2. Functional Capacity Assessment

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2.1. Exercise Tests in Cardiac Rehabilitation

2.1.1. Introduction

Exercise stress tests determine cardiovascular system response during exertion. Historically, exercise testing has been performed to provoke myocardial ischemia; however, indications have evolved over time [1]. Exercise capacity assessment delivers crucial information for exercise prescription guidance in cardiac rehabilitation programs, and cardiopulmonary exercise testing should ideally be executed. Exercise tests are typically performed on a treadmill or stationary bike; incremental exercise tests are the gold standard.

2.1.2. Indications

General indications for exercise tests include [2]:

- The detection of coronary artery disease (CAD) in patients with chest pain or potential symptom equivalents;
- Evaluation of the functional severity of coronary artery disease;
- Evaluation of physical capacity;
- Evaluation of exercise-related symptoms;
- Assessment of chronotropic competence, arrhythmias, and response to implanted cardiac electrical device therapy;
- Assessment of the response to medical interventions.

Stress tests in cardiac rehabilitation specifically allow for:

- Risk stratification for cardiac events during exercise based on functional capacity, coronary reserve, hemodynamic response (BP, HR), and the presence of exertional arrhythmia.
- Functional capacity assessment and exercise prescription upon admission to phases II or III, including:
    - determination of an adequate training model;
    - assessment of training progression during or at the end of the exercise program.
- Vocational and recreational activity planning after discharge from the program.

2.1.3. Contraindications

Absolute contraindications to exercise testing include [3]:

- Acute myocardial infarction (within two days);
- High-risk unstable angina;
- Uncontrolled symptomatic cardiac arrhythmias;
- Symptomatic severe aortic stenosis;
- Symptomatic heart failure;
- Acute pulmonary embolism;
- Active endocarditis;
- Acute myocarditis or pericarditis;
- Aortic dissection;
- Acute non-cardiac condition, which may affect exercise performance—e.g., infection, renal failure, and thyrotoxicosis;
- Lack of patient consent.

Relative contraindications for exercise testing include:

- Left main coronary artery stenosis or its equivalent;
- Moderate aortic stenosis;
- Electrolyte abnormalities;
- Systolic blood pressure > 180/110 mmHg;
- Tachyarrhythmia or bradyarrhythmia;
- Atrial fibrillation with an uncontrolled ventricular rate;
- Hypertrophic cardiomyopathy;
- Mental impairment;
- Physical inability to exercise adequately;
- High-degree atrioventricular block without a pacemaker.

In practice, the physician in charge decides whether relative contraindications to the exercise test balance the risk with the potential benefit of the information derived from the test.

2.1.4. Exercise Test Modalities

Depending on the method of exercise, exercise tests are usually performed on a treadmill or cycle ergometer [4]. Treadmills reflect a more physiological form of exercise but require more space and are more expensive than cycle ergometers. For test adequacy, it is important to use the treadmill handrails for balance only and to avoid gripping the handrails while exercising, in order to prevent peak oxygen uptake values being overestimated. Electrically braked cycles are calibrated in watts (W) and allow for a better ECG signal compared with treadmills; however, their biggest limitation is the termination of the test due to the fatigue of the quadriceps muscles. This affects test duration, and the maximal oxygen uptake attained is lower by 10–15% compared with that obtained on a treadmill [3]. From a technical point of view, bicycle tests should be executed in a proper way—i.e., with adequate seat adjustment and a knee flexion around 25 degrees of full extension.

2.1.5. Predicted Functional Capacity

Exercise capacity is reported in metabolic equivalents of tasks (METS). The MET unit reflects the resting volume oxygen consumption per minute (VO_2) for a 70 kg, 40-year-old man, with one MET equivalent to 3.5 mL/min/kg of body weight [5]. The appropriate assessment of predicted functional capacity determines the appropriate test protocol.

Functional capacity depends on [6]:

- Age;
- Sex;
- Habitual activity;
- Clinical status;
- Genetic conditions.

There are many formulas for predicted MET calculation [7,8]:

1. Morris formula for men:
   Predicted MET = 18.0 $-$ 0.15 $\times$ age (years)
2. Gulati formula for women:
   Predicted MET = 14.7 $-$ 0.13 $\times$ age (years)

Predicted functional capacities for men and women in relation to age according to the Morris and Gulati formulas:

Twenty years old: women 12.1 MET, men 15.0 MET.
Thirty years old: women 10.8 MET, men 13.5 MET.
Forty years old: women 9.5 MET, men 12.0 MET.
Fifty years old: women 8.2 MET, men 10.5 MET.
Sixty years old: women 6.9 MET, men 9.0 MET.
Seventy years old: women 5.6 MET, men 7.5 MET.

The Duke Activity Status Index and the Veterans Specific Activity Questionnaire have been developed to assess the intensities of activities of daily living [9,10].

Duke Activity Status Index (DASI) comprises 12 questions assessing daily activities, with each item equaling a specific metabolic cost in MET. Patients are asked to identify each activity they can perform (Table 4).

Oxygen uptake = (0.43 $\times$ sum of points from positive answers) + 9.6.

Table 4. Duke Activity Status Index.

Is the Patient Able to?	Points
Eat, dress, bath, use the toilet	2.75
Walk indoors	1.75
Walk 1–2 blocks on level ground	2.75
Climb a flight of stairs or walk up a hill	5.5
Run a short distance	8.0
Do dusting, washing dishes	2.7
Do vacuuming, swipe floors, carry groceries	3.5
Do heavy work around the house, e.g., scrubbing floors, lifting or moving heavy furniture	8.0
Do yardwork, e.g., raking leaves, weeding, pushing a power mower	4.5
Have sexual relations	5.25
Participate in moderate recreational activities, e.g., golf, bowling, dancing, doubles tennis, throwing a baseball or football	6.0
Participate in strenuous sports, e.g., swimming, singles tennis, football, basketball, skiing	7.5

Source: Adapted from [9].

Similarly, the Veterans Specific Activity Questionnaire (VSAQ) consists of 13 items estimating aerobic fitness in cardiac patients and measures the maximal level of physical activity that patients can achieve (Table 5). Predicted MET = 4.7 + 0.97 $\times$ the highest tolerable MET from questionnaire $-$ 0.06 $\times$ age.

2.1.6. Choice of the Individual Protocol

The choice of an appropriate protocol is essential. Depending on their intensity, exercise tests can be maximal (symptom-limited) or submaximal (predefined).

In cardiac rehabilitation settings, maximal tests are typically preferred. Indicators of maximal stress test include [11]:

- A rate–pressure product (maximal heart rate $\times$ systolic blood pressure) that is >20,000;
- Perceived exertion of 18 or more on the Borg scale;
- Exhaustion of the patient.

Table 5. Veterans Specific Activity Questionnaire.

MET	The Activity, Which Performed for a Period, Would Typically Cause Fatigue, Shortness of Breath, Chest Discomfort, or a Patients' Will to Stop
1	Eating, getting dressed, working at a desk
2	Taking a shower, shopping, cooking
3	Walking slowly on a flat surface for 1 or 2 blocks, a moderate amount of work around the house, such as vacuuming, sweeping the floors, or carrying groceries
4	Light yard work (i.e., raking leaves, weeding, pushing a power mower), painting
5	Walking briskly, social dancing
6	Heavy carpentry, mowing a lawn with a push mower
7	Carrying 60 pounds, performing heavy outdoor work (i.e., digging, spading soil, etc.), walking uphill
8	Carrying groceries upstairs, moving heavy furniture, jogging slowly on a flat surface, climbing stairs quickly
9	Bicycling at a moderate pace, sawing wood
10	Swimming briskly, bicycling up a hill, jogging 6 miles per hour
11	Carrying a heavy load (i.e., a child or firewood) up 2 flights of stairs
12	Running briskly, continuously (level ground, 8 min per mile)
13	Intermittent sprinting, running competitively, rowing competitively, or riding a bicycle

Source: Adapted from [11].

The submaximal test is terminated after achieving a goal, e.g., in patients < 40 years after myocardial infarction, the test may be terminated after achieving a heart rate of 140 bpm or tolerance equal to 7 METS. In patients > 40 years, the test can be terminated at 130 bpm or at a tolerance of 5 METS. Submaximal tests are traditionally conducted in the early phase after myocardial infarction following cardiac surgery and in patients with impaired left ventricular systolic function. Optimally, the test should be terminated after between 8 and 12 min.

The stress test can be graded (GXT) or ramped (with a constant load increase). Ramp tests demonstrate a good linear correlation between the load and the maximal oxygen consumption [12,13]. Ramp protocols provide a uniform hemodynamic response and therefore can be individualized. Considering recent studies, however, a delay of the initial oxygen uptake response upon the start of the incremental exercise test compared with constant work has been demonstrated. Thus, the first and the second ventilatory thresholds are attained at lower work rates during the constant work test for a given oxygen uptake value than they are during the incremental test [14].

Treadmill Stress Test Protocols

The most common treadmill protocol used is the Bruce (Table 6) protocol; however, due to its large and uneven load increments, it is preferred for individuals with a good predicted functional capacity [15].

Table 6. Bruce protocol.

Stage	Minutes	% Incline	Km/h	METS
1	3	10	2.7	5
2	3	12	4.0	7
3	3	14	5.4	10
4	3	16	6.7	13
5	3	18	8	15
6	3	20	8.8	18

Abbreviations: Km/h—kilometers per hour; METS—multiples of resting metabolic equivalent; Source: Adapted from [15].

The modified Bruce protocol was designed for individuals who cannot exercise vigorously (Table 7). It includes two lower workload stages at the beginning of the standard Bruce protocol.

Table 7. Modified Bruce protocol.

Stage	Minutes	% Incline	Km/h	METS
1	3	0	2.7	2.3
2	3	5	2.7	3.5
3	3	10	2.7	4.6
4	3	12	4.0	7.1
5	3	14	5.5	10.2
6	3	16	6.8	13.5

Abbreviations: Km/h—kilometers per hour; METS—multiples of resting metabolic equivalent; Source: Adapted from [2].

The Naughton protocol increases the load by approximately 1 MET in 2 min stages and is recommended for use in patients who have a low predicted functional capacity (Table 8).

Table 8. Naughton protocol [2].

Stage	Minutes	% Incline	Km/h	METS
1	2	0	1.6	1.8
2	2	0	3.2	2.5
3	2	3.5	3.2	3.5
4	2	7	3.2	4.5
5	2	10.5	3.2	5.4
6	2	14.	3.2	6.4
7	2	17.5	3.2	7.4
8	2	17.5	4	8.9
9	2	17.5	4.8	10.5
10	2	17.5	5.6	12.1

Abbreviations: Km/h—kilometers per hour; METS—multiples of resting metabolic equivalent; Source: Adapted from [2].

There are many available ramp treadmill protocols—e.g., the Bruce protocol (Table 9).

Table 9. Bruce Ramp Stress Test protocol [2].

Stage	Minutes	% Incline	Km/h	METS
1	1	0	1.6	1.8
2	1	5	2.1	2.9
3	1	10	2.7	4.6
4	1	10	3.4	5.5
5	1	11	3.7	6.3
6	1	12	4	7.1
7	1	12	4.5	7.8
8	1	13	5	8.9
9	1	14	5.5	10.2
10	1	14	6.1	11.2
11	1	15	6.6	12.6
12	1	16	6.8	13.5
13	1	16	7.2	14.4
14	1	17	7.7	15.9
15	1	18	8	17.2
16	1	18	8.5	18.2
17	1	19	9	20
18	1	20	9.3	21.4

Abbreviations: Km/h—kilometers per hour; METS—multiples of resting metabolic equivalent; Source: Adapted from [2].

Underutilized individualized ramp test protocols allow for precise test termination after 8 to 12 min but are still underexploited [16].

Leg Cycle Ergometer Stress Test Protocols

Leg cycle ergometer exercise test protocols depend on body mass and predict functional capacity [2]. Typically, a graded test consists of a 1–2 min warm-up (with a 10–20 Watt load or without a load); an initial load of 25 Watts (for inactive persons or individuals with a weight < 70 kg) or 50 Watts (for active persons or individuals with a weight > 70 kg), which is typically increased by 25 Watts every 3 min; then a cool-down without a load. A formula providing an approximate METs calculation following the bicycle stress test is provided in Table 10.

Table 10. Functional capacity calculation after cycle ergometer stress test [2].

Body Mass (kg)	METS	METS	METS	METS	METS	METS	METS
	50 W	75 W	100 W	125 W	150 W	175 W	200 W
60	4.3	5.7	7.1	8.6	10	11.4	12.9
70	3.7	4.9	6.1	7.3	8.6	9.8	11
80	3.3	4.3	5.4	6.4	7.5	8.6	9.6
90	2.9	3.8	4.8	5.7	6.7	7.6	8.6
100	2.6	3.4	4.3	5.1	6	6.9	7.7

Abbreviations: kg—kilogram; METS—multiples of resting metabolic equivalent; W—watts.
Source: Adapted from [2].

The steep ramp protocol created by Meyer allows for the calculation of the so-called maximal short-term exercise capacity (MSEC) and has been used for high-intensity interval training prescription. After a 3 min warm-up on a cycle without a load, the intensity is increased to 25 watt every 10 s (i.e., 150 watts is attained after 1 min). The patient continues the test until he/she can cycle at a pace of 60 revolutions/min [17].

2.1.7. The Patient's Preparation

The preparation for the stress test includes:

- Review of medical history;
- Physical examination;
- Explanation of the RPE Borg scale/angina scale;
- Correct connection of ECG electrodes;
- Convenient clothing.

On the test day, patients should not eat, drink caffeine, or smoke for 3 h before the test. Neither should they perform vigorous exercise within the 12 h prior to the testing. Patients should dress appropriately for exercise.

For a functional capacity assessment, patients should take their usual medications. For diagnostic stress tests, however, the withdrawal of some medications might be applied and should be discussed with a cardiologist, as, for example, beta-blockers attenuate exercise response [3]. In the case of patients with an implanted cardiac electrical device, testing personnel should know the reason for implantation and the current device parameters.

2.1.8. Measurements

Measurements taken during exercise testing, according to ACSM [2], are presented in Table 11.

Table 11. Monitoring intervals associated with exercise testing.

	Before Test	During Test	After Test
ECG	Monitored continuously, recorded in supine position	Monitored continuously, recorded during the last 15 s of each stage or the last 15 s of each 2 min period (in case of ramp protocols)	Monitored continuously, recorded immediately after exercise, during the last 15 s of the first min of recovery, then every 2 min
HR	Monitored continuously	Monitored continuously, recorded during the last 5 s of each minute	Monitored continuously, recorded during the last 5 s of each minute
BP	Measured and recorded in supine position and posture during exercise	Measured and recorded during the last 15 s of each stage or the last 45 s of each 2 min period (ramp protocols)	Measured and recorded immediately after exercise and then every 2 min
RPE	RPE scale should be explained	Recorded during the last 15 s of each stage or every 2 min (ramp protocols)	Peak exercise value to be obtained, not measured in recovery

Abbreviations: BP—blood pressure; ECG—electrocardiogram; HR—heart rate; RPE—rating of perceived exertion. Source: Adapted from [2].

2.1.9. Indications for Test Termination

Absolute indications for stress test termination include [18]:

- Chest pain;

- Drop in systolic blood pressure of >10 mm Hg from baseline with an increase in workload, if accompanied by other evidence of ischemia;
- Nervous system symptoms—e.g., ataxia, dizziness, or near syncope;
- Signs of poor perfusion (cyanosis or pallor);
- Sustained ventricular tachycardia;
- ST-segment elevation (≥1.0 mm in leads without diagnostic Q-waves (other than V1 or aVR));
- Inadequate ICD intervention in the case of sinus tachycardia or atrial fibrillation with a rapid ventricular rate above the ICD detection threshold;
- Difficulties in monitoring ECG or blood pressure;
- Patient's request to stop.

Relative indications for the termination of the test include:

- A drop in systolic blood pressure of ≥10 mm Hg from baseline with an increase in workload in the absence of other evidence of ischemia;
- ST-segment horizontal- or down-sloping depression > 2 mm or marked axis shift;
- Arrhythmias other than sustained ventricular tachycardia (premature ventricular contractions, supraventricular tachycardia);
- Heart block or bradyarrhythmia;
- Fatigue, shortness of breath, wheezing, leg cramps, or claudication;
- New bundle-branch block or intraventricular conduction delay that cannot be distinguished from ventricular tachycardia;
- Hypertensive response (systolic blood pressure of >250 mmHg and/or diastolic blood pressure of >/115 mmHg).

2.1.10. Stress Test Interpretation

The interpretation of exercise tests comprises ECG analysis, the assessment of chronotropic and blood pressure response, the evaluation of the level of functional capacity, and the presence of symptoms limiting exertion.

Exercise test report for cardiac rehabilitation should include the following information [3,18]:

- Test modality and protocol;
- Test duration;
- Heart rate and blood pressure values (resting on peak exercise, following exercise cessation);
- Functional capacity assessment in METS or watts (and as % of predicted);
- Reason for test termination;
- Rate of perceived exertion (Borg);
- Angina scale;
- Presence of arrhythmias;

- ECG analysis;
- Clinical interpretation.

The test result should also include the age-estimated functional capacity level as demonstrated inn Table 12 [19].

Table 12. Functional capacity classification.

Functional Capacity	**Percentage of the Age-Related Functional Capacity**
Excellent	143 and more
Good	120–142
Above average	108–119
Average	96–107
Below average	85–95
Poor	75–84
Very poor	39–74

Source: Adapted from [19].

2.1.11. Arm Ergometry

A mechanically or electrically braked arm ergometer can be applied for selected patients with lower extremity impairment caused by vascular, orthopedic, or neurological conditions—e.g., spinal injury, stroke, or leg amputation [20,21].

Moreover, it can be used for occupational evaluation in patients whose work primarily involves the arms and upper body. For testing purposes, work rate increments of 5–10 watts every 2–3 min at a pace of 60–70 revolutions per minute are suggested [22].

2.2. Cardiopulmonary Exercise Test

2.2.1. Rationale

Exercise tolerance is driven by three factors: pulmonary gas exchange, cardiovascular performance, and skeletal muscle metabolism [23]. For functional exercise testing, the Fick equation is fundamental, stating that oxygen uptake is a product of cardiac output and the arteriovenous oxygen difference at peak exercise [24].

The cardiopulmonary exercise test (CPET) utilizes a symptom-limited exercise test on a treadmill or cycle ergometer combined with respiratory gas exchange analysis—i.e., it incorporates measurements of respiratory oxygen uptake (VO_2), carbon dioxide production (VCO_2), and ventilatory measures. Hence, CPET is of great value for an assessment of cardiovascular, respiratory, and metabolic changes in response to exercise.

2.2.2. Indications

Indications for CPET include [25]:

- Differentiation between cardiac and pulmonary cause of dyspnea;
- Functional capacity assessment;
- Qualification to heart transplant or cardiac resynchronization therapy;
- Qualification for lung and heart–lung transplant;
- Prescription of exercise training intensity and evaluation of response to exercise training;
- Evaluation of response to therapeutic interventions;
- Preoperative evaluation.

Table 13 exhibits the American Thoracic Society (ATS) and American College of Chest Physicians (ACCP) indications for CPET [26].

Table 13. Indications for cardiopulmonary exercise testing.

Class	Indication
I (indicated)	1. Evaluation of exercise capacity and response to treatment in patients with heart failure, who are being considered for heart transplantation 2. Differentiation of cardiac versus pulmonary limitations as a cause of exercise-induced dyspnea or impaired exercise capacity when the cause in uncertain
IIa (good supportive evidence)	Evaluation of exercise capacity when indicated for medical reasons in patients for whom the estimates of exercise capacity from exercise test time or work rate are unreliable
IIb (weak supportive evidence)	1. Evaluation of the patient's exercise tolerance response to specific therapeutic interventions Determination of the intensity for exercise training as part of comprehensive cardiac rehabilitation
III (not indicated)	Routine use to evaluate exercise capacity

Abbreviations: AHA—American Heart Association. Source: Adapted from [26].

CPET is widely applied in the functional assessment of patients with heart failure to determine the severity of the disease (American College of Cardiology/American Heart Association recommendation Class IIa, Level of Evidence C), to identify candidates for cardiac transplantation (American College of Cardiology/American Heart Association Recommendation Class IIa, Level of Evidence B), and to facilitate the exercise prescription (American College of Cardiology/American Heart Association Recommendation Class I, Level of Evidence C) [27].

2.2.3. Technical Aspects

Patients should be instructed appropriately to attain the best possible effort. Prior to each cardiopulmonary exercise test, all CPET systems should be calibrated. This should include the calibration of airflow, volumes, and both the oxygen and carbon dioxide analyzers. It should be followed by spirometry to assess resting pulmonary function: forced expiratory volume in 1 s, forced vital capacity, and peak expiratory flow. CPET starts with 1–2 min registration, followed by warm-up (2–3 min). CPET should be performed as symptom-limited, and the optimal test duration is between 8 and 12 min. Thereby, patient–staff communication techniques during the test are essential for test safety and should be discussed before, including hand signs regarding symptom scoring—e.g., the Borg scale [26]. Both cycle ergometer and treadmill protocols can be used. The initial workload on a cycle ergometer for patients with heart failure is usually 20–25 W, which is increased by 15–25 W every 2 min until maximal exertion is attained. Optionally, ramp protocol (e.g., 10 W/min) can be executed. The modified Naughton protocol is recommended for treadmill exercise testing in patients with heart failure in order to increase the workload by approximately 1 MET for each 2 min stage [24,26]. Treadmill exercise testing has advantages over cycle ergometry, as patients, particularly those who are untrained, usually terminate cycle exercise because of quadriceps fatigue at an oxygen uptake that is on average 10% to 15% lower than oxygen uptake from a treadmill [28]. Furthermore, walking is a more familiar activity than cycling and involves a larger muscle mass. Electrocardiogram and blood pressure is monitored during the test, and BP should be recorded at rest and every 2 min or during the final 2 min of each stage (in the case of non-ramp protocol). Contraindications to cardiopulmonary exercise testing and criteria for terminating the exercise test are the same as those described earlier.

2.2.4. Parameters

CPET allows for cardiac and ventilatory parameter assessment. The main parameters assessed in CPET include [29]:

Peak Oxygen Uptake

Peak oxygen uptake is the volume of oxygen extracted from the air and inhaled over time, calculated in mL/min, and often normalized for body weight (mL/kg/min). One metabolic equivalent (MET) is the resting oxygen uptake in a sitting position and is equal to 3.5 mL/kg/min [5]. As oxygen uptake increases linearly with work, achieving a clear plateau in oxygen uptake has traditionally been used as the best evidence of maximal oxygen uptake [26]. Hence, maximal oxygen uptake is the best index of aerobic capacity and the gold standard for cardiorespiratory fitness assessment. In practice, this plateau may not be achieved before symptoms, with the termination of exercise. Consequently, peak oxygen uptake is often used as an estimate for maximal oxygen uptake (maximal and peak oxygen uptake are used interchangeably). Maximal oxygen uptake depends on age, sex, weight, height, fitness level, and ethnic origin. It can also be affected by training and patient motivation. A normal value for oxygen consumption is considered to be >20 mL/kg/min, and <10 mL/kg/min value is linked to poor prognosis [30,31]. Peak oxygen uptake has been demonstrated to predict prognosis in patients with heart failure in many studies. In a prospective study of 114 ambulatory patients with heart failure referred for cardiac transplantation, an oxygen consumption of <14 mL/kg/min has been used as a cutoff for the acceptance for cardiac transplantation [32].

Respiratory Exchange Ratio (RER)

RER is the ratio of carbon dioxide output/oxygen uptake (VCO_2/VO_2) and is the best non-invasive indicator of exercise intensity. RER increases during exercise due to either buffered lactic acid or hyperventilation. Resting RER is about 0.8, and RER > 1.0 indicates maximal exercise effort [33].

Anaerobic Threshold (AT) or Lactate Threshold

During light- to moderate-intensity incremental exercise, aerobic metabolism dominates and the blood lactates level remains stable (or is only marginally elevated). This initial, aerobic phase of CPET, lasts until 50–60% of peak oxygen uptake is attained, with expired ventilation (VE) showing a linear increase with oxygen uptake. As mentioned, at this phase the blood lactate level is relatively stable, as muscle lactic acid production is insignificant. The following period of exercise, however, with increasing effort intensity, is characterized by anaerobic metabolism, since oxygen supply is insufficient with the increasing metabolic requirements of the exercising muscles. Significant increases in lactic acid production in the muscles and in its concentration in blood are observed during this phase, and greater reliance on anaerobic metabolism is needed for continued energy production [25,26]. The oxygen uptake at the onset of blood lactate accumulation is called the first ventilatory threshold or the anaerobic threshold, above which blood lactate and pH start to increase and decrease, respectively, and ventilation accelerates to eliminate the excess carbon dioxide produced during the conversion of lactic acid to lactate [34]. The first ventilatory threshold is typically attained at 60–70% of maximal oxygen uptake [35,36]. Hence, AT estimates the onset of metabolic acidosis, is related to the oxygen uptake at which it occurs and should be expressed as a percentage of the predicted value of maximal oxygen uptake.

Several methods allow for the identification of the anaerobic threshold. AT can be determined both invasively (lactic acid) and noninvasively (ventilatory equivalent for oxygen and carbon dioxide methods: VE/VO_2, VE/VCO_2, V-slope, and the modified V-slope method).

In practice, the main non-invasive executed methods for estimating the anaerobic threshold are [24]:

The V-slope method: The anaerobic threshold is defined as the oxygen uptake at which the rate of increase in VCO_2 relative to VO_2 increases in the absence of hyperventilation. The AT determined by this method is a more reproducible estimate.

The ventilatory equivalents method: The AT is the VO_2 at which the ventilatory equivalent for O_2 (VE/VO_2 ratio) and end-tidal oxygen tension (PET O_2) begin to increase systematically without an immediate increase in the ventilatory equivalent for CO_2 (VE/VCO_2) and end-tidal CO_2 tension (PET CO_2).

AT usually occurs at 47% to 64% of the measured maximal oxygen uptake in a healthy individual. The value of AT is important for exercise prescription, as the heart rate value at AT is crucial [25]. Optimally, the exercise training heart rate should be 5% lower than the heart rate at anaerobic threshold (10% lower in heart failure individuals).

Exercise Oscillatory Breathing or Exercise Oscillatory Ventilation (EOV)

EOV is present in heart failure and has been described as the regular alteration of tidal volume with a crescendo–decrescendo pattern. The presence of EOV is a marker of significant hemodynamic impairment and is associated with worse clinical prognosis. If present, EOV should persist for 60% of the exercise test, with an amplitude of >15% [37].

A summary of the CPET variables is presented in Table 14.

Table 14. Cardiopulmonary exercise test variables [38].

CPET Variables	Definition	Values
VO_2	Describes functional capacity Indicates prognosis	Normal >20 mL/kg/min Severely reduced <10 mL/kg/min
VO_2%	Functional capacity in relation to predicted normal values	Normal >100% of predicted Moderately reduced 75–50% of predicted Severely reduced <50% of predicted
VE/VCO_2 slope	Reflects pulmonary ventilation and perfusion Indicates prognosis Increased in heart failure and in pulmonary hypertension	Normal <30 Moderately elevated: 36.0–44.9 Severely elevated: >45
Exercise oscillatory ventilation	Present in heart failure Predictor of poor prognosis	If present: must persist for 60% of the exercise test, with amplitude 15% or more
End-tidal carbon dioxide partial pressure (PET CO_2)	Reflects ventilation–perfusion mismatch within the pulmonary system	Normal values: Resting PET CO_2 >33 mmHg or 3–8 mmHg increases during an exercise test Abnormal: resting PET CO_2 < 33 mmHg and/or <3 mmHg increases during an exercise test
RER	Expresses the ratio of carbon dioxide production to oxygen consumption	Values >1.10 determines maximal exercise

Abbreviations: BP—blood pressure; CPET—cardiopulmonary exercise test; HR—heart rate; PET CO_2—end-tidal carbon dioxide partial pressure; RER—respiratory exchange ratio; VCO_2—carbon dioxide output; VE—minute ventilation; VE/VCO_2—ventilatory equivalent of carbon dioxide; VE/VO_2—ventilatory equivalent of oxygen; VO_2—oxygen uptake. Source: Adapted from [38].

2.2.5. Interpretation

Maximal effort is assumed in the presence of one or more of the criteria listed below [31,35]:

- Oxygen uptake and/or heart rate fail to increase with further increase in work rate;

- Peak respiratory exchange ratio (VCO_2/VO_2) > 1.10–1.15;
- Post exercise lactates level in blood > 8 mmol/L;
- Rating of perceived exertion > 8 on a 0–10 scale.

Among these, a plateau in the relationship of oxygen uptake versus work rate during incremental exercise is the gold standard for the determination of maximal effort.

A CPET report should include [23]:

- Reason for test;
- Diagnoses, medications, resting ECG, and BP;
- Basic data: age, height, weight;
- Exercise modality and protocol used;
- Modality of gas sampling;
- Reasons for test terminations;
- Symptoms;
- Subjective assessment of effort;
- Gas exchange and ventilatory data at peak and at the ventilatory threshold (if has been determined) in absolute values and as a percentage relative to reference;
- HR, BP, and ECG changes.

Norms for peak oxygen uptake for women and men at different ages:

For 20–29 years: women 36 ± 6.9 VO_2, men 43 ± 7.2 VO_2.
For 30–39 years: women 34 ± 6.2 VO_2, men 42 ± 7.0 VO_2.
For 40–49 years: women 32 ± 6.2 VO_2, men 40 ± 7.2 VO_2.
For 50–59 years: women 29 ± 5.4 VO_2, men 36 ± 7.1 VO_2.
For 60–69 years: women 27 ± 4.7 VO_2, men 33 ± 7.3 VO_2.
For 70–79 years: women 27 ± 5.8 VO_2, men 29 ± 7.3 VO_2.

The severity of the functional capacity impairment during incremental treadmill testing in heart failure (Weber–Janicki classification) is shown in Table 15 [39].

Table 15. Functional classification of patients with congestive heart failure.

Severity	Class	Peak VO_2, mL/kg per minute	AT	Maximal Cardiac Index, L/min/m^2
None to mild	A	>20	>14	>8
Mild to moderate	B	16–20	11–14	6–8
Moderate to severe	C	10–16	8–11	4–6
Severe	D	6–10	5–8	2–4

Abbreviations: AT—anaerobic threshold; mL/kg/min—milliliters per kilogram per minute; L/min/m^2—liters per minute per square meter; VO_2—oxygen uptake. Source: Adapted from [39].

2.3. *Walking Tests*

2.3.1. Six-Minute Walk Test

The six-minute walk test (6 MWT) measures the distance that a patient can walk quickly on a flat, firm surface within six minutes (Figure 2). The test should be performed in a minimally trafficked area, optimally in an enclosed corridor, but can be also performed outdoors [40]. A six-minute walk test on a treadmill is not recommended, as patients will be unfamiliar with the machinery and attain a significantly lower walk distance [41]. The six-minute walk test is a simple and safe method of approximate functional capacity assessment. As most patients do not achieve their maximal exercise capacity when walking at their own pace, the results of the 6 MWT should be considered complementary to conventional exercise testing [42,43]. The 6 MWT is not suitable for use in exercise risk stratification, as even brisk walking at a speed of 6 km/h (i.e., at an intensity of 4 METs) will not elicit an adequate intensity threshold—i.e., 5 MET—to guide exercise risk assessment [44]. In practice, 6 MWT has been used for exercise training qualification in patients following incomplete revascularization or early after cardiac surgery. On the other hand, as walking is a natural activity, the walking test is well tolerated and easy to administer. The 6 MWT has clear advantages over treadmill walking, reflecting the real situation, and can be more suitable for the elderly and patients with musculoskeletal disorders—e.g., with knee arthrosis. Furthermore, middle-aged patients and the elderly can consider the 6 MWT as a moderate- to high-intensity test. In numerous studies, a strong correlation has been found between the metabolic equivalent estimated from the 6 MWT and conventional treadmill exercise tolerance tests [45,46]. A strong correlation between peak oxygen uptake and distance covered during the 6 MWT was achieved by adding the terminal rating of perceived exertion [47].

Figure 2. The six-minute walk test. Source: Photo by authors.

Test requirements [2]:

- A walking course of 30 m in length;
- The starting point should be marked with brightly colored tape;
- The length should be marked every three meters;
- The turnaround point should be marked with a cone;
- Easy access to defibrillator, oxygen, and medications.

Appropriate patient preparation [48]:

- Patients should wear comfortable clothes and are allowed to use a stick or walking frame if necessary;
- The usual medications should be taken before the test;
- Patients are not allowed to exercise vigorously for up to two hours before the test;
- Patients should sit at the starting point ten minutes prior to the testing;
- Blood pressure, heart rate, and oxygen saturation should be documented before and after the test;
- Patients should be informed that they are allowed to slow down or stop and take a rest if necessary;

- Staff should inform the patient during the test about their time left after each minute;
- Staff should regularly encourage the patient to continue the test;
- Patient should be observed for at least 10 min following the test;
- Walk distance should be measured by counting the number of full laps and rounding to the nearest meter for the partial final lap.

Optimally, two tests should be performed due to the patient improving during the second one (learning curve effect). An increase in 6 MWT distance by 27 min on the second walk has been documented in a study including over 1500 patients with chronic pulmonary obstructive disease [49]. The six-minute walk test is considered safe; however, testing personnel should be certified in basic life support, and immediate access to emergency equipment should be provided. Absolute contraindications for 6 MWT include <7–10 days from primary angioplasty due to myocardial infarction and <24 h from elective coronary angioplasty. Relative contraindications include resting heart rate of >120 bpm, systolic blood pressure of >180 mmHg, and diastolic blood pressure of >100 mmHg [50].

Reasons for test termination include:

- Chest pain;
- Increasing dyspnea;
- Dizziness;
- Pallor;
- Diaphoresis;
- Leg cramps;
- Claudication;
- The patient's request to stop.

The test report should include:

- The patient's data;
- Current medications;
- Heart rate and blood pressure values (before and after the test);
- Borg scale at the end of test;
- Test distance;
- Data about stopping test;
- Symptoms;
- Conclusions.

The 6 MWT distance can be affected by many factors—e.g., BMI 25 kg/m^2 and age $\geq$75 years were found to be independent predictors of poor performance (i.e., <300 m) in a study by Pepera that included patients with heart failure. Furthermore, patients with heart failure have been found to have a shorter step length and to walk more slowly than controls during the 6 MWT [51].

Gibbons et al. attempted to determine the best 6-min walk distance from several repetitions in healthy volunteers. The reference value they found for 6 MWT was 698 $\pm$ 96 m [52].

Enright and Sherill developed reference equations for women and men to utilize the percentage of predicted 6 MWT distances [53]:

- For women: (2.11 $\times$ height in cm) $-$ (2.29 $\times$ body mass in kg) $-$ (5.78 $\times$ age) + 667 m.
- For men: (7.57 $\times$ height in cm) $-$ (5.02 $\times$ age) $-$ (1.76 v body mass in kg) + 309 m.

For patients after coronary artery bypass surgery and valve surgery, two formulas have been proposed; these include sex, the presence of diabetes, and atrial fibrillation [54]. The translation of the 6 MWT results into exercise prescription has been suggested, with 80% of the average 6 MWT speed corresponding to a high but tolerable exercise intensity and resulting in training benefits [55].

2.3.2. The Two-Minute Step Test

The two-minute step test (2 MST) was introduced in 1999 by Rikli and Jones as part of the Senior Fitness Test. The test requires that tested individuals march in place as fast as possible for 2 min while lifting their knees to a height midway between their patella and iliac crest when standing [56]. Similarly, like in the 6 MWT, the patients can slow down or stop the test if necessary. The norm for the 2 MST is 65 steps or more [57]. Rikli and Jones have demonstrated good inter-test reliability [58].

2.3.3. The Incremental Shuttle Walking Test

The incremental shuttle walk test (ISWT) is a symptom-limited, externally paced test performed along a 10 m course and involving walking back and forth between two cones set 0.5 m from either end of a 10 m course. The initial walking speed, indicated by an audible signal, is increased each minute until the patient is too fatigued to continue or cannot maintain the required speed. The number of completed shuttles—i.e., the ISWT total distance covered—is the test outcome. Unlike in the 6 MWT, there seems to be no learning effect in the ISWT [59]. In addition, the turning maneuver has no impact on the test result in stable patients with cardiovascular disease unless reduced mobility due to orthopedic limitations is present [60].

A relationship between the number of shuttles completed and the maximum oxygen uptake has been demonstrated, supporting the potential role of ISWT as a valuable tool for assessing changes in patients' functional capacity during cardiac rehabilitation. Numerous studies have addressed variables affecting test performance, with the ISWT distance correlating most strongly with step length and height [61]. As expected, the ISWT distance covered by men was further than that by women, with mean values of 395 and 269 m, respectively [62]. The ISWT results have been translated into exercise training intensity by the prescription of the walking exercise at an intensity equal to 70% of the peak ISWT speed [63].

2.4. Safety of Exercise Testing

Cardiovascular events during treadmill- or leg cycle ergometer-based exercise testing are rare. In 1971, a study by Rochmis and Blackburn on 170,000 exercise stress tests performed in over 70 medical centers demonstrated an overall mortality rate of one death per 10,000 tests and a serious cardiac complications rate of 4 per 1000 tests [64]. A further study by Gibbon demonstrated a total cardiac complication rate in men and women of 0.8 (0.3–1.9) complications per 10,000 tests; however, the biggest limitation was the fact that most of the study population was without known coronary disease [65]. A recent study by Pavy including 25,000 patients (34% after coronary artery bypass surgery, 18% after valve surgery, 21% after recent percutaneous coronary intervention) revealed a rate of 1 event per 8484 exercise stress tests [66]. Traditional laboratory-based exercise protocols are often replaced in daily clinical practice with the incremental shuttle walking test (ISWT). In a pilot study by Pepera, the safety of the submaximal ISWT, as well as exercise training, was assessed in 33 patients during a community-based cardiac rehabilitation program of at least 10 weeks duration [67]. Termination criteria for ISWT included: the patient feeling too breathless or fatigued to continue at the required speed, failure to complete the test within the allowed time, reaching 85% of the predicted heart rate (calculated as $210 - (0.65 \times \text{age})$), or completing all test levels. As expected, no major event was recorded for either the ISWT or training. The most clinically important event was silent ischemia (27% of ISWT), followed by atrial and ventricular ectopic beats (18% and 15%, respectively). Further studies are required, however, due to the small study population used.

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