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The Cosmed K4 telemetry system as an accurate device for oxygen uptake measurements during exercise

C. Hausswirth¹, A. X. Bigard², J. M. Le Chevalier¹

¹ Laboratoire de Biomécanique et de Physiologie, Institut National du Sport et de l'Education Physique, Paris, France

² Département de Physiologie Systémique, Centre d'Etudes et de Recherches de Médecine Aéronautique, Brétigny sur Orge, France

Corresponding Author: C. Hausswirth, Institut National du Sport et de l'Education Physique, Laboratoire de biomécanique et de physiologie 11, avenue du Tremblay 75012 Paris France

The purpose of this study was to test the accuracy of oxygen uptake ($\dot{V}O_2$) measurements using the Cosmed K4 portable telemetry system. This system of higher technology than the original Cosmed K2 device, contains a CO_2 electrode allowing measurements alternatively by either the Cosmed K4 system (K4) or the CPX Medical Graphics (CPX) during a maximum oxygen uptake ($\dot{V}O_{2max}$) ergocycle test, at rest and during several submaximal exercises (25, 50 and 75% of maximal work rate) in seven subjects. Heart rate values were comparable for exercise at the same work stage during gas collection using the two systems, indicating that the physiological stresses were similar. The $\dot{V}O_2$ values did not significantly differ at rest (4.40 ± 0.83 vs 4.16 ± 0.58 ml \cdot min⁻¹ \cdot kg⁻¹), at 25% W_{max} (20.97 ± 1.31 vs 21.32 ± 2.54 ml \cdot min⁻¹ \cdot kg⁻¹), at 50% W_{max} (33.32 ± 3.92 vs 33.50 ± 3.51 ml \cdot min⁻¹ \cdot kg⁻¹), at 75% W_{max} (47.01 ± 7.51 vs 47.49 ± 7.11 ml \cdot min⁻¹ \cdot kg⁻¹) and at maximal intensities (62.07 ± 8.48 vs 62.84 ± 11.31 ml \cdot min⁻¹ \cdot kg⁻¹) using K4 and CPX devices, respectively. The results of this study indicated that the K4 system was accurate for all oxygen uptake measurements from rest to maximum exercise levels. Key words: Validity, maximum oxygen uptake, respiratory exchange ratio, ventilation, respiratory rate

Introduction

Oxygen uptake ($\dot{V}O_2$) is often measured to determine the metabolic cost of physical activities in the field. This metabolic cost, defined as the steady-state aerobic demand for a given intensity, has been identified as an important factor to direct athletes in managing their training programs (7,12). Until recently, $\dot{V}O_2$ was measured by the Douglas bag method which involves the use of voluminous and bulky apparatus. As a result it was difficult to measure $\dot{V}O_2$ during physical exercise when not using a portable telemetric system.

Previous studies were conducted in order to evaluate the accuracy of some telemetric systems which measured $\dot{V}O_2$ (2,3,8). A thorough search of the literature revealed some interest for the K2 Cosmed apparatus (3, 9,10,11). However, since the K2 Cosmed system does not contain a CO_2 electrode, it is assumed that the respiratory exchange ratio (RER) is equal to 1.00. The K2 Cosmed system significantly underestimated $\dot{V}O_2$ measurements at low workloads in comparison with $\dot{V}O_2$ obtained from a standard metabolic cart (11).

A newer model of the K2 Cosmed apparatus has been developed. This system (K4 Cosmed, Roma Italy) contains a CO_2 electrode allowing direct measurements of the RER at rest or during exercise. It is much reduced in size and mass compared with the K2 telemetric system. However, before its implementation in the field, the accuracy of this telemetric system had to be tested.

Thus, the purpose of this study was to test the validity and the accuracy of the K4 Cosmed telemetric system for measuring oxygen uptake, minute ventilation, respiratory rate and respiratory exchange ratio in a laboratory exercise test at maximum and submaximum intensities.

Material and Methods

Subjects. Seven healthy, well-motivated male subjects, volunteered to participate in this study after

they were informed of the nature and possible inconveniences associated with the experiment. The subjects were familiar with all testing procedures and gave their written informed consent before participation. Subject's mean (\pm SD) age, weight and height were 32.2 ± 6.9 yrs, 71.2 ± 5.4 kg, 177.5 ± 5.2 cm, respectively. Two of the subjects were endurance trained triathletes, who trained 9-10 times per week. The five other subjects were physically active in a variety of sports (cycling and running) 3-4 times per week.

Maximum oxygen uptake evaluation. After a 48 hour restriction of strenuous physical activity, the subjects completed two incremental, continuous maximum bicycle ergometer exercise tests at three day interval, using either a metabolic measurement cart (type CPX, Medical Graphics, Saint-Paul, Minnesota, USA), (CPX), or the telemetric measurement system (type Cosmed K4, Roma, Italy), (K4). We used an electromagnetically braked bicycle ergometer (Excalibur, Lode, Groningen, The Netherlands) in which adjustment of the load was rate-independent. The copper disk is driven by the axle by a special chain and a gear belt transmission. The test began with a warm-up at 100W for 6 minutes and the workload was increased by 25 W every 2 minutes until volitional fatigue. During the two incremental exercises, oxygen uptake (VO_2), carbon dioxide output (VCO_2), minute ventilation (VE), respiratory rate (RR) and respiratory exchange ratio (RER) were continuously measured every 15 seconds using either CPX Medical Graphics (CPX) or the Cosmed K4 system (K4): the order for the use of the K4 or the CPX in the maximal exercise tests was randomized. A small connection was adapted on the soft face mask for the attachment of the low-resistance respiratory valve directing the exhaled air to either the metabolic measurement cart or the turbine flowmeter (Cosmed K4 system). The maximum oxygen uptake ($\text{VO}_{2\text{max}}$) was the average of the last three highest consecutive VO_2 values recorded. The criteria used for $\text{VO}_{2\text{max}}$ were those previously described (1). This always occurred during the next-to-last or last work rate, thus we are confident that we got a true $\text{VO}_{2\text{max}}$. The maximum work rate (max) was the highest work rate completed for 2 minutes and was measured during both CPX and K4 exercises.

Submaximum steady-rate tests. All subjects refrained from any recreational activity 24 hours before testing. They remained at rest on the bicycle ergometer for 12 minutes and exercised for 12 minutes at 25%, 12 minutes at 50% and 12 minutes at 75% W_{max} . Pedalling cadence was freely chosen by the subjects at the beginning of each work rate and was maintained during each submaximum test. All testing sessions were completed at the same time of day for each subject after eating a standard lunch (3 hours postabsorptive). The differences observed in HR were evaluated using a cardiofrequency meter (BHL-6000, Baumann-Haldi SA, Fleurier, Switzerland). The interval of calculation for VO_2 was set at 15 seconds. To collect the exhaled air, we reproduced the experimental procedure design by Bigard and Guezennec (3). A small connector, which was mounted on a soft face mask, allowed collection of the exhaled air with only one system (face mask) and analysis with either K4 or CPX without stopping the bicycle test. The resting measurements and each submaximum exercise lasted 12 minutes. With this alternated and repeated experimental procedure, two sets of data using each instrumentation were available. The two systems were used in a randomly assigned order.

Metabolic measurements. The Cosmed K4 telemetry system has not been previously described but has some identical characteristics compared with the K2 system widely described (5,8, 11). The K4 system is composed of a soft face mask to sample exhaled air, a sensor system to measure ventilation, oxygen and carbon dioxide concentrations in the expired air, allowing RER calculation. The respiratory flow is measured by a turbine (diameter of 28 mm versus 2 mm for the K2 system) fixed to the face mask. This flow sets in motion the mobile rotor blade which has a low mass and extremely reduced inertia. The rotation of the turbine is measured by an opto-electronic system that counts the revolutions per second. The system has also a transmitter unit, an electrode to pick-up heart rate and a Ni-Cd rechargeable battery (lasting about 1 hour) all attached to a chest harness, and a receiver unit. The flowmeter measures the airflow rate, calculates the volume of air expired per minute and counts the number of expiratory cycles per minute. To measure the concentration of oxygen, the exhaled air moves through a special capillary tube (Permapure) to the transmitter unit that contains a polarographic electrode for measurement the O_2 fraction in the expired gas (FEO_2). Oxygen moves through a membrane into an electrolytic solution. The CO_2 electrode is an infrared electrode. The K4 system was calibrated before each experiment according to the manufacturer recommended procedures (Operator Manual of K4 System). The transmitter was turned on for a minimum of 20 minutes before each test.

The O₂ and CO₂ analysers were calibrated using ambient air at the beginning of each testing session (20.93% and 0.03 %, respectively), and the turbine flowmeter was calibrated using a 3-1 syringe at the beginning of the study. The O₂ and CO₂ analyzer are thermostated and compensated for a barometric pressure and environmental humidity variations. Oxygen uptake is calculated according to the following formula:

$$\dot{V}O_{2, \text{STDP}} - \dot{V}_{E, \text{STDP}} \times \left\{ \left[1 - \frac{(F_{E}O_2 + F_{E}CO_2)}{1 - F_{i}O_2} \times F_{i}O_2 \right] F_{E}O_2 \right\}$$

VE = minute exhaled volume,

F_iO₂ = calibration value O₂

F_EO₂ = fractional concentration of oxygen in the expired air

The sampling and the printing of the most significant parameters, i.e. V_{O₂}, V_{CO₂}, VE, RER and HR were carried out at 15 second intervals. The radio transmission range in an open field is about 3 km using a small 30 cm long receiving antenna; for a wider range, special antenna can be used. The total weight carried by the subject is about 800g. Furthermore, the apparatus includes a communication interface to download all recorded parameters onto a personal computer. Data were collected and treated on the software "K4 for Windows".

The CPX analyser is constituted with two modules: a flowmeter module which measures ventilatory parameters and a gas module which measures FE_{O₂}, and FE_{CO₂}. Each subject wore the Cosmed K4's face mask and inhaled ambient air through one Bide of a low-resistance three-way valve (Hans Rudolph, Inc., Kansas City, MO, USA). Expired O₂ and CO₂ fractions were measured from a sampling port in the mouthpiece connected by way of a capillary sampling tube to an O₂ analyser constituted by a zirconium cell and a CO₂ analyser using an infrared electrode. The temperature of the samples and a barometer reading were taken. Before each submaximal and maximal test, both gas analyzers were calibrated with reference gases according to the manufacturer's recommendations, at O₂ and CO₂, concentrations of 12.01 and 5.01 %, respectively. On-line computation was obtained using customized software for V_{O₂}, VE, RR and RER determination. The interval between calculations of these parameters was set at 15 seconds.

Data and statistical analysis

1. During the two maximal tests, each subject's values for V_{O₂}, V_{CO₂}, VE, RR, RER and HR were evaluated using the K4 and the CPX system. The average of the last three values (V_{O₂}max, V_{CO₂}max, V_Emax, RRmax, RERmax and HRmax) recorded were used in the statistical analysis. Differences in the dependent variables resulting from the type of measurement system (K4, CPX) were studied using a Student's *t*-test for paired samples. Statistical significance was accepted at *P* < 0.05.

2. During the submaximum testing sessions, two series of 3 min data were available for each system of measurement. The first 2 minutes of data collection were eliminated at rest and during each work load. When subjects pedalled at 75% W_{max}, the first 3 minutes of data collection were similarly eliminated. The statistical comparisons between V_{O₂}, V_{CO₂}, V_E, RR, RER, and HR were performed using an analysis of variance (ANOVA) for repeated measures. The main effects of "workload" (x 4), "subjects" (x 7), and "system" (x 2) were evaluated on all variables. Results are expressed as mean ± standard deviation and significance was set a *P* < 0.05. The correlation coefficient (r) was calculated for V_{O₂}, V_{CO₂}, VE, RR and RER values, in order to determine the strength of the relation between measurements made by the different testing methods. Furthermore, the accuracy of the Cosmed K4 system of V_{O₂} measurements was determined according to the method of Bland and Altman (4). For this analysis, the measuring agreement of the K4 device for V_{O₂} calculation was estimated in indicating the differences in V_{O₂} between the two methods against their mean. The mean of the differences represented the bias between the two systems of measurement. This value plus and minus two standard

deviations represented the limits of agreement for VO_2 measurement using the Cosmed K4 system. The data were presented graphically comparing the difference between the methods versus their average value for VO_2 .

Results

Heart rate (HR) values were unaffected by the system of measurement ($P = 0.87$). As indicated in Tables 1 and 2, HR was almost identical during gas collection with either the K4 or the CPX at rest and for bicycle exercises (25% W_{max} , 50 % W_{max} , 75 % W_{max} and W_{max}). HR values were similar for each level using the two systems with repeated and alternated measures of respiratory parameters.

Maximal oxygen uptake ($\text{VO}_{2\text{max}}$), maximal carbon dioxide output ($\text{VCO}_{2\text{max}}$), maximal minute ventilation (VE_{max}), maximal respiratory rate (RR_{max}) and maximal respiratory exchange ratio (RER_{max}) values for the K4 and the CPX devices are shown in Table 1. These measurements were unaffected by the system ($P = 0.89$, $P = 0.84$, $P = 0.68$, $P = 0.91$, $P = 0.75$, respectively) (Table 1).

VO_2 , VCO_2 , VE , RR and RER measurements increased with the workload ($P < 0.001$) and were affected by an interindividual variability ($F = 113.7$; $P < 0.001$). The analysis of variance on VE measurements indicated no significant effect of the system ($P = 0.14$) (Table 1) (Fig. 1 a). In addition, the measurements of VE using the K4 or the CPX systems were highly correlated ($r^2 = 0.995$, $P < 0.001$). The 95 % confidence interval for the experimental lines covered the entire range of VE values.

Mean values of RR were unaffected by the system ($P = 0.26$), (Fig.1 b). Moreover, there was a high correlation between RR results obtained by use of K4 or CPX devices ($r^2 = 0.962$, $P < 0.001$).

The mean values of RER obtained during the submaximal exercises using the K4 did not significantly differ from those calculated with the CPX (Fig. 2a).

Correlations between VO_2 values measured with the two systems during the four sessions (rest, 25% W_{max} , 50% W_{max} and 75 % W_{max}) were highly significant ($P < 0.001$, $r^2 = 0.953$). VO_2 values (Fig. 2 b) and VCO_2 values (Fig. 3) calculated by the K4 system did not differ significantly ($P > 0.47$ and $P > 0.53$, respectively) from those calculated by the CPX device. As shown in Fig. 4, the confidence interval for the bias (i.e. mean difference between the two systems) was 3.13 to $-3.51 \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$. Almost all the individual values were within the limits of agreement, and for each of the exercise intensities, only one individual value was outside the limits of agreement at 25 % W_{max} .

Discussion

The aim of this investigation was to test a new telemetric system (type Cosmed K4) which includes the measurement of the fractional concentration of carbon dioxide in the expired gas (F_{eCO_2}). The main interest of our study was to compare the validity and accuracy of VO_2 measurements at whatever value of the respiratory gas exchange ratio (range 0.7 - 1.2), by use of either the Cosmed K4 system or the CPX Medical Graphics system. One interesting finding of this study indicated that VO_2 values calculated using the K4 system were not statistically different from VO_2 values obtained with the CPX system. The results showed a validity of the K4 system for VO_2 measurements in the same subjects during both submaximal and maximal exercises. A previous study (13) found some difference in VO_2 values obtained during two maximal exercise tests using either the Cosmed K2 system and the conventional Douglas bag method (3.57 ± 0.76 vs $3.69 \pm 0.761 \cdot \text{min}^{-1}$, respectively). The same difference was also recorded at low running speed (2.11 ± 0.43 vs $2.21 \pm 0.441 \cdot \text{min}^{-1}$, respectively).

Accuracy and validity of oxygen uptake and minute ventilation measurements show that the day-to-day variability in subject's response should be closely noted (10). In order to reduce differences resulting from the order of the use of the measurement systems, the two devices were used in a randomly assigned order during the 3 submaximal exercises (3). With this alternated and repeated experimental procedure, two sets of data using each instrumentation were available at rest and during the 25 and 50% W_{max} bicycle exercise, and only one segment of data collection was available at 75% W_{max} .

Moreover, the heart rate recorded at each exercise level was not significantly different between the two maximal tests and between the two systems during the three submaximal testing sessions. This strongly suggests that the amount of work performed during both exhaustive and submaximal exercises was unaffected by the type of device.

As it has been previously reported, the Cosmed K2 system was shown to be valid and reliable for oxygen uptake measurements at both submaximal and maximal intensities (6,9,10). However, Kawakami et al. (9) reported that RER measured by the Douglas bag method at maximal workload did not exceed 0.95 ± 0.06 . It is clear in this case that the measurement error (assuming RER = 1.00) did not affect the validity of $\dot{V}O_2$ max values. Lucia et al. (10) reported that at low-intensity work rates, the RER was less than 1.00 and the K2 apparatus tended to underestimate $\dot{V}O_2$ values. At maximal workload, mean RER values were 1.21, corresponding to the values generally recorded when achieved $\dot{V}O_2$ max. Using the correction factor provided by the manufacturer, it is suggested that when RER is equal to 1.2, the K2 apparatus overestimated $\dot{V}O_2$ max values by about 4%. DalMonte et al. (6), have previously demonstrated that the difference between fractional concentrations of oxygen in the inspired and expired air ($\dot{a}FEO_2$) was lower at maximal work rate by use of the K2 system, and then underestimated $\dot{V}O_2$ values. In addition, when RER was higher than 1.00, it has been shown that the K2 system overestimates $\dot{V}O_2$ values. Thus, correct measurements of $\dot{V}O_2$ max were expected in this study, in spite of some errors. However, it is clear that accurate measurements of $\dot{V}O_2$ at high levels of exercise (RER >1.1) need either $\dot{V}I$ or $\dot{V}ECO_2$ measurements, in addition to $\dot{V}E$ and $\dot{V}ECO_2$ data.

The main purpose of the present investigation was to report the first testing procedure of a new telemetric system (Cosmed K4) measuring $\dot{V}E$, $\dot{V}ECO_2$ and calculating RER on-line. Summing up, results of this study indicated a great accuracy of the measurements at three work stages (25,50 and 75% W_{max}), but also at W_{max} (RER = 1.19).

This lightweight and accurate telemetric system enables measurement of energy requirements for maximal or submaximal exercises, in different environmental conditions (laboratory or field-test situations). The continuous recording of $\dot{V}O_2$ during incremental progressive field tests is possible using the K4 system, in order to determine precisely ventilatory characteristics of each athlete. However, the polarographic electrode of oxygen analysis is very sensitive to temperature variations (5). The temperature at the O_2 and CO_2 electrodes should be stable prior to calibration. Thus the use of the K4 de-vice allows us to determine more precisely the energy cost of physical activities, either mild restricting activities (hiking, cycling, tour, walking on uneven field, riding...) or strenuous ones (triathlon, running races, cross-country, skiing...).

From the results of this study, we have tested the validity of a new telemetric system for measuring oxygen uptake during exercise. This new system is practical and useful for oxygen uptake measurements during both submaximal and maximal exercises. Further investigations are needed to test the validity of the K4 system using different modes of exercise and different environmental conditions (low-temperature, wind situation, moderate altitude...).

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Fig. 1 a Minute ventilation (\dot{V}_E , l. min^{-1}) measured using either the K4 or the CPX systems, at rest and for each exercise level. Values are means \pm SD. Exercise levels are expressed as a percentage of the maximal work rate (W_{max}).

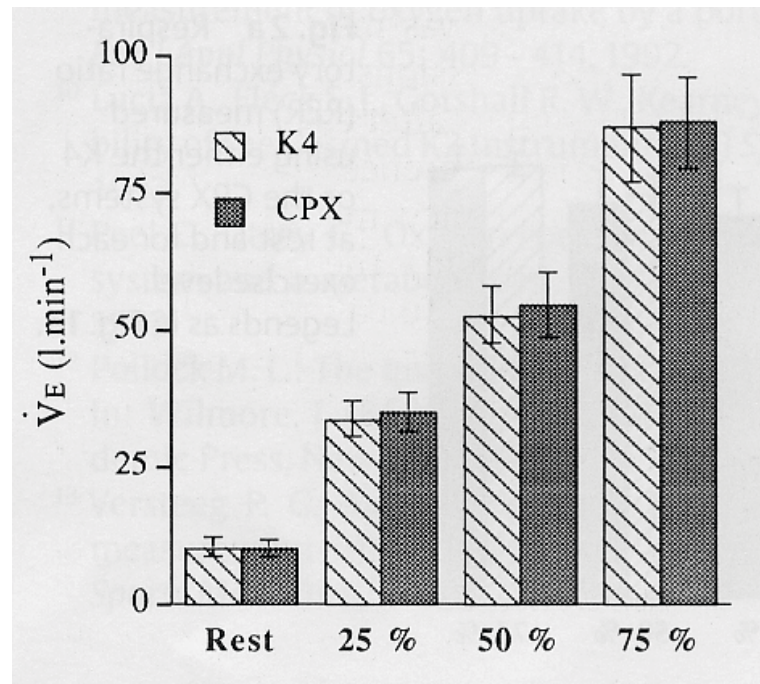


Fig.1 b Respiratory rate (RR, breath \cdot min^{-1}) measured using either the K4 or the CPX systems, at rest and for each exercise level. Legends as in Fig.1 a.

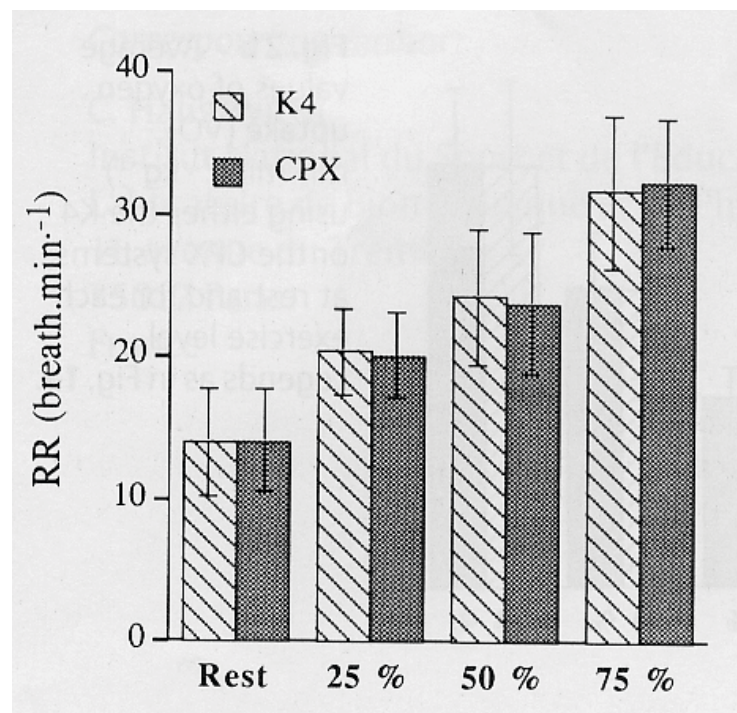


Fig. 2a Respiratory exchange ratio (RER) measured using either the K4 or the CPX systems, at rest and for each exercise level. Legends as in Fig. 1 a.

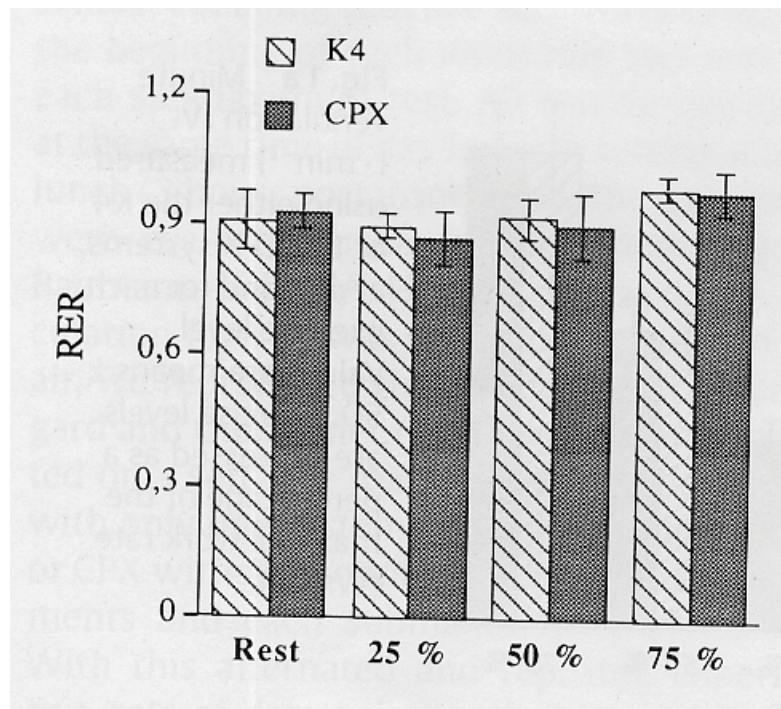


Fig. 2 b Average values of oxygen uptake ($\dot{V}O_2$, $\text{ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$) using either the K4 or the CPX systems, at rest and for each exercise level. Legends as in Fig. 1 a.

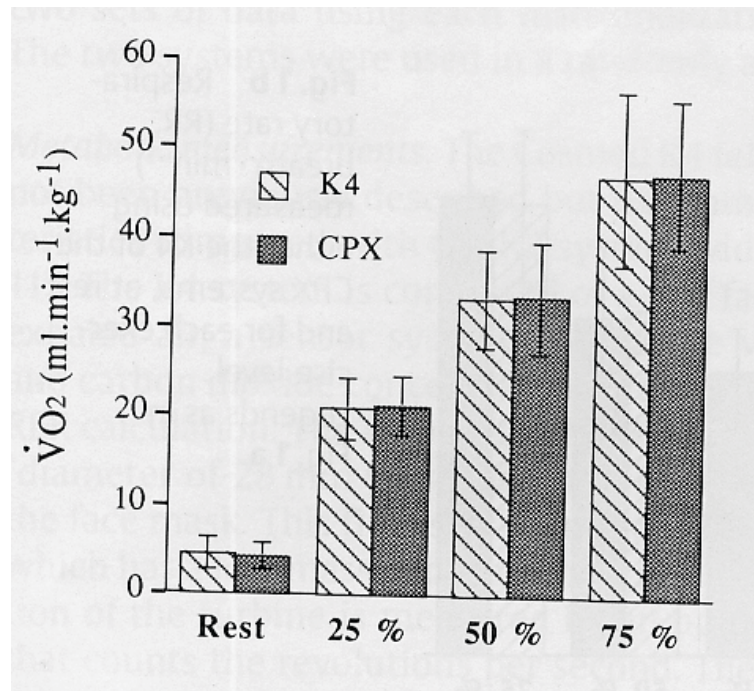


Fig. 3 Average values of carbon dioxide output ($\dot{V}CO_2$, ml \cdot min $^{-1}$ \cdot kg $^{-1}$) using either the K4 or the CPX systems, at rest and for each exercise level. Legends as in Fig. 1 a.

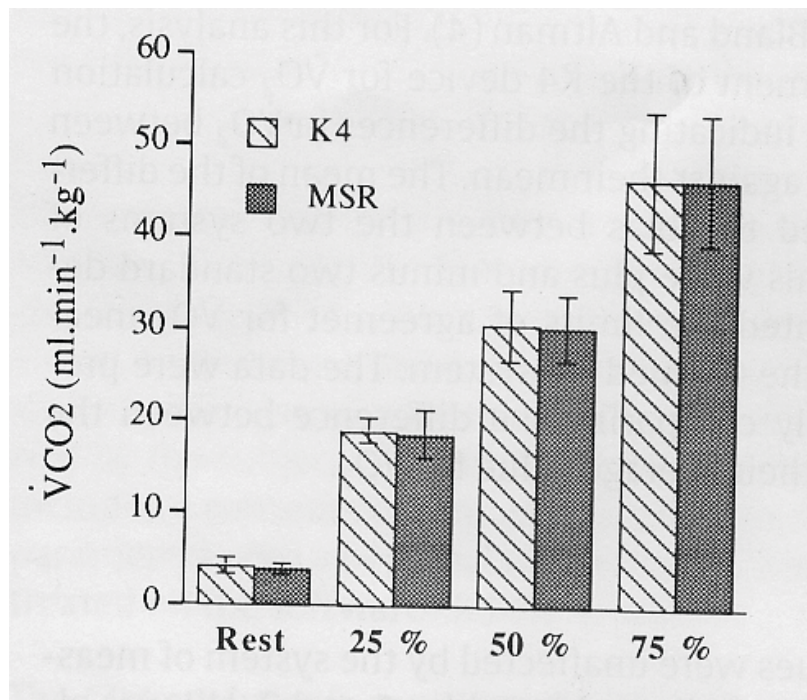


Fig. 4 The calculated bias between the two devices of measurement and the limits of agreement for $\dot{V}O_2$ measurement using the Cosmed K4 system: o rest; • 25% of maximal work rate (W_{max}); □ 50% W_{max} ; ■ 75% W_{max} .

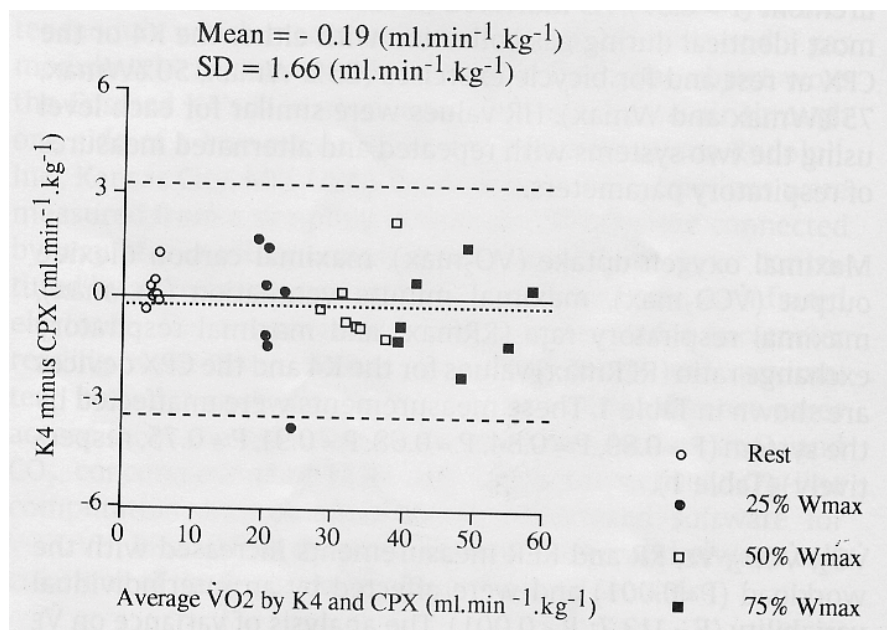


Table 1 Maximal exercise data with incremental protocol. Comparison of K4 and CPX systems.

Parameters	K4	CPX
	Means±SD	Means±SD
VO ₂ max, (ml • min ⁻¹ . kg ⁻¹)	62.07 ± 8.48	62.84 ± 11.31
VCO ₂ max, (ml • min ⁻¹ . kg ⁻¹)	73.85 ± 9.12	76.65 ± 11.02
VE max, (l • min ⁻¹)	157.41 ± 25.02	158.42 ± 25.78
RRmax, (breath • min ⁻¹)	51.28 ± 9.26	50.85 ± 8.55
RERmax	1.19 ± 0.06	1.22 ± 0.04
Wmax (watts)	339 ± 35	339 ± 35
HRmax, (beat • min ⁻¹)	183 ± 13.8	184 ± 14.3

VO₂max = maximal oxygen uptake, VCO₂max = maximal carbon dioxide output, VE_{max} = maximal minute ventilation, RR_{max} = maximal respiratory rate, RER_{max} = maximal respiratory exchange ratio, W_{max} = maximal work rate, HR_{max} = maximal heart rate. No statistical difference has been established.

Table 2 Heart rate (beats • min⁻¹; mean ±SD) during steady-state exercises.

Exercise level	K4	CPX
	Means±SD	Means±SD
Rest	64 ± 9.7	67 ± 10.0
25% W _{max}	96 ± 8.9	96±7.4
50% W _{max}	133 ± 9.3	134 ± 8.4
75% W _{max}	168±5.5	169±6.6

W_{max} = maximal work rate. No statistical difference has been established.