Singh TP, Wolfe RR, Sullivan NM, McCool P, Neish SR. Assessment of progressive changes in exercise performance in patients with a systemic right ventricle following the atrial switch repair. Pediatr Cardiol 2001;22(3):210-4.
15. Szymanski P, Klisiewicz A, Lubiszewska B, Konka M, Lipczynska M, Kusmierczyk M, Hoffman P. Factors associated with the presence of tricuspid valve regurgitation in patients with systemic right ventricles following atrial switch. Cardiol J 2010;17(1):29-34.
16. Miltner B, Lancellotti P, Seghaye MC; European Society of Cardiology. European Society of Cardiology guidelines for the management of complex grown-up congenital heart disease [in French]. Rev Med Liege 2014;69(1):16-25.