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Evaluation of physical performance by rectangular-triangular bicycle ergometry and computer-assisted ergospirometry[1])

Bestimmung der körperlichen Leistungsfähigkeit mittels rektangulär-triangulärer Fahrradergometrie und rechnerunterstützter Ergospirometrie

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With 13 figures and 3 tables

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Summary

A great deal of information about physical adjustment to work can be obtained from quantitative stress testing. Maximal stress limited by symptoms of exertional intolerance is the concept of the 2 min duration work increment test (rectangular-triangular exercise test). Compared to steady-state work tests strict observation of the standardized procedure- and computer assisted evaluation of ergospirometric parameters offer innovatory opportunities: (1) the test is of short duration (8–14 min), (2) the subjects recover rapidly, even from an exhausting test, (3) one is more likely to be able to observe plateauing of $\dot{V}_{O_2}$, should determination of maximal $\dot{V}_{O_2}$ be desired, (4) adaptation to increasing work rates and maximal work capacity is assessable, (5) computer technics provide on-line assessment of aerobic and anaerobic power in quantitative terms, (65) measurements proved to be highly reproducible, (7) the relationship between variables such as increments of heart rate and systolic blood pressure, respiratory minute volume, oxygen uptake during the early phase of the non-steady-state condition and the index of anaerobic power, and the influence of factors such as work load and work output, has been studied to derive standard values.

Soft-ware programs have been designed to estimate deviation of parameters actually measured from standard values in terms of multiples of the standard deviation of the standard regression line. In particular, evaluating oxygen uptake during short time-intervals (0.5 min) provides information about adequate adaptational forces of the cardio-circulatory system. Energy that is not accounted for by reactions involving the $\dot{V}_{O_2}$ measured is computed by substracting the caloric equivalent of oxygen uptake during work exceeding the steady-state level during rest from the energy demand to sustain a given work load aerobically. This index of anaerobic power is defined in kcal, cal/kg body wt., and as a percentage of the total amount of energy required (moderately trained athletes 350–500 cal/kg; sedentary people 200–300 cal/kg). A close relationship to parameters of metabolic acidosis (base excess) exists.

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It is concluded that the physical performance of sedentary people, athletes and patients with impaired cardio-pulmonary function can be more precisely qualified in quantitative terms by means of computer assisted rectangular-triangular ergospirometry. Results obtained in patients with diseased conditions must be carefully interpreted, their condition suggesting the use of more invasive investigations to reveal the pathophysiologic mechanism.

Exercise testing serves as a useful diagnostic tool in detecting an impaired functional capacity of the cardiopulmonary system. But only a standardized ergometry exerting an adequate intensity of physical stress is apt to reveal any abnormal response to work in quantitative terms (1, 2, 7, 14, 15, 18, 26).

Maximal stress limited by symptoms is the concept of the rectangular-triangular bicycle exercise test. The work load is increased by either 25 or 50 watts after a 2 min interval per load, unless the patient shows exhaustion or alarming symptoms of exertional intolerance (21). By means of computer technics ergospirometric parameters can be processed and documented on-line: complex indices of physical performance will be computed to describe aerobic and anaerobic power in quantitative terms and adaptational forces of cardio-respiratory function with reference to standard values (23).

The purpose of this paper is (A) to present methodological aspects in rectangular-triangular stress-testing, (B) to define patterns of ergometric and ergospirometric parameters and of an on-line processed index of anaerobic power in relation to work load and work output and (C) to describe the application of computer assisted on-line evaluation of aerobic and anaerobic power in estimating physical adjustment to work increments.

A. Procedure of rectangular-triangular bicycle ergometry and ergospirometry

Methods

The presentation of the procedure of rectangular-triangular stess-testing is based on personal experience with about 1500 exercise tests in healthy men and women aged 20 to 75 – 40 to 50 year old subjects predominantly –, in patients with coronary heart disease and impaired myocardial function and in trained athletes.

The patients exercise in a sitting position on an electrically braked bike (Ergotest, Fa. Jäger, Würzburg, FRG). ECG-analysis is based on the 12-leads-standard program or on the Frank-System (scalar). Any analogous signal can be documented by a six-channel pigment-tape-writer (EK-22, Fa. Hellige, Freiburg, FRG) or monitored on a four-channel screen (MS 203, Fa. Hellige). The heart rate is analysed beat-to-beat, the QRS-signal is display audible, blood-pressure is measured by the auscultatory method.

Primary ergospirometric parameters are evaluated by means of an open circuit system (Ergopneumotest and Pneumotest mit EDV – Olivetti P 652 –; Fa. Jäger). After peripheral preprocessing of expired air volumes, rate of respiration, CO_2- and O_2-gas concentrations and of heart rate, an external program-control-unit (Fa. Jäger) feeds the digitalized data into a minicomputer. Every thirty seconds a print-out is available: Expiratory volume per minute ($\dot{V}_E$ l/min, BTPS), tidal volume (V_T l), respiratory rate (f_r breath/min), % oxygen-concentration difference between inhaled and exhaled air, % carbondioxide concentration of exhaled air, oxygen uptake ($\dot{V}_{O_2}$ l/min, ml/kg body wt. × min, STPD), oxygen pulse (ml/beat), respiratory quotient and heart rate (beats/min). Data may be averaged over a predetermined period (e.g. resting period, steady state). Peak expiratory flow during exercise is documented graphically. We have designed soft-ware programs to compare variables actually measured to standard values by computing the differences in terms of multiples of the standard deviation of the regression line. After the first and second minute of each work load, variables such as oxygen uptake, expiratory minute volume and heart rate are processed in this way. At the end of each work period an index of anaerobic power is calculated.

During the resting and recovery periods blood samples of capillary blood are withdrawn for blood-gas-analysis (pH, pCO_2, pO_2; base excess. AVL-Gas Check, Graz, Austria).

Our procedure is based on strictly observing the exercise protocol:

1. No *admittance* prior to questionnaire about symptoms of cardio-pulmonary disease and physical fitness, and physical examination; preferably 12-leads ECG and chest X-ray should be available.
2. *Absolute contraindications* have to be ruled out (18, 21).
3. *Indications* to perform the test should be defined in detail (e.g. screening patients suspected of suffering from CHD or abnormal blood pressure regulation, assessing work capacity of athletes, etc.).
   [18, 21].
4. *Conception* of procedure is to be stated – whether a maximal symptom-limited stress test will be performed or an exercise test that has to be interrupted as soon as "target" criteria have been reached (e.g. f_h 130, $\dot{V}_{O_2}$ 1.5 l/min).
5. *Selection* of *parameters* in evaluating physical performance: We are applying a diagnostic procedure which includes various technics which become stepwise more and more invasive.

Our standard program consists of (a) rectangular-triangular bicycle ergometry, (b) ergospirometry and (c) evaluation of central hemodynamics in static and dynamic exercise.

Physical adjustment to work is generally assessed by strict observation and evaluation of subjective and objective criteria which have to be checked continually or periodically respectively.

Subjective parameters

(a) Having exercised for more than one minute under a given load the patient is asked to state his *perceived exertion* corresponding to a rate scale (PER, *G. Borg;* 6, 21).
Preferably, the patient should tolerate a work intensity that he himself judges as "very, very hard" (PER = 18/19).

(b) The subject is told to inform the physician immediately about *onset of symptoms* such as shortness of breath, chest discomfort or pain, dizziness and marked claudication. Applying a rate scale proved useful in quantifying angina pectoris (21).

(c) Psychological aspects such as *motivation* to tolerate exhausting work and cooperation are not easily assessed.

Objective parameters

In non-invasive stress testing, four basic criteria should be assessible for monitoring.

(a) *Tolerated work load* related to predicted maximal load implies evaluation of the intensity of physical stress and impairment of physical performance in quantitative terms, if the test has to be interrupted (FAI % = functional aerobic impairment, *R. A. Bruce;* 7).

Pedaling against a minimal load (20 watts) was chosen as the first load. In subjects evidently not suffering from significantly impaired myocardial function the load was increased to 50 watts. Further increments – 25 or 50 watts – depend on the subject's predicted maximal load, physical condition, random abnormal reactions and signs of intolerance to the actual load.

(b) *Heart rate* is derived from beat-to-beat analysis of the QRS-signal. Audible reproduction of the QRS-complex should be available to provide detection of premature ventricular contractions. "Target" heart rate levels (85 % of $f_{h\ max}$) are not accepted as criteria to interrupt the test.

(c) The *electrocardiogram* is recorded and displayed continually. We prefer the Wilson chest-leads program in analysing cardiac rhythm and detecting ST-T-alterations.

(d) *Arterial blood pressure* is measured by the auscultatory method (the pattern of breathing is observed, but respiratory frequency is not measured routinely).

Before applying more invasive technics in stress-testing we will perform the rectangular-triangular bicycle ergometry with evaluation of the subjective and objective parameters mentioned above to gain preliminary informations about the patient's work tolerance.

Computer-assisted evaluation of *ergospirometric parameters* serves as a basis for discovering the underlying pathophysiological mechanism of intolerance to physical stress. Criteria of *respiration* and *gas exchange* are processed at time-intervals of 0.5 min: $\dot{V}_E$, V_T, f_r, % O_2-difference between exhaled and inhaled air, % CO_2, $\dot{V}_{O_2}$, RQ, oxygen-pulse and heart rate. At the end of each work load an index of anaerobic power is calculated, whereas actual values of $\dot{V}_{O_2}$, $\dot{V}_E$ and the augmentation of the heart rate are compared to normal ranges (22, 23). Applying computer technics has several advantages: 1. On-line analysis of parameters documented by alphanumeric print-out and plotterdiagram, 2. calculation of derived parameters, 3. statistical analysis of measured data and 4. integration of all that has been processed into a feedback system to assist the physician who is supervising the test.

During the early recovery period capillary blood samples are taken for *blood gas analysis* to assess metabolic acidosis and the magnitude of respiratory compensation (12, 14).

Investigation of *central hemydynamics* in stress-testing has become more easily practicable by means of microheart-catheterization. Evaluation of arterial blood pressure and pulmonary artery pressure values, variation of cardiac output with on-line computation of derived parameters (23) and ergospirometric data more exactly will qualify and define disease states of the cardio-pulmonary system (9, 24).

6. Maximal stress limited by symptoms has been stated to be the concept of rectangular-triangular stress-testing. An *interruption*

of the test is indicated by standard criteria such as the following: Severe fatigue, perceived exertion rate 18/19 unless alarming symptoms arise (rhythm disturbances, ST-T-alterations, excessively high blood pressure or decreasing systolic blood pressure, failure to increase systolic pressure, complaints of angina pectoris and severe dyspnea; 18, 21).

7. *Analysis and interpretation* of the results obtained must be based upon personal experience and profound knowledge of fundamentals in exercise physiology and pathophysiology (1, 3, 15, 26).

In the final report on the test performed we recommend listing data as follows: Highest work load tolerated (Wl_{max}, watts), total duration for which this load has been tolerated ($t_{Wl\,max}$), total amount of work performed (= work output; Wl_{tot}, watts × min), duration of total work period, (t_{tot}, min), values of blood pressure and heart rate measured during the resting period and maximal work respectively, FAI % (work load tolerated ÷ work load predicted × 100) and watts/kg body wt.

Ergospirometric parameters are presented in terms of the highest values observed: $\dot{V}_{O_2}$ (l/min, ml/kg × min and *METS*), O_2-pulse, $\dot{V}_E$, V_T, RQ, index of anaerobic power (kcal, cal/kg body wt. and percentage of total energy of work output), oxygen debt (kcal, cal/kg body wt.; referring to a recovery period of 5 min) and data obtained from the blood gas analysis (pH, pO_2 and delta BE; 14). Finally, reasons for stopping the test, any abnormal sign or symptom of exertional intolerance – onset related to work intensity – are stated and discussed, including interpretation of ECG, blood pressure and heart rate regulation.

Comment

The two-minute duration work increment test (rectangular-triangular stress-test) has several advantages: 1. the test is of short duration, 2. the subjects recover rapidly, even from an exhausting test, 3. one is more likely to observe plateauing of $\dot{V}_{O_2}$, should determination of maximal $\dot{V}_{O_2}$

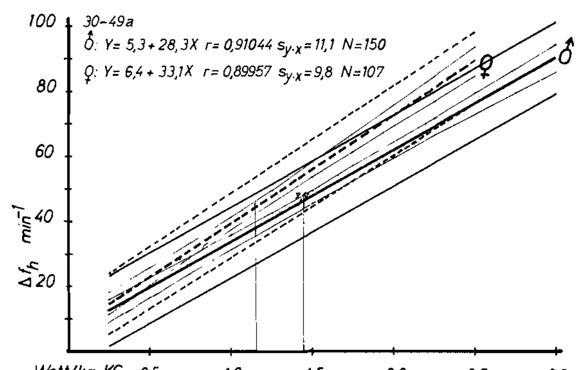


Fig. 1. Relationship between increment of heart rate exceeding resting level and work load during bicycle ergometry.

be desired, 4. steady-state work load levels may be defined in terms of percentage of $\dot{V}_{O_2 \, max}$ (hemodynamic investigation), 5. the onset of limiting symptoms can be related to work intensity, work output, oxygen uptake, heart rate, pulmonary ventilation and any other parameter, 6. measurements proved to be highly reproducible, 7. the standard values of several ergospirometric parameters were derived and 8. adaptation of physical work capacity to increasing work rates can be judged.

In stress-testing, abnormal response of the subject and alarming symptoms of exertional intolerance should not escape notice, as the test must be interrupted. But valuable information might be lost if the test is stopped at too a low level of work intensity. Ultimately, the primary goal is guaranteeing absolute safety to the patient at a tolerable risk. Computer-assisted analysis of ergospirometric parameters will meet these conditions best.

B. Standard values of measurements in rectangular-triangular bicycle ergometry – Results and comments

1. *Heart rate* (f_r)

The relationship between the increase of heart rate above resting level and different work loads (defined in watts/kg body wt.; Broca-Index 92–105) is illustrated in fig. 1). In sedentary middle-aged women the intercept is more elevated than in men, as identical work loads result in a greater stress due to lower female work capacity. In elderly people aged 50 to 65 the mean values of watts/kg shift leftwards, the slope tends to be unchanged (21).

2. *Systolic blood pressure* (BP_{syst})

Whether blood pressure regulation is assessed correctly by the auscultatory method remains somewhat doubtful. Nevertheless, data obtained by this method are accepted as important and reliable information in detecting abnormal blood pressure regulation (13). The relationship between the increase of systolic blood pressure (delta BP_{syst}) above resting

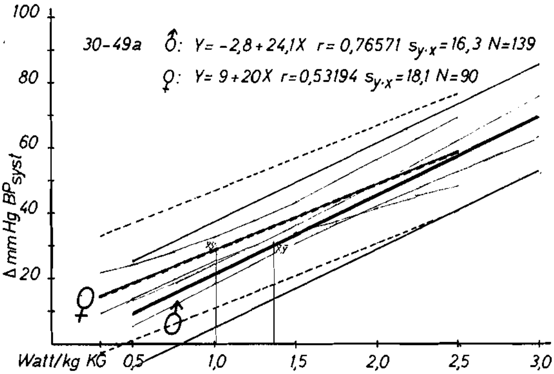


Fig. 2. Relationship between increment of systolic blood pressure and work load during bicycle ergometry.

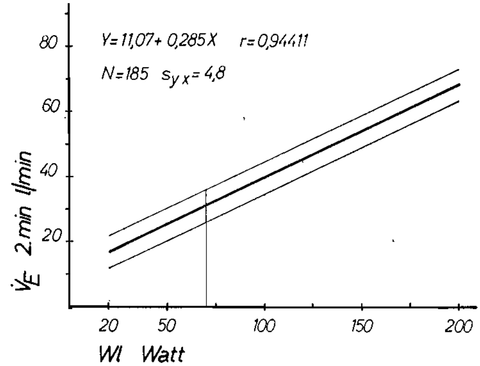


Fig. 3. Relationship between respiratory minute volume (2 min) and work load during bicycle ergometry in healthy men and women aged 20 to 45. (Work loads below 75 % of $\dot{V}_{O_2max}$).

level and the tolerated work load (watt/kg body wt.) is illustrated in fig. 2. In elderly people the mean values of watt/kg shift leftwards, the slope tends to be unchanged.

3. *Respiratory minute volume* ($\dot{V}_E$)

In computer-assisted evaluation of ergospirometric parameters data being processed refer to 0.5 min periods. $\dot{V}_E$ taken from the fourth 0.5-min period of a work load of two-minute duration was found to be linearly related to work loads (watts) not exceeding intensity of 75 % of the subjects' maximal aerobic capacity ($\dot{V}_{O_2\,max}$). Work loads of higher intensity have been excluded, for metabolic acidosis acts as a stimulus to hyperventilation. Fig. 3 illustrates the relationship between $\dot{V}_E$ and work load in healthy men and women aged 20 to 45.

Respiratory minute volumes actually measured are compared to standard values by on-line computation of the difference in terms of multiples of the standard deviation of the regression line. Non-linear increase in $\dot{V}_E$ relative to the linear increase of $\dot{V}_{O_2}$ indicates onset of respiratory compensation for metabolic acidosis (anaerobic threshold; 27).

4. *Oxygen uptake, aerobic power* ($\dot{V}_{O_2}$)

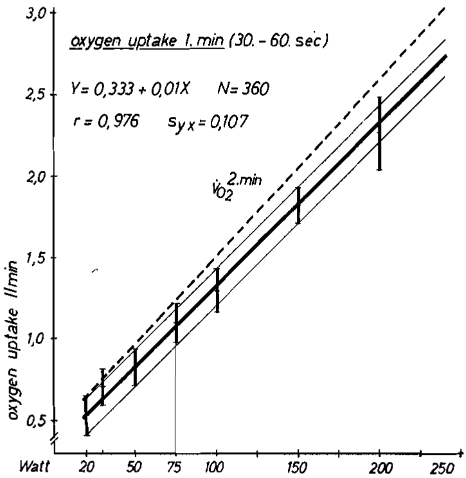
Maximum aerobic power is defined as the highest attainable rate of aerobic metabolism during the performance of rhythmic dynamic muscular work that exhausts the subject within 5–10 minutes (1, 11, 20, 25). During the two minute duration work increment test one is more likely to be able to observe pleateauing of $\dot{V}_{O_2}$, should determination of maximal $\dot{V}_{O_2}$ be desired.

Oxygen uptake is related to heart rate, stroke volume and arterio-venous oxygen difference through the equation:

$$\dot{V}_{O_2} = f_h \times SV \times D_{av}$$

(Cardiac output is the product of f_h and SV. A useful index of stroke volume and arterio-venous oxygen difference is the oxygen-pulse, because oxygen pulse =

$$\frac{\dot{V}_{O_2}}{f_h} = SV \times D_{av}).$$



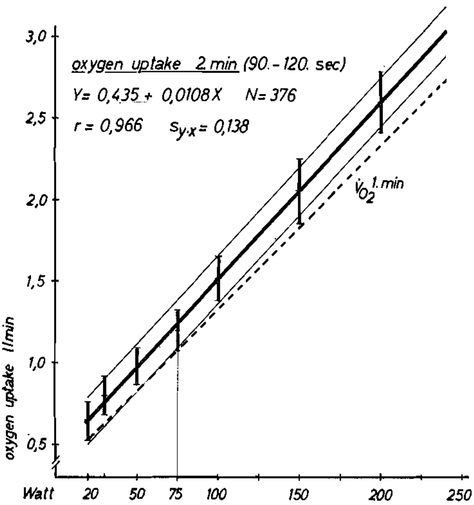


Fig. 4 and 5. Relationship between oxygen uptake and work load (below 75 % of $\dot{V}_{O_2max}$) in sedentary men and women aged 20–45. Oxygen uptake is related to the second and fourth 0.5-min periods of a two-minute duration work load.

In this way, on-line computation of oxygen uptake during short time intervals provides useful information about adaptational forces of the cardiac-pulmonary system to increasing work loads.

Heart rate and stroke volume are adjusted during the unsteady state of exercise so that the relationship between cardiac output and oxygen uptake is similar to that of the steady-state (5, 10). During the early non-steady-state phase of cycle ergometer work of low intensity with a constant load $\dot{V}_{O_2}$ increases to its steady state as a single exponential function, with a half-time of approximately 30 seconds (28). During constant load work of high intensity the kinetics of $\dot{V}_{O_2}$ towards its steady state is characterized by two exponential processes (29).

Table 1. On-line computation of oxygen-uptake and anaerobic power related to work load and work output. Data taken from moderately trained athletes (A) (tolerating at least 300 Watts) and from fit sedentary men (B) (work output exceeding 1040 Watts-min).

N. N.	age	body weight	1st min $\dot{V}O_2$	2nd min W1 *50 Watts* W.o. 140 Wmin	kcal anaerob pw	%	1st min $\dot{V}O_2$	2nd min W1 *100 Watts* W.o. 340 Wmin	kcal anaerob pw	%	1st min $\dot{V}O_2$	2nd min W1 *150 Watts* W.o. 640 Wmin	kcal anaerob pw	%	1st min $\dot{V}O_2$	2nd min W1 *200 Watts* W.o. 1040 Wmin	kcal anaerob pw	%	1st min $\dot{V}O_2$	2nd min W1 *250 Watts*
S. A.	21	73	0.93	1.09	1.4	14.7	1.28	1.66	4.45	19.2	1.98	2.27	7.42	17	2.75	2.96	11.6	16.3	3.19	3.84
F. S.	21	69	0.90	1.03	2.7	28.3	1.34	1.45	5.65	24.4	2.03	2.19	8.83	20.2	2.52	2.78	13.1	18.4	3.39	3.75
T. G.	26	74	0.62	0.95	3.3	34.3	1.52	1.59	6.5	28.1	2.07	2.06	11.2	25.9	2.42	2.62	17.3	24.3	3.15	3.60
T. R.	25	78	0.78	1.19	1.91	20	1.35	1.56	4.7	20.2	2.01	2.13	8.54	19.6	2.53	3.02	13.0	18.3	2.90	3.60
S. W.	22	75	0.77	0.91	0.06	0.7	1.3	1.54	2.63	11.4	1.92	2.13	6.4	14.6	2.4	2.77	10.6	14.9	3.18	3.50
H. G.	22	74	0.86	0.94	2.37	24.8	1.41	1.66	5.95	25.6	1.87	2.08	11.2	25.7	2.35	2.52	18.4	25.9	3.00	3.20
W. J.	26	75	0.86	1.02	2.66	27.8	1.38	1.58	7.02	30.3	1.97	2.15	12.34	28.3	2.58	2.82	18.2	25.6	3.18	3.30
L. A.	21	73	0.81	1.09	1.91	20.0	1.47	1.78	4.9	21.2	2.12	2.42	8.53	19.5	2.66	3.04	13.2	18.7	2.96	3.40
S. F.	30	91	0.91	1.00	3.25	34.1	1.15	1.64	8.06	34.8	1.63	2.15	14.58	33.4	2.46	2.39	23.2	32.7	2.71	3.10
$\bar{x}$	A.		0.83	1.02	2.17	22.7	1.34	1.61	5.5	23.9	1.96	2.17	9.89	22.7	2.51	2.77	15.4	21.7	3.07	3.50
s			0.09	0.09	1.01	10.5	0.11	0.09	1.60	6.9	0.14	0.11	2.6	6.01	0.13	0.22	4.1	5.8	0.20	0.20

N. N.	age	body weight	1st min $\dot{V}_{O_2}$	2nd min W1 *50W att* W.o. 140 Wmin	kcal anaerob pw	%	1st min $\dot{V}_{O_2}$	2nd min W1 *100 Watt* W.o. 340 Wmin	kcal anaerob pw	%	1st min $\dot{V}_{O_2}$	2nd min W1 *150 Watt* W.o. 640 Wmin	kcal anaerob pw	%	1st min $\dot{V}_{O_2}$	2nd min W1 *200 Watt* W.o. 1040 Wmin	kcal anaerob pw	%	1st min $\dot{V}_{O_2}$	2nd min W1 *250 Watt*
G. E.	22	69	0.72	0.93	1.61	16.9	1.11	1.55	5.38	22.8	1.88	1.96	8.93	20.5	2.35	–	12.5	21.8		
P. H.	24	83	0.85	1.22	1.62	16.9	1.44	1.69	4.68	20.2	2.07	2.22	8.31	19.0	2.53	2.76	14.0	19.7	3.15	3.40
B. H.	21	63	0.90	1.10	3.23	33.8	1.29	1.40	7.6	32.8	1.59	1.94	14.11	32.3	2.20	2.32	22.7	32.0		
R. H.	29	78	0.71	0.95	3.8	39.7	1.34	1.48	9.0	39.0	1.67	1.82	15.9	36.4	2.23	2.46	24.6	34.7	2.58	3.00
M. E.	20	67	0.92	0.94	0.32	3.37	1.38	1.51	3.3	14.1	1.87	2.34	7.59	17.4	2.81	3.02	10.9	15.4		
G. H.	20	70	0.64	0.82	4.05	42.4	0.97	1.55	9.64	41.6	1.72	2.16	14.3	32.8	2.49	2.53	20.5	28.9		
L. M.	35	75	0.83	1.02	2.34	24.5	1.24	1.51	7.16	30.9	1.74	1.99·	14.3	32.7	2.18	2.51	23.0	32.4		
F. F.	37	66	1.02	1.00	0.00	0.0	1.27	1.66	3.67	15.8	1.86	2.06	8.43	19.3	2.16	2.55	16.4	23.2		
B. R.	44	67	0.74	1.05	2.57	26.9	1.31	1.33	6.47	27.9	1.85	2.00	12.05	27.6	2.28	2.49	20.0	28.21		
x̄	B.		0.81	1.00	2.17	26.1	1.26	1.52	6.3	27.2	1.86	2.05	11.5	26.4	2.36	2.58	19.0	26.8		
s			0.12	0.11	1.42	13.3	0.14	0.11	2.24	9.7	0.14	0.16	3.24	7.4	0.21	0.22	4.8	6.8		

The relationship between oxygen uptake and a work load not exceeding 75 % of $\dot{V}_{O_2\,max}$ in healthy, untrained men and women aged 20 to 45 is illustrated in fig. 4 and 5. The oxygen uptake during the second and fourth 0.5-min periods of a two-minute duration work load is linearly correlated to the work rate ($r_1 = 0.976$; $r_2 = 0.966$; standard deviation $s_{y \cdot x1} =$ 0.107 l/min; $s_{y \cdot x2} = 0.138$ l/min).

During ergometer work of low intensity, $\dot{V}_{O_2}$ after one minute of work does not differ widely from the oxygen uptake obtained one minute later, suggesting that an adequate state of aerobic metabolism and circulation is achieved more rapidly than during work loads of higher intensity.

Computer-assisted evaluation of ergospirometric parameters provides processing of indices to characterize normal physiological responses, such as the following: Oxygen uptake ($\dot{V}_{O_2\,1st,\,2nd\,min}$) is compared to standard values by computing the difference in terms of multiples of the standard deviation (s_{VO_2}) of the regression line.

Compared to sedentary people oxygen uptake in athletes (see table 1) is found to increase more rapidly, ensuing from improved physical performance and higher aerobic power ($s\dot{V}_{O_2}$ [+] 1.5). In elderly subjects and patients with impaired myocardial pump function (hypokinetic circulation), oxygen uptake evidently stays below the standard values ($s\dot{V}_{O_2}$ [–] 1.0).

5. Index of anaerobic power

In the working muscle the energy store of adenosin triphosphate (ATP) is converted into mechanical energy by muscle contraction and work. The concentration of intramuscular ATP is continually regenerated by the transphosphorylation of creatine phosphate (CP). Ultimately, ATP and CP stores are maintained by the catabolism of carbohydrates and fatty acids undergoing complete oxydation.

The aerobic process requires that three important conditions be met: 1. that the muscle fibers in the contracting units have adequate mitochondrial density to support the aerobic ATP-generating requirements of the work, 2. that intermediates and enzymes do not provide rate limitation in the *Krebs* cycle at that work rate, and 3. that adequate O_2 is delivered to the mitochondrial electron transport chain. When aerobic degradation of the substrate is limited by one or more of these factors, anaerobic metabolism ensues and sustains the production rate of ATP at the expense of glycolysis. Deriving energy from anaerobiosis is manifested in an increased muscle and blood lactate content (8, 12).

The pattern of $\dot{V}_{O_2}$ during rectangular-triangular bicycle ergometry helps provide insight into the adequacy of O_2 to perform work completely aerobically. For low intensity of work, energy not accounted for by reactions involving the $\dot{V}_{O_2}$ measured is supplied by: 1. Utilization of high energy phosphate stores, predominantly as CP, and 2. by oxidative reactions utilizing stored O_2, reflected by the reduced mixed venous O_2 content and quantitatively, to a less extent, by the reduced mean tissue O_2 partial pressure. For high intensity work, however, when energy requirements are not met either by energy sources cited above or by $\dot{V}_{O_2}$, the additional energy required is derived from anaerobiosis (3, 26). Applying computer technics in rectangular-triangular stress-testing, we succeeded in on-line (and off-line) processing of an index of anaerobic power that is documented via keyboard printer at the end of each work load (22). To compute that index we have developed a subroutine-software program: Subtracting the caloric equivalent of oxygen uptake during work exceeding the steady-state level during rest from the energy demand to sustain a given load aerobically, an index of anaerobic power may be defined in terms of kcal, cal/kg body wt., and as a percentage of the total amount of energy required (see fig. 6). Measurements of oxygen uptake must be related to 0.5-min intervals at least.

Anaerobic power =

$$\sum_{i=1}^{n}[Wl_j \times t \times k_1 \times k_2 - \sum_{m=1}^{n=4}(\dot{V}_{O_2\,mj} - \dot{V}_{O_2\,R}) \times k_3]$$

i	number of work rates
Wl_j	work load (watts; entered via keyboard)
t	duration of work period (e.g. 2 min)
k_1	4.7619 (factor based on work efficiency of 21 %; assessible by indirect calorimetry on work rates below anaerobic threshold; extra-oxygen uptake for pedaling against zero-load has not been eliminated).
k_2	0.014328 (conversion factor of watts to kcal/min)
k_3	5.05 (conversion factor of oxygen-uptake to kcal/min)
$\dot{V}_{O_2\,mj}$	oxygen uptake during a period of 30 seconds
$\dot{V}_{O_2\,R}$	oxygen uptake during steady-state phase of rest

The relationship between anaerobic power and work output (total work performed) is illustrated in fig. 7.

Regression line g_1 is based on data obtained from sedentary middle-aged subjects (30–50 years old), exercising with loads up to 75 % of $\dot{V}_{O_2\,max}$. Regression line g_2 represents the relationship between anaerobic power and maximal work load tolerated (PER = 18/19) in young fit subjects, aged 20–35. During exhausting work in trained athletes maximal values of anaerobic power have been found ranging between 30 and 45 kcal (350 to 480 cal/kg body wt.), in terms of % of the total amount of energy required aerobically, 20 to 25 % respectively.

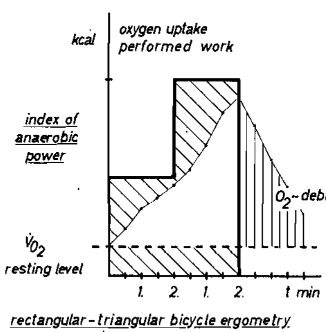


Fig. 6. Idealized respresentation of caloric equipment of anaerobic power assesssed by on-line computation during rectangular-triangular bicycle exercise (ergospirometry).

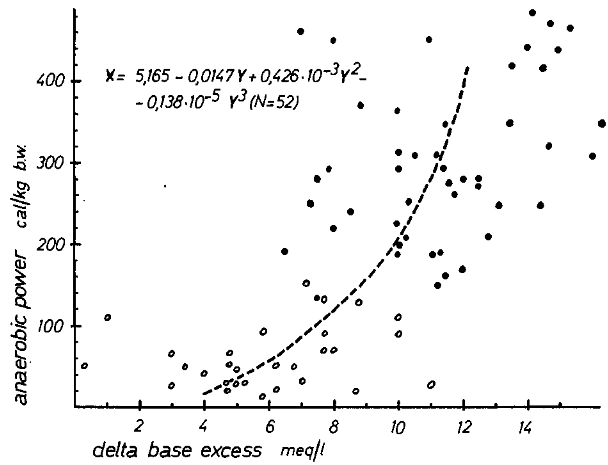


Fig. 6a. Relationship between the computed index of anaerobic power and a parameter of metabolic acidosis (delta base excess) in sedentary people (○) and moderately trained athletes (●). ($n_1 = 4$; $n_2 = 48$; $F = 21{,}04$; $p = 0.01$.)

Anaerobic power and metabolic acidosis

A significant relationship ($r = -0.95$) has been found between the increase in the concentration of lactate and hydrogen ions in the artery blood at rest, during and after exercise (12). Therefore, the calculated index of anaerobic power may be related to data obtained from the blood gas analysis after exercise: pH and base excess. The base excess itself is influenced almost exclusively by the changes in the non-volatile acids, the most important of which are lactate and pyruvic.

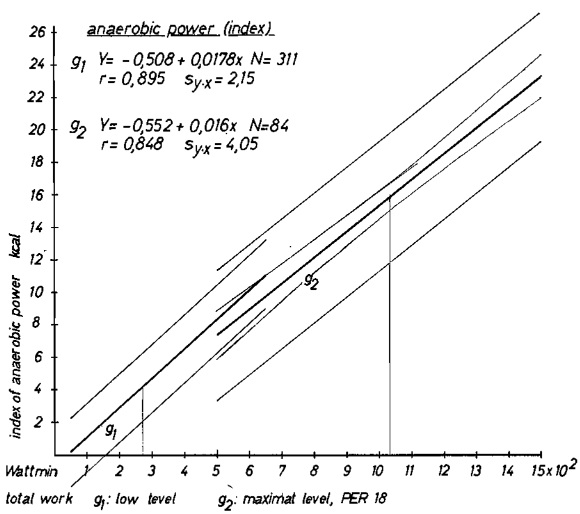


Fig. 7. Relationship between anaerobic power and work output. Regression line g_1 illustrates data obtained from sedentary middle-aged subjects, 30–50 years old; g_2 represents measurements taken in fit subjects aged 20–35.

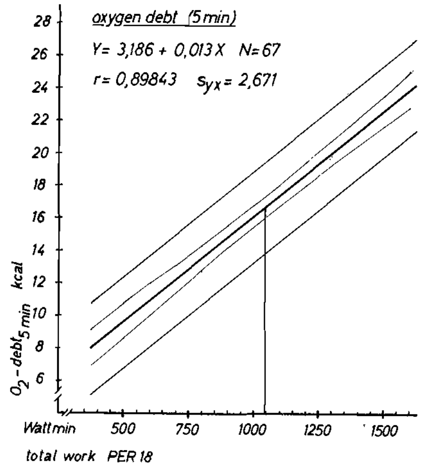


Fig. 8. Relationship between oxygen debt (assessed during 5 min) and work output in fit subjects aged 20–35.

A curvilinear relationship exists between the computed index of anaerobic power (cal/kg body wt.) and delta base excess (p = 0.01).

As soon as anaerobiosis considerably contributes as a source of energy for muscular work, the delta base excess exceeds 5 meq/l (14) and the computed index of anaerobic power increases above 40 cal/kg body wt.

6. *Oxygen debt* $_{5\ min}$

Oxygen uptake exceeding the resting values is summed up during 5 minutes of the early recovery period and expressed in terms of kcal, representing an index of the oxygen debt. The relationship between oxygen debt and work output (perceived exertion rate 18/19) in young subjects aged 20 to 35 is illustrated in fig. 8.

A final conclusion cannot be presented at the moment as to which of the following compartments of the oxygen debt that index is most reliable for: 1. restorage of aerobic compartment (refilling to oxygen stored), 2. restorage of anaerobic compartment (re-establishing ATP- and CP-levels and re-synthesis of lactate), and 3. metabolic compartment (oxygen supply for increased cardio-respiratory function, increased body temperature and adrenalin output and tissue repair) (3, 16).

Margaria and co-workers have devised a test to assess maximal anaerobic power in a short burst of maximal activity. The index of mechanical energy derived refers to the splitting of high energy phosphate compounds (17).

Reproducibility of measurements in rectangular-triangular bicycle ergometry

13 untrained male subjects aged 18 to 25 were examined twice. Maximal symptom-limited stress tests were performed repeatedly at intervals of at least 6 weeks.

The statistical evaluation of measurements is illustrated in fig. 9. The individual data of heart rate, systolic blood pressure and oxygen uptake

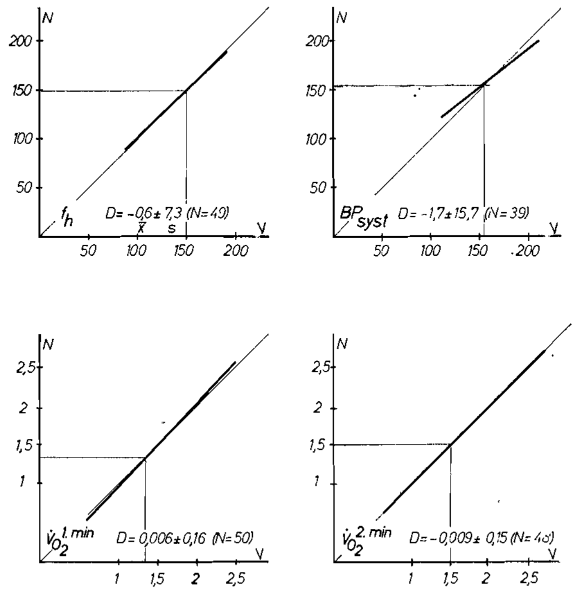


Fig. 9. Reproducibility of measurements in rectangular-triangular stress testing: Heart rate (f_h), systolic blood pressure (BP_{syst}) and oxygen uptake related to work load. Mean difference of analysis of paired data in 13 untrained male subjects aged 18–25. (V = first, N = second test, Δ = mean difference.)

are represented by regression lines that correspond closely to the line of identity. Mean differences of the paired data of each variable are negligible; standard deviations equal data derived for the standard deviations of normal ranges of the particular variables. The relationship between anaerobic power and work output referring to various levels of work intensity is found to be unchanged when measured repeatedly (see fig. 10).

C. Evaluation of physical performance in quantitative terms – Aerobic and anaerobic power, physical adjustment

On-line computation and rating of ergospirometric variables and derived parameters proved to be very useful in evaluating limiting factors of the cardio-respiratory function in quantitative terms. Integrating these data and the patients' subjective complaints into a feedback-system is apt to assist the physician considerably in supervising the exercise test. Besides standard criteria for interrupting the test, delayed increase of $\dot{V}_{O_2}$, plateauing of $\dot{V}_{O_2}$ and maximal values of anaerobic power (kcal; cal/kg body wt.) are more likely to verify exhaustion, especially if effects of physical training have to be judged.

Carefully quantified exercise in patients led to discovery of the underlying pathophysiological mechanism. Nevertheless, interpretation of data obtained in diseased states remains difficult as physical adjustment to work might be impaired by various factors which can only be assessed by more invasive investigations such as lung function tests, evaluation of

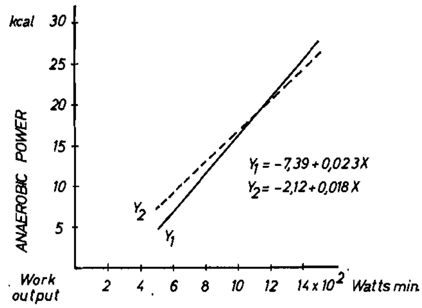


Fig. 10. Variation of repeated measurement of anaerobic power related to work output.

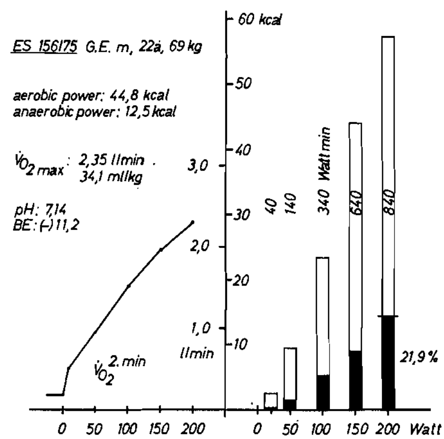


Fig. 11. Physical performance of a young untrained man (pat.: G. E., see table 1) evaluated by on-line computation of ergospirometric parameters.

central hemodynamics, left-heart catheterization, ventriculography and coronary angiography (15, 19, 24).

As an example of results obtained in rectangular-triangular exercise testing, data of moderately trained athletes and fit, sedentary men are listed in table 1. Parameters of anaerobic power, percentage of anaerobic power, $\dot{V}_{O_2\ 1st\ min}$ and $\dot{V}_{O_2\ 2nd\ min}$ have been related to work loads and total work output (50 watt increments!) to demonstrate the relationship between indices of aerobic and anaerobic power involved in adjustment to physical stress in subjects with different work capacity.

The relationship between work load and oxygen uptake, work output and anaerobic power in a sedentary man (pat. G. E.) is illustrated in fig. 11. Application of on-line computation of oxygen-uptake and of anaerobic power in a young moderately trained man (pat. T. R.) is illustrated in fig. 12.

In trained athletes oxygen uptake per work load increases more rapidly, thus resulting in a lower index of anaerobic power as compared to sedentary men.

N.N.	age	body weight	1st min $\dot{V}_{O_2}$	2nd min Wl *20 Watts* W.o. 40 Wmin	kcal anaerob pw	%	1st min $\dot{V}O_2$	2nd min Wl *50 Watts* W.o. 140 Wmin	kcal anaerob pw	%	1st min $\dot{V}O_2$	2nd min Wl *75 Watts* W.o. 290 Wmin	kcal anaerob pw	%	1st min $\dot{V}O_2$	2nd min Wl *100 Watts* W.o. 490 Wmin	kcal anaerob pw	%	1st min $\dot{V}O_2$	2nd min Wl *150 Watts*
F. E.	54	62	0.53	0.57	0.88	32.2	0.70	0.89	3.32	34.6	1.05	1.11	5.85	29.6	1.25	1.36	9.87	29.5	1.00	0.00
cal. ml/kg				9.14	14.2			14.5	53.4			17.9	94.4			21.86	159.2			

1st min $\dot{V}O_2$	2nd min Wl *250 Watts* W.o. 1540 Wmin	kcal anaerob pw	%	1st min $\dot{V}O_2$	2nd min Wl *300 Watts* W.o. 2140 Wmin	kcal anaerob pw	%	Work output Watts min	kcal anaerob pw	cal/kg	%	l/min $\dot{V}O_2$ max	ml/kg	pH	delta BE
3.19	3.84	15.9	15.1	3.80	4.20	20.8	14.3	2140	20.8	297.8	14.3	4.20	60.02	7.24	(—) 10
3.39	3.75	17.0	16.2	4.11	3.97	21.3	14.6	2140	21.3	310.3	14.6	4.11	60.02	7.10	(—) 16
3.15	3.66	23.4	22.3	3.69	3.68	31.3	21.4	2465	36.7	496.0	21.2	4.08	55.11	7.12	(—) 14.4
2.90	3.64	19.4	18.5	3.42	4.30	25.7	17.6	2840	34.9	447.0	18.0	4.69	60.1	7.15	(—) 15
3.18	3.52	15.1	14.3	3.83	3.83	20.9	14.3	2140	20.9	278.6	14.3	3.83	51.0	7.20	(—) 12.5
3.00	3.24	25.7	24.5	3.62	3.73	33.9	23.2	2140	33.9	457.9	23.2	3.73	50.5	7.27	(—) 8
3.18	3.31	25.2	23.9	3.62	4.09	33.0	22.6	2140	33.0	440.0	22.6	4.09	54.5	7.20	(—) 13.5
2.96	3.47	20.1	19.2					2090	25.3	346.0	17.7	3.75	51.4	7.20	(—) 11.5
2.71	3.47	20.1	19.2					2090	25.3	346.0	17.7	3.75	51.4	7.20	(—) 11.5
2.71	3.18	33.5	31.7	3.27	3.38	42.6	31.4	1990	42.6	468.0	31.4	3.38	37.1	7.19	(—) 14.5
3.07	3.51	21.7	20.6	3.66	3.94	26.5	18.2	**2231**	29.9	**393.6**	**19.6**	3.98	**53.3**	**7.19**	(—) **12.8**
0.20	0.23	5.9	5.6	0.24	0.23	5.5	3.8	261	8.0	84.2	5.6	0.37	7.2	0.05	(—) 2.6

1st min $\dot{V}_{O_2}$	2nd W1 *250 Watts* W.o. 1540 Wmin	kcal anaerob pw	%	1st min $\dot{V}_{O_2}$	2nd W1 *300 Watts* W.o. 2140 Wmin	kcal anaerob pw	%	Work outpur Watts min	kcal anaerob qw	cal/kg	%	l/min $\dot{V}_{O_2}$ max	ml/kg	pH	delta BE
								840	12.5	181.7	21.9	2.35	34.09	7.14	(—) 11.2
3.15	3.47	20.2	19.2					1540	20.1	242.9	19.2	3.24	41.75	7.18	(—) 14.5
								1265	26.9	427.8	31.2	2.69	42.6	7.20	(—) 14.5
2.58	3.00	36.2	34.4					1540	36.2	464.1	34.4	3.00	38.5	7.28	(—) 7
								1040	10.9	163.0	15.4	3.02	45.0	7.20	(—) 11.4
								1490	24.7	353.5	24.3	3.08	44.0	7.28	(—) 13
								1040	22.9	318.9	32.4	2.50	33.5		
								1040	16.4	248.4	23.2	2.55	38.6	7.25	(—) 10.5
								1040	20.0	298.7	28.2	2.49	37.2		
								1203	21.2	298.4	25.6	2.79	39.47	7.22	(—) 11.7
								1203	21.2	**298.4**	**25.6**	2.79	**39.47**	**7.22**	(—) **11.7**
								262	7.7	103.0	6.4	0.37	4.14	0.05	(—) 2.6
1.34	—	12.8	30.6					**615**	12.8		**30.6**	1.43		**7.28**	(—) **7**
									206			**23.0**			

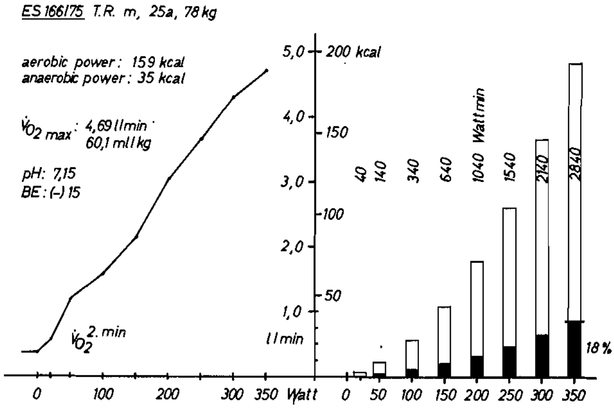


Fig. 12. Physical performance of a moderately trained young man (pat.: T. R., see table 1).

Maximal anaerobic power related to body weight tends to be much higher in trained subjects, as follows: 422 cal/kg (pat. T. R.) and 181.7 cal/kg (pat. G. E.), total work output 2840 watts-min and 930 watts-min respectively.

It must be taken into account that maximal values of anaerobic (and aerobic power) are mainly influenced by the patients' willingness to run into severe exhaustion. During heavy work, respiratory muscles may tax as much as 10 percent of the total oxygen uptake; therefore, the calculated index of the anaerobic power of the working muscles is underestimated (3).

As disparity of the relationship between metabolic parameters, e.g. base excess, and the processed index of anaerobic power may be brought about by excessive respiratory compensation of metabolic acidosis on the one hand and by hyperkinetic cardio-circulatory adjustment to physical stress

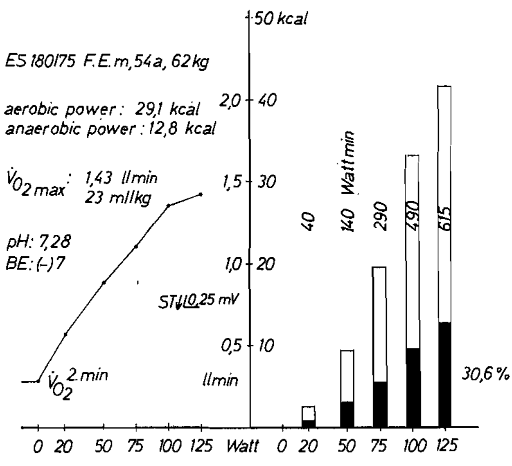


Fig. 13. Work capacity of a middle-aged man (CHD, myocardial infarction) after physical rehabilitation (pat.: F. E., see table 2).

Table 3. Criteria of physical performance

(1) Aerobic power ($\dot{V}_{O_2}$ l, ml/kg b. w., O_2-pulse) and adaptation to increasing work rates
(2) Anaerobic power (kcal, cal/kg b. w., %)
(3) Tolerance of metabolic acidosis (pH, BE)

on the other hand. As the deviations of the respiratory minute volume and of the oxygen uptake from standard values are rated by means of computer-assisted evaluation of ergospirometric parameters, it is more likely to detect these abnormal reactions.

Stress-testing in patients with coronary heart disease is mainly used to ascertain symptoms and electrocardiographic signs of myocardial ischemia. Additionally, informations will be available to plan physical rehabilitation programs individually if physical performance is assessed in quantitative terms.

Fig. 13 illustrates the response to symptom-limited work in a 54-year-old man suffering from coronary heart disease (inferior myocardial infarction; regular training): The patient had to stop cycling, partly due to electrocardiographic signs of marked ST-depression and partly due to plateauing of $\dot{V}_{O_2}$. The patient did not complain either about chest pain or about dyspnea at a work rate of 125 watts (80 % of predicted maximal load). Referring to work load and output tolerated, oxygen uptake stays behind and anaerobic power is found to be elevated (12.8 kcal; 206 cal/kg body wt.; 30.6 %), suggesting the hypodynamic circulation revealed by hemodynamic investigations during steady-state exercise (see tab. 2). It is assumed that this patient has achieved the upper limit of work capacity obtainable by physical training.

Abbreviations

BE	base excess (mep/l)
delta BE	difference between resting and post exercise BE
BP_{syst}	systolic blood pressure (mm Hg)
D_{av}	arterio-venous oxygen difference (Vol. %)
FAI %	functional aerobic impairment
f_h	heart rate (beats/min)
f_r	respiratory rate (breath/min)
O_2-P	oxygen pulse (ml/beat)
PER	perceived exertion rate (rate score 6–20)
RQ	respiratory quotient
SV	stroke volume (ml)
t_{tot}	duration of total work (min)
$\dot{V}_E$	exspiratory volume (l/min BTPS)
$\dot{V}_{O_2}$	oxygen uptake (l/min STPD)
$\dot{V}_{O_2\ 1st\ min,\ 2nd\ min}$	oxygen uptake related to the second and fourth 0.5-min period of a two-minute duration work load (rectangular-triangular exercise test)
Wl_{max}	highest work load tolerated (watts)
Wl_{tot}	work output; total amount of work performed (watts × min)

Zusammenfassung

Mittels standardisierter rektangulär-triangulärer Fahrradergometrie können neue Aspekte für leistungsphysiologische Untersuchungen gewonnen werden. Im Gegensatz zu Belastungstests mit Steady-state-Bedingungen wird bei diesem Testverfahren zu jeder zweiten Minute die Belastungsintensität erhöht, bis der Proband symptomlimitiert ausbelastet ist. Neben der Analyse einfacher Parameter (tolerierte Belastungsstufe, Herzfrequenz, Blutdruck, Ekg, Ermüdungsgrad und subjektive Beschwerden) ergeben sich durch die rechnerunterstützte Auswertung und Bewertung von ergospirometrischen Meßwerten unter rektangulär-triangulärer Belastung folgende Vorteile: 1. Der Test ist von kurzer Dauer (8–14 min), 2. auch nach erschöpfender Belastung erholen sich die Probanden rasch, 3. die Bestimmung der maximalen Sauerstoffaufnahme wird wahrscheinlich, da die Abflachung der $\dot{V}_{O_2}$-Kurve beobachtet werden kann, 4. das Verhalten kardio-respiratorischer Parameter unter einer ansteigenden Belastung wird einer Bewertung zugänglich (Adaptation), 5. bereits während des Arbeitsversuches können die Anteile der aeroben und anaeroben Energiebereitstellung quantitativ erfaßt werden, 6. die Untersuchungsergebnisse sind ausgezeichnet reproduzierbar, und 7. Normalwertsbereiche für die Beziehungen zwischen dem Anstieg der Herzfrequenz und des systolischen Blutdruckes, dem Atemminutenvolumen, der Sauerstoffaufnahme und der anaeroben Energiebereitstellung und der Belastungsintensität bzw. geleisteten Arbeit wurden erstellt.

Software-Programme wurden entwickelt, um Abweichungen gemessener Parameter vom Sollwertsbereich als Vielfaches der Standardabweichung der jeweiligen Regressionsgeraden on line zu erfassen. Im besonderen erlaubt die kontinuierliche Messung der O_2-Aufnahme über halbminütige Perioden eine Aussage über die Anpassung des kardiozirkulatorischen Systems an eine ansteigende Belastung.

Aus der Differenz des Energiebedarfes für die durch zwei Minuten aerob zu tolerierende Belastungsstufe und der aktuellen Sauerstoffaufnahme über dem Ruhebedarf wird ein Index für die anaerobe Energiebereitstellung und deren prozentueller Anteil am gesamten Energiebedarf am Ende jeder Belastungsstufe kumulativ errechnet (untrainierte Normalpersonen: 200–300 cal/kg KG; Sportler 350–500 cal/kg KG). Der Basen-Überschußwert als Parameter der metabolen Azidose weist eine enge Beziehung zu diesem unblutig und noch während der Untersuchung bestimmbaren Index der anaeroben Energiebereitstellung auf. Mit Hilfe der rechnerunterstützten Analyse ergospirometrischer Meßwerte unter rektangulär-triangulärer Belastung ergeben sich neue Möglichkeiten, die körperliche Leistungsfähigkeit und deren limitierende Faktoren bei Normalpersonen, Trainierten und Patienten umfassend zu beschreiben. Der Untersuchungsleiter wird die anfallenden Daten mit seiner persönlichen Erfahrung in ein Feedback-System zur Steuerung der Belastung integrieren, wodurch auch bei Risikopatienten der Untersuchungsablauf sicher gestaltet werden kann.

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