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AHA SCIENTIFIC STATEMENT

Cardiopulmonary Exercise Test Interpretation Across the Lifespan in Congenital Heart Disease: A Scientific Statement From the American Heart Association

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ABSTRACT: Survivorship from congenital heart disease has improved rapidly secondary to advances in surgical and medical management. Because these patients are living longer, treatment and disease surveillance targets have shifted toward enhancing quality of life and functional status. Cardiopulmonary exercise testing is a valuable tool for assessing functional capacity, evaluating cardiac and pulmonary pathology, and providing guidance on prognosis and interventional recommendations. Despite the extensive evidence supporting the ability of cardiopulmonary exercise testing to quantitatively evaluate cardiovascular function, there remains confusion on how to properly interpret cardiopulmonary exercise testing in patients with congenital heart disease. The purpose of this statement is to provide a lifespan approach to the interpretation of cardiopulmonary exercise testing in patients with congenital heart disease. This is an updated report of the American Heart Association's previous publications on exercise in children. This evidence-based update on the significance of cardiopulmonary exercise testing findings in pediatric, adolescent, and adult patients with various congenital cardiac pathologies and surgically modified physiology is formatted in a way to guide cardiopulmonary exercise testing interpretation practically for the clinicians and exercise physiologists who care for patients with congenital heart disease. Focus is placed on the indications for exercise testing, expected findings, and how exercise testing should guide the management of patients with various congenital heart disease subtypes. Areas for future intervention that could lead to improved care and outcomes for those with congenital heart disease are noted.

Key Words: AHA Scientific Statements ■ exercise test ■ heart defects, congenital ■ pulmonary heart disease ■ quality of life ■ survivorship

This statement is intended for physicians, nurses, advanced practice clinicians, exercise physiologists, and other health care professionals involved in cardiopulmonary exercise testing (CPET) or exercise training of children and adults with congenital heart disease (HD). This statement intends to build on previous American Heart Association publications on CPET in children and adults with congenital HD. Information on CPET methodology and requirements as well as indications and contraindications for CPET are found in these statements.[1,2] CPET allows objective measurement of exercise capacity, which may

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be overestimated when self-reported by patients, may unmask impairments and arrhythmias even in asymptomatic patients, and is an integral part of decision-making. This is vitally important in congenital HD because they have many different complex processes that can affect exercise capacity (Figure 1). Additionally, CPET can be used to guide exercise prescription to ensure safety and optimal exercise intensity. A review of commonly used CPET parameters is included in the Table. Although this statement will focus on the metabolic parameters during CPET and less on exercise ECG, rhythm and conduction patterns are critically important to comprehensive CPET in those with congenital HD.

This statement is unique in that it aimed to provide the American Heart Association readership with a lifespan approach to the indications, usefulness, and interpretation of CPET in patients with congenital HD. At the core of this statement, we provide an evidence-based update on the significance of CPET in pediatric, adolescent, and adult patients with various congenital cardiac pathologies and surgically modified physiology. Because congenital HD encompasses many complex and different pathologies, the authors selected the most tested pathologies based on our extensive experience in the field with these lesions grouped in the upcoming sections. The spectrum of expected peak oxygen consumption (peak $\dot{V}O_2$) values by lesion is presented in Figure 2. This statement is designed to provide practical guidance for CPET interpretation for the clinicians and health care professionals who care for patients with congenital HD, including supplemental tables with summaries of expected CPET findings for common congenital HD lesions. Areas of potential future investigations that could lead to improved care and outcomes for those with congenital HD have been identified.

CPET testing is important in the management and risk stratification of patients after heart transplantation, and patients with cardiomyopathy, heart failure, and pulmonary hypertension. Additionally, exercise testing is essential in the diagnosis and management of pediatric patients with conduction disease, channelopathies, and those with cardiac implantable electronic devices. The expected findings and potential safety modifications for the testing of patients without congenital malformations should be covered in a future American Heart Association scientific statement.

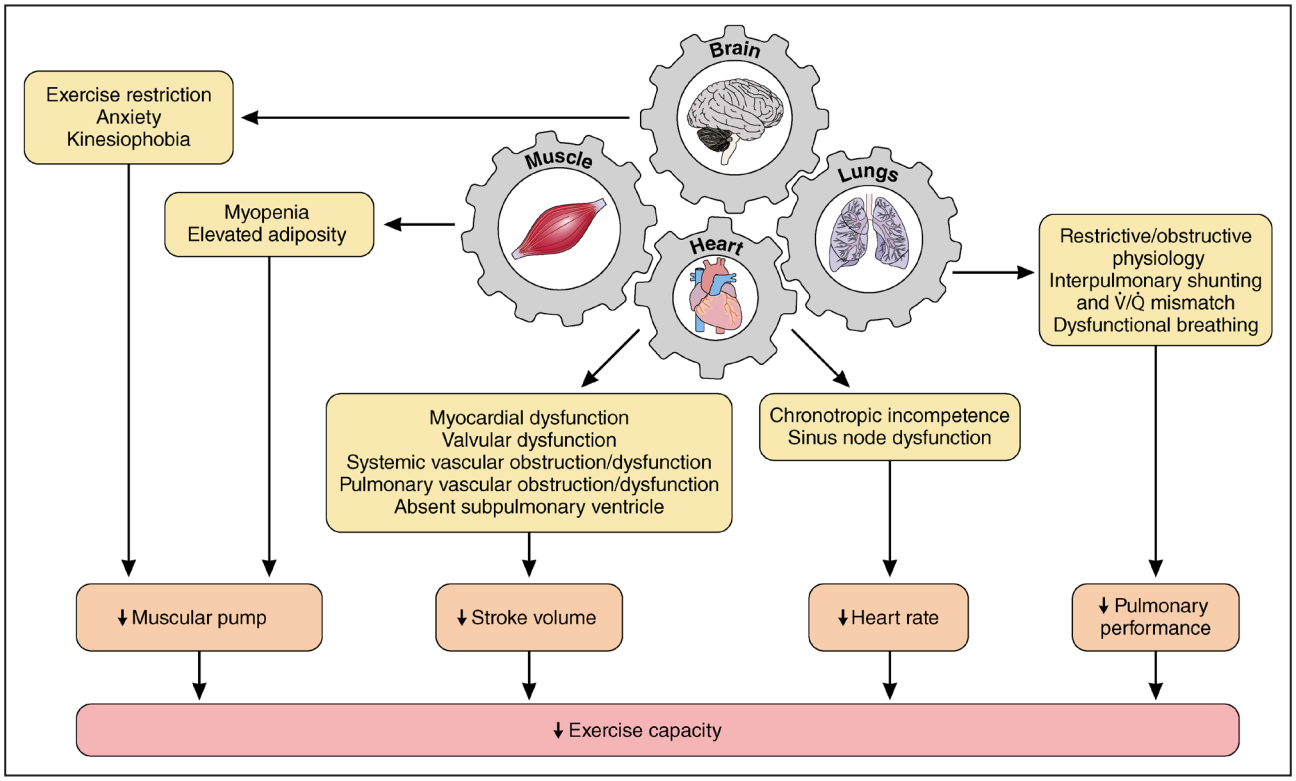

Figure 1. Diagram demonstrating the complex relationships between the cardiac, pulmonary, muscular, and nervous systems and how potential derangements in these systems can affect exercise performance in those with congenital heart disease.
V̇/Q̇ indicates ventilation/perfusion.

Table. Summary of the Key Variables Used During Cardiopulmonary Exercise Testing and the Significance of Each Variable

Exercise variable	Significance
Peak $\dot{V}O_2$	Measure of central oxygen uptake, oxygen transport, and oxygen consumption by the musculature and peripheral tissues during exercise
	Presented as an absolute value (mL/min), indexed to body weight (mL/min per kilogram), or as a percent of predicted (percent)
	Normal >80% to 85% of predicted
	Most widely used measure of cardiorespiratory fitness
	Most studied CPET variable in congenital HD
	Often secondary to a combination of cardiac, pulmonary, and muscular pathology
VAT	The $\dot{V}O_2$ at the transition from aerobic to anaerobic metabolism
	Normal varies by age (often 40%–70% of predicted peak $\dot{V}O_2$)
	Most widely used measure of fitness on submaximal effort test
	Often ↓ if cardiac disease or deconditioning
HR	Measured continuously during exercise
	Normal >85% of predicted (some laboratories use 20±10 bpm for children <16 y old)
	↓ if chronotropic incompetence, conduction deficit, or if submaximal effort
O_2pulse	Represented as $\dot{V}O_2$/HR
	Often ↓ when impaired stroke volume or abnormalities in oxygen extraction
SpO_2	Measured continuously during exercise testing
	Normal depends on underlying physiology (>92% if no known cardiac shunt)
VE/VCO_2 slope	Measure of ventilatory efficiency
	Normal <30
	Often abnormal (↑) in those with ↓ LVEF, $\dot{V}/\dot{Q}$ mismatch, or ↓ SpO_2 (right-to-left shunting)
OUES	Measures oxygen extraction
	Effort independent variable
	Abnormal in heart failure and pulmonary disease
SBP	Measured at rest and during exercise
	Should increase at least 20 mm Hg during exercise
	Abnormal if ↑ if >220 mm Hg during exercise
ST-segment changes	Assessment of myocardial ischemia
	Often unreliable in those with baseline conduction or repolarization abnormalities common in congenital HD
Oscillatory ventilation	Periodic breathing during exercise
	Characterized by periods of hyperpnea and hypopnea without interposed apnea
	Typically present when regular oscillations present for >60% of exercise with amplitude >15% of average min ventilation
HR reserve	Difference between peak and resting heart rate
	Prognostic significance in congenital HD

CPET indicates cardiopulmonary exercise test; HD, heart disease; HR, heart rate; LVEF, left ventricular ejection fraction; O_2pulse, oxygen pulse; OUES, oxygen uptake efficiency slope; SBP, systolic blood pressure; SpO_2, pulse oximetry; VAT, ventilatory anaerobic threshold; VE/VCO_2 slope, the slope of minute ventilation/carbon dioxide production; $\dot{V}O_2$, oxygen consumption; peak $\dot{V}O_2$, peak oxygen consumption; $\dot{V}/\dot{Q}$, ventilation/perfusion; ↓, lower; and ↑, higher.

SIMPLE LESIONS, UNREPAIRED AND REPAIRED

Indications

There is no consensus on indications for exercise testing in youth with uncomplicated congenital HD, such as an isolated atrial septal defect (ASD), ventricular septal defect, or patent ductus arteriosus. Although prior thinking was that when these defects are closed, the patients were cured; recent evidence suggests this is not the case. Thus, guidelines for adults recommend exercise testing as needed for patients with favorable physiology and every 6 to 24 months for patients depending on physiologic stage.[3] The use of periodic exercise testing can identify decreased exercise capacity, propensity for arrhythmias, and promote confidence to engage in moderate to vigorous physical activity and exercise.[4] Additionally, for patients with ASDs and modest pulmonary hypertension, exercise testing may guide clinical decision-making.[4,5]

Findings

Important CPET findings for patients with simple lesions are described in Supplemental Table 1. The few studies evaluating exercise capacity in children with isolated ventricular septal defects have had varied results, from no difference to reduced submaximal and maximal exercise variables after surgery that persist up to 10 years later.[6] Patients with relatively small ASD shunts (ratio of pulmonary to systemic blood flow <1.5) may improve exercise parameters once the defect is closed.[4] Data from a small Danish study showed significant exercise impairment in asymptomatic patients with small ASDs, even those that spontaneously closed during the study.[7] Other population-based or imaging/exercise correlate studies show increased morbidity and mortality, lower cardiac index, decreased functional capacity, and shorter life spans in patients with small unrepaired ASDs.[4] A small series of former premature infants with prior patent ductus arteriosus closure had mostly normal exercise capacity, although prematurity itself was associated with lower exercise capacity; those with surgical closure may have a higher risk of vocal cord dysfunction that could impact exercise capacity.[8]

Management and Prognosis

Although the use of CPET in this population has been limited, it has uncovered surprising impairments that were previously unknown.[4,6] In patients with repaired or unrepaired uncomplicated defects, functional capacity appears to decline with age faster than controls.[4,9] Further research is warranted to evaluate whether serial CPET can be of prognostic significance and if exercise therapy can be protective in those with a low peak

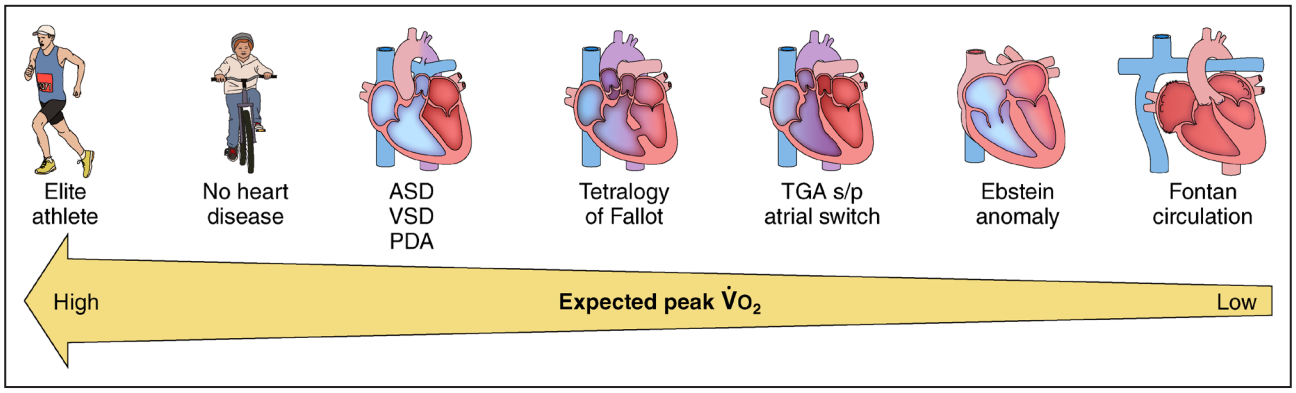

Figure 2. The range of peak oxygen consumption across the spectrum of congenital heart disease.
ASD indicates atrial septal defect; PDA, patent ductus arteriosus; s/p, status post; TGA, transposition of the great arteries; $\dot{V}O_2$, oxygen consumption; and VSD, ventricular septal defect.

$\dot{V}O_2$ in uncomplicated congenital HD as seen in other forms of congenital HD.

Take-Home Points

Despite being considered uncomplicated lesions, peak $\dot{V}O_2$ is often abnormally low and declines faster with age in patients with ASDs and ventricular septal defects. Low peak $\dot{V}O_2$ is associated with poor outcomes and can be improved with exercise therapy in other lesions, but specific values for this population are unknown due to the marked paucity of data and underuse of CPET.

DEXTRO-TRANSPOSITION OF THE GREAT VESSELS

Indications

Patients with dextro-transposition of the great arteries (D-TGA) and a previous atrial switch (Senning, Mustard) have a systemic right ventricle (RV) and a risk of progressive RV failure. They may have baseline mild desaturation, because coronary sinus blood is not incorporated in the baffle and are at risk for additional desaturation due to baffle leaks.[3,5] The atrial switch operation increases the risk of sinus node dysfunction and atrial arrhythmias. CPET should be used to evaluate and trend contractility derangement, exertional desaturation, and conduction/rhythm abnormalities. CPET is recommended every 1 to 3 years based on physiological stage.[3]

Patients with D-TGA and previous arterial switch surgery may have RV outflow tract obstruction (RVOTO), aortic insufficiency, mildly reduced chronotropy, and ischemia related to coronary reimplantation. CPET evaluates functional capacity in the setting of RVOTO, arrhythmia, chronotropy, and ischemia in patients with exertional symptoms.[3] For both types of repairs of D-TGA, CPET can be used to assess new symptoms or clinical findings and can be used serially as surveillance to trend functional capacity over time. CPET frequency recommendations vary based on physiological stage.[3]

Findings

Important CPET findings for patients with D-TGA are described in Supplemental Table 2. Patients with prior atrial switch have significant abnormalities in CPET. The average peak $\dot{V}O_2$ is lower and is associated with a ventilatory anaerobic threshold that is reached earlier compared with normal subjects.[10,11] Diminished peak $\dot{V}O_2$ results from decreased stroke volume and a blunted heart rate (HR) response.[10] Baffle obstruction and abnormal baffle compliance result in decreased venous return and lower stroke volume. Systemic RV function, exercise tolerance, and chronotropic response deteriorate over time.[10] Decline in peak $\dot{V}O_2$ and oxygen pulse (O_2pulse) are more pronounced during childhood and adolescence and suggest stroke volume deficit during somatic growth.[11] Peak O_2pulse may decline further and parallel progressive systemic RV dysfunction. The ventilatory response to exercise is inefficient as demonstrated by elevated slope of minute ventilation/carbon dioxide production ($VE/\dot{V}CO_2$ slope) and low end-tidal carbon dioxide, and is more pronounced with either right-to-left shunting secondary to baffle leak or heart failure with ventilation/perfusion mismatch.[11]

Peak $\dot{V}O_2$ in D-TGA in patients after arterial switch surgery is well-preserved although slightly lower compared with healthy peers and with slight deterioration over time.[12] Ventricular septal defect repair, residual RVOTO, and earlier surgical era are associated with worse peak $\dot{V}O_2$.[12,13] The peak HR is lower, although it does not significantly reduce peak $\dot{V}O_2$.[14] Variant coronary artery patterns do not affect peak

$\dot{V}O_2$, although they are associated with lower peak HR.[12,14]

Management and Prognosis

Patients with atrial switch with limited peak $\dot{V}O_2$ primarily due to chronotropic insufficiency should be considered for pacemaker evaluation.[3] Exertional hypoxemia should prompt evaluation for baffle leak.[3] Sudden cardiac death, arrhythmias, and heart failure are adverse late outcomes of atrial switch for D-TGA.[14] Exercise variables associated with adverse outcomes include abnormalities in peak $\dot{V}O_2$, HR, pulse oximetry, and VE/VCO_2 slope (Figure 3).[10,11] As evidence of systemic RV failure mounts, heart failure management and transplant evaluation may be bolstered by findings on serial CPET.

Symptomatic patients undergoing arterial switch surgery with ST changes on CPET may benefit from additional noninvasive or invasive imaging, although coronary ischemia is uncommon.[3,12] Screening for ischemic changes induced by exercise should be considered in patients who actively participate in moderate to vigorous physical activity, although sudden death is rare in this population.[5] Patients with RVOTO and low peak $\dot{V}O_2$ may benefit from evaluation for potential intervention. The small annual decline in peak $\dot{V}O_2$ might be addressed with exercise counseling and prescription, but data are currently lacking.

Take-Home Points

Patients with D-TGA treated via atrial switch often have profoundly abnormal peak $\dot{V}O_2$ secondary to impaired chronotropy and stroke volume. Patients with D-TGA treated via arterial switch can have a lower peak $\dot{V}O_2$, particularly if there is residual RVOTO. CPET can be used to assess for ischemia in D-TGA after arterial switch surgery, although coronary ischemia is uncommon.

TETRALOGY OF FALLOT AND RELATED PHYSIOLOGY

Indications

Patients with tetralogy of Fallot (TOF) can have multiple functional derangements following repair, including pulmonary insufficiency, branch pulmonary artery stenosis, arrhythmias, and right ventricular dysfunction. In response, the American Heart Association guidelines for adults with TOF recommend routine CPET every 1 to 5 years (no such guidelines exist for children or adolescents).[3] CPET has prognostic significance, may unmask arrhythmias, and is an integral part of decision-making for pulmonary valve replacement (PVR).[3,15]

Findings

Important CPET findings for patients with TOF are described in Supplemental Table 3. Peak $\dot{V}O_2$ is significantly impaired throughout adolescence and adulthood, with a mean of 68% predicted.[15] This impairment in peak $\dot{V}O_2$ likely starts at younger ages with an accelerated decline in peak $\dot{V}O_2$ into adulthood. A study of 300 patients with TOF observed a reduced or blunted increase in peak $\dot{V}O_2$ throughout adolescence, rather than the expected rise that is associated with growth and maturation.[16] Additionally, in adults, there is an accelerated loss of fitness with an overall mean decline in peak $\dot{V}O_2$ of 1.4% per year.[17] Interestingly, no clinical or imaging characteristics (including magnetic resonance imaging) discriminated between those who did and did not have a significant decline in peak $\dot{V}O_2$ over time, suggesting CPET may provide independent insights for identifying patients at risk of cardiac-related events, death, or in need of intervention.[17]

Another important CPET variable, the VE/VCO_2 slope has been a strong predictor of adverse outcomes in

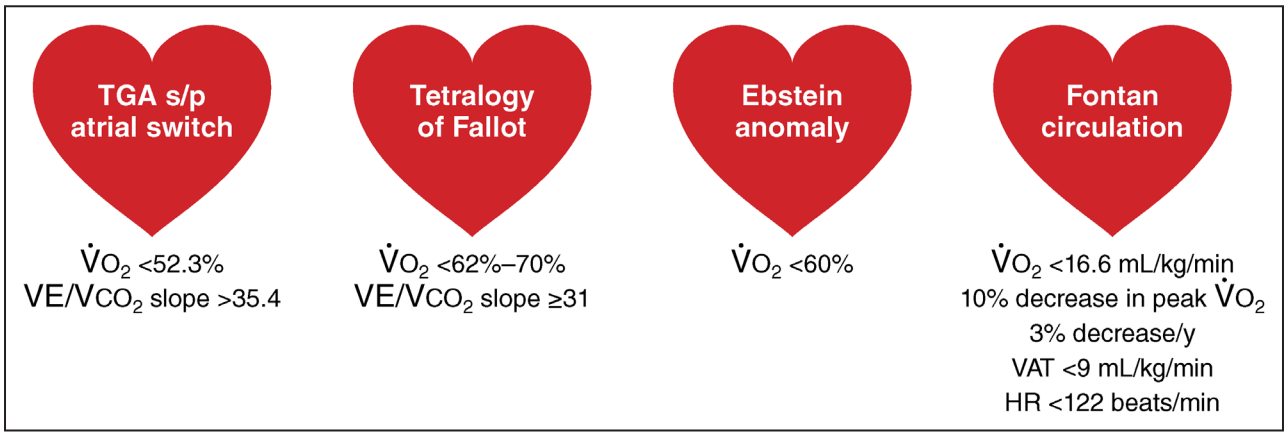

Figure 3. Key noteworthy cardiopulmonary values that carry specific prognostic significance in certain congenital heart disease lesions.

HR indicates heart rate; s/p, status post; TGA, transposition of the great arteries; VAT, ventilatory anaerobic threshold; VE/VCO_2 slope, the slope of minute ventilation/carbon dioxide production; and $\dot{V}O_2$, oxygen consumption.

patients with congenital HD.[18] An elevated VE/V_{CO_2} slope ≥31 can suggest important pulmonary blood flow maldistribution secondary to residual branch pulmonary stenoses and resultant ventilation/perfusion mismatch.

Management and Prognosis

A peak $\dot{V}_{O_2}$ <65% to 70% of predicted is 1 criterion for consideration of PVR.[3,19] PVR improves imaging variables but does not appear to reliably improve peak $\dot{V}_{O_2}$. Research suggests that significant improvements in exercise capacity are more typical in patients who have impaired exercise capacity (≈60% predicted) before PVR.[20] Importantly, exercise therapy can improve peak $\dot{V}_{O_2}$, and routine CPET use could identify those in need of cardiac rehabilitation.[21]

Patients with TOF are at greatest risk for death or sustained ventricular tachycardia when the VE/V_{CO_2} slope is ≥31, peak $\dot{V}_{O_2}$ is ≤65% predicted, and QRS duration (from resting ECG) is ≥170 milliseconds; these thresholds are also significant if observed in isolation (Figure 2).[18] A peak $\dot{V}_{O_2}$ <62% predicted was associated with reduced 5-year freedom from death or ventricular arrhythmias.[15] For children and adolescents undergoing PVR, a peak $\dot{V}_{O_2}$ ≥70% predicted a shorter length of stay.[19] Although the exact threshold of VE/V_{CO_2} slope is debated, a value >31 was independently associated with a risk of cardiac-related events or death.[15] Because CPET data are valuable for long-term follow-up, adverse outcomes, and serial assessment to aid in decision-making around PVR, numerous authors have advocated for routine longitudinal CPET testing for optimal research, knowledge, and patient care.[3,15,19]

Take-Home Points

Peak $\dot{V}_{O_2}$ <65% to 70% is a criterion for consideration of PVR and in children when <70% may correlate with worse surgical outcomes. In adults, peak $\dot{V}_{O_2}$ <65% and VE/V_{CO_2} slope ≥31 are associated with greater reintervention rates, cardiac-related events, and death. Although PVR can improve imaging variables, PVR alone does not appear to improve exercise capacity, and serial CPETs are warranted to identify patients who would benefit from exercise therapy.

SINGLE VENTRICLE ANATOMY AFTER FONTAN PALLIATION

Indications

Patients with a Fontan circulation have complex physiology that can result in multiple abnormalities, including arrhythmias, impaired cardiac stroke volume, ventricular dysfunction, conduction abnormalities, and abnormal skeletal muscle physiology, among others. CPET is useful for serial monitoring of people living with a Fontan circulation. International guidelines recommend that testing be performed at 1- to 3-year intervals as part of routine surveillance to quantitate peak and submaximal exercise parameters, assess for serial changes, and arrhythmia assessment to guide clinical decision-making.[3,22,23]

Findings

A summary of typical CPET findings is presented in Supplemental Table 4. On average, children, adolescents, and adults with a Fontan circulation reach around 55% to 70% of predicted peak $\dot{V}_{O_2}$, primarily because of attenuated preload.[24,25] Approximately 10% to 30% of patients with Fontan physiology have high physical performance (>80% of predicted peak $\dot{V}_{O_2}$).[26,27] Some large series have reported a steady decline in predicted peak $\dot{V}_{O_2}$ over time[28,29]; however, this decline is not inevitable.[30] Stable or improving peak $\dot{V}_{O_2}$ is associated with participation in regular moderate to vigorous physical activity.[27,30]

Although the ventilatory anaerobic threshold is reduced, it tends to be closer to normal predicted ventilatory anaerobic threshold values than peak levels.[25,31] Chronotropic incompetence is common, particularly in the setting of atriopulmonary and lateral tunnel-type Fontan connections, related to intrinsic conduction abnormalities and scarring.[32] Recovery of HR following exercise is frequently delayed.[26,33] Reduced O_2pulse, reflecting attenuated stroke volume, is also impacted by abnormal skeletal muscle oxygen extraction capacity.[24] O_2pulse kinetics (the rate of increase and time to peak) are also abnormal during exercise, further reflecting cardiac limitation secondary to stroke volume.[34]

Pulmonary abnormalities are common, and restrictive lung disease is often present secondary to previous cardiothoracic surgery and weakened respiratory musculature.[24,25,35] The VE/V_{CO_2} slope is increased, usually >30, reflecting either ventilation/perfusion mismatch (secondary to nonpulsatile pulmonary blood flow, maldistribution, and reduced pulmonary vascular reserve) or a right-to-left shunt.[24,25] Approximately one-third of individuals with a Fontan exhibit exertional oscillatory breathing (defined as >15% amplitude change in minute ventilation occurring in >60% of the exercise test duration).[36] Despite the high frequency of pulmonary derangements, the breathing reserve at peak exercise is rarely reduced, pointing to the fact that cardiac abnormalities remain the chief factor in reduced peak $\dot{V}_{O_2}$.[24]

Oxygen saturations are commonly reduced at rest, and further desaturation may occur during exercise.[24,25] If oxygen desaturation is secondary to a patent fenestration, closure may result in an improvement in peak $\dot{V}_{O_2}$.[25] Decision-making about closure of right-to-left

shunts needs to be individualized and the benefits of higher saturations balanced against greater venous impedance and potentially lowered cardiac output.

Increasingly, CPET has been undertaken in conjunction with hemodynamic testing, which can provide a more comprehensive evaluation of exercise limitations. Invasive CPET allows for direct measurement of the mean Fontan pressure and cardiac output. Additional details are noted in Supplemental Table 4.

Management and Prognosis

CPET has been validated in multiple studies as having prognostic significance.[29,37] Lower peak $\dot{V}O_2$, higher VE/VCO_2 slope, and lower work rates predict a greater likelihood of worsening heart failure, arrhythmias, unplanned admissions, and need for cardiac surgery or transcatheter intervention (Figure 2).[29,38] Additionally, a decline in peak exercise parameters on serial CPET, including peak $\dot{V}O_2$, maximal workload, and HR reserve, identifies those most likely to have major adverse cardiovascular events. Every 10% decline in peak $\dot{V}O_2$ has been associated with a hazard ratio as high as 2.[29,38] The presence of exercise oscillatory ventilation is associated with 3.9 times increased hazard of death, transplant, and nonelective hospitalizations.[36]

The prognostic accuracy of CPET can be significantly expanded by combining it with clinical information such as the presence of prior arrhythmia or previous heart failure admissions.[25] CPET is also useful in evaluating asymptomatic individuals with severe atrioventricular valve regurgitation and severe ventricular dysfunction. Confirmation of low exercise performance, (ie, <43% of predicted peak $\dot{V}O_2$ or absolute peak $\dot{V}O_2$ <16 mL/kg per minute) in this context can be used to aid clinical decision-making on conservative management versus structural intervention or heart transplant.[37] Isolated CPET has been used as a surrogate end point in pharmacologic trials; however, a decline in peak $\dot{V}O_2$ in serial testing seems to be a more useful surrogate biomarker.

Arterial desaturation >5% to 7% during exercise in symptomatic individuals can be used to guide potential interventions such as eliminating large right-to-left shunts, pathway obstructions, and treating raised pulmonary vascular resistance pharmacologically.[23]

Although frequently used in the risk assessment of individuals with a Fontan contemplating pregnancy, data on potentially prognostic CPET parameters are lacking.

Take-Home Points

Peak $\dot{V}O_2$ is typically depressed to 55% to 70% of predicted. Major adverse cardiovascular events, such as death or transplantation, are predicted by a serial decline in peak $\dot{V}O_2$ and the presence of oscillatory breathing. VE/VCO_2 slope is frequently elevated at ≥30.

ATRIOVENTRICULAR VALVE DISEASE INCLUDING EBSTEIN ANOMALY

Indications

Patients with complex anomalies of the atrioventricular valve and Ebstein anomaly (EA) have one of the lowest exercise capacities among patients with congenital HD, only higher than the single ventricle population.[39] Additionally, peak $\dot{V}O_2$ tends to decrease over time, and the rate of decline per year is most pronounced during childhood and adolescence.[40] In these patients, CPET is a useful tool to identify patients with notable decreases in functional capacity, for risk stratification, and for clinical decision-making.[41] Adult guidelines recommend CPET every 1 to 3 years based on physiological stage.[3]

Findings

Important CPET findings for patients with EA are described in Supplemental Table 5. In adults with EA, peak $\dot{V}O_2$ represents an independent predictor of adverse cardiovascular events, with an estimated 32% increase in risk for every 5% decrease in peak $\dot{V}O_2$.[41] Although surgical repair in patients with EA or severe tricuspid regurgitation (TR) has been shown to improve exercise tolerance,[42] it does not seem to prevent the progressive decline in exercise capacity over time.[40] The decline in exercise capacity over time in patients with EA appears to be related to a progressive decline in right atrial and left ventricular diastolic function, leading to an inadequate increase in stroke volume with exercise.[40,42] In a study of 76 adults with EA and severe TR, 37% of those in the TR surgery group had an increase in exercise capacity, and the changes in exercise capacity were related to changes in cardiac function leading to a proper increase in cardiac output.[42]

Similarly, CPET studies in patients with mitral valve regurgitation showed that exercise-induced changes in mitral valve regurgitation severity impair the increase in stroke volume observed during progressive exercise. In adults with mitral valve regurgitation, adverse clinical events (eg, death, heart failure, new atrial fibrillation), or surgery are estimated to be more frequent in patients with reduced exercise capacity, even adjusting for age and mitral valve regurgitation severity.[43] Important CPET findings for patients with mitral valve stenosis are discussed in Supplemental Table 5.

Management and Prognosis

Progressive decline in peak $\dot{V}O_2$ and the presence of symptoms are key factors in the decision-making toward surgery in patients with EA.[3,22] Therefore, follow-up CPET for patients with EA and moderate or severe TR may be clinically useful.[44] For patients with EA, serial CPET should be performed regardless of symptoms,

and peak $\dot{V}O_2$ values should be interpreted in relation to atrial and ventricular function. In adults with EA, a peak $\dot{V}O_2$ <60% predicted was associated with a higher risk of death, nonelective hospitalization, and surgical repair at midterm follow-up, and lower event-free survival among patients regardless of TR surgery (Figure 2).[41,42]

Although no consensus exists on the optimal timing of CPET in the follow-up of patients with EA and severe TR as well as a critical cutoff value for peak $\dot{V}O_2$, the prognostic value of CPET results is undeniable. The relevance of CPET results resides in the correlation of peak $\dot{V}O_2$ values with the physiological factors limiting exercise capacity in these patients, including right atrial and left ventricular dysfunction and severity of the valve lesion.[43]

Take-Home Points

Peak $\dot{V}O_2$ is often profoundly abnormal in patients with EA. A peak $\dot{V}O_2$ <60% is associated with negative clinical outcomes in adults with EA.

AORTIC DISEASE INCLUDING VALVULAR AND ARCH ABNORMALITIES

Indications

CPET has a role in the evaluation and management of congenital HD affecting the aorta and aortic valve including aortic stenosis (AS), aortic regurgitation (AR), and coarctation of the aorta (CoA). There are published indications for CPET in adults with acquired AS.[45] Indications include identifying falsely asymptomatic patients, identifying patients for whom intervention can be delayed, and evaluating for ischemia and arrhythmia.[45] These indications are applied to congenital AS with some data supporting this practice.[46]

There are fewer studies evaluating AR CPET indications, but CPET may be used to evaluate for coronary hypoperfusion, objectively assess symptoms, and unmask symptoms.[45]

In patients with repaired CoA, CPET evaluates for exercise-induced hypertension and re-CoA.[47] In addition, CPET is an important tool to help guide moderate to vigorous physical activity and exercise recommendations for pediatric, adolescent, and adult patients with congenital AS, AR, and CoA.[5]

Findings

Important CPET findings for patients with AS, AR, and CoA are described in Supplemental Table 6. CPET findings in AS include preserved peak $\dot{V}O_2$, although some adult and pediatric studies report mildly decreased or low normal peak $\dot{V}O_2$.[46,48] Low peak $\dot{V}O_2$ suggests an inability to maintain cardiac output due to AS, diastolic disease, or both, especially in the setting of low peak O_2pulse.[49] In adults with severe AS, echocardiogram findings do not predict abnormal CPET results[50]; however, in a small retrospective study, children with moderate or severe AS on echocardiogram were noted to have CPET abnormalities.[46] In this study, ST changes were noted in severe AS, and the echocardiogram degree of AS was related to peak systolic blood pressure and inversely related to work.[46]

Pediatric patients with AR typically have normal CPET findings; however, children with significant LV dilation (>±4 SD) may exhibit blunted maximal heart rate, systolic hypertension, and ST depression.[45,49] Another small pediatric study reported that patients with moderate to severe AR were well compensated, but a small subset had low peak $\dot{V}O_2$ and blunted peak O_2pulse, suggesting an abnormal stroke volume response.[49] No echo parameters differentiated this subset.[49]

Peak $\dot{V}O_2$ in patients with CoA repair may be mildly reduced.[51] Exercise-induced hypertension may be seen in patients with CoA even with a good repair and is predictive of future hypertension.[52] Exercise-induced hypertension and VE/$\dot{V}CO_2$ slope ≥27 were risk factors for developing hypertension in normotensive adults with prior CoA repair.[47]

Management and Prognosis

In adults with AS, predictors of poor outcomes and indications for intervention are associated with the following CPET findings: symptoms, ST changes, or blunted blood pressure response.[3,5] In the absence of exertional symptoms, the clinical significance of ST changes is less clear in pediatric AS.[53] Decreased peak $\dot{V}O_2$ with low peak O_2pulse, exertional symptoms, or ST changes suggest additional evaluation is warranted.

In pediatric AR, a peak $\dot{V}O_2$ <75% predicted and low peak O_2pulse can indicate the need for further evaluation and possible intervention.[46] In adult AR, abnormal CPET is associated with increased mortality and recommends intervention.[53]

Patients with CoA with exercise-induced hypertension may benefit from the initiation of antihypertensive medications, but long-term studies are needed.[47] The finding of lower extremity hypotension immediately after CPET is of uncertain clinical significance. When there are abnormal CPET findings for any of these lesions, additional evaluation may be needed before discussing sports participation.[5]

Take-Home Points

In patients with AS, peak $\dot{V}O_2$ tends to be preserved, but exercise-induced ST-segment changes or hypertension are associated with poor outcomes. In patients

with AR, the presence of CPET abnormalities, including low peak $\dot{V}O_2$, is associated with mortality and the need for intervention. Exercise-induced hypertension is common in patients with repaired CoA and is predictive of future hypertension.

OTHER POPULATIONS

Although this statement has focused on those with congenital HD, it is acknowledged that there are other populations tested in pediatric exercise labs that are not mentioned in this statement. Supplemental Table 7 highlights a few of these noncongenital HD but common pathologies seen in the pediatric exercise laboratory with their expected findings.

CONCLUSIONS

This statement provides health care professionals with an evidence-based update on important targeted CPET findings in common congenital and surgically modified cardiac pathologies. CPET has diagnostic and prognostic value in assessing cardiorespiratory capacity, symptomology, and longitudinal trends. Serial testing beginning in childhood or early adolescence is important to unmask vulnerabilities associated with poor patient outcomes and identify earlier opportunities for interventions including exercise training. The evidence reinforces exercise testing as an integral part of the lifespan approach to caring for those with congenital HD.

ARTICLE INFORMATION

The American Heart Association makes every effort to avoid any actual or potential conflicts of interest that may arise as a result of an outside relationship or a personal, professional, or business interest of a member of the writing panel. Specifically, all members of the writing group are required to complete and submit a Disclosure Questionnaire showing all such relationships that might be perceived as real or potential conflicts of interest.

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Disclosures

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This table represents the relationships of writing group members that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all members of the writing group are required to complete and submit. A relationship is considered to be "significant" if (a) the person receives $5000 or more during any 12-month period, or 5% or more of the person's gross income; or (b) the person owns 5% or more of the voting stock or share of the entity, or owns $5000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

*Modest.

†Significant.

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