CARDIOPULMONARY EXERCISE TESTING SYSTEM FOR MEDICINE, FITNES AND REHABILITATION

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ABSTRACT

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"). The increased metabolic rate during exercise requires an appropriate increase in O_2 flow into the muscles. Simultaneously, the CO_2 produced by the muscles must be removed. Heart rate, pulmonary ventilation, breathing frequency and blood pressure are measured during the examination. From these data, many of other standard parameters are calculated. 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.

I. INTRODUCTION

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 [1, 3-9].

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 noninvasively measured during the examination. Also amount of oxygen and carbon dioxide are measured in patient breath. From these data, many of other standard parameters are calculated by means of computer. In this paper, the systems for automatic measuring and evaluating are described. Application of these systems is possible in work medicine, sport medicine and rehabilitation.

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 pneumotachorgaph or other type of in-line flow or volume measurement device. Expired gas is then passed into mixing chamber from which gas is sampled and analyzed for O_2 and CO_2 concentrations. Differences in O_2 and CO_2 concentrations from the beginning to the end of each breath are smoothed, and the resultant O_2 and CO_2 concentrations are equal to the volume-weighted average concentrations or "mixed expired" O_2 and CO_2 concentrations.

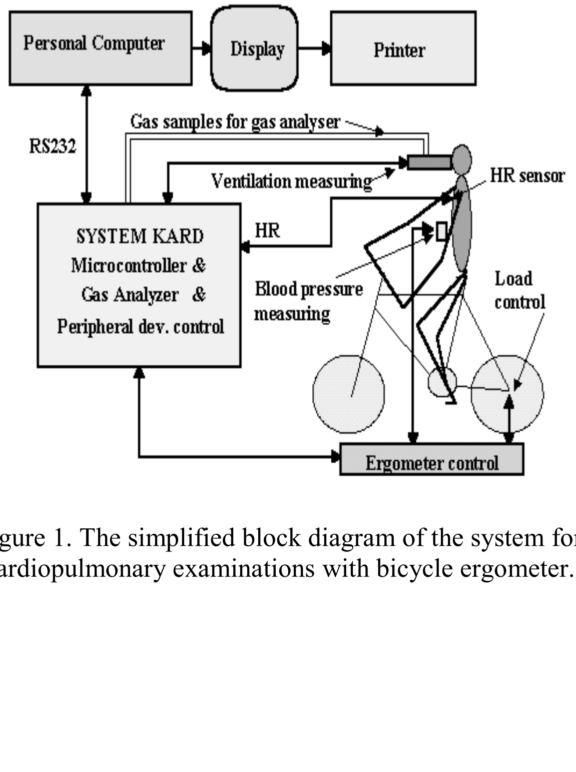

Figure 1. The simplified block diagram of the system for cardiopulmonary examinations with bicycle ergometer.

II. MATERIALS AND METHODS

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.).

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 [10-17].

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 (POLAR belt) is used for heart rate measuring [2] and information is wireless transmitted.

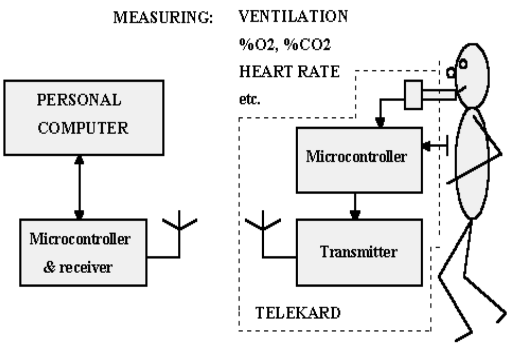

Figure 2. The TELEKARD system. The wireless data transmission is used.

The following devices are used for KARD system:

a) Flow - turbine flow meter, 26 mm, VE range 10 - 250 l/min.
b) % O_2 Expiratory - Chemical oxygen sensor, range 0 to 100%.
c) % CO_2 Expiratory - Infrared carbon dioxide sensor, 0 - 10 % CO_2, dual detector technology, 45 x 60 x 35 mm).
d) Heart pulse - heart rate meter SPORTTESTER is used.
e) Pressure sensor - differential dual ports integrated silicon pressure sensor on chip signal conditioned, temperature compensated and calibrated [2] is used.
f) Pump - micro diaphragm gas sampling pump is connected to a gas analyzer.
g) ER900 bicycle ergometer operating in load range from 20 to 900 watts and additionally provides an integrated blood pressure measurement. This ergometer allows to transfer data via analog or digital interfaces (RS232) [10].
h) The treadmill ergometer can be used as a good alternative to the more common bicycle ergometer.

The similar components are used for TELEKARD system. The KARD system, Figure 3. collect physiologic data and transfer it every 1 sec to personal computer. The KARD system collect physiologic data and transfer it every 1 sec to personal computer. The blood pressure is measuring, sampling frequency is 120 sec during submaximal load and 60 sec during maximal load. Electrocardiograms (ECG) are measured for monitoring purposes. The most expensive part in the KARD is O_2 and CO_2 gas sensors. Both these sensors measure partial pressure of the gas and therefore are affected by water vapor, pressure in the sampling gas systems, and changes in barometric pressure and altitude. The effect of temperature and pressure can be eliminated, by applying correction using the ideal gas law.

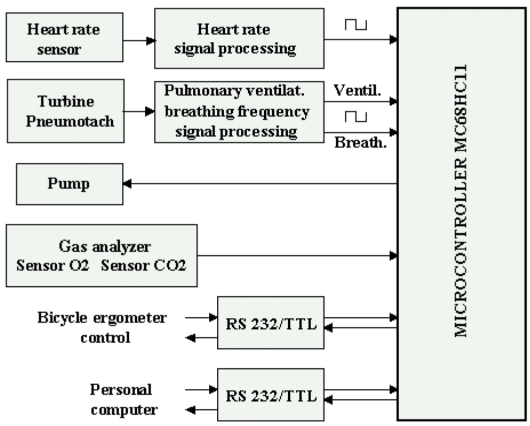

Figure 3. The simplified block diagram of the KARD system.

III. RESULTS

During the exercise testing the KARD or TELEKARD acquires the following main signals: Heart frequency, Flow, % O_2 Expiratory, % CO_2 Expiratory. These signals are processed in PC - KONSIL software [6]. The standard parameters calculated by the program are the following:

Symbol	Name	Units
VE	Ventilation	l/min, BTPS
RF	Respiratory frequency	1/min
Vt	Tidal volume	l, BTPS
VO2	Oxygen uptake	l/min,STPD
VCO2	Production of CO_2	l/min, STPD
FeO2	mixed expired O_2	%, dry
FeCO2	mixed expired CO_2	%, dry
HR	Heart rate frequency	bpm
RQ	Respiratory quotient	---
VE/VO2	Ventilatory Equiv. for O_2	---
VE/VCO2	Ventilatory Equiv. for CO_2	---

VO2/HR	Oxygen pulse	ml/bpm
VO2/Kg	VO2 per Kg	ml/min*Kg
VO2peak	Maximum value VO2	ml/min, STPD
VEmax	Maximum value VE	l/min, BTPS
HRmax	Maximum value HR	bpm
VO2/HRmax	Max. value VO2/Max. HR	ml/bpm
RFmax	Maximum value RF	1/min

The measured data are stored in a table every 5 or 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.

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 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.

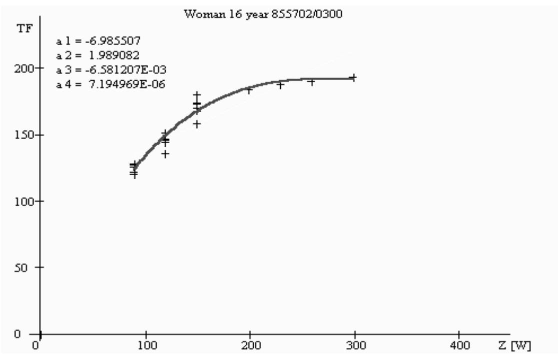

Figure 4. Example of polynomial least-squares approximation.
Graph: Heart rate frequency = f(load).
Heart rate = -6.98 + 1.989*L - 6.58E-3*L^2 + 7.19E-6*L^3 (L=Load [W])

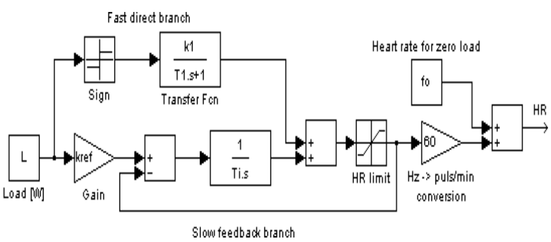

Figure 5. Model of heart rate dependence on physical load.

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, athlets, patients with ischemic heart disease and patients after atropin administration.

One of the most important value is anaerobic threshold (Lactate threshold) [1]. The anaerobic threshold is defined as the level of exercise VO2 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 O2 breathing equivalent is lowest, it is often called an aerobic-anaerobic transition where different metabolic and ventilatory thresholds can be defined [1]. In steady-state below the anaerobic threshold, no anaerobic mechanism support bioenergetics, and the O2 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 VO2. It is relatively easy to detect the development of cellular lactic acidosis by measuring the rate of increase in VCO2 relative to that of VO2 during a progressively increasing exercise test. Statistical regression method was used [3]. Sue et al. [4] simplified the method, observing that the VCO2 versus VO2 relationship below the threshold had a slope consistently at a slightly less then 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 VCO2 relative to VO2. When these variables are plotted against each other, the relationship is composed of two apparently linear components, the lower of witch 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.

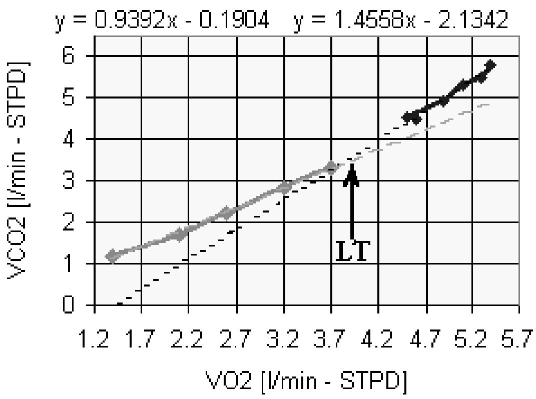

Figure 6. Example of V-slope method for anaerobic threshold = LT (Lactate Threshold) location. VCO2 as a function of oxygen uptake (VO2). Regression equations are: a) VCO2 = 0.939 * VO2 - 0.191
b) VCO2 = 1.456 * VO2 - 2.134
Anaerobic threshold (LT) from this equations:
VO2 = 3.76, VCO2 = 3.34

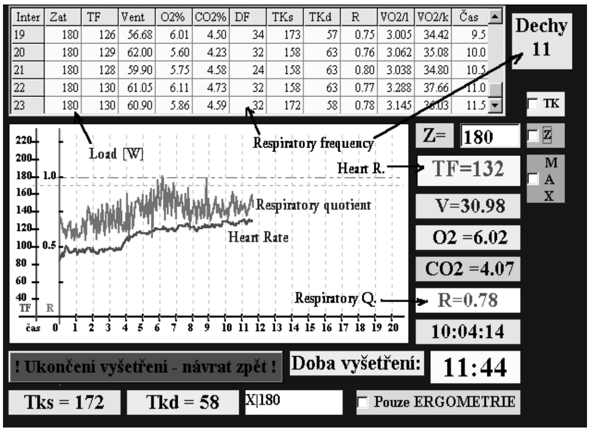

Figure 7. The screen during the real time measuring. The graphs of heart rate and respiratory quotient are displayed.

In Figure 7, the screen copy of real time stress test is shown. The measured data are stored in a table every 30 sec, or in special case, every 5 sec.

IV. DISCUSSION

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. In Figure 8, the KARD system with face mask, ventilation and heart rate sensor is shown. In Figure 9, the photo of stress test during cardiopulmonary exercise on bicycle ergometer is shown. For heart rate measuring, the Sporttester (POLAR belt) is used.

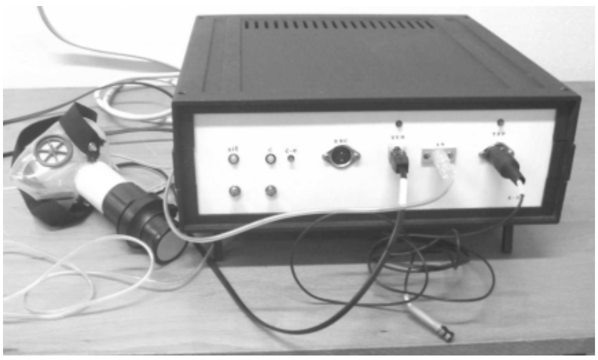

Figure 8. The KARD system with mask, ventilation and heart rate sensor and gas analyzer. KARD box size: 300 x 270 x 110 mm, weight: 2.2 kg.

V. 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 then 15 years and is used in approx. 20 hospitals. They enable to test on bicycle or treadmill ergometer.

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

Figure 9. The photo of cardiopulmonary exercise testing in laboratory.

ACKNOWLEDGMENT

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VI. 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., 60:2020-2027, 1986.
4. Sue et al., Metabolic acidosis during exercise in patients with chronic obstructive pulmonary disease, Chest, 94:931-938, 1988.
5. W. L. Eschenbacher, A. Mannina, An algorithm for the interpretation of cardiopulmonary exercise tests, Chest, 97, pp. 263-267, 1997

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, 272-277, 1999.
7. H. Lollgen, J. U. Winter, E. Erdmann, Ergometrie, Springer-Verlag Berlin Heidelberg, 1995.
8. M. Metra, P. Fafggiano, A. D'Aloia, S. Nodari, A. Gualeni, D. Roccagni, L. Cas, Use of cardiopulmonary exercise testing with hemodynanic monitoring in the prognostic assessment of ambulatory patients with chronic heart failure, Journal of Am Coll Cardiol 33/4, 943-950, 1999.
9. N. I. Coplan at al., Comparison of submaximal treadmill and supine bicycle exercise, Amer. Heart Journal. 128, 416-418, 1994.
10. Erich Jaeger Info, Erich Jaeger GmbH &Co, KG, 2nd Edition, 1999.
11. M. Stork, Wireless Data Transmission for Spiroergometric Exercise Testing, Proceedings University of West Bohemia, Vol 2/1998, s. 141-152, ISSN 1211-9652, ISBN 80-7082-478-6, 1998.
12. M. Stork, The System for Spiroergometric Data Measuring and Evaluation, Measurement 2001, Proceedings, ISBN 80-967402-5-3, EAN 9788096740253, pp. 305-308, 2001.
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, SCS 2001, Internal Symposium on Signal Circuits and Systems, Proceedings, Iasi, Romania, ISBN 973-8050-99-5, pp. 137-139, July 10-11 2001.
15. M. Stork, The Hardware and Software for Cardiopulmonary Exercise Testing, SIMBIOSIS 2001, VI International Conference Proceedings, ISBN 80-214-0893-6. Poland, pp. 149-154, 2001.
16. M. Stork, Median Filters For Some Artifacts And Impulse Noise Filtering, 16-th Biennal International Eurasip Conference Biosignal 2002, Brno, ISSN 1211-412X, ISBN 80-214-2120-7, pp. 126-128, 2002.
17. M. Stork, The Laboratory and Telemetry systems for Cardiopulmonary Exercise Testing, IFMBE Proceedings, 2 nd European Medical and Biological Engineering Conference, EMBEC '02, Vienna, Austria, ISBN 3-901351-62-0, Part 1, pp. 518-519, December 2002.

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 O_2 uptake indicate a left ventricular dysfunction. Values not reaching the anaerobic threshold may be due to pulmonary or muscular limitations or lack of motivation.