

The Computer Based Measuring and Evaluating System for Cardiopulmonary Exercise Testing

Milan Stork

Department of Applied Electronics
Faculty of Electrical Engineering, University of West Bohemia
P.O.Box 314, 30614 Plzen
Czech Republic
stork@kae.zcu.cz

Abstract – Exercise testing offers the investigator the possibility of simultaneously studying the cellular, cardiovascular and ventilatory systems responses under conditions of precisely controlled stress. Exercise tests in which gas exchange is not determined cannot realistically evaluate the ability of the cardiovascular and ventilatory systems to perform their common major function, i.e., gas exchange with cells. Exercise testing with appropriate gas exchange measurements can also serve to grade the adequacy of cardiorespiratory function. This is of significant practical impact because of the increased number of therapeutic options now available for conditions that cause exercise limitation. Moreover, an individual patient may have mixed defects (e.g., cardiac and respiratory), and consequently, it is often necessary to determine the relative contribution of each to the patient's symptoms. Exercise testing can also provide vital information regarding the limits of systemic function before surgery or other therapy. Heart rate, pulmonary ventilation, breathing frequency and blood pressure are automatically measured during the examination. Also amount of oxygen and carbon dioxide are measured in patient breath and load is also set by computer. From these data, many of other standard parameters are calculated by means of personal computer. In this paper, the system for automatic cardiopulmonary examination measuring and evaluating is described. Application of this system is possible in work medicine, sport medicine and rehabilitation. Furthermore it allows for the analysis of training or rehabilitation effects, of drug effects as well as of technical applications (for example setting of cardiac pacemakers).

1. INTRODUCTION

Physical exercise testing requires the interaction of physiologic mechanism that enable the cardiovascular and respiratory systems to support the increased energy demands of contracting muscles. Both systems are consequently stressed during exercise. Their ability to respond adequately to this stress is a measure of their physiologic competence (or "health"). An appreciation of the normal response profiles of the gas transport systems that support cell respiration is essential to recognize the abnormal response patterns that characterize the many disease states that affect them. The increased metabolic rate during exercise requires an appropriate increase in O₂ flow into the muscles. Simultaneously, the CO₂ produced by the muscles must be removed to avoid severe tissue acidosis with its adverse effects on cellular function. To satisfy the increased gas exchange needs of the muscle cell during exercise, precise coupling of the supporting physiologic mechanism is required. This involves the lungs, the pulmonary circulation, the heart, and the peripheral circulation. A treadmill or bicycle ergometer permits a controlled and reproducible exercise stress.

Because the subject is relatively stationary, blood pressure and heart rate may be obtained repeatedly, and a continuously monitored electrocardiogram (ECG) incorporating 1, 3 or 12 leads may be used. Expired minute ventilation is determined using a pneumotachograph or other type of in-line flow or volume measurement device. The breath by breath measuring system is used for expired gas, which is sampled and analyzed for O₂ and CO₂ concentrations. Differences in O₂ and CO₂ concentrations from the beginning to the end of each breath are smoothed, and the resultant O₂ and CO₂ concentrations are equal to the volume-weighted average concentrations or "mixed expired" O₂ and CO₂ concentrations [1]. For noninvasively physical load response investigation, 2 cardiopulmonary data measuring systems (ECG measuring - not included) were developed:

a) The **KARD** is a system for exercise testing which is used in laboratory.

b) The **TELEKARD** is a telemetric portable exercise testing system that allows monitor cardiopulmonary function in laboratory as well as in the field (sport medicine, rehabilitation etc.).

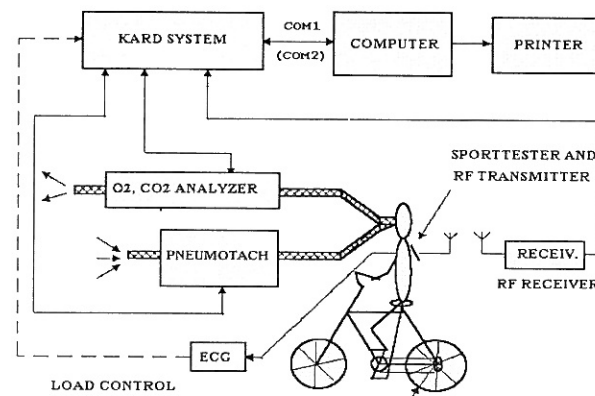


Figure 1. The laboratory KARD system for stress test. KARD system is based on MC68HC11 microcontroller. If needed, ECG can be connected for heart rate measuring.

For data evaluating, the program **KONSIL** was developed. The program is the same for booth system. In Figure 1, the KARD system is shown. This is a "wire connected" system.

In Figure 2, the block diagram of the **TELEKARD** system is drawn. This is a "wireless" device. The equipment is composed of a unit (carried by the object) which transmits the measured data to a receiver in real time. The receiver is connected to personal computer (PC) which shows the information on the display, evaluates,

memorizes and prints data.

The turbine with digital output is used for ventilation measuring. The heart rate meter SPORTTESTER is used for heart rate measuring [2] and information is wireless transmitted.

The following devices are used for TELEKARD system:

- Flow - turbine flow meter, 26 mm, VE range 10 - 250 l/min.
- %O₂ Expiratory - Zirconia oxygen sensor, range 0 to 100%.
- %CO₂ Expiratory - Infrared carbon dioxide sensor, 0 - 10 % CO₂, dual detector technology.
- Heart pulse - heart rate meter SPORTTESTER is used.
- Pressure sensor - differential dual ports integrated silicon pressure sensor on chip signal conditioned, temperature compensated and calibrated is used.
- Temperature sensor - digital thermometer and thermostat DS1620 is used for external temperature measuring.
- Pump - micro diaphragm gas sampling pump is connected to a gas analyzer.

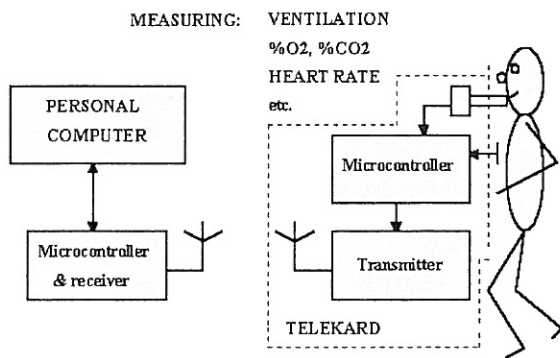


Figure 2: The TELEKARD system. The wireless data transmission (433 MHz) is used.

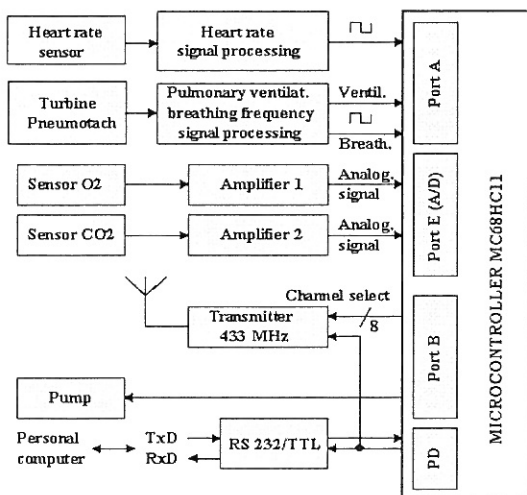


Figure 3: Block diagram of the TELEKARD system.

The signals a) - f) are processed in MC68HC711E9 microcontroller and for telemetric system are transmitted via a FM transmitter to a receiver, where they are being elaborated and presented to the user using PC [11, 14]. The blocks of 32 bytes are multiply transmitted for error removing. The sampling frequency is 5 sec. The FM

transmitter used has 138 channels, 12,5 kHz spacing, RF output 10 mW. The receiver has the same working frequencies, 138 channels digitally adjustable. During the test, the data are also stored in serial EEPROM memory and they can be read at the end of the examination. This is important in case the connection between the transmitter and the receiver is lost during the examination. In Figure 3 there is a block diagram of the TELEKARD [17].

II. COLLECTING AND ANALYZING PHYSIOLOGIC DATA DURING THE STRESS TEST

During the exercise testing the KARD or TELEKARD acquires the following main signals: Heart frequency, Flow, %O₂ Expiratory, %CO₂ Expiratory. These signals are processed in PC - KONSIL software [12]. The standard parameters calculated by the program are shown in Table I.

TABLE I

LIST OF CALCULATED PARAMETERS

Symbol	Name	Units
VE	Ventilation	l/min, BTPS
RF	Respiratory frequency	1/min
Vt	Tidal volume	l, BTPS
VO ₂	Oxygen uptake	l/min, STPD
VCO ₂	Production of CO ₂	l/min, STPD
FeO ₂	mixed expired O ₂	%, dry
FeCO ₂	mixed expired CO ₂	%, dry
HR	Heart rate frequency	bpm
RQ	Respiratory quotient	---
VE/VO ₂	Ventilatory Equiv. for O ₂	---
VE/VCO ₂	Ventilatory Equiv. for CO ₂	---
VO ₂ /HR	Oxygen pulse	ml/bpm
VO ₂ /Kg	VO ₂ per Kg	ml/min*Kg
VO ₂ peak	Maximum value VO ₂	ml/min, STPD
VEmax	Maximum value VE	l/min, BTPS
HRmax	Maximum value HR	bpm
VO ₂ /HRmax	Max. value VO ₂ /Max. HR	ml/bpm
RFmax	Maximum value RF	1/min

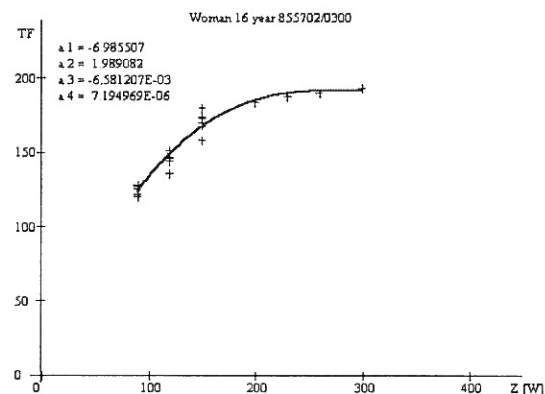


Figure 4: Example of polynomial least-squares approximation.

Graph: Heart rate frequency = f(load).

$$\text{Heart rate} = -6.98 + 1.989 \cdot L - 6.58 \cdot 10^{-3} \cdot L^2 + 7.19 \cdot 10^{-6} \cdot L^3 \quad (L = \text{Load [W]})$$

The measured data are digitally filtered and stored in main table every 30 sec. The user can edit the data acquired during the test, or after the test. All measured data and personal data of the patient are stored in Microsoft

database (*.MDB). The program can display and print many types of protocols and graphs. The curve can be filtered by least-squares data smoothing. The program KONSIL enables to find automatically some important value from the data measured [15].

In some cases, the models of different functional dependencies are also important. In most of the graphs the functional dependencies based on polynomial least-squares (LMS) are used and coefficients are displayed. This function is useful mainly for sport testing (comparing different types of load). Example is shown in Figure 4.

Another model of heart rate dependence on physical load is introduced in the Figure 5. The model was developed for four groups of people: with average physical conditions, athletes, patients with ischemic heart disease and patients after atropin administration.

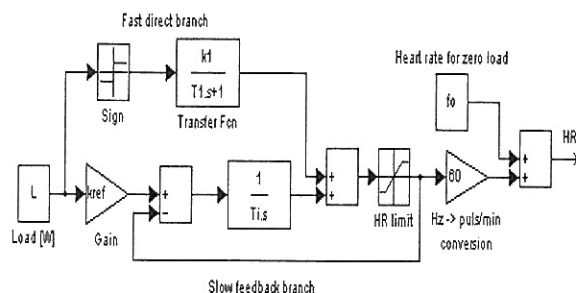


Figure 5. Model of heart rate dependence on physical load

One of the most important value is anaerobic threshold (Lactate threshold) [3]. The anaerobic threshold is defined as the level of exercise VO_2 above which aerobic energy production is supplemented by anaerobic mechanism and is reflected by increase in lactate and lactate/pyruvate ratio in muscle or arterial blood. As within this threshold range various physiological variables like pH and standard bicarbonate change rapidly and the O_2 breathing equivalent is lowest, it is often called an aerobic-anaerobic transition where different metabolic and ventilatory thresholds can be defined [5]. In steady-state below the anaerobic threshold, no anaerobic mechanism support bioenergetics, and the O_2 debt has reached a maximum. Constant work rate exercise performed at a level above the anaerobic threshold results in delay or an inability to reach a constant VO_2 . It is relatively easy to detect the development of cellular lactic acidosis by measuring the rate of increase in VCO_2 relative to that of VO_2 during a progressively increasing exercise test. Statistical regression method was used [3]. Sue et al. [4] simplified the method, observing that the VCO_2 versus VO_2 relationship below the threshold had a slope consistently at a slightly less than 1.0, and that the slope changed to a value greater than 1.0 above the anaerobic threshold. The program KONSIL has a possibility to detect anaerobic threshold based on V-slope method. Above threshold, the increase in lactic acid production results in an acceleration of the rate, of increase in VCO_2 relative to VO_2 . When these variables are plotted against each other, the relationship is composed of two apparently linear components, the lower of which has slope of slightly less than 1.0, whereas the upper component has a slope steeper than 1.0. The intercept of these two slopes is lactate threshold (LT), shown in Figure 6.

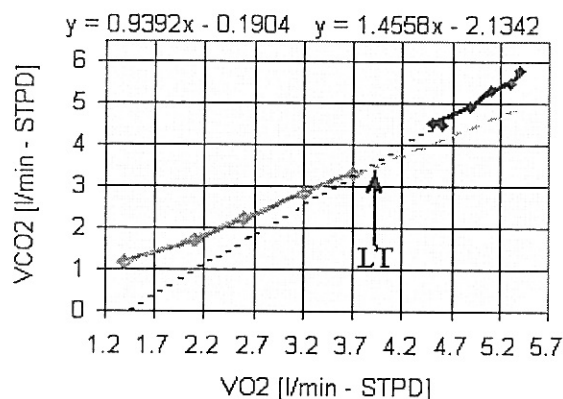


Figure 6. Example of V-slope method for anaerobic threshold = LT (Lactate Threshold) location. VCO_2 as a function of oxygen uptake (VO_2). Regression equations are: a) $VCO_2 = 0.939 * VO_2 - 0.191$ b) $VCO_2 = 1.456 * VO_2 - 2.134$ Anaerobic threshold (LT) from this equations is: $VO_2 = 3.76$, $VCO_2 = 3.34$

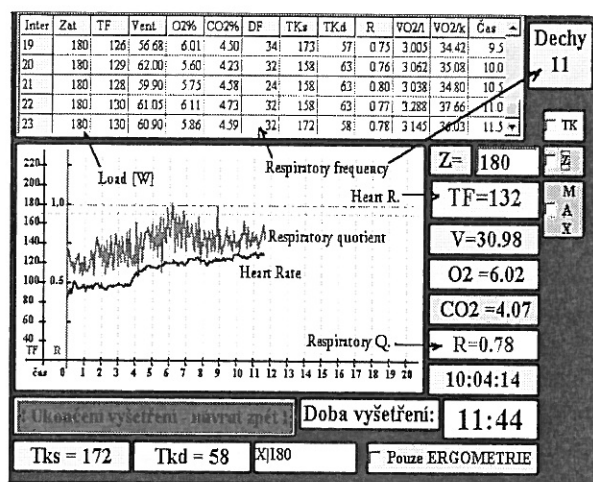


Figure 7. The screen during the real time measuring. The graphs of heart rate and respiratory quotient are displayed.

In Figure 7, the screen copy of real time stress test is shown. The measured data are stored in a main table every 30 sec, but every 1 sec on hard disc file.

The KARD system and software is possible to use treadmill or bicycle ergometer. While in Great Britain and US treadmill ergometers are primarily used, in Germany, Austria, Switzerland and Czech Republic bicycle ergometers are preferred [10]. Treadmills have some advantages over cycle ergometers. A subject performing on a treadmill generally has a maximum VO_2 approximately 5 to 10 % higher than on cycle ergometer. Some subject and patients are simply not able to cycle because of problems of coordination. On the other hand, treadmills require more space than a cycle ergometer, demand extra caution during testing, and may introduce movement artifacts in measurements of ventilation and pulmonary gas exchange. Because work rate can only be approximated from body weight, speed and grade, oxygen uptake measurements are highly desirable during exercise. Work efficiency during treadmill walking cannot be precisely determined because of the difficulty in estimating work rate. Cycle ergometers enable one to make precise estimation of the work rate. Advantages of the cycle ergometer over the treadmill include the ability to vary the

work rate in step, incremental, or ramp fashion, smaller size and potentially greater safety [6, 7, 8, 9].

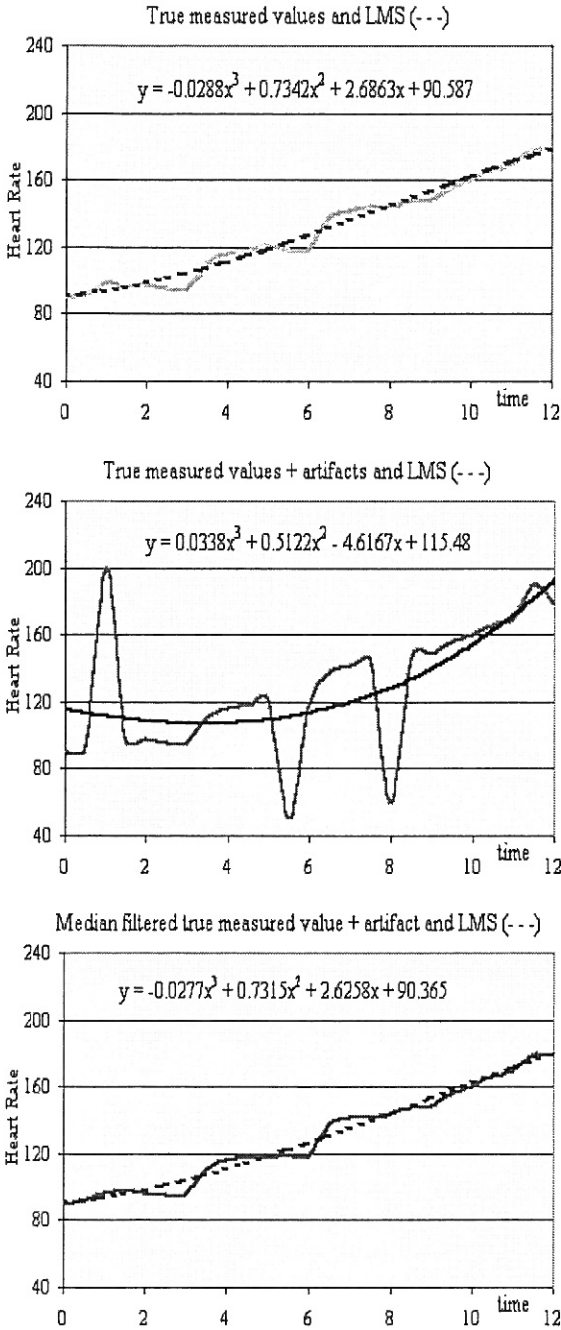


Figure 8. Example of artifact filtration by polynomial least-squares (3 order) and median filter $L=5$.
Top - Measured values without artifacts
Middle - Measured values + artifacts and values filtered by LMS
Bottom - Measured values + artifacts after filtration by median filter and LMS

III. ARTIFACT FILTRATION

During exercise, measuring of heart rate, ventilation and gas exchange have additional potential problems, especially movement artifact. The measured values can be filtered by least-squares (LMS) data smoothing or by nonlinear median filter, or by combination of both algorithm.

Median filtering is a popular method of noise removal,

employed extensively in applications involving speech, signal and image processing. This non-linear technique has proven to be a good alternative to linear filtering as it can effectively suppress impulse noise while preserving edge information.

The standard median (SM) filter is a simple nonlinear smoother that can suppress noise while retaining sharp sustained changes (edges) in signal values. It is particularly effective in reducing impulsive-type noise [16]. The output of SM filter at a point is the median value of the input data inside the window centered at the point. If is $\{x(k) \mid 1 \leq k \leq L\}$ and $\{y(k) \mid 1 \leq k \leq L\}$, respectively, the input and output of the one-dimensional (1-D) SM filter of window size $2N + 1$, then

$$y(k) = \text{med}\{x(k-N), \dots, x(k-1), x(k), x(k+1), \dots, x(k+N)\} \quad (1)$$

Here to account for startup and end effect, $x(1)$ and $x(L)$, respectively, are repeated N times at the beginning and at the end of the input.

The recursive median (RM) filter is a modification of the SM filter defined in (1x). Specifically, the output $y(k)$ of the RM filter of size $2N + 1$ is given by

$$y(k) = \text{med}\{y(k-N), \dots, y(k-1), x(k), x(k+1), \dots, x(k+N)\} \quad (2)$$

At the beginning of the filtering, it is assumed that $y(1-N) = \dots = y(0) = x(1)$; the end effect is considered as a SM filtering. RM filtering can extract signal roots better than SM filtering, and is useful alternative to SM filtering in some applications. In general, RM filters are implemented by modifying an SM filtering algorithm [16] and, as a consequence, the implementation of RM filters is computationally and structurally more complex than that of SM filters.

The weighted median filter is a generalization of the SM filter, where a nonnegative integer weight is assigned to each position in the filter window.

Definition: For the discrete-time continuous-valued input vector $x = [x_1, x_2, \dots, x_R]$, the output y of the weighted median filter of span N associated with the integer weights

$$w = [w_1, w_2, \dots, w_R] \quad (3)$$

is given by

$$y = \text{MED}[w_1 \diamond x_1, w_2 \diamond x_2, \dots, w_R \diamond x_R] \quad (4)$$

where $\text{MED}[\cdot]$ denotes the median operation and \diamond denotes duplication, i.e.:

$$p \diamond x = \overbrace{x, x, \dots, x}^{p \text{ times}} \quad (5)$$

Frequency analysis and impulse response have no meaning in median and rank order filtering. The impulse response of a median filter is zero. As a result, new tools had to be developed to analyze and characterize the behavior of these nonlinear filters, deterministically and statistically. The basic descriptor of the deterministic properties of median filters is their root signal set, that is a set of signals which are invariant to further filtering [3]. The basic statistical descriptor of median filters is the set of output distributions which are used to study the noise attenuation properties of median filters.

In Figure 8 is example of filtering heart rate frequency data with artifact. From this figure can be seen, that filtration by simple median filter is very effective for artifacts suppression.

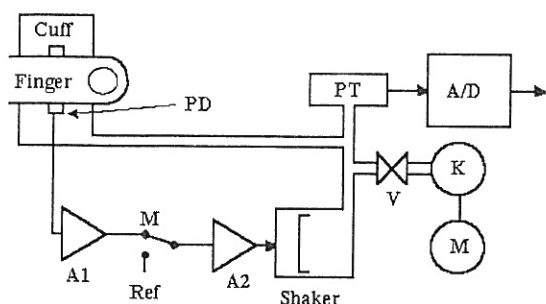


Figure 9. Simplified block diagram of measuring system

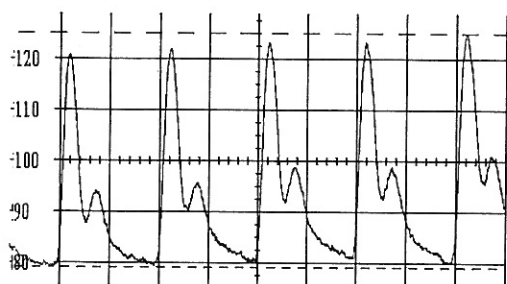


Figure 10. Example of continuous non-invasive blood pressure measuring result.

IV. CONTINUOUS INDIRECT ARTERIAL BLOOD PRESSURE MONITORING

Non-invasive continuous measurement of blood pressure (after stress test) is based on the method, defined for the first time by J. Penaz in 1973 [18]. The technique is based on the concept that if an externally applied pressure in the cuff is equal to the arterial pressure at all times, the vascular blood volume in the finger is constant. It is valid in condition that the cuff pressure is pre-set at a reference value corresponding to the unloaded vascular volume. The block diagram is shown on Figure 9.

Basic part of the measurement system is photoelectric plethysmograph. It consists of the LED diode shining through the finger and a photodiode detecting the light changes. It is equipped with a transparent inflatable cuff on the human finger, which is controlled by a servocontrol loop. Plethysmographic signal represents blood volume changes in the finger, is processed and either displayed as plethysmogram, or at the same time fed in the servo-control system [19].

Example of continuous, blood pressure measuring result is shown in Figure 10.

V. PRACTICAL STRESS TEST RESULTS

The system's noninvasive nature and ease of use makes it ideally suited for clinical situations where monitoring of cardiovascular and ventilatory systems responses under conditions of precisely controlled stress is desirable. Exercise testing with appropriate gas exchange measurements can also serve to grade the adequacy of cardiorespiratory function and can benefit from the convenience of this simple, inexpensive test. From measured data, many of standard parameters are calculated by means of computer.



Figure 11. The KARD system with mask, ventilation and heart rate sensor and gas analyzer. KARD box size: 300 x 270 x 110 mm, weight: 2.2 kg.



Figure 12. The photo of cardiopulmonary exercise testing in laboratory

In Figure 11, the KARD system with face mask, ventilation and heart rate sensor is shown. In Figure 12, the photo of stress test during cardiopulmonary exercise on bicycle ergometer is shown. For heart rate measuring, the Sporttester (POLAR belt) is used.

VI. CONCLUSION

Exercise testing using treadmill or bicycle is easy to administer, non-invasive and acceptable to the patient, yet the results of an integrative cardiopulmonary exercise test yield significant insight into the physiological state of the patient. A properly administered exercise test allows the objective and quantitative assessment of the patient's performance, reserves and limits that are necessary to make a correct differential diagnosis and institute appropriate therapy.

The new KARD system is used in functional laboratory, medical faculty of Charles university in Plzen, Czech Republic. The programs and systems for automatic stress testing have been developed in cooperation with doctors for more than 15 years and is used in approx. 20 hospitals. They enable to test on bicycle or treadmill ergometer.

The intelligent KARD system can automatically set (during the examination):

a) Load as a result of HR and respiration quotient.

- b) Find single or mixed defect (cardiac and respiratory)
- c) Find lactate threshold

The intelligent KARD system can automatically recommend and evaluate (after the examination):

- d) On the basis of testing results the program enables selecting alternatives of long-term physical activity that optimally suits each individual.
- e) Statistical evaluating of group athletes or patients or evaluating repeated examination of one patient.

Only a small part of the program KONSIL was shown in this contribution. The telemetric system TELEKARD for functional diagnosis is in development.

VII. ACKNOWLEDGMENT

This research work has been supported by grant MSM 232200008

VIII. REFERENCES

- [1] K. Wasserman, et al., *Principles of Exercise Testing and Interpretation*, Lea & Febiger, ISBN 0-8121-1634-8, 1994
- [2] *Heart Rate Monitoring and Exercise*, Journal of Sport Sciences, Vol. 16, ISSN 0264-0414, summer 1998.
- [3] Beaver et al., *A new method for detecting the anaerobic threshold by gas exchange*, Journal of Applied Physiol., 1986, 60:2020-2027.
- [4] Sue et al., *Metabolic acidosis during exercise in patients with chronic obstructive pulmonary disease*, Chest, 1988, 94:931-938.
- [5] W. L. Eschenbacher, A. Mannina, *An algorithm for the interpretation of cardiopulmonary exercise tests*, Chest, 1997, pp. 263-267.
- [6] J. Kobashigawa, D. Leaf, N. Lee, M. Glesson, H. Liu, M. Hamilton, J. Moriguchi, N. Kawata, E. Herlihy, *A controlled trial of exercise rehabilitation after heart transplantation*, N. Engl Journal of Med, 340/4, 1999, 272-277.
- [7] H. Lollgen, J. U. Winter, E. Erdmann, *Ergometrie*, Springer-Verlag Berlin Heidelberg, 1995.
- [8] M. Metra, P. Fafgiano, A. D'Aloia, S. Nodari, A. Gualeni, D. Roccagni, L. Cas, *Use of cardiopulmonary exercise testing with hemodynamic monitoring in the prognostic assessment of ambulatory patients with chronic heart failure*, Journal of Am Coll Cardiol 33/4, 1999, 943-950.
- [9] N. I. Coplan et al., *Comparison of submaximal treadmill and supine bicycle exercise*, Amer. Heart Journal. 128, 1994, 416-418.
- [10] *Erich Jaeger Info*, Erich Jaeger GmbH & Co, KG, 2nd Edition, 1999.
- [11] M. Stork, "Wireless Data Transmission for Spiroergometric Exercise Testing" in *Proceedings of University of West Bohemia, Vol 2/1998*, ISSN 1211-9652, ISBN 80-7082-478-6, 1998, pp.141-152.
- [12] M. Stork, "The System for Spiroergometric Data Measuring and Evaluation" in *Proceedings of Measurement 2001*, ISBN 80-967402-5-3, EAN 9788096740253, 2001, pp. 305-308.
- [13] M. Stork, *Hardware and Software for Spiroergometric Examination*, Medicina Sportiva Bohemica & Slovaca, ISSN 1210-548, Vol. 10, No.2, 2001.
- [14] M. Stork, "Telemetry System for ECG and Spiroergometric Data Transmission and Evaluation" in *Proceedings of SCS 2001, Internal Symposium on Signal Circuits and Systems*, Iasi, Romania, ISBN 973-8050-99-5, July 10-11 2001, pp. 137-139.
- [15] M. Stork, "The Hardware and Software for Cardiopulmonary Exercise Testing" in *Proceedings of SIMBIOSIS 2001, VI International Conference*, ISBN 80-214-0893-6. Poland, 2001, pp. 149-154.
- [16] M. Stork, "Median Filters For Some Artifacts And Impulse Noise Filtering" in *Proceedings of 16-th Biennial International Eurasip Conference Biosignal 2002*, Brno, ISSN 1211-412X, ISBN 80-214-2120-7, 2002, pp. 126-128.
- [17] M. Stork, "The Laboratory and Telemetry systems for Cardiopulmonary Exercise Testing" in *Proceedings of IFMBE, 2 nd European Medical and Biological Engineering Conference, EMBEC '02*, Vienna, Austria, ISBN 3-901351-62-0, Part 1, December 2002, pp. 518-519.
- [18] J. Penaz, "Photoelectric Measurement of Blood Pressure, Volume and Flow in the Finger" in *Proceedings of 10th International conference on Medical and biological Engineering*, Dresden, 1973.
- [19] M. Stork, P. Holejskova "Continuous Indirect Arterial Blood Pressure Monitoring and Evaluating" in *Proceedings of 16-th Biennial International Eurasip Conference Biosignal 2002*, Brno, ISSN 1211-412X, ISBN 80-214-2120-7, pp. 138-140.

APPENDIX

Interpretation hints for cardiopulmonary exercise testing

Heart rate - Healthy subject and patients with limited cardiac capacity only have a small (<25%) or even no reserve (maximal heart rate: 220 - age).

Breathing frequency - Rarely exceeds 50/min; higher values indicate a restrictive ventilatory disorder.

Oxygen pulse - Low, age-corrected value indicates limited cardiac capacity or insufficient training condition (direct correlation to stroke volume).

Oxygen uptake - Global criterion for cardiopulmonary capacity (depending on weight, training condition and genetic disposition).

Tidal volume - In presence of a restrictive lung disease, tidal volume almost reaches inspiratory vital capacity.

Respiratory quotient (RQ) - RQ > 1.0 indicates that exercise exceeds the anaerobic threshold. RQ > 0.8 at the start of exercise; suspected hyperventilation - no Steady-State condition.

Anaerobic threshold - Values < 43 % of the age-dependent maximal O₂ uptake indicate a left ventricular dysfunction. Values not reaching the anaerobic threshold may be due to pulmonary or muscular limitations or lack of motivation.