French Society of Cardiology guidelines on exercise tests (part 2): Indications for exercise tests in cardiac diseases

Dany-Michel Marcadet, Bruno Pavy, Gilles Bosser, Frédérique Claudot, Sonia Corone, Herve Douard, Marie-Christine Iliou, Bénédicte Vergès-Patois, Pascal Amedro, Thierry Le Tourneau, et al.

French Society of Cardiology guidelines on exercise tests (part 2): Indications for exercise tests in cardiac diseases

Société française de cardiologie recommandations pour les épreuves d'effort (partie 2) : indications des épreuves d'effort en cardiologie

Dany-Michel Marcadet[a,1], Bruno Pavy[b,*,1], Gilles Bosser[c,d,1], Frédérique Claudot[e,f], Sonia Corone[g], Hervé Douard[h], Marie-Christine Iliou[i], Bénédicte Vergès-Patois[j], Pascal Amedro[k,l], Thierry Le Tourneau[m], Caroline Cueff[m], Taniela Avedian[a], Alain Cohen Solal[n], François Carré[o,1]

[a] *Cardiac Rehabilitation Department, Turin Clinic, 75008 Paris, France*
[b] *Cardiac Rehabilitation Department, Loire-Vendée-Océan Hospital, boulevard des Régents, BP2, 44270 Machecoul, France*
[c] *Paediatric and Congenital Cardiology Department, M3C Regional Competences Centre, University Hospital, 54511 Vandoeuvre-les-Nancy, France*
[d] *EA 3450, Development, Adaptation and Disadvantage, Faculty of Medicine, University of Lorraine, 54600 Villers-lès-Nancy, France*
[e] *Platform for Clinical Research Assistance, University Hospital, 54511 Vandoeuvre-les-Nancy, France*
[f] *EA 4360 APEMAC, Faculty of Medicine, University of Lorraine, 54600 Villers-lès-Nancy, France*
[g] *Cardiac Rehabilitation Department, Bligny Medical Centre, 91640 Briis-sous-Forges, France*
[h] *Cardiac Rehabilitation Department, Bordeaux University Hospital, 33604 Pessac, France*
[i] *Cardiac Rehabilitation Department, Corentin-Celton Hospital, 92130 Issy-Les-Moulineaux, France*

Abbreviations: BP, blood pressure; CAD, coronary artery disease; CPET, cardiopulmonary exercise test; CHD, congenital heart disease; ET, exercise test; PAD, peripheral artery disease; VCO_2, carbon dioxide output; VE, volume of expired gas; VO_2, oxygen uptake.

* Corresponding author.
E-mail address: pavy.bruno@wanadoo.fr (B. Pavy).

[1] In addition to being authors, Dany-Michel Marcadet, Bruno Pavy, Gilles Bosser and François Carré are members of the drafting committee.

[j] *Cardiac Rehabilitation Department, Les Rosiers Clinic, 21000 Dijon, France*
[k] *Paediatric and Congenital Cardiology Department, M3C Regional Reference Centre, University Hospital, 34295 Montpellier, France*
[l] *Physiology and Experimental Biology of Heart and Muscles Laboratory, PHYMEDEXP, UMR CNRS 9214—Inserm U1046, University of Montpellier, 34295 Montpellier, France*
[m] *Cardiology Functional Evaluation Department, University Hospital Laennec, 44800 Nantes, France*
[n] *Cardiology Department, Hospital Lariboisière, 75010 Paris, France*
[o] *Department of Sport Medicine, Pontchaillou Hospital, University of Rennes 1, Inserm 1099, 35043 Rennes, France*

KEYWORDS
French guidelines;
Exercise test;
Indications

Summary The exercise test is performed routinely in cardiology; its main indication is the diagnosis of myocardial ischemia, evaluated along with the subject's pretest probability and cardiovascular risk level. Other criteria, such as analysis of repolarization, must be taken into consideration during the interpretation of an exercise test, to improve its predictive value. An exercise test is also indicated for many other cardiac diseases (e.g. rhythm and conduction disorders, severe asymptomatic aortic stenosis, hypertrophic cardiomyopathy, peripheral artery disease, hypertension). Moreover, an exercise test may be indicated for specific populations (women, the elderly, patients with diabetes mellitus, patients in a preoperative context, asymptomatic patients and patients with congenital heart defects). Some cardiac diseases (such as chronic heart failure or arterial pulmonary hypertension) require a cardiopulmonary exercise test. Finally, an exercise test or a cardiopulmonary exercise test is indicated to prescribe a cardiac rehabilitation programme, adapted to the patient.

MOTS CLÉS
Recommandations françaises ;
Tests d'effort ;
Indications

Résumé Le test d'effort est un examen couramment pratiqué en cardiologie. L'indication principale est l'évaluation de l'ischémie myocardique en fonction de la probabilité prétest et du niveau de risque d'évènement cardiovasculaire. Au-delà de l'analyse de la repolarisation, d'autres critères doivent être pris en considération pour améliorer sa valeur prédictive. Le test d'effort est aussi indiqué dans d'autres pathologies cardiaques (comme les troubles du rythme et de la conduction, le rétrécissement aortique asymptomatique sévère, les cardiomyopathies hypertrophiques, l'artérite des membres inférieurs, l'hypertension artérielle) et dans des populations particulières (femmes, sujets âgés, diabétiques, en préopératoire, chez les sujets asymptomatiques et dans les cardiopathies congénitales). Certaines pathologies (comme l'insuffisance cardiaque et l'hypertension pulmonaire) nécessitent un test d'effort avec la mesure des gaz expirés. Enfin, le test d'effort et la mesure des gaz expirés sont indispensables pour prescrire un programme de réadaptation.

Background

Given that the current French guidelines date from 1997, the Groupe exercice readaptation et sport (GERS; Exercise Rehabilitation and Sport Group) has decided to publish new guidelines, taking into account the various works that have been published over the past decades [1,2]. Part 1 of these new guidelines provides an overview of the safety conditions and methodology required to perform and interpret an exercise test (ET) or a cardiopulmonary ET (CPET); here, part 2 focuses on the extended indications for ETs and CPETs in cardiology, with respect to different classes (Table 1) and evidence levels (Table 2).

ET for coronary artery disease

Coronary artery disease (CAD) is the main indication for an ET in cardiology. The indication for a diagnostic ET is based on the pretest probability of CAD (Fig. 1).

The clinical pretest probability of CAD is evaluated based on age, sex and type of pain involved [3]. Angina is defined

Table 1 Recommendation classes.

Recommendation class	Definition	Suggested wording to use
Class I	Evidence and/or general agreement that a given treatment or procedure is beneficial, useful/effective	Is recommended/is indicated
Class II	Conflicting evidence and/or a divergence of opinion about the usefulness/efficacy of the given treatment or procedure	
Class IIa	Weight of evidence/opinion is in favor of usefulness/efficacy	Should be considered
Class IIb	Usefulness/efficacy is less well established by evidence/opinion	May be considered
Class III	Evidence and/or general agreement that the given treatment or procedure is not useful/effective, and in some cases may be harmful	Is not recommended

Table 2 Levels of evidence.

Level of evidence A	Data derived from multiple randomized clinical trials or meta-analyses
Level of evidence B	Data derived from a single randomized clinical trial or large non-randomized studies
Level of evidence C	Consensus of opinion of the experts and/or small studies, retrospective studies, registries

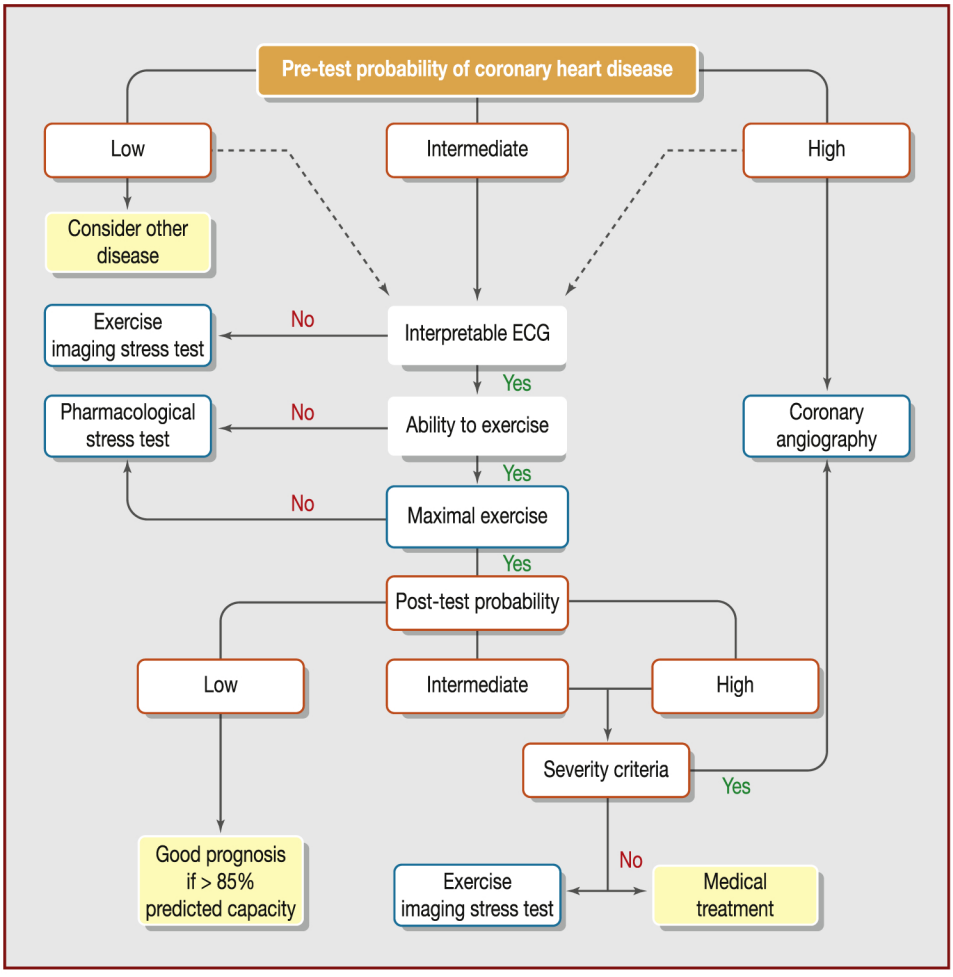

Figure 1. Diagnostic exercise test for coronary artery disease.

Table 3 Clinical pretest probability of coronary artery disease, modified according to [3].

Age (years)	Typical angina		Atypical angina		Angina unlikely	
	Men	Women	Men	Women	Men	Women
30—39	Intermediate	Intermediate	Intermediate	Low	Intermediate	Low
40—49	High	Intermediate	Intermediate	Low	Intermediate	Low
50—59	High	Intermediate	Intermediate	Intermediate	Intermediate	Low
60—69	High	Intermediate	Intermediate	Intermediate	Intermediate	Intermediate
70—79	Very high	High	High	Intermediate	Intermediate	Intermediate
≥ 80	Very high	High	High	Intermediate	Intermediate	Intermediate

Low: < 15%; intermediate: 15—65%; high: 66—85%; very high: > 85%.

by three criteria: retrosternal constrictive chest pain triggered by exertion, digestion or emotional stress; pain lasting several minutes (< 20 minutes); and pain relieved by rest or nitroglycerin use. The angina is typical when all three criteria are met, atypical when only two criteria are present, and unlikely otherwise. The pretest probability can be stratified as low, intermediate or high, depending on the symptoms, age and sex of a given patient (Table 3).

In addition, consideration of associated cardiovascular risk factors will allow the pretest probability of CAD to be better defined [4]. The cardiovascular risk estimation should be stratified, according to the European Society of Cardiology guidelines, into low, moderate, high or very high risk (Table 4) [5].

In most cases, the ET is the first-line diagnostic test for CAD. Imaging techniques should be used when an intermediate probability persists after the ET [6,7]. An imaging diagnostic test is indicated as first line when the electrocardiogram is not interpretable (Fig. 1). Of note, a pharmacological stress test should be favored in the case of physical inability.

During an acute coronary syndrome, an ET may be performed 6 hours after the onset of symptoms, provided that the clinical, biological and electrocardiographic variables remain normal [8]. In such cases, or in the context of stable angina, functional capacity constitutes a major variable for assessment of prognosis.

Moreover, an ET allows a given patient's cardiac rehabilitation programme to be better defined [9]. In this setting, an ET may be safely performed as early as 1 week after coronary revascularization (angioplasty or surgery) [10—12].

An ET may be used as a screening tool to assess the evolution of CAD, as well as to optimize its medical treatment. An ET is indicated in the context of relapsing angina or unexplained reduction in functional capacity [13] (Table 5).

ET for rhythm and conduction disorders

An ET is indicated in the context of syncope, palpitations, family history of sudden cardiac death or hereditary arrhythmogenic cardiovascular disease and any symptoms occurring during effort [14].

In addition to assessing prognosis, an ET may help to evaluate the efficacy of an antiarrhythmic treatment [2], as well as confirm the proper function of an implanted cardiac stimulator or defibrillator [15].

In the context of chronic atrial fibrillation, an ET provides useful data, with the goal of optimizing ventricular rate [16].

Table 4 Cardiovascular risk categories, adapted according to [5].

Very high risk	Documented cardiovascular disease (previous AMI, ACS, coronary or arterial revascularization, stroke/TIA, aortic aneurysm or PAD)
	Cardiovascular disease imaging, such as significant plaque (coronary angiography or carotid ultrasound)
	Diabetes mellitus with target organ damage (proteinuria) or with major cardiovascular risk factor
	Severe chronic kidney disease (GFR < 30 mL/min/1.73 m^2)
	Calculated score ≥ 10%
High risk	Markedly elevated single cardiovascular risk factors
	Other people with diabetes mellitus (except young people with type I diabetes without major cardiovascular risk factor)
	Moderate chronic kidney disease (GFR 30—59 mL/min/1.73 m^2)
	Calculated score ≥ 5% and < 10%
Moderate risk	Calculated score ≥ 1% and < 5%
Low risk	Calculated score < 1%

ACS: acute coronary syndrome; AMI: acute myocardial infarction; GFR: glomerular filtration rate; PAD: peripheral artery disease; TIA: transient ischemic attack.

Table 5 Exercise test indications in the context of coronary artery disease.		
Diagnosis of CAD	An ET is recommended to investigate CAD when the clinical pretest probability is intermediate (Table 1), the resting electrocardiogram is interpretable and the patient is able to perform physical exercise [3,6]	I A
	If the patient is taking an antianginal agent, treatment should be maintained while performing the ET; when the test is normal, a second test should be considered after treatment withdrawal, given that safety measures are taken[a]	IIa C
	When the pretest probability is high (Table 1), an ET should be performed to further define the degree of disease severity, providing an indication for medical treatment or coronary angiography	IIa C
	When the clinical pretest probability is low (Table 1), an ET may be performed if the estimated cardiovascular risk is high or very high [4,5]	IIb B
	An ET may be performed beyond 6 hours after symptom onset in a patient hospitalized for angina, provided that the clinical, biological and electrocardiographic variables remain normal [8]	IIb B
Evaluation of CAD	An ET or CPET is recommended to prescribe an adapted physical activity and cardiac rehabilitation programme [9]	I A
	An ET should be performed after revascularization to assess the success of the intervention and serve as a reference for follow-up visits	IIa C

CAD: coronary artery disease; CPET: cardiopulmonary exercise test; ET: exercise test.
[a] The patient must be told to use sublingual nitroglycerin if chest pain occurs during daily activities, in which case a prompt cardiological consultation is warranted.

Table 6 Exercise test indications in the context of rhythm or conduction disorders.	
An ET is recommended for exercise-induced symptoms such as syncope, abnormal fatigue, palpitations	I C
An ET should be considered for the evaluation of antiarrhythmic treatment efficacy (medication or ablation)	IIa C
An ET should be considered for fine tuning of implanted cardiac stimulators or defibrillators	IIa C
An ET may be considered for the evaluation of ventricular response in patients with atrial fibrillation	IIb C
An ET may be considered for the evaluation of a pre-excitation electrocardiogram pattern	IIb C

ET: exercise test.

In case of congenital atrioventricular block, an ET can evaluate the chronotropic response as well as functional capacity; both of these factors are required when making a decision about pacemaker implantation [17].

In the presence of a pre-excitation electrocardiogram pattern, such as in Wolf-Parkinson-White syndrome, an ET not only allows evaluation of a beat-to-beat disappearance of the pre-excitation pattern (which would favor a benign accessory pathway), but also assessment of atrial vulnerability or the onset of re-entry tachycardia (Table 6) [18].

ET for evaluation of valvular diseases

An ET or cardiopulmonary exercise test (CPET) is included in the work-up of significant, albeit asymptomatic, valvular diseases, to objectify possible unrecognized symptoms and better define management and prognosis.

An ET is recommended in asymptomatic patients with severe aortic stenosis (surface $\leq 1\,cm^2$ or $\leq 0.6\,cm^2/m^2$ or maximal transvalvular velocity $\geq 4\,m/s$ or medium gradient $\geq 40\,mmHg$). The ET may reveal atypical symptoms, reduced functional capacity or an abnormal systolic blood pressure (BP) response (decrease or increase of $< 20\,mmHg$) [19]. Although rare, an ET can trigger arrhythmias. ST-segment depressions occur frequently, but do not have any diagnostic value for CAD. Two recent studies in small populations highlighted the added value of CPET in asymptomatic patients with aortic stenosis. For these patients, surgery may be discussed when the oxygen uptake (VO_2) peak is < 85% of the theoretical value or 14 mL/min/kg, and the volume of expired gas/carbon dioxide output (VE/VCO_2) slope is > 34 [20,21]. ET and CPET are contraindicated in symptomatic aortic stenosis [19] (Table 7).

Regarding other valvular pathologies (mitral stenosis, mitral regurgitation, aortic regurgitation), an ET is indicated when the clinical picture does not match the echocardiographic findings.

ET for chronic heart failure

An ET (particularly a CPET) has a major role in the assessment and follow-up of patients with chronic heart failure.

The CPET gives an objective evaluation of maximal exercise capacity—the main prognostic factor for patients with chronic heart failure. The VO_2 peak is the principal decision criterion for cardiac transplantation [22—24]. A VO_2 peak

Table 7 Exercise test indications in the context of valvular diseases.	
A CPET (or, if unavailable, an ET) should be considered in asymptomatic patients with severe aortic stenosis, to orient the therapeutic decision, given the occurrence of certain abnormalities (e.g. a reduction in VO_2 peak, exercise angina, a reduction or < 20 mmHg increase in systolic BP or ventricular arrhythmia) [19–21]	IIa B
A CPET (or, if unavailable, an ET) should be considered when the clinical picture does not match echocardiographic findings in the context of valvular disease, other than aortic stenosis	IIa C
An ET is not recommended in symptomatic severe aortic stenosis [19]	III B

BP: blood pressure; CPET: cardiopulmonary exercise test; ET: exercise test.

Table 8 Exercise test indications in the context of chronic heart failure.	
A CPET (or, if unavailable, an ET) is recommended to optimize exercise training programmes [9,23]	I A
A CPET (or, if unavailable, an ET) is recommended to assess functional capacity, and to establish the indication for ventricular device implantation or heart transplantation [22,26]	I C
A CPET (or, if unavailable, an ET) should be considered for assessment of unexplained dyspnea or myocardial ischemia in a patient with chronic heart failure	IIa C

CPET: cardiopulmonary exercise test; ET: exercise test.

value < 11–12 mL/min/kg in a patient on beta-blockers (or < 14 mL/min/kg without beta-blockers) is an indication for transplantation.

The main variables to consider for outcome in chronic heart failure include a low VO_2 peak value, an increased VE/VCO_2 slope (> 45), a low BP increase [25] and the observation of exercise ventilatory oscillations [26] — all of which are markers of poor prognosis [24].

Other variables are proposed to refine the prognosis assessment for patients with heart failure. The oxygen uptake efficiency slope (a function derived from the slope of VO_2 versus log VE) is usually decreased in the context of marked chronic heart failure [26]. Moreover, circulatory power (the product of the VO_2 peak and the maximal systolic BP) is reduced with more severe disease [25]. Of note, ventilatory power (the ratio of systolic BP over the VE/VCO_2 slope) allows a more accurate evaluation of right ventricular and pulmonary functions [26] (Table 8).

ET for other cardiac diseases

Hypertrophic cardiomyopathy

A CPET (or, if unavailable, an ET) is indicated in the prognostic assessment of hypertrophic cardiomyopathy, and provides a useful aid in the therapeutic plan decision (alcohol septal ablation, septal myomectomy or transplantation) [27]. The criteria for such a decision are a low VO_2 peak, an increased VE/VCO_2 slope [27], an abnormal systolic BP response (decrease or plateau at peak effort) [28] or the presence of a complex ventricular arrhythmia (particularly in patients aged < 30 years) (Table 9) [29].

Pulmonary hypertension

In patients with either primary or secondary pulmonary hypertension, a CPET should be preferred to an ET. It is useful to note that pulmonary hypertension is no longer considered as a contraindication to ET or CPET [2,30].

A CPET, which provides additional diagnostic and prognostic information to the 6-minute walk test, is recommended at the time of diagnosis, during follow-up at 6-month to 12-month intervals or in the context of worsening symptoms [30] (Table 9).

The VO_2 peak and the VE/VCO_2 slope are two main factors for patient risk stratification: a VO_2 peak > 15 mL/min/kg (> 65% of the predicted VO_2) and a VE/VCO_2 slope < 36 indicate low mortality at 1 year, whereas a VO_2 peak < 11 mL/kg/min (< 35% predicted) and a VE/VCO_2 slope $\geq$ 45 are related to a high risk of complications [30].

Peripheral artery disease

Observation of a postexercise ankle pressure decrease can objectify claudication, even if the resting ankle brachial index is > 0.90. An ankle pressure decrease of > 30 mm Hg (or an ankle brachial index decrease of > 20%) beyond 1 minute of recovery is indicative of peripheral artery disease (PAD) [31].

An ET with an arm ergometer may be an alternative to the bicycle or treadmill to detect silent CAD in patients with PAD [32].

An ET can also evaluate the impact of physical training in a patient with PAD. An improvement in functional capacity is a marker for good prognosis [33] (Table 9).

Table 9 Exercise test indications in the context of other cardiovascular diseases.		
Hypertrophic cardiomyopathy	A CPET (or, if unavailable, an ET) should be considered to assess functional capacity and prognostic markers, such as ventricular arrhythmia and BP response to exercise [27–29]	IIa B
	An ET should be considered every 1–2 years to follow up on BP response and evaluate treatment efficacy	IIa C
Pulmonary hypertension	In patients with pulmonary hypertension, a CPET is recommended at the time of diagnosis and at 6-month to 12-month intervals for follow-up; a CPET should also be performed in the presence of worsening symptoms; the VO_2 peak and VE/VCO_2 slope are used to further stratify the patient's risk [30]	I C
PAD	With the use of a treadmill ergometer, an ET is indicated to objectify claudication, to quantify the ischemia causing the symptoms and to assess functional capacity (the main prognostic marker) [31,32]	I B
	An ET is indicated to prescribe and properly guide a physical activity programme, adapted to the patient [33]	I B
Arterial hypertension	An ET is indicated in symptomatic hypertensive patients, presenting a normal resting electrocardiogram, to diagnose coronary artery disease [34]	I B
	An ET should be considered in all hypertensive patients to better define prognosis (functional capacity, BP response) or to prescribe an adapted physical activity programme (for leisure or professional purposes)	IIa C
Diabetes mellitus	An ET is indicated for diagnosis of CAD in symptomatic patients with diabetes whose resting electrocardiogram is normal and interpretable [39]	I B
	An ET should be considered in sedentary patients with diabetes to screen for symptoms triggered by moderate/vigorous exercise and/or to prescribe an adapted physical activity programme [40]	IIa B

BP: blood pressure; CAD: coronary artery disease; CPET: cardiopulmonary exercise test; ET: exercise test, PAD: peripheral artery disease; VE: volume of expired gas; VO_2: oxygen uptake; VCO_2: carbon dioxide output.

Arterial hypertension

The interpretation of an ET in patients with hypertension with a normal resting electrocardiogram is similar to that in subjects without hypertension. However, an elevated systolic BP during exercise may increase the risk of false positives [34]. A significant ST-segment depression may be associated with left ventricular hypertrophy, even in the absence of significant CAD [35]—highlighting the importance of conducting a multivariable analysis in this patient population (Table 9) (see part 1).

Diabetes mellitus

A patient's cardiovascular risk increases depending on the time lapse since the onset of diabetes, the patient's age and various associated risk factors. The ET must focus on assessing the presence of myocardial ischemia, given that silent ischemia exists in up to 30–35% of patients with diabetes (Table 9) [36,37].

Chronotropic incompetence is frequent in diabetic patients (33%), and is strongly correlated with a risk of major adverse cardiac events [38].

Although an ET in patients with diabetes is of similar diagnostic and prognostic value for CAD as an ET in those without diabetes, the symptoms in the diabetic population are less typical [39,40].

Of note, measures must be taken to prevent hypoglycemia during the ET.

Specific populations

Before non-cardiac surgery

Complementary examinations are currently indicated for some patients with a high preoperative risk [41]. The preoperative risk level depends on the patient's co-morbidities and the type of surgery performed (vascular surgery alone, such as aortic or peripheral artery surgery, represents a cardiac risk of > 5%). A low ventilatory threshold value (< 11 mL/min/kg) and a peak VO_2 < 16 mL/min/kg during a CPET translate into a high perioperative risk (Table 10) [42,43].

The female patient

Women often present atypical symptoms. Moreover, estrogen intake may modify some findings on the resting electrocardiogram. The risk of mortality is doubled in women who present with atypical symptoms and demonstrate a functional capacity of < 85% of the predicted value [7,44].

A normal ET in a woman carries a strong negative predictive value. A first-line imaging stress test does not offer

Table 10 Exercise test indications in specific populations.

Non-cardiac surgery (preoperative context)	A CPET (or, if unavailable, an ET) should be considered in the preoperative context of vascular surgery to improve perioperative care, especially in patients exhibiting low functional capacity (< 4 METs) and/or high cardiovascular risk [41,42]	IIa B
	An ET is not indicated in asymptomatic patients with low or moderate cardiovascular risk before non-vascular surgery	III C
Female patients	An ET is indicated as a first-line test in women aged > 50 years with angina, who exhibit a normal resting electrocardiogram [7]	I B
	An ET is not recommended in low-risk premenopausal female patients for diagnosis of CAD [45]	III C
Athletes	An ET is indicated in symptomatic athletes who plan to continue vigorous physical activity (> 6 METs or sport competition) [6,46]	I B
	An ET may be considered in asymptomatic athletes with a high or very high cardiovascular risk, who plan to continue vigorous physical activity (> 6 METs or competitive sports) [46]	IIa C
	An ET is not recommended in asymptomatic athletes with a low cardiovascular risk (score < 1%)	III C
Asymptomatic patients	An ET may be considered in asymptomatic subjects who carry at least a moderate cardiovascular risk level and work in high-risk occupations (e.g. firefighters, military, policemen, pilots, etc.) or wish to begin vigorous activity (> 6 METs) [16,47]	IIb C

CPET: cardiopulmonary exercise test; ET: exercise test; MET: metabolic equivalent of the task.

significant benefit. Thus, the use of a scoring system is preferred as a first-line strategy (Table 10) (see part 1) [7,45].

The elderly patient

An ET in an elderly patient requires an adapted exercise protocol (i.e. short increments). The diagnostic value of the ET is increased in this population, carrying good sensitivity. Arrhythmias are more frequent in the elderly. Functional capacity is the main variable that predicts survival [16].

The athletic subject

An ET is useful to screen for cardiovascular disease in athletes presenting with symptoms or an abnormal clinical examination, or when there is an unexplained reduction in physical performance. It is mandatory to adapt the ET protocol to reach maximal functional capacity. Abnormalities that are seen on a resting electrocardiogram (such as conduction and repolarization patterns), but disappear during exercise, are typically considered benign. The normalization of resting inverted T waves during an ET has no benign value. Trained athletes may present more false positive ST-segment depressions than untrained subjects [46]. A CPET may also be conducted to assess abnormal dyspnea (Table 10).

The asymptomatic subject

Because of the low prevalence of cardiovascular disease in asymptomatic subjects, the predictive value of the ET is weaker in this population. For subjects who present risk factors that position them at high cardiovascular risk, an abnormal ET (i.e. demonstrating low functional capacity or abnormal electrocardiogram findings) may further define a subset of patients at increased risk of CAD (Table 10) [16,40,47].

Pediatric and adult patients with congenital heart disease

The equipment and exercise protocol used for the ET must be adapted to the child's morphology and functional capacity [48]. Only children measuring > 120 cm may use a bicycle ergometer, preferably with a ramp protocol [24,48]. On a treadmill, the Bruce protocol is most commonly used [24,48].

Safety measures are compulsory, and are similar to those recommended for adult patients (see part 1). Although complications are rare, it is necessary to respect the contraindications and criteria for ET termination (see part 1) [48].

An ET is indicated in children to evaluate functional signs related to exercise (i.e. dyspnea, syncope, chest pain). In the context of congenital heart disease (CHD), an ET (or preferably a CPET) is indicated for the evaluation of functional capacity, preparticipation sports assessment, preoperative assessment and postoperative follow-up (screening for arrhythmias or conduction disorders, evaluation of coronary re-implantations, residual obstructions, cyanosis, residual shunt, etc.) (Table 11) [49–52].

Furthermore, a CPET is useful to guide cardiac rehabilitation for adults and children with CHD. The VO_2 peak reflects prognosis and quality of life in patients with CHD [53].

An ET is also fully indicated in the presence of angina (even if atheromatous plaques are exceptional in children) to investigate congenital abnormalities, such as an abnormal coronary artery tract, or in the context of Kawasaki disease [48].

Table 11 Exercise test indications in pediatric and adult patients with congenital heart disease.	
An ET should be considered in the child [48,51]: to evaluate symptoms that are triggered or aggravated by exercise; to assess the response to exercise when a cardiac pathology exists (congenital or acquired), including ischemia or arrhythmia; or to evaluate the efficacy of medical or surgical treatments	IIa C
A CPET should be considered in the child or adult with a congenital heart disease [48–52]: to assess prognosis; to evaluate the patient's functional capacity and prescribe an adapted physical activity programme; or before a cardiac rehabilitation programme	IIa C

CPET: cardiopulmonary exercise test; ET: exercise test.

Table 12 Interpretation of cardiopulmonary exercise test variables in different types of congenital heart disease.

	Respiratory tests	BP	HR, %MHR, HRR	ST-segment	SaO_2	VO_2 peak (% predicted)	VE/VCO_2 slope
Surgically corrected CHD	Restrictive syndrome						
Left-to-right shunt						Reduced (shunt)	
LVOTO		Coarctation					
Tetralogy of Fallot						Reduced PV replacement	Increased PV replacement
Systemic RV			Chronotropic incompetence			Reduced	Increased
TGA, arterial switch				Ischemia			
Coronary artery anomaly				Ischemia			
Right-to-left shunt					Decreased	Reduced	Increased
Cavopulmonary connection			Chronotropic incompetence			Reduced	Increased
Eisenmenger's syndrome					Decreased	Reduced	Increased

BP: blood pressure; CHD: congenital heart disease; HR: heart rate; HRR: heart rate reserve; LVOTO: left ventricular outflow tract obstruction; MHR: maximal heart rate; PV: pulmonary valve; RV: right ventricle; SaO_2: oxygen saturation; TGA: transposition of the great arteries; VE: volume of expired gas; VO_2: oxygen uptake; VCO_2: carbon dioxide output.

The different CPET variables used in the evaluation of CHD in children and adults are summarized in Table 12.

Conclusions

These new recommendations highlight two important factors. First, interpretation of the ET must be based on a multivariate analysis to assess the risk of CAD. Second, the indications for an ET have been broadened to include most cardiac pathologies, with the goal of assessing prognosis, particularly when coupled with expired gas analysis.

Sources of funding

None.

Acknowledgments

The authors thank the reviewers: Richard Brion, Jean-Louis Bussière, Jean-Michel Chevalier, Stéphane Doutreleau, Sophie Durand, Pascal Guillo, Jean-Michel Guy, Sophie Kubas, Catherine Monpère, Bernard Pierre and Jean-Yves Tabet, on behalf of the Exercise Rehabilitation and Sport Working Group of the French Society of Cardiology; Emmanuel Messas, on behalf of the Aorta-Peripheral Vessel Working Group; Philippe Commeau, on behalf of the Atheroma and Interventional Cardiology Working Group;

Thibaud Damy, on behalf of the Heart Failure and Cardiomyopathies Working Group; Nicolas Sadoul, on behalf of the Arrhythmias and Cardiac Stimulation Working Group; and Thierry Denolle, on behalf of the Hypertension subsidiary.

Disclosure of interest

The authors declare that they have no competing interest.

References

[1] [Guidelines of the French Society of Cardiology for exercise testing of adults in cardiology]. Arch Mal Coeur Vaiss 1997;90:77—91.

[2] Fletcher GF, Ades PA, Kligfield P, et al. Exercise standards for testing and training: a scientific statement from the American Heart Association. Circulation 2013;128:873—934.

[3] Montalescot G, Sechtem U, Achenbach S, et al. 2013 ESC guidelines on the management of stable coronary artery disease: the Task Force on the management of stable coronary artery disease of the European Society of Cardiology. Eur Heart J 2013;34:2949—3003.

[4] Wolk MJ, Bailey SR, Doherty JU, et al. ACCF/AHA/ASE/ASNC/HFSA/HRS/SCAI/SCCT/SCMR/STS 2013 multimodality appropriate use criteria for the detection and risk assessment of stable ischemic heart disease: a report of the American College of Cardiology Foundation Appropriate Use Criteria Task Force, American Heart Association, American Society of Echocardiography, American Society of Nuclear Cardiology, Heart Failure Society of America, Heart Rhythm Society, Society for Cardiovascular Angiography and Interventions, Society of Cardiovascular Computed Tomography, Society for Cardiovascular Magnetic Resonance, and Society of Thoracic Surgeons. J Am Coll Cardiol 2014;63:380—406.

[5] Piepoli MF, Hoes AW, Agewall S, et al. 2016 European Guidelines on cardiovascular disease prevention in clinical practice: The Sixth Joint Task Force of the European Society of Cardiology and Other Societies on Cardiovascular Disease Prevention in Clinical Practice (constituted by representatives of 10 societies and by invited experts). Developed with the special contribution of the European Association for Cardiovascular Prevention & Rehabilitation (EACPR). Eur Heart J 2016;37:2315—81.

[6] Fihn SD, Blankenship JC, Alexander KP, et al. 2014 ACC/AHA/AATS/PCNA/SCAI/STS focused update of the guideline for the diagnosis and management of patients with stable ischemic heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines, and the American Association for Thoracic Surgery. Preventive Cardiovascular Nurses Association, Society for Cardiovascular Angiography and Interventions, and Society of Thoracic Surgeons. J Thorac Cardiovasc Surg 2015;149:e5—23.

[7] Shaw LJ, Mieres JH, Hendel RH, et al. Comparative effectiveness of exercise electrocardiography with or without myocardial perfusion single photon emission computed tomography in women with suspected coronary artery disease: results from the What Is the Optimal Method for Ischemia Evaluation in Women (WOMEN) trial. Circulation 2011;124:1239—49.

[8] Amsterdam EA, Kirk JD, Diercks DB, Lewis WR, Turnipseed SD. Immediate exercise testing to evaluate low-risk patients presenting to the emergency department with chest pain. J Am Coll Cardiol 2002;40:251—6.

[9] Pavy B, Iliou MC, Verges-Patois B, et al. French Society of Cardiology guidelines for cardiac rehabilitation in adults. Arch Cardiovasc Dis 2012;105:309—28.

[10] Iliou MC, Pavy B, Martinez J, et al. Exercise training is safe after coronary stenting: a prospective multicentre study. Eur J Prev Cardiol 2015;22:27—34.

[11] Pavy B, Iliou MC, Meurin P, et al. Safety of exercise training for cardiac patients: results of the French registry of complications during cardiac rehabilitation. Arch Intern Med 2006;166:2329—34.

[12] Roffi M, Wenaweser P, Windecker S, et al. Early exercise after coronary stenting is safe. J Am Coll Cardiol 2003;42:1569—73.

[13] Izzo P, Macchi A, De Gennaro L, Gaglione A, Di Biase M, Brunetti ND. Recurrent angina after coronary angioplasty: mechanisms, diagnostic and therapeutic options. Eur Heart J Acute Cardiovasc Care 2012;1:158—69.

[14] Priori SG, Blomstrom-Lundqvist C, Mazzanti A, et al. 2015 ESC Guidelines for the management of patients with ventricular arrhythmias and the prevention of sudden cardiac death: The Task Force for the Management of Patients with Ventricular Arrhythmias and the Prevention of Sudden Cardiac Death of the European Society of Cardiology (ESC). Endorsed by: Association for European Paediatric and Congenital Cardiology (AEPC). Eur Heart J 2015;36:2793—867.

[15] Voss F, Schueler M, Lauterbach M, Bauer A, Katus HA, Becker R. Safety of symptom-limited exercise testing in a big cohort of a modern ICD population. Clin Res Cardiol 2016;105:53—8.

[16] Gibbons RJ, Balady GJ, Bricker JT, et al. ACC/AHA 2002 guideline update for exercise testing: summary article: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Committee to Update the 1997 Exercise Testing Guidelines). Circulation 2002;106:1883—92.

[17] Gonzalez Corcia MC, Remy LS, Marchandise S, Moniotte S. Exercise performance in young patients with complete atrioventricular block: the relevance of synchronous atrioventricular pacing. Cardiol Young 2016;26:1066—71.

[18] Ergul Y, Ozturk E, Ozyilmaz I, et al. Utility of exercise testing and adenosine response for risk assessment in children with Wolff-Parkinson-White Syndrome. Congenit Heart Dis 2015;10:542—51.

[19] Baumgartner H, Falk V, Bax JJ, et al. 2017 ESC/EACTS Guidelines for the management of valvular heart disease. Eur Heart J 2017;38:2739—91.

[20] Domanski O, Richardson M, Coisne A, et al. Cardiopulmonary exercise testing is a better outcome predictor than exercise echocardiography in asymptomatic aortic stenosis. Int J Cardiol 2017;227:908—14.

[21] Levy F, Fayad N, Jeu A, et al. The value of cardiopulmonary exercise testing in individuals with apparently asymptomatic severe aortic stenosis: a pilot study. Arch Cardiovasc Dis 2014;107:519—28.

[22] Guazzi M, Adams V, Conraads V, et al. EACPR/AHA Joint Scientific Statement. Clinical recommendations for cardiopulmonary exercise testing data assessment in specific patient populations. Eur Heart J 2012;33:2917—27.

[23] Ponikowski P, Voors AA, Anker SD, et al. 2016 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure: The Task Force for the diagnosis and treatment of acute and chronic heart failure of the European Society of Cardiology (ESC). Developed with the special contribution of the Heart Failure Association (HFA) of the ESC. Eur J Heart Fail 2016;18:891—975.

[24] Wasserman K, Hansen J, Sietsema K, et al. Principles of exercise testing and interpretation: including pathophysiology and clinical applications. 4th ed. Philadelphia: Lippincott, Williams and Wilkins; 2005.

[25] Cohen-Solal A, Tabet JY, Logeart D, Bourgoin P, Tokmakova M, Dahan M. A non-invasively determined surrogate of cardiac power ('circulatory power') at peak exercise is a

powerful prognostic factor in chronic heart failure. Eur Heart J 2002;23:806—14.
[26] Myers J, Arena R, Cahalin LP, Labate V, Guazzi M. Cardiopulmonary exercise testing in heart failure. Curr Probl Cardiol 2015;40:322—72.
[27] Elliott PM, Anastasakis A, Borger MA, et al. 2014 ESC Guidelines on diagnosis and management of hypertrophic cardiomyopathy: the Task Force for the Diagnosis and Management of Hypertrophic Cardiomyopathy of the European Society of Cardiology (ESC). Eur Heart J 2014;35:2733—79.
[28] Olivotto I, Maron BJ, Montereggi A, Mazzuoli F, Dolara A, Cecchi F. Prognostic value of systemic blood pressure response during exercise in a community-based patient population with hypertrophic cardiomyopathy. J Am Coll Cardiol 1999;33:2044—51.
[29] Monserrat L, Elliott PM, Gimeno JR, Sharma S, Penas-Lado M, McKenna WJ. Non-sustained ventricular tachycardia in hypertrophic cardiomyopathy: an independent marker of sudden death risk in young patients. J Am Coll Cardiol 2003;42:873—9.
[30] Galie N, Humbert M, Vachiery JL, et al. 2015 ESC/ERS Guidelines for the diagnosis and treatment of pulmonary hypertension: The Joint Task Force for the Diagnosis and Treatment of Pulmonary Hypertension of the European Society of Cardiology (ESC) and the European Respiratory Society (ERS): Endorsed by: Association for European Paediatric and Congenital Cardiology (AEPC). International Society for Heart and Lung Transplantation (ISHLT). Eur Heart J 2016;37:67—119.
[31] Aboyans V, Criqui MH, Abraham P, et al. Measurement and interpretation of the ankle-brachial index: a scientific statement from the American Heart Association. Circulation 2012;126:2890—909.
[32] Garber CE, Monteiro R, Patterson RB, Braun CM, Lamont LS. A comparison of treadmill and arm-leg ergometry exercise testing for assessing exercise capacity in patients with peripheral arterial disease. J Cardiopulm Rehabil 2006;26:297—303.
[33] Murphy TP, Cutlip DE, Regensteiner JG, et al. Supervised exercise, stent revascularization, or medical therapy for claudication due to aortoiliac peripheral artery disease: the CLEVER study. J Am Coll Cardiol 2015;65:999—1009.
[34] Miller TD, Christian TF, Allison TG, Squires RW, Hodge DO, Gibbons RJ. Is rest or exercise hypertension a cause of a false-positive exercise test? Chest 2000;117:226—32.
[35] Marwick TH, Torelli J, Harjai K, et al. Influence of left ventricular hypertrophy on detection of coronary artery disease using exercise echocardiography. J Am Coll Cardiol 1995;26:1180—6.
[36] Cosson E, Paycha F, Paries J, et al. Detecting silent coronary stenoses and stratifying cardiac risk in patients with diabetes: ECG stress test or exercise myocardial scintigraphy? Diabet Med 2004;21:342—8.
[37] Ryden L, Grant PJ, Anker SD, et al. ESC Guidelines on diabetes, pre-diabetes, and cardiovascular diseases developed in collaboration with the EASD: the Task Force on diabetes, pre-diabetes, and cardiovascular diseases of the European Society of Cardiology (ESC) and developed in collaboration with the European Association for the Study of Diabetes (EASD). Eur Heart J 2013;34:3035—87.
[38] Zafrir B, Azencot M, Dobrecky-Mery I, Lewis BS, Flugelman MY, Halon DA. Resting heart rate and measures of effort-related cardiac autonomic dysfunction predict cardiovascular events in asymptomatic type 2 diabetes. Eur J Prev Cardiol 2016;23:1298—306.
[39] Lee DP, Fearon WF, Froelicher VF. Clinical utility of the exercise ECG in patients with diabetes and chest pain. Chest 2001;119:1576—81.
[40] Ross R, Blair SN, Arena R, et al. Importance of assessing cardiorespiratory fitness in clinical practice: a case for fitness as a clinical vital sign: a scientific statement from the American Heart Association. Circulation 2016;134: e653—99.
[41] Societe Francaise d'Anesthesie et de Reanimation, Societe Francaise de Cardiologie. [Perioperative assessment of cardiac risk patient in non-cardiac surgery]. Ann Fr Anesth Reanim 2011;30:e5—29.
[42] Goodyear SJ, Yow H, Saedon M, et al. Risk stratification by preoperative cardiopulmonary exercise testing improves outcomes following elective abdominal aortic aneurysm surgery: a cohort study. Perioper Med (Lond) 2013;2:10.
[43] Guazzi M, Arena R, Halle M, Piepoli MF, Myers J, Lavie CJ. 2016 focused update: clinical recommendations for cardiopulmonary exercise testing data assessment in specific patient populations. Circulation 2016;133:e694—711.
[44] Gulati M, Black HR, Shaw LJ, et al. The prognostic value of a nomogram for exercise capacity in women. N Engl J Med 2005;353:468—75.
[45] Mieres JH, Shaw LJ, Arai A, et al. Role of noninvasive testing in the clinical evaluation of women with suspected coronary artery disease: Consensus statement from the Cardiac Imaging Committee, Council on Clinical Cardiology, and the Cardiovascular Imaging and Intervention Committee, Council on Cardiovascular Radiology and Intervention, American Heart Association. Circulation 2005;111: 682—96.
[46] Borjesson M, Urhausen A, Kouidi E, et al. Cardiovascular evaluation of middle-aged/senior individuals engaged in leisure-time sport activities: position stand from the sections of exercise physiology and sports cardiology of the European Association of Cardiovascular Prevention and Rehabilitation. Eur J Cardiovasc Prev Rehabil 2011;18:446—58.
[47] Lauer M, Froelicher ES, Williams M, Kligfield P. Exercise testing in asymptomatic adults: a statement for professionals from the American Heart Association Council on Clinical Cardiology, Subcommittee on Exercise, Cardiac Rehabilitation, and Prevention. Circulation 2005;112:771—6.
[48] Paridon SM, Alpert BS, Boas SR, et al. Clinical stress testing in the pediatric age group: a statement from the American Heart Association Council on Cardiovascular Disease in the Young, Committee on Atherosclerosis, Hypertension, and Obesity in Youth. Circulation 2006;113:1905—20.
[49] Kempny A, Dimopoulos K, Uebing A, et al. Reference values for exercise limitations among adults with congenital heart disease. Relation to activities of daily life-single centre experience and review of published data. Eur Heart J 2012;33:1386—96.
[50] Khan AM, Paridon SM, Kim YY. Cardiopulmonary exercise testing in adults with congenital heart disease. Expert Rev Cardiovasc Ther 2014;12:863—72.
[51] Rhodes J, Ubeda Tikkanen A, Jenkins KJ. Exercise testing and training in children with congenital heart disease. Circulation 2010;122:1957—67.
[52] Takken T, Blank AC, Hulzebos EH, van Brussel M, Groen WG, Helders PJ. Cardiopulmonary exercise testing in congenital heart disease: (contra)indications and interpretation. Neth Heart J 2009;17:385—92.
[53] Amedro P, Picot MC, Moniotte S, et al. Correlation between cardio-pulmonary exercise test variables and health-related quality of life among children with congenital heart diseases. Int J Cardiol 2016;203:1052—60.