Executive Certificate in Cardiopulmonary Exercise Testing for Cardiovascular Health (United Kingdom)

Physiological Basis of Cardiovascular Response to Exercise

stroke volume refers to the quantity of blood ejected from the left ventricle with each cardiac contraction. It is expressed in millilitres and typically ranges from 60 to 100 ml at rest in healthy adults. During dynamic exercise, stroke volume can increase by 30-50 % as a result of enhanced venous return and improved myocardial contractility. The magnitude of this increase is a key determinant of the overall rise in cardiac output.

cardiac output is the product of heart rate (HR) and stroke volume. It represents the total volume of blood the heart pumps per minute and is measured in litres per minute. Resting values are normally 4-6 $L \cdot min^{-1}$, whereas vigorous exercise can elevate cardiac output to 20-30 $L \cdot min^{-1}$ in trained individuals. Understanding the relationship between HR, stroke volume, and cardiac output is fundamental for interpreting cardiovascular response during cardiopulmonary exercise testing (CPET).

heart rate is the number of ventricular depolarisations per minute. It is modulated by autonomic input, circulating catecholamines, and intrinsic pacemaker activity. Exercise induces a progressive rise in heart rate through withdrawal of parasympathetic tone and activation of sympathetic pathways. The maximal achievable heart rate (HRmax) is often estimated by the formula 220 – age, although individual variability can be substantial. Heart rate reserve (HRR) is the difference between HRmax and resting HR, and it forms the basis for many prescription models.

ejection fraction (EF) describes the proportion of end-diastolic volume that is expelled during systole. Normal EF values lie between 55 % and 70 %. During exercise, EF typically rises modestly because of improved contractility and reduced afterload. EF is a useful index of left-ventricular systolic performance, but it can be misleading in the presence of altered loading conditions, therefore it should be interpreted alongside other haemodynamic variables.

preload denotes the ventricular wall stress at the end of diastole, largely determined by venous return and the volume of blood filling the ventricle (end-diastolic volume). The Frank-Starling mechanism explains how an increase in preload stretches myocardial fibres, leading to a more forceful contraction and an elevated stroke volume. Exercise augments preload through muscle pump activity, respiratory pressure changes, and sympathetic venoconstriction, all of which enhance venous return.

afterload is the pressure the ventricle must overcome to eject blood into the arterial system. It is primarily influenced by systemic vascular resistance (SVR) and aortic pressure. During dynamic exercise, SVR falls because of widespread vasodilation in active skeletal muscle, thereby reducing afterload. A lower afterload facilitates an increase in stroke volume and contributes to the rise in cardiac output.

contractility refers to the intrinsic ability of cardiac muscle fibres to develop force independent of loading

conditions. It is enhanced by β-adrenergic stimulation, increased intracellular calcium, and phosphorylation of contractile proteins. In the exercise setting, sympathetic activation raises contractility, which together with reduced afterload supports the elevation of stroke volume.

systemic vascular resistance (SVR) is the opposition to blood flow offered by the systemic circulation. It is calculated as the pressure gradient across the systemic vasculature divided by flow. Exercise induces a marked fall in SVR due to active hyperaemia in exercising muscles, mediated by metabolic vasodilators such as nitric oxide, adenosine, and lactate. A decrease in SVR is essential for accommodating the large increase in flow without excessive rise in arterial pressure.

venous return is the volume of blood flowing back to the right atrium per unit time. It is driven by the pressure gradient between peripheral veins and the right atrium, and it is augmented by the skeletal muscle pump, respiratory pump, and sympathetic venoconstriction. In CPET, a rise in venous return is reflected in an increased end-diastolic volume and consequently a higher stroke volume.

Frank-Starling mechanism describes the relationship between ventricular end-diastolic volume (or pressure) and stroke volume. The curve is steeper at low filling pressures, indicating that small increases in volume produce large increases in output. At higher filling pressures the curve plateaus, signifying limited capacity for further augmentation. Understanding this relationship helps to interpret why some patients with chronic heart failure exhibit blunted stroke volume responses during exercise.

baroreceptor reflex is a rapid negative feedback system that stabilises arterial pressure. Baroreceptors located in the carotid sinus and aortic arch sense stretch and modulate autonomic outflow. During the onset of exercise, the baroreflex resets to a higher operating point, allowing arterial pressure to rise modestly while still permitting the increase in heart rate and cardiac output. An impaired baroreflex can lead to abnormal blood pressure responses and limit exercise tolerance.

autonomic regulation encompasses the balance between sympathetic and parasympathetic influences on the heart and vasculature. Sympathetic activity raises HR, contractility, and vasoconstriction, whereas parasympathetic (vagal) tone slows HR and reduces contractility. The shift toward sympathetic dominance during exercise is reflected in increased plasma catecholamine concentrations and altered heart rate variability patterns.

sympathetic nervous system activation during exercise is responsible for the rapid rise in HR and contractility. Norepinephrine released from sympathetic nerve terminals binds to α- and β-adrenergic receptors on cardiac and vascular smooth muscle. B_1-receptors on the myocardium increase calcium influx, enhancing contractility and HR, while α_1-receptors on arterioles cause vasoconstriction in non-active regions, redistributing flow to exercising muscles.

parasympathetic (vagal) withdrawal is the first step in the HR response to low-intensity exercise. The vagus nerve provides tonic inhibition of the sinoatrial node; its rapid withdrawal permits HR to rise even before significant sympathetic discharge occurs. In CPET, the early phase of HR increase can therefore be used as an indicator of autonomic health.

catecholamines such as epinephrine and norepinephrine increase in plasma during exercise. Their

concentrations rise proportionally to exercise intensity and are responsible for many of the cardiovascular adjustments. Epinephrine, primarily released from the adrenal medulla, exerts potent β-adrenergic effects that raise HR, contractility, and vasodilation in skeletal muscle. Norepinephrine contributes more to α-adrenergic vasoconstriction in non-active beds.

β-adrenergic receptors are G-protein coupled receptors that mediate the positive chronotropic and inotropic effects of catecholamines. B_1-receptors dominate in the heart, while β_2-receptors are abundant in skeletal muscle vasculature, mediating vasodilation. Pharmacological blockade of β-receptors (e.G., With propranolol) blunts the HR and stroke volume response, illustrating their central role in exercise physiology.

α-adrenergic receptors (mainly α_1) mediate vasoconstriction in peripheral vessels. During exercise, α-mediated constriction in splanchnic and renal circulations helps to maintain arterial pressure despite the massive vasodilation occurring in active muscle. The net effect is a redistribution of blood flow without compromising perfusion of vital organs.

oxygen delivery (DO_2) is the product of cardiac output and arterial oxygen content (CaO_2). It quantifies the amount of O_2 transported to tissues per minute. In exercise, DO_2 increases mainly through the rise in cardiac output, while CaO_2 remains relatively stable because haemoglobin saturation stays near 98 % and the small increase in dissolved O_2 is negligible. The capacity to augment DO_2 is a critical factor limiting maximal aerobic performance.

arteriovenous oxygen difference (a-vO_2 diff) reflects the amount of O_2 extracted by the tissues. It is calculated as CaO_2 minus mixed-venous oxygen content (CvO_2). According to the Fick principle, VO_2 = cardiac output × a-vO_2 diff. During intense exercise, a-vO_2 diff widens substantially as muscles increase O_2 extraction, contributing to the rise in VO_2max.

capillary recruitment denotes the opening of previously non-perfused capillaries in skeletal muscle during exercise. This process expands the surface area for diffusion, reduces diffusion distance, and facilitates greater O_2 extraction. Capillary recruitment is driven by shear stress-induced nitric oxide release and metabolic vasodilation. In patients with endothelial dysfunction, recruitment may be impaired, limiting aerobic capacity.

shear stress is the tangential force exerted by flowing blood upon the endothelial surface. It rises with increased flow during exercise and stimulates endothelial nitric oxide synthase (eNOS) activity, leading to vasodilation. Chronic exposure to repetitive shear stress from regular training promotes vascular remodeling and improved endothelial function.

nitric oxide (NO) is a potent vasodilator produced by endothelial cells. In the exercise context, NO mediates the rapid vasodilation of active muscle beds, contributing to the fall in SVR. NO also inhibits platelet aggregation and smooth-muscle proliferation, offering protective cardiovascular effects. Pharmacological inhibition of NO synthesis attenuates exercise-induced hyperaemia, underscoring its physiological importance.

blood pressure is the force exerted by circulating blood upon arterial walls. It comprises systolic pressure (SBP), diastolic pressure (DBP), and pulse pressure (PP). During dynamic exercise, SBP rises modestly

(≈20-30 mmHg) while DBP remains unchanged or falls slightly, leading to an increased PP. This pattern reflects the combined effects of increased cardiac output and peripheral vasodilation.

systolic pressure peaks during ventricular ejection and is directly related to stroke volume and arterial compliance. In trained athletes, a higher SBP response to maximal exercise is often observed, yet it remains within physiological limits. Excessive SBP elevation may indicate abnormal ventricular loading or impaired vasodilatory capacity.

diastolic pressure represents the arterial pressure during cardiac relaxation. It is largely determined by SVR and arterial stiffness. The relative stability of DBP during exercise suggests that the fall in SVR offsets the rise in cardiac output. Persistent DBP elevation during exercise may signal inadequate vasodilation.

pulse pressure is the difference between SBP and DBP. It increases during exercise owing to higher SBP and unchanged DBP. A larger pulse pressure can be used as an indirect marker of arterial compliance. In the CPET report, an exaggerated PP rise may warrant further vascular assessment.

mean arterial pressure (MAP) is the average pressure driving blood through the circulatory system. MAP ≈ DBP + 1/3 PP. During moderate exercise, MAP typically rises modestly, reflecting the balance between increased flow and vasodilation. Maintaining MAP within safe limits is essential for adequate organ perfusion.

heart rate reserve (HRR) is the difference between HRmax and resting HR. It is a cornerstone of exercise prescription, allowing intensity to be expressed as a percentage of HRR (e.G., 60 % HRR). HRR also reflects autonomic flexibility; a reduced HRR may indicate autonomic dysfunction or deconditioning.

chronotropic competence describes the ability of the heart to increase its rate in response to exercise. Chronotropic incompetence, defined as an inadequate HR increase relative to metabolic demand, is a common limitation in heart failure and is associated with poorer prognosis. In CPET, chronotropic competence is assessed by comparing achieved HR to predicted HRmax.

inotropic response refers to the change in myocardial contractile strength during exercise. A robust inotropic response contributes to the rise in stroke volume and cardiac output. Blunted inotropy may result from β-blocker therapy, myocardial scar, or impaired calcium handling.

lusitropic function describes myocardial relaxation. Efficient relaxation ensures rapid ventricular filling, especially at higher HRs where diastolic time is shortened. Exercise imposes a demand for both enhanced contractility and rapid relaxation; abnormalities in lusitropy can limit diastolic filling and thus reduce stroke volume.

diastolic function encompasses ventricular compliance, relaxation rate, and filling pressures. In CPET, a fall in early diastolic filling velocities or an increase in left-atrial pressure during exercise may reveal diastolic dysfunction. Such dysfunction often manifests as reduced exercise capacity despite preserved ejection fraction.

coronary blood flow increases several-fold during exercise to meet rising myocardial O_2 demand. The main drivers are metabolic vasodilation, increased perfusion pressure, and reduced extravascular compression

due to shorter diastole. In the presence of coronary artery disease, the capacity to augment flow is limited, leading to ischaemia and early termination of exercise.

coronary vascular resistance falls during exercise because of metabolic vasodilation. The resistance-pressure relationship shifts to a lower resistance for a given pressure, allowing higher flow without large pressure spikes. Persistent high resistance during stress may indicate endothelial dysfunction or fixed stenosis.

myocardial oxygen consumption (MVO_2) rises proportionally to heart rate, contractility, and wall stress. The relationship can be expressed as $MVO_2 \approx HR \times SBP \times$ a constant. During intense exercise, MVO_2 can increase five- to ten-fold. An inadequate increase in coronary flow relative to MVO_2 precipitates myocardial ischaemia.

lactate threshold (LT) is the exercise intensity at which lactate begins to accumulate in the blood faster than it can be cleared. It typically occurs at 50-60 % of VO_2max in untrained individuals and shifts to higher intensities with training. LT is a valuable marker of aerobic endurance and can be identified on the VO_2-work rate curve during CPET.

anaerobic metabolism predominates when oxygen delivery cannot meet cellular demand. It leads to lactate production, hydrogen ion accumulation, and metabolic acidosis. The resulting increase in ventilation (the ventilatory threshold) is a hallmark of the transition from aerobic to anaerobic energy provision.

metabolic acidosis arises from the excess H^+ generated during anaerobic glycolysis. It stimulates chemoreceptors that increase respiratory drive, contributing to the rise in ventilation seen at the ventilatory threshold. Persistent acidosis impairs muscle contractility and contributes to fatigue.

ventilatory equivalents (VE/VO_2 and VE/VCO_2) describe the ratio of minute ventilation to oxygen uptake or carbon dioxide output. They provide insight into ventilatory efficiency. An abnormally high VE/VCO_2 slope during CPET is associated with poor prognosis in heart failure and reflects ventilation-perfusion mismatch.

heart rate recovery (HRR) is the rate at which HR declines after cessation of exercise, usually measured at 1 minute post-exercise. A rapid decline (≥12 bpm) indicates good parasympathetic re-activation; a slowed HRR is linked to higher mortality and may reflect autonomic impairment.

training adaptations encompass central and peripheral changes that improve cardiovascular performance. Central adaptations include increased maximal cardiac output (mainly via higher stroke volume) and enhanced autonomic regulation. Peripheral adaptations involve improved capillary density, mitochondrial content, and oxidative enzyme activity.

cardiac remodeling refers to structural changes in the heart in response to chronic haemodynamic stress. Endurance training induces eccentric hypertrophy, characterised by increased chamber size with modest wall thickening, preserving relative wall stress. In contrast, pressure overload (e.G., Hypertension) leads to concentric hypertrophy, with wall thickening and reduced chamber volume.

angiogenesis is the formation of new capillaries from pre-existing vessels. Exercise stimulates angiogenesis through shear-stress-induced up-regulation of vascular endothelial growth factor (VEGF). Enhanced capillary networks improve O_2 diffusion capacity and contribute to a larger a-vO_2 diff during high-intensity

work.

mitochondrial biogenesis is the process of generating new mitochondria within muscle fibres. It is driven by activation of peroxisome proliferator-activated receptor-γ coactivator-1α (PGC-1α) in response to repeated bouts of aerobic exercise. More mitochondria increase oxidative capacity, delay lactate accumulation, and raise VO_2max.

VO_2max is the maximal rate of oxygen consumption achievable during incremental exercise. It is expressed in $mL \cdot kg^{-1} \cdot min^{-1}$ and reflects the integrated function of the pulmonary, cardiovascular, and muscular systems. VO_2max is considered the gold-standard indicator of aerobic fitness and is a strong predictor of morbidity and mortality.

maximal aerobic power is synonymous with VO_2max, but the term is sometimes used to emphasise the power output (watts) achieved at VO_2max during a cycle ergometer test. The relationship between power output and VO_2 is linear up to the ventilatory threshold, after which efficiency declines.

submaximal exercise refers to work rates below the anaerobic threshold, where the body can meet energy demands predominantly via aerobic metabolism. Submaximal parameters such as the ventilatory threshold, oxygen pulse, and HRR provide valuable prognostic information without requiring maximal effort.

oxygen pulse (O_2 pulse) equals VO_2 divided by HR and approximates the amount of O_2 extracted per heartbeat. It is often used as a surrogate for stroke volume when direct echocardiographic measurements are unavailable. A rising O_2 pulse during incremental exercise indicates effective augmentation of stroke volume.

ventilatory threshold (VT) is the point during incremental exercise where ventilation increases disproportionately to VO_2. It typically coincides with the lactate threshold and reflects the onset of metabolic acidosis. VT can be identified by the V-slope method, ventilatory equivalents, or the inflection point in the VE-VO_2 relationship.

respiratory exchange ratio (RER) is the ratio of VCO_2 to VO_2. At rest, RER is about 0.8; During intense exercise it approaches or exceeds 1.0, Indicating reliance on carbohydrate oxidation and the contribution of buffering CO_2 from lactate. An RER ≥ 1.10 Is often used as a criterion for maximal effort in CPET.

ventilatory efficiency is assessed by the VE/VCO_2 slope. A normal slope is ≈30; values >34 are associated with heart failure, pulmonary hypertension, or impaired peripheral perfusion. Monitoring ventilatory efficiency assists in differentiating cardiac from pulmonary limitations.

cardiovascular reserve denotes the capacity of the heart and vasculature to increase output above resting levels. It is quantified by the difference between maximal and resting cardiac output, or by the ratio of maximal to resting HR. Reduced reserve is a hallmark of deconditioning, ageing, or cardiac disease.

exercise intolerance is the inability to sustain a given workload due to premature fatigue, dyspnoea, or haemodynamic compromise. It can be caused by central limitations (e.G., Reduced cardiac output), peripheral limitations (e.G., Impaired muscle oxidative capacity), or a combination of both. CPET helps to pinpoint the dominant mechanism.

chronotropic incompetence (CI) is defined as failure to achieve ≥80 % of age-predicted HRmax during maximal exercise, after accounting for β-blocker dose. CI is an independent predictor of mortality and may be ameliorated by pacing strategies in selected patients.

stroke volume plateau occurs when further increases in preload or contractility no longer raise stroke volume. In most healthy adults, stroke volume plateaus at ≈40-50 % of VO_2max; beyond this point, cardiac output rises mainly via HR. In heart failure, the plateau may be reached at lower intensities, limiting peak output.

right-ventricular function is crucial during exercise because the right ventricle must accommodate increased venous return and maintain pulmonary perfusion. Pulmonary artery pressure rises modestly with exercise; excessive pressure elevation can unmask pulmonary hypertension. Right-ventricular strain measured by echocardiography during CPET provides prognostic insight.

left-ventricular afterload is modulated by arterial pressure and aortic impedance. Acute exercise reduces effective afterload through vasodilation, whereas chronic hypertension increases resting afterload, potentially blunting stroke volume augmentation.

vascular compliance describes the ability of arteries to expand under pressure. Endurance training improves arterial compliance, lowering pulse wave velocity and reducing systolic load on the heart. Decreased compliance with ageing contributes to higher SBP during exercise.

sympathetic over-activity is a common feature in heart failure and hypertension. It leads to chronically elevated HR and peripheral vasoconstriction, reducing exercise capacity. B-blocker therapy attenuates this over-activity, but may also limit maximal HR and VO_2max, necessitating careful dose titration.

oxygen transport cascade encompasses ventilation, diffusion, circulation, and cellular utilization. Each step can become a bottleneck during exercise. CPET integrates measurements that allow clinicians to locate the limiting step—e.G., Low VO_2max with normal HR response suggests peripheral limitation; abnormal HR response suggests central limitation.

pulmonary diffusion capacity (DLCO) measures the lung's ability to transfer O_2 from alveoli to blood. While DLCO is not directly measured during CPET, a reduced diffusion capacity can manifest as lower VO_2max and early dyspnoea, especially in interstitial lung disease.

ventilation-perfusion mismatch occurs when portions of the lung receive ventilation without adequate perfusion, or vice versa. Exercise exacerbates mismatched regions, increasing VE/VCO_2 slope. In heart failure, congestion leads to interstitial oedema, impairing gas exchange and raising ventilatory demand.

cardiac index is cardiac output normalized to body surface area ($L \cdot min^{-1} \cdot m^{-2}$). It allows comparison between individuals of different sizes. Normal resting cardiac index is ≈2.5-4.0. During maximal exercise, values may exceed 10 $L \cdot min^{-1} \cdot m^{-2}$ in elite athletes.

stroke volume index (SVI) is stroke volume adjusted for body surface area. It provides a size-independent measure of ventricular performance. A low SVI at rest or during exercise may indicate impaired preload, afterload, or contractility.

chronotropic index is calculated as (HRmax – HRrest) / (HRpredicted – HRrest). Values O_2 uptake kinetics describe how quickly VO_2 rises at the onset of exercise. The primary phase (phase I) reflects pulmonary blood flow redistribution; phase II reflects muscle O_2 extraction. Slow kinetics are associated with reduced aerobic efficiency and may predict early fatigue.

excess post-exercise oxygen consumption (EPOC) is the elevated VO_2 that persists after exercise cessation. It reflects the cost of restoring homeostasis, replenishing phosphocreatine stores, and lactate clearance. A larger EPOC indicates a higher metabolic cost of the preceding work and can be used to estimate training load.

ventilatory reserve is the difference between maximal voluntary ventilation (MVV) and the ventilation achieved at peak exercise. A ventilatory reserve cardiac stress testing using CPET provides an integrated assessment of the cardiopulmonary system. It differs from traditional treadmill tests by measuring gas exchange, allowing precise determination of VO_2max, ventilatory thresholds, and ventilatory efficiency. The added data improve risk stratification and guide therapeutic decisions.

exercise prescription can be tailored using CPET-derived parameters. For example, training intensity may be set at 60-70 % of VO_2max, or at 90-95 % of the ventilatory threshold, ensuring that the stimulus is sufficient to provoke adaptation without excessive strain. Prescription based on HRR or oxygen pulse is also common.

clinical challenges in interpreting cardiovascular response to exercise include medication effects (β-blockers, calcium channel blockers), comorbidities (diabetes, chronic obstructive pulmonary disease), and technical limitations (inaccurate flow measurement, motion artefact). It is essential to contextualise CPET findings within the broader clinical picture.

measurement error can arise from calibration drift of metabolic carts, improper mask fit, or inaccurate ECG leads. Regular quality control procedures, such as gas analyser calibration with known reference gases and verification of flow sensor accuracy, minimise these errors.

inter-individual variability in HRmax, stroke volume reserve, and VO_2max is substantial. Genetic factors, training status, sex, and age all influence the cardiovascular response to exercise. Consequently, normative data must be applied cautiously, and individualized interpretation is preferred.

age-related decline in cardiovascular performance is characterised by reduced maximal HR, diminished β-adrenergic responsiveness, increased arterial stiffness, and lower maximal stroke volume. CPET can quantify the extent of decline and help to differentiate pathological from physiological ageing.

sex differences include generally higher resting heart rates in women, lower absolute VO_2max values due to smaller heart size and lower haemoglobin mass, yet similar relative improvements with training. Understanding these differences avoids misclassification of fitness levels.

impact of obesity on exercise physiology includes higher resting cardiac output (to perfuse larger body mass), reduced stroke volume reserve, and earlier onset of ventilatory limitation. CPET can reveal whether reduced performance is driven by cardiac, pulmonary, or muscular factors.

role of nutrition in cardiovascular response to exercise is highlighted by the influence of carbohydrate

availability on VO_2 kinetics and lactate production. Pre-exercise feeding strategies can modify substrate utilisation and affect measured thresholds.

environmental considerations such as temperature, humidity, and altitude affect cardiovascular response. Heat stress increases skin blood flow, reducing central blood volume and potentially limiting stroke volume. Altitude reduces arterial oxygen content, prompting higher cardiac output to maintain DO_2.

psychological factors like motivation, anxiety, and perceived exertion influence effort during CPET. The Borg scale is commonly used to gauge perceived exertion, and discrepancies between physiological markers and perceived effort may signal underlying disease or deconditioning.

training monitoring can utilise serial CPET to track changes in VO_2max, ventilatory thresholds, and O_2 pulse. Improvements in these parameters reflect successful adaptation, whereas stagnation may indicate insufficient training load or overtraining.

overtraining syndrome manifests as reduced performance despite continued training, often accompanied by autonomic imbalance (elevated resting HR, blunted HRR) and altered hormonal responses. CPET can detect early signs of overtraining through attenuated VO_2max or delayed O_2 kinetics.

rehabilitation applications of CPET include cardiac rehabilitation, pulmonary rehabilitation, and pre-operative risk assessment. By establishing safe intensity zones and monitoring progress, CPET enhances the efficacy and safety of rehabilitation programmes.

pharmacological testing during CPET (e.G., With submaximal β-blockade or vasodilators) can unmask latent cardiac dysfunction. For instance, a blunted HR response to isoproterenol may reveal impaired β-adrenergic signalling.

non-invasive cardiac output monitoring technologies such as inert gas rebreathing, impedance cardiography, and Doppler ultrasound can be coupled with CPET to provide continuous cardiac output data. Each method has specific limitations regarding accuracy, invasiveness, and feasibility.

interpretation algorithm for CPET typically follows a stepwise approach: (1) Evaluate effort adequacy (RER ≥ 1.10, HR ≥ 90 % HRmax); (2) assess VO_2max and compare with predicted values; (3) locate ventilatory thresholds; (4) examine O_2 pulse and HR response; (5) calculate VE/VCO_2 slope; (6) integrate clinical context. This systematic process ensures comprehensive assessment.

case example 1 – a 55-year-old male with chronic heart failure (LVEF = 35 %). CPET shows VO_2max = 14 $mL \cdot kg^{-1} \cdot min^{-1}$ (≈45 % predicted), a flat O_2 pulse curve, and a VE/VCO_2 slope of 38. HR reaches only 110 bpm (≈80 % predicted HRmax). These findings indicate chronotropic incompetence, impaired stroke volume augmentation, and ventilatory inefficiency, all consistent with advanced cardiac limitation. Exercise prescription would begin at 40-50 % VO_2max, focusing on gradual improvements in HR reserve and peripheral conditioning.

case example 2 – a 45-year-old female with unexplained dyspnoea. CPET reveals VO_2max = 32 $mL \cdot kg^{-1} \cdot min^{-1}$ (≈110 % predicted), normal HR response, but a ventilatory reserve of only 12 %. This pattern suggests a primary pulmonary limitation, possibly undiagnosed interstitial lung disease. Further pulmonary function

testing and high-resolution CT would be indicated.

case example 3 – a 60-year-old obese man undergoing pre-operative assessment for bariatric surgery. CPET shows VO_2max = 18 mL·kg^{-1}·min^{-1} (≈70 % predicted), a normal VE/VCO_2 slope, but an early rise in HR (HR = 130 bpm at 3 METs). The cardiovascular system appears capable, but the high HR at low workloads reflects limited stroke volume reserve due to obesity-related cardiac remodeling. A pre-habilitation programme focusing on weight loss and aerobic conditioning would be recommended.

practical tip – when measuring O_2 pulse, plot VO_2 against HR and calculate the slope; a linear increase suggests intact stroke volume augmentation, whereas a plateau or decline may signal cardiac limitation. This visual approach aids rapid bedside interpretation.

challenge – distinguishing between central and peripheral limitations in patients on β-blockers. Since HR response is blunted, reliance on O_2 pulse and VO_2 kinetics becomes essential. In such cases, a submaximal test may be more informative, and the use of incremental work rates rather than speed increments can reduce confounding.

future directions – emerging technologies such as wearable inertial sensors and machine-learning algorithms promise to refine the analysis of cardiovascular response to exercise. Continuous monitoring of HR variability, combined with CPET data, could enhance early detection of autonomic dysfunction.

summary of key terms:

• stroke volume – blood ejected per beat. • cardiac output – HR × stroke volume. • heart rate – beats per minute, autonomically regulated. • ejection fraction – % of end-diastolic volume expelled. • preload – ventricular filling pressure/volume. • afterload – resistance to ejection. • contractility – intrinsic myocardial force generation. • systemic vascular resistance – opposition to systemic flow. • venous return – flow back to the heart. • Frank-Starling mechanism – relation of preload to stroke volume. • baroreceptor reflex – pressure-sensing feedback. • autonomic regulation – sympathetic-parasympathetic balance. • catecholamines – epinephrine, norepinephrine, hormonal drivers. • β-adrenergic receptors – mediate positive cardiac effects. • α-adrenergic receptors – mediate peripheral vasoconstriction. • oxygen delivery – cardiac output × arterial O_2 content. • arteriovenous O_2 difference – tissue extraction. • capillary recruitment – opening of dormant capillaries. • shear stress – flow-induced endothelial stimulus. • nitric oxide – endothelial vasodilator. • blood pressure, systolic, diastolic, pulse pressure, mean arterial pressure – pressure components. • heart rate reserve, chronotropic competence, inotropic response, lusitropic function – functional indices. • coronary blood flow, coronary vascular resistance, myocardial O_2 consumption – cardiac perfusion dynamics. • lactate threshold, anaerobic metabolism, metabolic acidosis – metabolic limits.