

Feasibility of mobile cardiopulmonary exercise testing

Adrian Attinger^a, Claudia Tüller^a, Tjeu Souren^b, Michael Tamm^a, Christian Schindler^c, Martin H. Brutsche^a

^a Pneumology, University Hospital Basel, Basel, Switzerland

^b VIASYS Healthcare GmbH, Hoechberg, Germany

^c Institute for social and preventive medicine, University of Basel, Basel, Switzerland

Summary

Questions under study: Evaluation of cardiopulmonary capacity and work ability is often done by cardiopulmonary exercise testing under laboratory conditions. Mobile CPET devices allow measurements under specific real-life conditions, ie at the patient's workplace. We investigated the feasibility and validity of mobile CPET in healthy controls.

Method: We compared oxygen uptake measured by mobile CPET (MCPET) with that by standard CPET (LCPET), and we compared oxygen uptake with markers of self-reported physical exhaustion. Twenty-two healthy subjects (15 male, 21–49 years) underwent LCPET and 6 outdoors 12-min running tests (MCPETs) at different intensities. Physical exhaustion and the time they could continue exercising (T_{EX}) was reported for each level. Standard descriptive statistics were applied.

Results: Of 132 MCPETs, performed in 22 sub-

jects, 128 (97%) were of suitable quality. The face-mask was well tolerated and nobody felt uncomfortable at any time. On average VO_2 [peak] was 21% (SD 9%) higher with MCPET compared to LCPET (median 3.60, range [2.22, 5.14] versus median 2.63, range [1.67, 4.16] $L \cdot \text{min}^{-1}$), but showed a strong correlation ($r^2 = 0.90$). MCPET- VO_2 at steady state correlated with subjectively rated physical exhaustion, and with TEX .

Conclusions: Out-of-laboratory MCPET was feasible, correlated with parameters of standard CPET, and correlated with markers of physical exhaustion. After validation in patients, MCPET could be used for a rational evaluation of cardiopulmonary capacity and work ability in selected patients.

Key words: cardiopulmonary exercise test; impairment; work ability; endurance; telemetry

Introduction

For the evaluation of cardiopulmonary capacity, work ability and prognosis of patients with proven or suspected cardiac or pulmonary diseases, resting measurements such as pulmonary function or echocardiography are not in all cases conclusive [1–4]. Often, a maximal cardiopulmonary exercise test (CPET) is done during diagnostic work-up, and different studies document its diagnostic value and impact on clinical decision-making [3, 5, 6]. Especially in patients whose work-related complaints are disproportionate to the resting lung function CPET is helpful. However, CPET is usually performed under laboratory conditions (indoors, air conditioning) with either a treadmill or a cycle ergometer. This differs from real-life conditions experienced at work (temperature, humidity, dust), and the continuous type of exercise (cycling, walking) might not reflect physical activity during work (on-and-off exercises, intervals of high exercise-load). Therefore, to draw direct conclusions from CPET to work ability might not be

adequate in some patients. Recently, different telemetric mobile devices for cardiopulmonary exercise testing have become available. They allow per-

Abbreviations

CPET	Cardiopulmonary exercise test
MCPET	Mobile cardiopulmonary exercise test
LCPET	Laboratory-based cardiopulmonary exercise test
Er	Subjectively rated respiratory exhaustion on a visual analogue scale
Em	Subjectively rated muscular exhaustion on a visual analogue scale
Eo	Subjectively rated overall exhaustion on a visual analogue scale
Tex	Subjectively estimated time to exhaustion for a given exercise intensity
VO_2	Oxygen uptake (L/min)
FEV_1	Forced expiratory volume in the first second
ATS	American Thoracic Society
VAS	Visual analogue scale

forming CPET independent from a pulmonary laboratory. Until now, no study evaluated feasibility and clinical usefulness of mobile CPET (MCPET).

The aim of this study was to compare exercise

parameters measured during a conventional laboratory-based symptom-limited maximal CPET with MCPET, and to correlate exercise parameters measured during MCPET with subjectively rated markers of physical exhaustion.

Methods

Study population

Healthy volunteers between age 20 and 60 years were recruited. Exclusion criteria included the presence of known diseases, any long-term medication, and the inability to wear a facemask. All subjects gave informed written consent. The local ethical committee EKBB approved the study.

Study design

We performed a controlled trial in healthy volunteers. On day 1, a symptom-limited maximal CPET was performed. On a second study day, not more than 4 weeks apart, a test series of 6 MCPETs was performed.

Maximal symptom-limited CPET (LCPET)

The maximal symptom-limited CPET was performed according to ATS-guidelines using an indoor cycle-ergometer (Jaeger ER 900 L; CardioSoft Vers. 3.0, Marquette Hellige GmbH, Freiburg, Germany). A 12-lead electrocardiograph was used, and ventilation, oxygen consumption and CO₂ production was measured (Sensor Medics V_{max} 20, V. 4.0; Sensor Medics Incorporation, Yorba Linda, California, USA). After 2 minutes of unloaded pedalling, a maximal symptom-limited ramp test with a workload increment of 30 W/min was performed.

Mobile outdoor CPET (MCPET)

Participants performed a series of 6 steady-state 12-minute running tests on a running track at 6 increasing exercise levels. Exercise parameters were measured using a telemetric mobile spiroergometer (Oxycon Mobile® software v. 4.6, VIASYS Healthcare GmbH, Würzburg, Germany; figure 1). The equipment weighs 950 grams and consists of a facemask connected to a volume sensor and a gas analyzer, a polar belt, and a portable sensor unit and a data-storing unit. Heart rate, ventilation (VE), oxygen consumption (VO₂) and carbon dioxide production (VCO₂) were measured and registered on a flash card by the data-storing unit. The 6 exercise levels were defined as follows: 1. slow-walking, 2. slow walking and rapid walking in intervals of 30 seconds, 3. slow walking and slow running in intervals of 30 seconds, 4. slow running and intermediate running in intervals of 30 seconds, 5. slow running and rapid running in intervals of 30 seconds, and 6. continuous running at maximum speed (figure 2). MCPET was performed outdoors on a 400 m running track in a stadium. Between each of the 6 exercise levels full recovery was obtained. For each exercise level VO₂ [peak] and VO₂ [steady state] was recorded. VO₂ [steady state] was the mean oxygen uptake during the last 8 minutes of each 12-minute test. For the calculation of the VO₂ [percent of personal best] during MCPET the VO₂ [steady state] was compared to VO₂ [peak], which was the maximal VO₂ reached during either of the 6 tests. After each exercise level the degree of respiratory exhaustion (ER), of muscular exhaustion (EM) and of overall physical exhaustion (EO) was estimated by each participant using a visual analogue scale. Therefore, each participant drew a mark according to the subjectively perceived intensity on a 10 cm unscaled line after each single exercise level. Later the distance was measured in millimetres and transformed in ratings from 0–100. In addition, each subject estimated the time he or she could continue to exercise (T_{Ex}) at the respective exercise intensity. For both, LCPET and MCPET, VO₂ [anaerobic threshold] was assessed using the v-slope method.

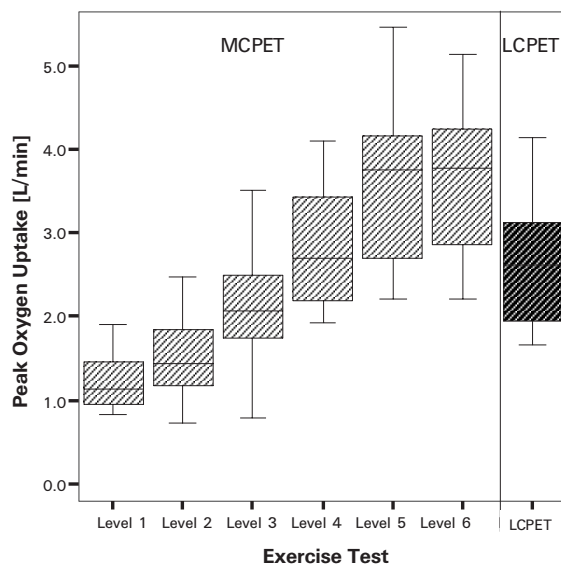
Figure 1

A volunteer wearing the telemetric MCPET device (Oxycon Mobile®) used in this study. The mobile device consists of a face mask connected to a volume sensor, a gas analyzer, a polar belt (not visible), a portable sensor unit, and data storing unit. The equipment weighs 950 grams.



Figure 2

Box plot representation of peak oxygen uptake during symptom-limited incremental LCPET and the 6 different exercise levels during MCPET on the running track. LCPET and the series of 6 MCPETs were done on two independent days. The 6 different exercise levels cover a significant and increasing range of exercise intensity including levels with interval-type exercise.



Validation of CPET measurements with a metabolic simulator

Ventilation, oxygen uptake and CO₂-production of LCPET- and MCPET-equipments were validated with a metabolic simulator (VIASYS Healthcare GmbH, Hoehberg, Germany). The simulator consisted of a

motor-driven piston pump and two high precision mass flow controllers for injection of CO₂ and N₂. Metabolic levels of up to 4 L·min⁻¹ and breathing frequencies of up to 80 bpm were produced with an accuracy of ±1%. LCPET showed slightly reduced VO₂-values at high simulated VO₂ (VO_{2,SIM}) flows. This systematic error was corrected within acceptable limits (±3%) using the following quadratic regression model: $VO_{2,SIM} = 0.90 * VO_{2,LCPET} + 0.07 * VO_{2,LCPET}^2$. MCPET VO₂ measurements showed less than 3% difference to the simulated VO₂. Therefore, it was not necessary to apply any correction to MCPET values.

Statistics

For this study we did not formulate a specific hypothesis. Therefore, it was not possible to perform a formal power calculation. MCPET and LSPET data were cleaned from technical problems. Data analysis was done using SPSS (v. 11, SPSS Inc, USA). Data are generally presented as median (minimum, maximum). Correlation of VO₂ [peak] from LCPET and MCPET was analyzed using the Pearson correlation coefficient. To assess associations of different parameters across exercise levels, individual rank correlation coefficients (Spearman-Rho) were computed for each subject. For each association, we report the median of the respective correlation coefficients (95%-confidence limits) across subjects.

Results

Between August and September 2003, 22 healthy volunteers participated in the study. Study participants were between 21 and 49 years old; all had normal baseline lung function, 3 (14%) were

smokers, and 7 (34%) were female. Twenty-one of them (96%) had all exercise tests done within 4 weeks. Of the 132 MCPET tests performed 128 (97%) were of suitable quality. Four had to be excluded due to loss of the heart rate belt (n = 1), the plugging of the sensor with sputum (n = 1) and to the loss of connection between sensor unit and data storing unit (n = 2). The face mask was well tolerated and nobody felt uncomfortable at any time.

Results of exercise tests are summarised in table 1 and figure 2. In all individuals the LCPET test and at least one of the 6 MCPETs were maximal as defined by reaching a maximal heart rate of >80% of predicted normal values. During LCPET participants reached a median performance of 273 (range 183, 411) Watts.

Comparison of VO₂ [peak] determined by LCPET and by MCPET (running at highest level) showed a strong correlation (r² = 0.90, figure 3). On average VO₂ [peak] was 21% (SD 9%) higher with MCPET compared to LCPET (median 3.60, range [2.22, 5.14] versus median 2.63, range [1.67, 4.16] L·min⁻¹). VO₂ [anaerobic threshold] of LCPET and MCPET showed a significant correlation (r² = 0.35).

Figure 3

Correlation of peak oxygen uptake during LCPET and MCPET. The comparison of VO₂ [peak] measured during LCPET in the laboratory and outside on a running track (MCPET) showed a significant linear correlation (r² = 0.9). However, VO₂ [peak] was on average 21% (SD 9%) higher with MCPET compared to LCPET. As the comparative measurements using a metabolic calibrator all were within 3%, this difference is unlikely to be the consequence of a technical problem.

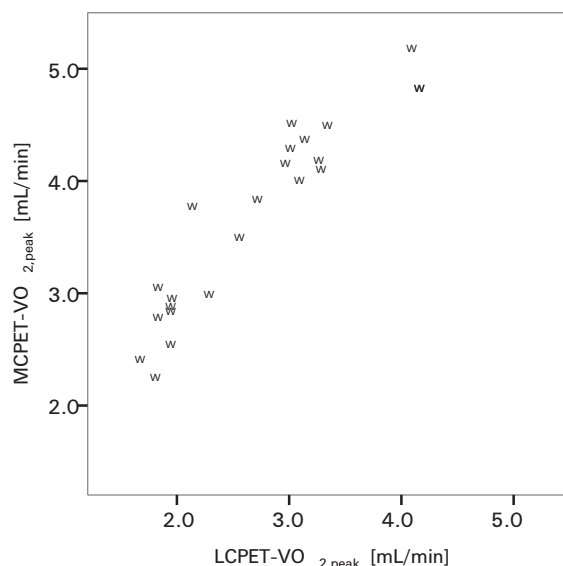


Table 1

Exercise parameters and subjective ratings of physical exhaustion.

Exercise level	MCPET						LCPET maximal
	1	2	3	4	5	6	
VO _{2,peak} [L·min ⁻¹]	1.14 (0.84, 1.91)	1.44 (0.74, 2.47)	2.06 (1.22, 2.83)	2.70 (1.94, 4.10)	3.77 (2.22, 5.47)	3.60 (2.22, 5.14)	2.63 (1.67, 4.16)
VO _{2,peak} [mL·kg ⁻¹ ·min ⁻¹]	16.8 (12.8, 18.5)	21.0 (9.6, 24.2)	30.0 (16.7, 32.6)	37.8 (20.8, 41.6)	48.3 (29.2, 54.9)	50.9 (30.8, 59.8)	36.8 (24.9, 54.0)
VO ₂ [% , pred]	47 (29, 60)	56 (36, 78)	81 (39, 120)	101 (64, 150)	133 (87, 168)	135 (97, 171)	97 (67, 132)
VO ₂ [% , personal best]	26 (15,41)	37 (18, 60)	52 (31, 80)	67 (55, 96)	86 (55, 96)	93 (73, 98)	-
Heart rate [bpm, peak]	101 (80, 123)	116 (80, 148)	138 (110, 169)	167 (123, 201)	192 (172, 209)	193 (174, 207)	179 (150, 209)
Heart rate [% , pred]	52 (44, 62)	62 (44, 80)	75 (56, 93)	92 (62, 103)	99 (91, 114)	101 (89, 113)	92 (80, 108)
E _M [VAS]	3 (0,10)	10 (0,20)	15 (0,40)	50 (5,80)	80 (40, 99)	95 (50, 100)	-
E _R [VAS]	5 (0,20)	10 (0,30)	15 (0,40)	50 (10, 70)	80 (30, 100)	95 (50, 100)	-
E _O [VAS]	3 (0,10)	8 (0,20)	10 (0,40)	50 (5,80)	80 (10, 99)	90 (20, 100)	-
T _{Ex} [min]	600 (120, 1440)	315 (60, 1000)	180 (30, 800)	80 (64, 150)	5 (0,30)	2 (0,6)	-

Results are given as median (range). Abbreviations: oxygen uptake (VO₂), laboratory-based cardiopulmonary exercise test (LCPET), mobile cardiopulmonary exercise test (MCPET), subjectively rated respiratory (Er), muscular (Em), and overall (Eo) exhaustion on a visual analogue scale (VAS), subjectively estimated time to exhaustion for a given exercise intensity (Tex).

Figure 4

Muscular, respiratory and overall exhaustion in relation to oxygen uptake [percent personal best] in 22 healthy control subjects. Each panel represents the results of an individual test person. Subjectively rated markers of exhaustion showed a relevant interindividual variability.

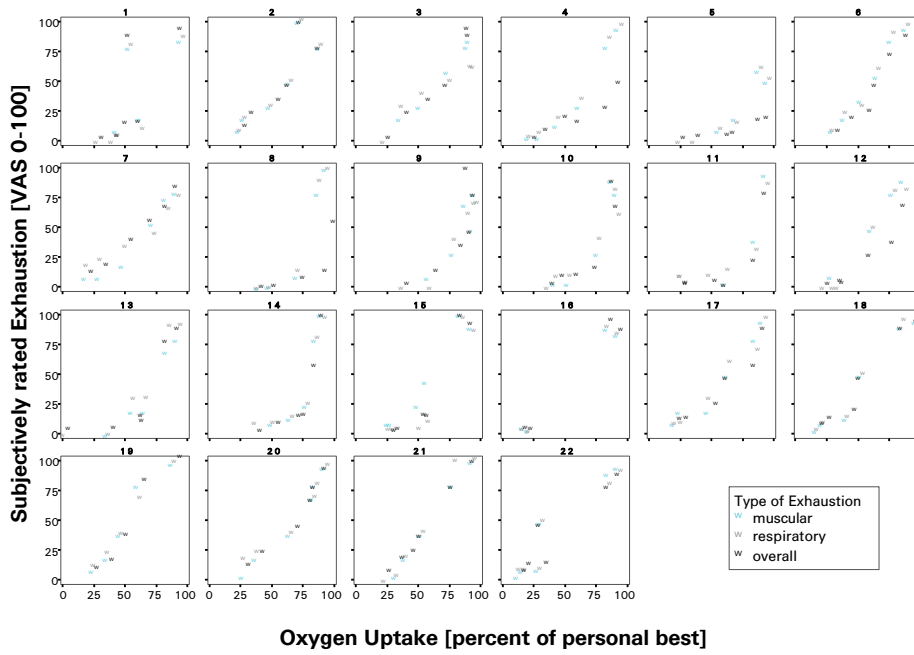


Figure 5

Relationship between the estimated time to exhaustion and peak oxygen uptake [percent personal best] in 22 healthy control subjects. Each panel represents the results of an individual test person. Although clear rank correlations existed within subjects there was a relatively large interindividual variability.

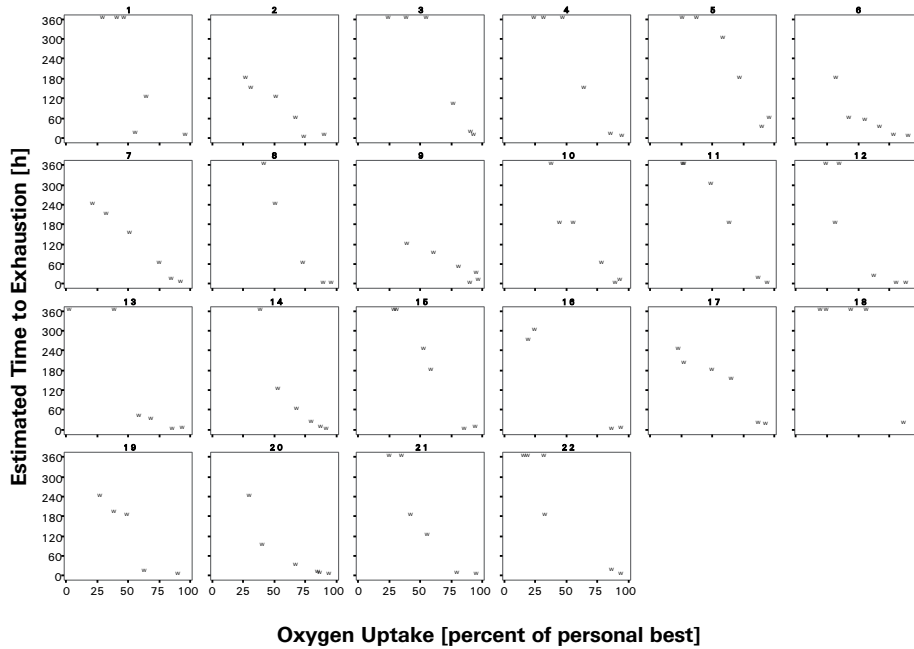
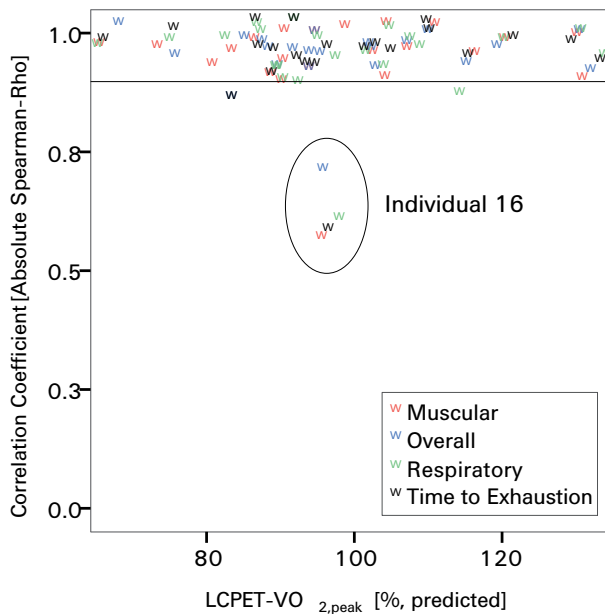


Figure 6

Scatter plot of rank correlation coefficients (Spearman-Rho) between peak oxygen uptake [percent personal best] and subjectively rated markers of exhaustion, as well as the estimated time to exhaustion, in absolute values of all 22 healthy control individuals. Overall, within individuals the correlation coefficients were typically >0.9. Only one individual (16) had somewhat more difficulties in rating subjective exhaustion and had correlation coefficients between 0.6 and 0.8.



The median (95%-confidence limits) of individual rank correlation coefficients between VO_2 [steady state] and subjective markers of respiratory ER, muscular EM, and overall exhaustion EO across different exercise levels were 0.99 (0.91, 0.99), 0.99 (0.92, 0.99) and 0.98 (0.92, 0.98), re-

spectively. The median of individual rank correlation coefficients between exercise level and estimated time of being able to sustain the respective exercise level was -0.99 (-0.99 , -0.90) (figures 4-6).

Discussion

In this study MCPET proved to be feasible in an outdoor situation and presented a high degree of accuracy when compared to a metabolic simulator. We found a good correlation between VO_2 [peak] during a symptom-limited ramp protocol on a cycle ergometer and during running at maximal speed on a track (MCPET). The oxygen uptake measured during the outdoors running test was higher compared to the laboratory-based measurement on a cycle ergometer. Furthermore, oxygen uptake reached during MCPET correlated well with subjectively rated muscular, respiratory and overall exhaustion on an individual level, but was affected by relevant interindividual variability.

MCPET gave reliable results in 97% of the tests. Comparison with a metabolic calibrator before and after 132 MCPETs showed that the measurements were all within 3% up to a ventilation of 120 L/min. The technical problems that occurred during MCPET were twice due to the equipment and twice to the connection between the sensor unit and the data storing unit.

Peak oxygen uptake measured during MCPET correlated very well with VO_2 [peak] of a conventional maximal CPET, but they were not the same. In different studies, comparison of a maximal treadmill exercise test and a maximal cycle exercise test VO_2 [peak] resulted in about 7-11% higher values for treadmill exercises [7-10]. This is well established in healthy volunteers, but might be different in patients with severe COPD [11]. Furthermore, in competitive cyclists VO_2 [peak] of cycle exercise was near the one of the treadmill exercise [12]. The somewhat larger difference between the cycle CPET and MCPET (+21% higher values) in our study might be due to the fact that study participants were allowed to run freely on a running track and not constrained to a treadmill. There might be more muscle groups involved during unrestrained running at own speed than on a treadmill, where the movements are somewhat more limited. This is also witnessed by the fact that the peak heart rate was higher during MCPET at the highest intensity level compared to LCPET. Additionally, MCPETs took place outdoors during summer time with temperatures of 28-30 °C and full insulation. This was not comparable to the air-conditioned pulmonary function laboratory. We do not think that wearing the mobile CPET equipment (950 grams) might have significantly influenced VO_2 [peak]. Other studies

that compared oxygen uptake during free running and under laboratory conditions are lacking. To our knowledge we are the first to perform such a comparison.

The rating of perceived exhaustion for an individual has been shown to be reliable with a coefficient of variation of 4 to 6% in other studies [13, 14]. Our data showed that perception of muscular, respiratory and overall physical exhaustion correlated well with exercise intensity as measured by oxygen uptake. However, there were large interindividual differences. It was shown previously that the personal estimation and perception of exercise differs between individuals, according to physical fitness and psychological factors [15-17]. These factors might be even more important in patients with cardiac or pulmonary disease, and when work ability is assessed in situations with a differing degree of motivation.

There was a relationship between the sustained oxygen uptake and the estimated time, during which a steady state or interval-type exercise could continue. A laboratory-based pilot study found similar results for incremental exercises up to the ventilatory threshold, where the relationship had an inflection [18]. It is, however, difficult to define an exact level of exercise that could be continued for 2, 4 or 6 hours because of a relevant interindividual variability, that may be related to the degree of physical fitness and motivation [19]. We are not sure whether the estimated time to exhaustion would approximate the measured time to exhaustion well enough, as the runs were limited by time, not by exhaustion within the current study. In a recently published study with trained athletes the measured time to exhaustion during a constant submaximal run exercise did not significantly correlate to the predicted exhaustion time values, calculated from linear extrapolation of perceived exhaustion [19]. Whether the estimated time to exhaustion correlated to the measured time to exhaustion was not described, and exercise was done only at one level. Therefore, their data cannot be directly compared to our data. This question should be addressed in further studies.

Exercise testing has been proposed to be an integral part of evaluation of work ability [5], but until now measurements during work were only possible in a very limited way. MCPET allows a real-time measurement of physical parameters in the relevant environment, and comparison of the

VO₂ measured during work to the VO₂ [peak] of a patient. This information might help to decide if or how many hours a patient can work in the future. As we did our measurements with healthy persons, our data must be interpreted with caution and further studies with certain groups of patients, for example patients with COPD or chronic heart failure, are needed before drawing firm conclusions. However, MCPET could significantly contribute to an objective assessment of work ability in difficult cases. In this study we showed that MCPET was feasible, reliable and correlated with results of a maximal exercise test and markers of physical exhaustion. In our opinion mobile CPET should soon become a tool for the assessment of work ability, especially for selected patients with heart or lung diseases.

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Correspondence:

Martin H. Brutsche, MD, PhD

Pneumology

University Hospital Basel

Petersgraben 4

CH-4031 Basel

Switzerland

E-Mail: mbrutsche@ubbs.ch

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