

Validation of the Cosmed K4b² Portable Metabolic
Measurement System

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ABSTRACT

The purpose of this study was to determine the validity of the Cosmed K4b² portable metabolic measurement system against the criterion Douglas bag (DB) method at rest and during incremental exercise. Seven male subjects completed two graded exercise tests on a cycle ergometer while fractional expired oxygen ($F_{E}O_2$) and carbon dioxide ($F_{E}CO_2$), oxygen uptake (VO_2), carbon dioxide production (VCO_2), minute ventilation (V_E), and respiratory exchange ratio (R) were measured by either the K4b² or the DB method. The results show that the K4b² is accurate for the determination of VO_2 , VCO_2 , V_E , and R at work rates from rest through 200W, despite significant differences in $F_{E}O_2$ ($P<0.01$) and $F_{E}CO_2$ ($P<0.05$). These differences in $F_{E}O_2$ and $F_{E}CO_2$ are due to the special characteristics of the K4b² breath-by-breath system. At 250W the K4b² significantly underestimated VCO_2 ($P<0.01$) and R ($P<0.05$) compared to the DB method, but no significant differences were seen for the other gas exchange variables at this work rate.

Keywords: oxygen uptake, ventilation, exercise, gas exchange, validity

INTRODUCTION

The measurement of oxygen uptake (VO_2) is important in the assessment of $\text{VO}_{2\text{max}}$ and the determination of the energy cost of activities. These variables are traditionally measured via indirect calorimetry using a metabolic cart. However, the large size of most metabolic carts limits these measurements to a laboratory setting. While many activities can be simulated in the laboratory (e.g. walking on a treadmill), other activities, including occupational and recreational activities, cannot be duplicated in the laboratory. Attempts to collect expired air in the field for later analysis in the laboratory meant using cumbersome equipment that often interfered with the activities under investigation. The development of miniaturized metabolic measurement systems has allowed VO_2 to be measured outside the laboratory in a natural environment.

Portable metabolic measurement systems have been used to quantify the energy cost of a wide range of activities. In our own laboratory, these devices have been used to quantify the energy cost of a variety of occupational, leisure-time, and exercise activities in healthy older and younger individuals (1, 18, 19). Others have examined the energy cost of snow shoveling in healthy individuals (8) and lawn mowing in patients with coronary artery disease (9).

Current technology has resulted in the miniaturization of the equipment needed to determine VO_2 , allowing measurements to be made easily in the field. This technology has been refined over the years, progressing from portable instruments that only measured ventilation (V_E) and VO_2 , such as the Oxylog and Cosmed K2, to ambulatory devices that measure both VO_2 and

carbon dioxide production (VCO_2). These latter instruments allow the calculation of respiratory exchange ratio (R) and the determination of substrate utilization.

One such instrument is the K4b² metabolic measurement system (Cosmed, S.r.l., Rome, Italy). The K4b² is designed to be worn by the subject during activity—the entire system weighs about 1.5 kg, operates on battery power, and is capable of transmitting test data in real-time to a PC base station via telemetry as well as storing data in memory (see Figure 1). The K4b² is the latest in a series of portable metabolic measurement systems developed by Cosmed, S.r.l. The K2 contained only an oxygen analyzer, which permitted the measurement of VO_2 and energy expenditure in the field. The Cosmed K4 was a smaller instrument that included a CO_2 analyzer to allow measurement of both VO_2 and VCO_2 in the field. Both of these instruments were determined to be valid for the measurement of oxygen uptake and energy expenditure (7, 10, 13, 15). The K4b² added breath-by-breath measurement capability, and a recent study reported on the validity of this device for the measurement of energy expenditure at rest and during exercise (14).

Subsequent to the validation study of the K4b² by McLaughlin et al., (14), the instrument was changed to include a more stable CO_2 analyzer and updated software. These changes may have altered the measurement of CO_2 and the calculation of gas exchange variables. Therefore, before this instrument could be used with confidence, a careful validation was required. The purpose of this study was to evaluate the accuracy of the updated K4b² for the measurement of V_E and the fraction of oxygen and carbon dioxide in expired air ($F_{E}O_2$ and $F_{E}CO_2$), as well as the calculation of VO_2 , VCO_2 , and R at rest and during incremental exercise.

MATERIALS AND METHODS

Seven healthy male subjects volunteered to participate in this study. Prior to participating in the study each subject was informed of the testing protocol and potential risks, and signed an informed consent document. This study was approved by the Institutional Review Board of the University of Tennessee, Knoxville prior to the initiation of data collection. The characteristics of the subjects (mean \pm SE) were: age 29.3 \pm 2.3 years, height 180.7 \pm 1.7 cm, weight 73.0 \pm 2.5 kg, and BMI 23.8 \pm 0.7 kg \cdot m⁻².

Each subject completed two graded exercise tests on a calibrated cycle ergometer (Monark Ergonomic 818E, Varberg, Sweden) on different days, separated by a period of one week. Ideally, the tests would have been conducted simultaneously, but a previous study (14) showed that placing a non-rebreathing valve in series with the K4b² flow meter altered the V_E readings from the K4b². According to documentation from Hans Rudolf, Inc. and Cosmed, S.r.l., the resistance to flow was similar for both the Hans Rudolf 2700 Series valve (inspired: 7.2 cm H₂O; expired: 10.3 cm H₂O at 700 L \cdot min⁻¹) and the K4b² flow meter (8.4 cm H₂O at 720 L \cdot min⁻¹) so this would not have contributed to differences in ventilation. During one test, metabolic measurements were made using the K4b² and during the other test expired air was collected in meteorological balloons and analyzed by the Douglas bag (DB) method (5). The test order was counter-balanced so that half of the subjects completed the K4b² test first and half completed the DB method test first. The subjects were asked to refrain from exercise for two days before testing to reduce the likelihood of glycogen depletion affecting substrate utilization during the validation tests. In order to minimize the effect of diet on substrate utilization during exercise,

the subjects were instructed to maintain the same diet for three days before each test. Three-day dietary records were analyzed using Nutritionist Five (Version 2.2, First Data Bank, Inc., San Bruno, CA) software to confirm that the composition of the diets were similar prior to each test.

The exercise test consisted of ten minutes of rest seated on the cycle ergometer followed by five minutes of cycling at 50W, 100W, 150W, 200W and 250W. Expired air was analyzed during the final five minutes of rest and the final two minutes of each exercise stage to ensure that the subjects had reached steady state. The subjects were encouraged to exercise to exhaustion or until they had completed the 250W stage. Only four subjects completed the 250W stage. After the test was completed the subjects performed a cool-down and, after several minutes of rest and observation, were allowed to leave the laboratory.

For the DB method test, the subjects breathed through a mouthpiece connected to a Hans-Rudolf large non-rebreathing valve (2700 series, Hans Rudolf Inc., Kansas City, MO). A nose clip was used to prevent nasal breathing. Expired air was collected for the last five minutes of rest and during the final two minutes of each five-minute exercise stage in meteorological balloons (Kaysam Worldwide, Inc., Totowa, NJ). Fractions of expired O₂ and CO₂ were analyzed using an Applied Electrochemistry S-3A oxygen analyzer (Applied Electrochemistry, Inc., Sunnyvale, CA) and a Beckman LB-2 carbon dioxide analyzer (Beckman Instruments, Inc., Fullerton, CA), respectively. Before testing, the analyzers were calibrated using gases of known concentrations (15.06% O₂, 5.97% CO₂) that were previously analyzed via the micro-Scholander technique (17). A second gas mixture (18.02% O₂, 2.98% CO₂) was used to verify the linearity of the analyzers. The volume of expired air was measured using a 120 L gasometer (Warren E.

Collins, Inc., Braintree, MA). The calculation of V_E , VO_2 , VCO_2 , and R was accomplished following standard metabolic equations (16). An average value was calculated for each variable for the final five minutes of rest and the last two minutes of each exercise stage. At the end of each test, a post-test calibration check was completed by sampling calibration gas to evaluate analyzer drift during the test.

For the K4b² tests, gas exchange variables were measured continuously; following the test the breath-by-breath data were averaged over one minute intervals. The average of the last five minutes of rest and the final two minutes of each exercise stage were used for comparison with the DB method test data. Prior to each test, the K4b² turbine flow meter was calibrated according to the manufacturer's instructions using a 3 L calibration syringe (Hans Rudolf, Inc., Kansas City, MO). The O₂ and CO₂ sensors were calibrated with the same gas mixture (15.06% O₂, 5.97% CO₂) used to calibrate the reference system. Additionally, a room air calibration and delay calibration were performed as specified in the K4b² User Manual (6). At the end of each test the calibration gas was sampled by the K4b² to evaluate analyzer drift during the test.

Statistical analysis was completed using SPSS for Windows statistical software (Release 10.0.5, SPSS, Inc., Chicago, IL). Differences in $F_{E}O_2$, $F_{E}CO_2$, VO_2 , VCO_2 , V_E , and R between the K4b² and the DB method were determined by two-way repeated-measures ANOVA for rest, 50W, 100W, 150W, and 200W. Since only four subjects completed the 250W stage, differences between the K4b² and Douglas bags were determined by paired t-tests for this work rate. The significance level was set at the 0.05 level for all comparisons.

RESULTS

Figure 2 presents a summary of the data for $\dot{V}O_2$, $\dot{V}CO_2$, V_E , R, $F_{E}O_2$, and $F_{E}CO_2$ for the DB method and the K4b². Significant differences were found between the K4b² and the DB method for $F_{E}O_2$ ($P<0.01$) and $F_{E}CO_2$ ($P<0.05$) at rest and at work rates between 50–200W. The small differences in $\dot{V}O_2$, $\dot{V}CO_2$, V_E , and R between the K4b² and the DB method were not found to be significant at any of these work rates. At 250W, significant differences between the K4b² and the DB method were found for $\dot{V}CO_2$ ($P<0.01$) and R ($P<0.05$) for the four subjects who completed this stage. The differences in $\dot{V}O_2$, $\dot{V}CO_2$, and V_E were not found to be significant at this work rate.

DISCUSSION

The purpose of this study was to evaluate the accuracy of the Cosmed K4b² for the measurement of $F_{E}O_2$, $F_{E}CO_2$, $\dot{V}O_2$, $\dot{V}CO_2$, V_E , and R at rest and during incremental exercise. The K4b² accurately measured V_E compared to the DB method at all work rates. Although V_E tended to be lower in the K4b² tests, the differences between the two methods were small (between 1.0–1.6 L•min⁻¹) from rest through 150W, 5.6 L•min⁻¹ at 200W. However, at 250W the mean difference was 8.5 L•min⁻¹, although none of these differences were statistically significant. The K4b² significantly underestimated $F_{E}O_2$ and overestimated $F_{E}CO_2$ at work rates from rest through 200W. Because of the similar V_E between the K4b² and DB method and the significant underestimation of $F_{E}O_2$ and overestimation of $F_{E}CO_2$ by the K4b², differences in $\dot{V}O_2$

and VCO_2 would be expected. However, there were no significant differences in VO_2 between the two systems at any work rate and the small differences in VCO_2 were significant only at 250W.

The large differences in $F_{E}O_2$ and $F_{E}CO_2$ between the K4b² and the DB method are due to the special characteristics of the K4b² breath-by-breath system. At the beginning of each expiration, the K4b² flow meter starts spinning immediately to measure the volume of expired air but the software allows the first 70 ml of each breath to escape before computing the average expired O_2 concentration. The purpose of this 70 ml "threshold" is to avoid the detection of double breaths. As a consequence, the initial 70 ml of each breath (containing ambient air in the facemask and flow meter) are not considered in the calculation of $F_{E}O_2$ and $F_{E}CO_2$. The K4b² software mathematically adjusts for the volume of O_2 contained in the breathing apparatus at the beginning of each inspiration and expiration, so the resulting VO_2 is the same as that measured by the DB method.

With the DB method the entire breath, including the ambient air in the breathing valve, is collected in the bag and analyzed, so the subject's expired gas is diluted by the small volume of ambient air in the breathing valve at the beginning of expiration. Because of this difference, data from the K4b² must be interpreted carefully when comparing it to the DB method. Although both methods are equally valid, the K4b² yields lower values for $F_{E}O_2$ (and higher values for $F_{E}CO_2$) compared to the DB method (see Figure 3). The following example conceptually shows the different methods used to calculate VO_2 by the DB method and the K4b². (A detailed description of the exact equation used by the K4b² to calculate VO_2 is given in the Appendix.)

DB Method: $VO_2 = (V_I \times F_{I}O_2) - (V_E \times F_E O_2)$

$$VO_2 = (33.9 \text{ L}\cdot\text{min}^{-1} \times 0.2093) - (33.8 \text{ L}\cdot\text{min}^{-1} \times 0.1658)$$

$$VO_2 = 1.49 \text{ L}\cdot\text{min}^{-1}$$

K4b²: $VO_2 = (V_I \times F_{I}O_2) - (V_E \times F_E O_2) - (V_D \times (F_{I}O_2 - F_{ET}O_2))$

$$VO_2 = (33.9 \text{ L}\cdot\text{min}^{-1} \times 0.2093) - (33.8 \text{ L}\cdot\text{min}^{-1} \times 0.1618) - \\ (2.0 \text{ L}\cdot\text{min}^{-1} \times (0.2093 - 0.1427))$$

$$VO_2 = 1.49 \text{ L}\cdot\text{min}^{-1}$$

In the K4b² equation, VO_2 is calculated as the volume of O_2 inspired ($V_I \times F_{I}O_2$) minus the volume of O_2 expired ($V_E \times F_E O_2$), similar to the DB method equation. However, the lower $F_E O_2$ measured by the K4b² does not result in the calculation of a higher VO_2 compared to the DB method. This is due to the fact that the K4b² equation also corrects for the small volume of oxygen contained in the dead space (V_D) of the breathing apparatus at the onset of inspiration and expiration ($V_D \times (F_{I}O_2 - F_{ET}O_2)$), resulting in the calculation of a VO_2 that is identical to the DB method despite a lower $F_E O_2$.

The results indicate that the K4b² is accurate for the measurement of VO_2 and VCO_2 at rest and during exercise of increasing intensity through 200W. The differences in mean VO_2 between the two systems were less than $60 \text{ ml}\cdot\text{min}^{-1}$ except at 250W where the difference was $106 \text{ ml}\cdot\text{min}^{-1}$. None of the differences in VO_2 were found to be statistically significant. The differences in mean VCO_2 were less than $100 \text{ ml}\cdot\text{min}^{-1}$ from rest through 200W (NS) except at 250W, where the difference was $300 \text{ ml}\cdot\text{min}^{-1}$ ($P < 0.01$).

The differences in mean R between the K4b² and the DB method were less than 0.04 from rest through 200W (NS). However, at 250W the difference between the two methods was 0.06 (P<0.05). This difference in R is due to the significantly lower VCO₂ measured by the K4b² at this work rate. This indicates that the K4b² is accurate for the estimation of R and substrate utilization at rest through 200W, but not at higher work rates. Although the actual R does not accurately reflect substrate use at high work rates, it is still of interest since an R>1.15 is often used as a criterion for VO_{2max} (11, 12). We believe that the comparison in R between the two systems is valid since the subjects were asked to refrain from exercise for two days before testing to reduce the likelihood of glycogen depletion affecting substrate utilization during the validation tests. Additionally, the subjects were instructed to consume the same diet for three days prior to each test, minimizing the effect of diet on substrate utilization. Indeed, analysis of the diets indicated that the composition of the diets were very similar prior to each test (K4b² test: 2291 kcals, 31% fat, 54% carbohydrate; DB method test: 2161 kcals, 31% fat, 54% carbohydrate).

At the beginning and end of each test, calibration gas was sampled by the K4b² to evaluate analyzer drift during the test. The mean drift in O₂ was -0.23% (18.02% to 17.79%) and the mean drift in CO₂ was -0.02% (2.98% to 2.96%). These values for drift were similar to those measured by the reference system: -0.10% O₂ (18.02% to 17.92%) and -0.02% CO₂ (2.98% to 2.96%). It appears that the updated CO₂ analyzer resulted in stable measurements throughout the duration of the tests and was an improvement from the CO₂ drift reported previously (14).

The purpose of this study was to evaluate the accuracy of the updated K4b² portable metabolic measurement system at rest and during incremental exercise following an update of

the CO₂ analyzer and operating software. Compared to the previous validation (14), the results of the present study indicate an improvement in the accuracy of the K4b². Although the present study showed significant differences in F_EO₂ and F_ECO₂ between the K4b² and DB method at rest through 200W, no significant differences in VO₂, VCO₂, or V_E were seen at these work rates. These differences in F_EO₂ and F_ECO₂ are due to the characteristics of the K4b² breath-by-breath system. At 250W the K4b² significantly underestimated VCO₂ (P<0.01) and R (P<0.05) compared to the DB method, but no significant differences were seen for the other gas exchange variables at this work rate. In contrast to these findings, the previous study showed small but significant differences in VO₂ from 50–200W (less than 96 ml•min⁻¹). In conclusion, these findings suggest that the K4b² is accurate for the measurement of energy expenditure at rest through high work rates and is an appropriate instrument for assessing the energy cost of activities.

ACKNOWLEDGEMENTS

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APPENDIX

The K4b² computes the oxygen uptake using the breath-by-breath method similar to that described previously by Beaver and colleagues (2, 3). To compute the VO₂ during each breath, the following formula (4) is used:

$$VO_2 = [(V_T \times K_i \times F_I O_2) - O_{2Exp} - (V_D \times (F_I O_2 - F_{ET} O_2))] \times 60/T_{Tot} \times STPD$$

The term $V_T \times K_i \times F_I O_2$ represents the volume of oxygen inspired (O_{2Insp}) during the current breath, where K_i represents the nitrogen correction factor to convert from expiratory to inspiratory ventilation volumes.

The term O_{2Exp} is the volume of oxygen expired during the current breath. Every 10 msec, the K4b² multiplies the gas volume that has moved through the flow meter by the O₂ concentration of the expired gas. These "instantaneous" values are summed to compute the variable O_{2Exp} .

The term $V_D \times (F_I O_2 - F_{ET} O_2)$ is a correction for the dead space ventilation of the facemask. When the subject begins to inspire, the first 70 ml of air that is inspired is not ambient air (20.93% O₂), but end-tidal air from the previous expiration (approximately 15% O₂). Hence, the end-tidal O₂ fraction is subtracted from the ambient O₂ fraction and multiplied by the dead space of the facemask to account for the end-tidal air in the facemask inspired at the start of each breath. This value is subtracted from the difference between O_{2Insp} and O_{2Exp} to correct for the

ventilation of air trapped in the facemask. Although the adjustment is a minor one, it mathematically corrects for the higher $F_{E}O_2$.

The term $60/T_{Tot}$ is used to convert the oxygen uptake (L) for each breath to $L \cdot \text{min}^{-1}$. This rate is multiplied by the STPD correction factor to convert the VO_2 to $L \cdot \text{min}^{-1}$ (STPD).

The K4b² incorporates a delay time of approximately 500 msec so that the gas fractions and flow are in phase for the calculation of gas exchange variables. The precise duration of this delay is determined during the "delay" calibration procedure before each test, as described in the instruction manual (6). The delay time consists of the sum of two components: a) the time necessary for the gas sample to be transported from the facemask to the analyzers (~350 msec), and b) the analyzer response time (~150 msec). When the subject begins to expire, the change in ventilation is detected about 500 msec prior to the change in expired gas concentrations; hence a delay factor is needed to bring them back "in phase" with one another for the calculation of gas exchange variables over the same time interval.

In the K4b² software, a "threshold" ventilation must be exceeded in order for a valid breath to be detected. At the start of expiration, the software waits for 70 ml of gas to pass through the turbine flow meter before the flow and gas fraction signals are integrated. This feature reduces the occurrence of "double breaths", where an interrupted breath is detected as two breaths instead of one. This also permits the dead space of the facemask (containing ambient air at the beginning of expiration) to be flushed out before the computation of the variable " O_{2Exp} " begins. For this reason, the K4b² $F_{E}O_2$ values are lower than the $F_{E}O_2$ measured by the DB method. In the DB

method, all the expired air is collected in the bag, including the ambient air that was trapped in the dead space of the breathing valve at the beginning of expiration. Thus, in comparison to the K4b², the Douglas bag contains a volume of gas that has been "diluted" by ambient air.

In summary, the K4b² VO₂ values are virtually identical to those measured by the DB method, despite significant differences in F_EO₂ and F_ECO₂. This is not a consequence of "compensating errors" in ventilation and gas fractions, but is due to a different method of computing VO₂ when using a breath-by-breath system. Both methods appear to be equally valid.

Definition of symbols

V _T	tidal volume of each breath (L)
K _i	nitrogen correction factor
F _I O ₂	fractional concentration of O ₂ in inspired air
O _{2Exp}	volume of oxygen expired during the current breath (L)
V _D	dead space volume of the facemask (L)
F _{ET} O ₂	fractional concentration of O ₂ in end-tidal air
T _{Tot}	total time of respiratory cycle (sec)
STPD	corrects values to standard temperature, pressure, and dry

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LIST OF FIGURES

Figure 1. The Cosmed K4b² portable metabolic measurement system.

Figure 2. The mean \pm SE values measured by the Douglas bag method (DB, ■) and the K4b² (□) for: a) $\dot{V}O_2$ (L•min⁻¹), b) $\dot{V}O_2$ (L•min⁻¹), c) V_E (L•min⁻¹), d) R; e) $F_{E}O_2$, and f) $F_{E}CO_2$ (* P<0.05, ** P<0.01).

Figure 3. Comparison of the method of measurement of V_E , $F_{E}O_2$, and $F_{E}CO_2$ by the K4b² and the Douglas bag (DB) method.

Figure 1.

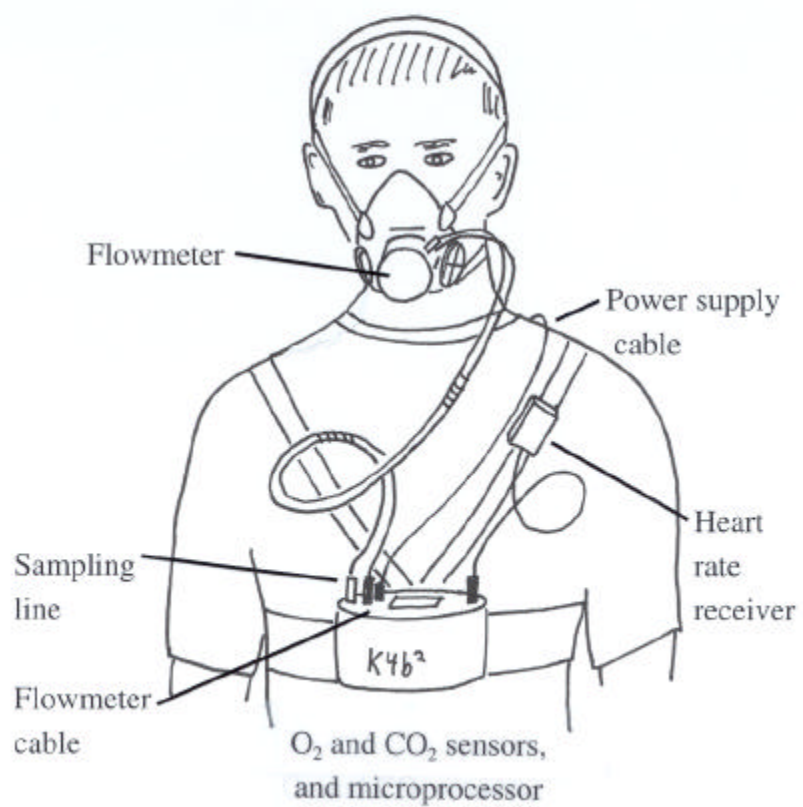


Figure 2.

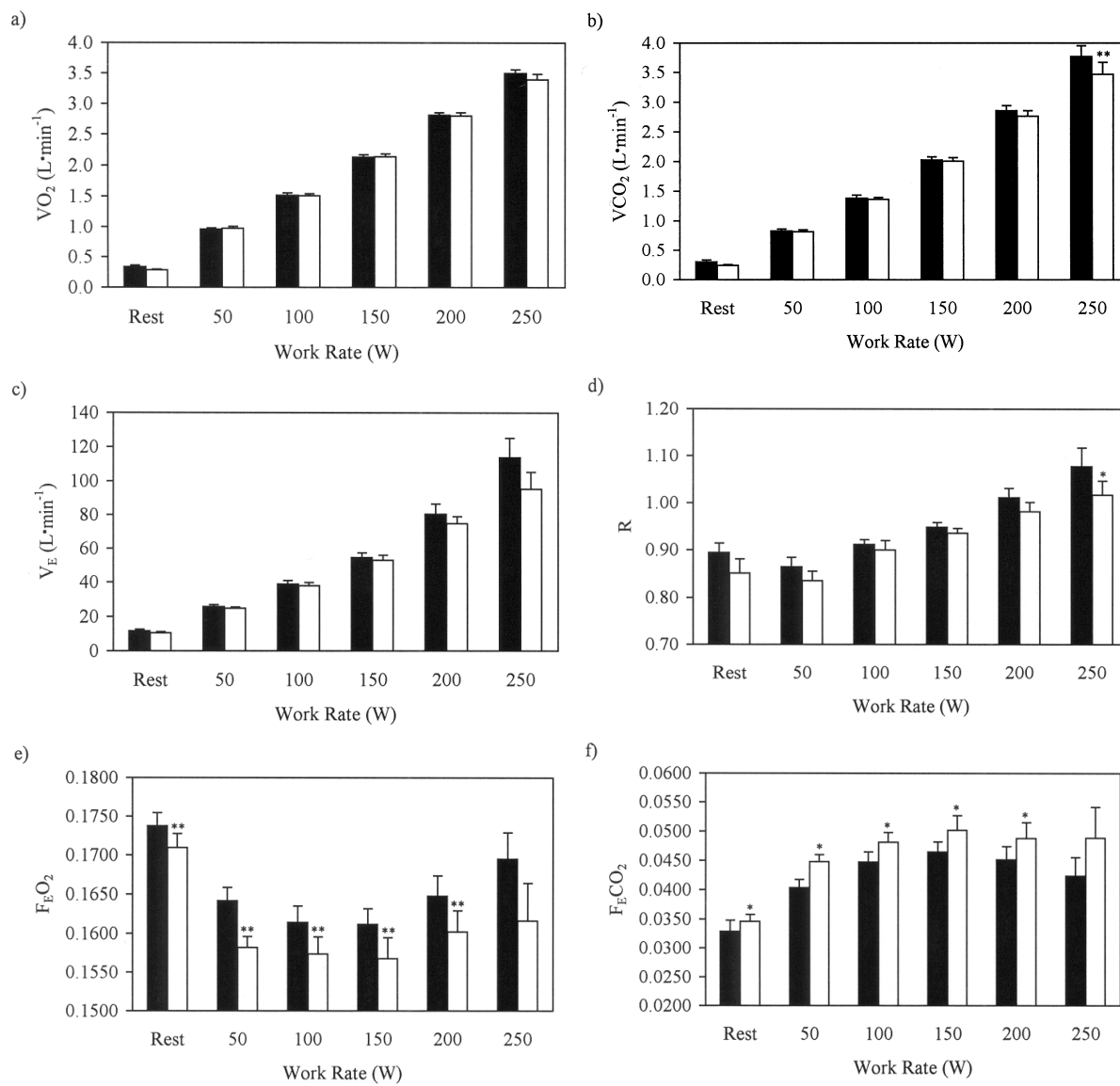
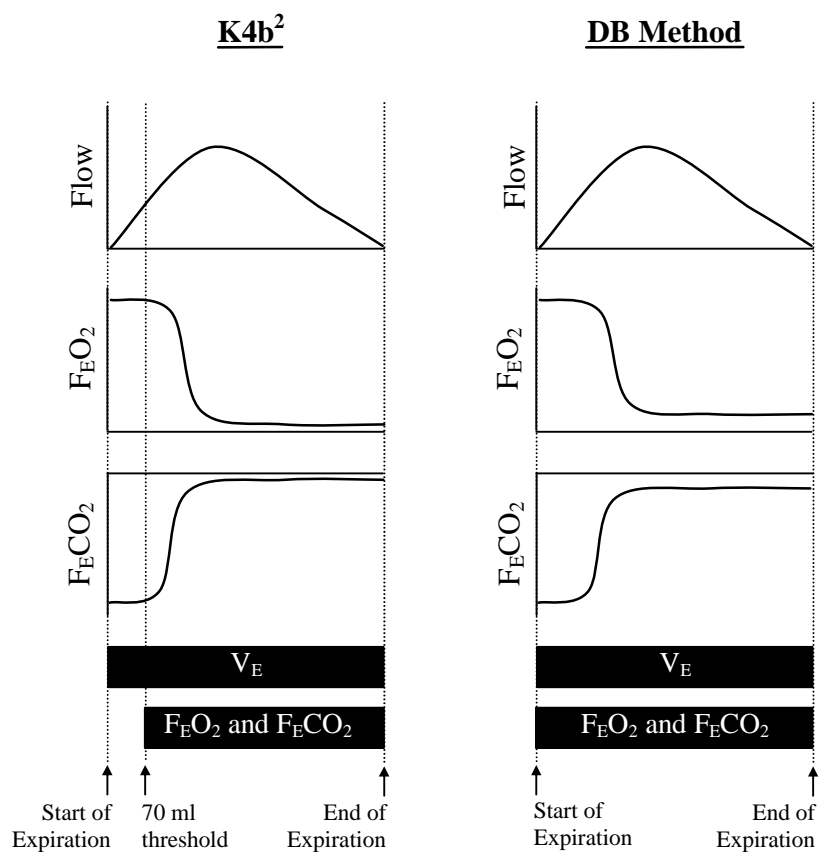


Figure 3.



In the K4b² test, when the subject begins to expire, the flow meter starts spinning immediately to measure the volume of expired air. After 70 ml of air passes through the flow meter, the integration of expired air begins, resulting in the measurement of a lower F_EO₂ and higher F_ECO₂ compared to the DB method.

In the DB method test, the entire breath, including the ambient air contained in the apparatus dead space, is collected in the bag and analyzed. This results in the measurement of a higher F_EO₂ and lower F_ECO₂ compared to the K4b².