Cardiopulmonary exercise test in clinical practice, evaluation of myocardial ischemia
Andreea Varga1,2, Ioan Tilea1,2, Pietro Palermo3

Abstract: In patients presenting cardiovascular, pulmonary, muscular and metabolic diseases, exercise testing continues to be a predictive and diagnosis source of information. Diagnosis and assessment of coronary artery disease (known or suspected) encompass clinical and risk factors evaluation and well-defined non-invasive and invasive tests. Cardiopulmonary exercise test (CPET) is an evidence-based evaluation technique in Europe, USA and other countries. It consists in applying, directly supervised by a physician, a standardized incremental physiological stress (using cycle ergometer or treadmill) until the patient reaches the anaerobic threshold. CPET can assess the presence of myocardial ischemia, by three parameters: oxygen pulse, maximum oxygen uptake curve and elevation and relationship between maximum oxygen uptake variation and load variation. Furthermore, the CPET is useful in assessing the prognosis of cardiac patients, in choosing the most effective treatment, and in evaluating the response to treatment post-acute coronary syndrome, post-primary percutaneous coronary intervention or assessment of unexplained dyspnoea or myocardial ischemia in heart failure patients. CPET has a higher sensitivity, specificity, positive predictive value and negative predictive value as compared to standard ECG stress testing in patients with suspected myocardial ischemia. In this paper a brief review of current indications, analysis of standardized nine panel plot interpretation of CPET parameters related to myocardial ischemia are depicted.

Keywords: cardiopulmonary exercise test, indications, oxygen consumption, anaerobic threshold, myocardial ischemia.

Rezumat: La pacienții care prezintă afecțiuni cardiovasculare, pulmonare și metabolice, testarea fiziologică la efort continuă să fie o sursă de informație predictivă și diagnostică. Evaluarea factorilor de risc, clinic precum și utilizarea adecvată a metodelor neinvasive și invasive sunt fundamentale în diagnosticul și evaluarea bolii cardiace ischemice (cunoscute sau suspectate).

Testul de efort cardiopulmonar (CPET) reprezintă o metodă bine-definită de evaluare neinvariantă utilizată în Europa, SUA și alte țări. Ea constă în aplicarea, direct supravegheată de către medic, a unui stres fiziologic progresiv standardizat (folosind un cicloergometru sau covor rulant) până când pacientul atinge pragul anaerob. CPET poate evalua prezența ischemiei miocardice, prin trei parametri: pulsul de oxigen, aspectul curbei maxime de absorbție a oxigenului și relația dintre variația maximă a absorbției de oxigen și modificarea încârcăturii la efort. Suplimentar, CPET este util în evaluarea prognosticului pacienților cardiovasculari, în alegerea celei mai eficiente scheme de tratament și în evaluarea răspunsului la tratamentul post sindrom coronarian acut, post intervenție coronariană percutană primară sau în diagnosticul dispneei inexplicabile, a ischemiei miocardice la pacienți cu insuficiență cardiacă. CPET are o sensibilitate, specificitate, valoare predictivă pozitivă și valoare predictivă negativă mai ridicată comparativ cu testul standard de efort ECG la pacienții cu ischemie miocardică suspectată.

În acest articol sunt trecute în revistă indicațiilor actuale, analiza interpretării standardizate ale noii panouri a parametrilor testului de efort cardiopulmonar corelați cu ischemie miocardică.

Cuvinte cheie: test de efort cardiopulmonar, indicații, consum de oxigen, prag anaerob, ischemie miocardică.

1 „George Emil Palade” University of Medicine, Pharmacy, Science and Technology, Targu Mures, Romania.
2 Department of Cardiology, IInd Clinic of Internal Medicine, Emergency Clinical County Hospital, Targu Mures, Romania
3 Centro Cardiologico Monzino, Istituto di Ricovero e Cura a Carattere Scientifico (IRCCS), Milan, Italy

Contact address:
Ioan Tilea, MD, PhD, MSc
Department M3 of Clinical Sciences-Internal Medicine, Discipline of Family Medicine, „George Emil Palade” University of Medicine, Pharmacy, Science and Technology, 38 Ghe. Marinescu Street, Postal code 540139, Targu Mures, Romania.
E-mail: ioan.tilea@umfst.ro
Pietro Palermo, MD
Centro Cardiologico Monzino, IRCCS, Via Parea, 4, 20138 Milan, Italy.
E-mail: pietro.palermo@ccfm.it
Cardiopulmonary exercise testing (abbreviated CPET or CPX) is a non-invasive diagnostic technique used to evaluate the physiologic response of the cardiovascular, pulmonary and muscle-energetic systems to an increase in physical stress, especially in cardiovascular and pulmonary disease suspected or diagnosed patients. It is a distinct exercise testing that provides accurate and objective quantification of cardiorespiratory fitness (peak VO₂).

CPETs are used, and should be used more and more, with cardiac patients. Indeed, the CPET evaluates the functional capacity and helps to identify the cardiac, pulmonary or peripheral origin of a possible reduced functional capacity.

Furthermore, the CPET is useful in assessing the prognosis of cardiac patients, in choosing the most effective treatment, and in evaluating the response to treatment. The term “cardiac disease” comprises several disorders that show typical and different pattern of gas kinetic during exercise. For this reason, it is im-

**INTRODUCTION**

In patients presenting cardiovascular (CV), pulmonary or association of both diseases, exercise testing continues to be a predictive and diagnosis source of information. Diagnosis and assessment of coronary artery disease (known or suspected) encompass clinical and risk factors evaluation and well-defined non-invasive and invasive tests.

Currently, non-invasive tests commonly used to diagnose the presence of coronary artery disease (CAD) can vary in sensitivity (45-97%) and specificity (61-95%), accordingly to different authors. Recommendations for using non-invasive tools need to take into account the pre-test probability (PTP). In patients with stable angina symptoms and PTP at 15% to 65% intervals, an exercise ECG test could be used as an initial evaluation test. Electrocardiogram exercise testing has inherent limits described elsewhere, wide variability in reported sensitivity (45-50%) and specificity (85-90%), respectively.

List of abbreviations used in text

AT  Anaerobic threshold
CAD  Coronary artery disease
CPET (or CPX)  Cardiopulmonary exercise test
CTEPH  Chronic thromboembolic pulmonary hypertension
CV  Cardiovascular
FEV1  Forced expiratory volume measured during the first second of the forced breath
HF  Heart failure
HR  Heart rate
HR/VO₂  Heart rate – Oxygen uptake relationship
IC  Inspiratory capacity
MVV= FEV1x40  Maximal voluntary ventilation: volume of air expired in a specified period during repetitive maximal effort
PAH  Pulmonary arterial hypertension
Peak VO₂  Oxygen utilisation (mLO₂ x kg⁻¹ x min⁻¹)
PETCO₂  End-tidal partial pressure of CO₂ (mmHg)
PETO₂  End-tidal partial pressures of O₂ (mmHg)
PVOD  Pulmonary Veno-Occlusive Disease
PTP  Pretest probability
RC  Respiratory compensation
RER  Respiratory exchange ratio (respiratory quotient), RER=VCO₂/VO₂
SPTD  Standard conditions: temperature 0 degrees Celsius, pressure 760 mmHg and dry
VC  Vital capacity
VCO₂  Carbon dioxide production/min corrected for STPD conditions
VD/VT  Dead Space to Tidal Volume ratio
VE  Ventilation
VE/VCO₂  Minute ventilation/carbon dioxide production
VO₂  Oxygen consumption/min corrected for STPD conditions
VO₂/HR  Oxygen pulse
VO₂max  Maximal O₂ uptake
VT  Tidal volume (mLO₂ x kg⁻¹ x min⁻¹)
WR  Work rate
ΔVO₂/ΔWR  Oxygen delivery (uptake)
important to know the specific typical behaviour of each cardiac disease before analysing the tests.

Using treadmill or electromagnetically braked cycle ergometer (preferred in most European countries), the progressive incremental workload exercise test (ramp) is frequently used for patients clinical evaluation; it is the most appropriate to obtain data about cardiac and pulmonary function, the functional capacity, the prognosis, and the response to therapy.

In the last two decades, applications of CPET are increasing, being used in diagnostic, appraising therapeutic regimens and prognostic recommendations in heart failure (HF) patients, valvular diseases, hypertrophic cardiomyopathy, pulmonary interstitial and vascular diseases. The use of CPET affords combined data illustrating exercise physiology in addition to non-invasive measurements (especially echocardiographic) of cardiac anatomy and function. Table 1 outline the current indications of CPET.

The combined analysis of several parameters, which are obtained by incremental workload protocols, provides the most accurate information.

Data provided by the CPET relevant to gas exchange measurements (ventilation versus CO₂ output VE/VCO₂ peak, analysis of O₂ pulse and ∆VO₂/∆WR slope) can lead to identifying exercise-induced myocardial ischaemia, especially when conduction of rhythm disturbances are present at rest.

In a recently published study, Belardinelli et al. present that in patients with chest pain, CPET indicates a better diagnostic and predictive accuracy than standard exercise test in detection or rule-out obstructive CAD.

Current guidelines for the management of stable CAD do not include CPET in the diagnostic algorithm of myocardial ischemia.

A supervised CPET is recommended to prescribe an adapted physical activity and cardiac rehabilitation programme post-acute coronary syndrome, post-primary percutaneous coronary intervention or assessment of unexplained dyspnoea or myocardial ischemia in HF patients.

Nevertheless, in patients with diabetes mellitus usefulness of CPET complementary to standard exercise testing needs further evidence, in order to assess functional capacity and exercise-induced ischemia, especially when resting electrocardiogram is normal and interpretable. Presence of anginal symptoms secon-

Table 1. Adapted current indications for CPET

<table>
<thead>
<tr>
<th>1. Evaluation of exercise tolerance</th>
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<tr>
<td>Determination of functional impairment or capacity (peak VO₂)</td>
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<td>Evaluation of exercise limitation and improvements in exercise tolerance after heart surgery in patients with congenital heart disease</td>
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<td>Exercise prescription and monitoring response to exercise training for cardiac rehabilitation</td>
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<th>4. Evaluation of patients with respiratory disease</th>
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<tr>
<td>Functional impairment assessment</td>
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<tr>
<td>• Functional and prognostic evaluation of patients with chronic obstructive pulmonary disease</td>
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<td>• Functional and prognostic evaluation of patients with interstitial lung diseases, including documentation of therapeutic response to potentially toxic therapeutic regimens</td>
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<td>• Functional and prognostic evaluation of patients with pulmonary vascular disease (PAH, PVOD, pulmonary capillary haemangiomatosis, CTEPH, and other)</td>
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<td>• Functional and prognostic evaluation of patients with cystic fibrosis</td>
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<td>• Detection of exercise-induced bronchoconstriction</td>
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<th>5. Specific clinical applications</th>
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<td>Preoperative evaluation</td>
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<td>• Lung cancer resection surgery</td>
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<td>• Lung volume reduction surgery (i.e. for emphysema patients)</td>
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<td>• Elderly patients undergoing major abdominal surgery (assessing cardiovascular reserve and calculating CV risk)</td>
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<tr>
<td>• Evaluation for lung or heart–lung transplantation</td>
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Exercise evaluation and a prescription for pulmonary rehabilitation |
Evaluation for impairment–disability
dary to abnormalities of coronary artery tract where the presence of ischemia (ST-segment changes) can be assessed using CPET.

**CARDIOPULMONARY EXERCISE NINE-PANEL PLOT**

Using CPET to evaluate the gas exchange between the body cells and atmosphere through the interconnected cardiovascular and respiratory systems, can delineate the pathophysiology of performance restraint. The nine-panel graphical array describes the cardiovascular, ventilatory, ventilation-perfusion matching and metabolic responses to exercise. Starting from 1997, specific recommendations of graphical CPET panels, panels display and axes, were published. In 2017, Dumitrescu and Rosenkranz presented an update on the graphical data display for clinical CPET.

**Panel 1 – VO2 and VCO2 gas kinetics**

Panel 1 is the first panel to be observed in the identification of possible exercise limitation. The VO2 and VCO2 gas kinetics analysis could enlighten a possible cardiovascular or respiratory limitation. In healthy subjects performing a 10 minutes CPET, there is a linear increment of workload to O2 consumption (VO2). Continuously to workout, VO2 increases at a standard rate of 10ml/min/W. Within the panel, the parameters and their position, slope, and linearity correspondence should be analysed: VO2, VCO2 versus time and work rate.

**Panel 2 – Heart rate and oxygen pulse**

The oxygen pulse (VO2/HR) defines the ratio of oxygen consumption to heart rate, inference of the VO2 normalized for the heart rate (HR). The oxygen pulse is a defined cardiac performance index, particularly of the systolic output. In healthy subjects, the oxygen pulse increases as the workload increases and it reaches a plateau associated with a linear increase in HR. This pattern is a proper demonstration of a well-adjusted and adequate rise of the systolic output, correspondent to the HR and therefore, the cardiac output in response to exercise. A limitation of the systolic output is manifest in anaemia, hypoxemia or in the presence of muscle impairment.

**Panel 3 – Respiratory equivalent. VO2 and VCO2 relationship (V-slope). The first method of anaerobic threshold (AT) estimation**

Heart rate and VCO2 calculated over VO2 in panel 3, graphically presents the heart frequency tendency end the relation of VO2 and VCO2. Plotting the VO2 and the VCO2 with axes using the same scale, allows calculating the anaerobic threshold (AT). Up to the AT, the VCO2 rises linearly to VO2. Subsequently to the AT, the VCO2 increases more rapidly and the slope of the curve depends on the degree of lactic acidosis buffering. The point of inflexion or the change of slope identifies the AT. The AT is reached anticipative in patients with altered cardiac function or muscle de-conditioning.

**Panel 4 – Ventilatory equivalent for O2 and CO2 (VE/VO2 and VE/VCO2). The second method of AT estimation**

This panel graphically presents the tendency of ventilatory equivalents, the ratio of VE to VO2 and VE to VCO2 versus time and work rate. The analysis of ventilatory equivalents provides information to the clinician on the presence of dead space/current volume ratio (VD/VT) alterations, concomitant to the ventilation/perfusion ratio (V/Q) alterations. Furthermore, analysing the ventilatory equivalents, the AT point can be identified. VE/VO2 slope outline an initial reduction followed by parallel direction to the work axis up to the AT. Therefore, it starts to increase related to ventilation increase, as a consequence of the CO2 necessary to the lactic acidosis tamponade. During the isocapnic tamponade period, on the other hand, the VE/VCO2 slope remains constant up to the respiratory compensation (RC) point. Beyond the point of RC also VE/VCO2 increases, and this is due to the particular acidosis stimulus no longer compensated on the ventilatory drive.

**Panel 5 – Ventilation**

This panel presents the course of ventilation (L/min) during an increasing workload; an increase in ventilation (change of slope of the curve) at the moment of workload above the anaerobic threshold (AT), is evident. The increase in the ventilatory drive is secondary to the increase in CO2, as a result of the lactic acidosis buffering and the increase in cellular metabolism. A second and further increase in ventilation is noticeable, which determines a second change in the curve slope, and a point of respiratory compensation is defined. At this moment the buffer systems are no longer able to compensate the pH, so that acidosis appears, being a strong stimulation for hyperventilation. The phase of isocapnic tamponade defines the start phase of the anaerobic threshold up to the point of respiratory compensation. The next phase at the respiratory compensation point is named uncompensated acidosis or respiratory compensation phase.
Panel 6 – Ventilatory efficacy
The VE/VCO₂ report provides indications on the organism’s efficiency in eliminating the CO₂ produced during the metabolic processes. The slope of the curve defines the entity of ventilation increase, necessary to eliminate a given carbon dioxide production. A high slope value is associated with inefficient ventilation. There is no linearity of VE and VCO₂ above the respiratory compensation point. VE/VCO₂ relationship is validated as a powerful prognostic parameter for cardiac and pulmonary disease. The y-axis intercept derived from the chart is related to the dead space ventilation.

Panel 7 – End-tidal partial pressures of O₂ (PETO₂, mmHg) and end-tidal partial pressure of CO₂ (PETCO₂, mmHg). The third method of AT estimation
The possible presence of ventilation/perfusion mismatch by decreased PETCO₂ value is recognized in the ventilation/perfusion mismatch, and in case of hyperventilation. A concomitant increase of respiratory exchange ratio (panel 8) confirms and identify a situation of hyperventilation.

Figure 1. Presents CV, ventilatory, ventilation-perfusion matching and metabolic responses to exercise, displayed in standard nine-panel plot in a 51-year-old athlete.
**Panel 8 – Respiratory exchange ratio (respiratory quotient) (RER, R); RER=VCO₂/VO₂**

The metabolic pathway of chemical energy production involves the use of oxygen for energy substrates oxidation (mainly carbohydrates and lipids) and CO₂ produced by oxidative reactions. In the ATP production when fatty acids are used, O₂ molecules are needed to oxidize a fatty acid molecule and 16 molecules of CO₂ are produced (RER=16/23=0.7). The carbohydrates oxidation involves the utilization of six O₂ molecules and six molecules of CO₂ are produced (RER=6/6=1). During CPET on the y-axis, RER begins at 0.8 and the rise above 1.0 validates a maximal exercise test²¹,²⁴.

**Panel 9 – Tidal volume, ventilation and respiratory frequency**

The behaviour of ventilation is represented by the relation of tidal volume (VT) and ventilation (VE). The patient’s vital capacity (VC) and inspiratory capacity (IC) is pictured in a parallel line to the x-axis, and the maximum voluntary ventilation (MVV=FEV₁x40) on a parallel line to the y-axis. The origin isogram determines the ventilatory frequency. Breathing reserve is computed as MVV-VE using panel nine parameters²⁴.

Figure 1. The 9 panel plot data display and interpretation. Cardiopulmonary exercise test of a 51-year old athlete. Ramp test with an increment of 20 W/Min. Nine-panel plot display of the results, with 10-second averaging. Panels marked in red (1,2,3): „Circulatory axis“, indicating that these panels show parameters important for the evaluation of circulatory function and circulatory reserve. Panels marked in green (1,5,9): „Ventilatory axis“, indicating that these panels show parameters important for the evaluation of ventilatory function and ventilatory reserve. Panels marked in blue (1,4,6,7): „Ventilatory efficiency axis“, indicating that these panels show parameters important for the evaluation of ventilatory efficiency and the relationship of ventilation to perfusion during exercise. Panels marked in grey (8): „General metabolic changes“ (RER).

(Courtesy of Dr. med Daniel Dumitrescu, Klinik für Allgemeine und Interventionelle Kardiologie/Herz-und Diabeteszentrum Nordrhein-Westfalen, Germany)

**FUNCTIONAL CAPACITY LIMITATION**

Different cardiac, ventilatory, pulmonary or peripheral vessel abnormalities can induce exercise limitations. CPET focuses on a number of questions related to physiology and pathophysiology workout, though identification of the unique cause of limitation is complex.

By equating the CPET derived parameters, panel analyse, it becomes feasible to identify disorders underlying abnormalities²⁴,²⁵ (Table 2).

**CPET TO ASSESS MYOCARDIAL ISCHEMIA**

Systematize clinical exercise test interpretation relies on key CPET variables for diagnostic and prognostic utility in patients with ischemic heart disease. The use of CPET to detected cardiovascular dysfunction induced by mild ischemia was not conclusive in previous studies; still, changes in specific parameters were identified as a response at incremental workload in extended myocardial ischemia.²⁶ Several case reports and research papers revealed the same exercise-induced left ventricular dysfunction detected by CPET, in both microvascular and macrovascular coronary artery disease (CAD)²⁷,²⁸. In particular cases, if the ECG is not accurate for myocardial ischemia (i.e. intraventricular blocks, pacemakers) gas exchange analysis can provide valuable information on O₂ consumption and O₂ supply imbalance in mitochondria²⁷.

Concomitant use of complementary functional methods with current cardiac imaging studies demonstrated a blunt value in the diagnosis of myocardial dysfunction, secondary to non-obstructive coronary artery disease in symptomatic patients. CPET can

**Table 2**

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<tr>
<th>Reduced peak VO₂ (all limitations)</th>
<th>Ventilatory limitation</th>
<th>Ventilation-perfusion mismatching</th>
<th>Metabolic substrates abnormality</th>
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<tr>
<td>Cardiovascular limitation</td>
<td>Ventilation (Panel 5)</td>
<td>VE/VCO₂ (Panel 6)</td>
<td>Respiratory exchange ratio (RER)</td>
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<td>ECG changes</td>
<td>Tidal volume, ventilation and respiratory frequency (Panel 9)</td>
<td>Increased ventilatory equivalent (panel 4)</td>
<td>Anaerobic threshold – first (AT1, VT1)</td>
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<tr>
<td>VO₂/WR (Panel 1)</td>
<td>Increase in residual functional capacity</td>
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<td>Anaerobic threshold – second (AT2, VT2)</td>
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<tr>
<td>VO₂/HR (Panel 2)</td>
<td>Exhaustion of ventilatory reserve</td>
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<tr>
<td>HR/VO₂ (Panel 3)</td>
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As a marker of cardiovascular limitation, in a Finnish population, Khan et al. concluded that maximal O\textsubscript{2} uptake (peak VO\textsubscript{2}) reduction is directly associated with non-fatal myocardial infarction and heart failure events\textsuperscript{30}. Preserving a high peak VO\textsubscript{2} was demonstrated as a protective prognosis value\textsuperscript{31}.

**Work rate - VO\textsubscript{2} to watt, (VO\textsubscript{2}/WR) – Panel I**

Abnormal pattern, reduction or non-linear relationship of work rate in a standardized CPET represents the first signs of exercise limitation, and indices of left ventricular restraint in case of myocardial ischemia. The VO\textsubscript{2}/Work rate presents the coupling of external to cellular respiration, graphically represented by the ability of O\textsubscript{2} consumption to track the workout increase. The \(\Delta\text{VO}_2/\Delta\text{W}\) ratio follows a standard course along with the low workload, with a straight decline consecutive to myocardial ischemia inducing myocardial dyskinesis at the AT point. The VCO\textsubscript{2} progress increases abruptly as the VO\textsubscript{2} continues to decline\textsuperscript{24}. There is also a documented correlation of the ECG changes at the moment or subsequently to \(\Delta\text{VO}_2/\Delta\text{W}\) decrease.\textsuperscript{16} The study of Popovic and collab. validate the \(\Delta\text{VO}_2/\Delta\text{W}\) recumbent cycle-ergometer CPET as an evident additional value in the prognosis of CAD\textsuperscript{32}. 

![Figure 2. CPET in a patient with unexplained dyspnea and multiple cardiovascular risk factors. During CPET, no ECG changes at maximal effort and no chest pain. Reduction in heart rate and pulse oxygen and down sloping of VO\textsubscript{2}/W relation is observed in panel 3. Coronary angiogram revealed severe stenosis in the distal-right coronary artery (arrow) (Case of Dr. Pietro Palermo).](image)
Oxygen pulse (VO₂/HR), reduce response – Panel 2
Oxygen pulse (oxygen consumption and heart rate, VO₂/HR, mL/heartbeat) and stroke volume (mL/heartbeat, blood volume ejected to the aorta during the systole) are both parameters indicator of left ventricular performance during workload. Decline or flattening of the VO₂/HR curve plotted over workload time indicate the oxygen pulse and stroke volume reduction, as a subtle indicator of myocardial ischemia induced by left ventricular dysfunction. Chaudry et al. tested the new mathematical model DHR-WR slope, expressing the changes in HR slope in late exercise plotted to the workload, demonstrating an increased sensitivity and negligible specificity reduction of the undertreated atherosclerosis diagnosis.

Heart rate – Oxygen uptake (HR/VO₂) relationship – Panel 3 (V-slope in AT determination)
Progressively increase and concomitant with altering of the linearity of HR to VO₂ will be observed in the panel, in myocardial ischemia pattern.

CONCLUSION
CPET demonstrated the role in CAD assessment. Particular CPET parameters and panel analyse, extend possibilities of myocardial ischemia detection outside the limits of using more expensive, harmful and invasive traditional investigating procedures. In patients with suspected myocardial ischemia, CPET has a higher sensitivity, specificity, positive predictive value and negative predictive value as compared to standard ECG stress testing.

Conflict of interest: none declared.
Acknowledgements: This paper is partially supported by the University of Medicine, Pharmacy, Science and Technology of Târgu Mureş Research Grant number 615/8/17.01.2019.
All authors contributed equally to this paper and should be viewed as first authors.

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