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ON-LAND VALIDATION OF THE UNDERWATER METABOLIC ASSESSMENT SYSTEM (UMAS)

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DEPARTMENT OF NATIONAL DEFENCE - CANADA

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ABSTRACT

The recent increase in underwater research has produced an accompanying need for methods to assess energy and ventilatory requirements of diving activities. In response, The Defence and Civil Institute of Environmental Medicine (DCIEM) designed and built the Underwater Metabolic Assessment System (UMAS). It consisted of a low-resistance, open-circuit, bag-in-box breathing apparatus and its main feature was its compact size allowing it to be worn on a diver's back in water or in air. Moreover, it was simple, adjustable, and allowed control of respiratory hydrostatic loading. The results of a study to validate its on-land (dry) performance by comparing the results to the performance of a commercially available standard metabolic cart (Jaeger Ergo-Oxyscreen) are described. Nine male volunteers, aged 26-36, participated in these steady state and maximal exercise trials. Expiratory tidal volume and expired fractions of carbon dioxide and oxygen were measured. Values for oxygen consumption, carbon dioxide production and ventilation were then calculated for both the UMAS and the metabolic cart. In all cases, the relationships between the two systems were highly correlated and significant. The UMAS proved to be a reliable and accurate system for on-land measurement of metabolic and respiratory parameters. Canada. (AW)

INTRODUCTION

It is well accepted that divers are exposed to various physical stresses which can influence their ability to work underwater. Although oxygen consumption ($\dot{V}_{O_2}$) is the most widely accepted measure of energy output, the development of a system to measure it during work underwater has proven challenging. This paper describes one such system, the Underwater Metabolic Assessment System (UMAS) developed at the Defence and Civil Institute of Environmental Medicine (DCIEM) and the results of a study to validate its on-land performance.

Background

In the past 20 years, increasing emphasis has been placed on the importance of equipment design in relation to the effects on diver performance [1]. This surge has also brought about a need for methods to assess the energy and ventilatory requirements of diving activities. Dwyer [2] offers a thorough review of past developments.

Traditional application of indirect calorimetry has been considered; however, obstacles exist in applying land-based techniques to underwater conditions. Increased ambient pressure, pressure differentials, water resistance, and the thermal properties of water are the most important problems encountered. Hence, a technique was required which could account for these factors as well as a number of other problems that accompany working in water.

The first and most obvious problem associated with working in water is the ingress of water into equipment. This can be prevented by including water-tight seals within the system's connections. Second, hydrostatic pressure differentials between the respiratory tract and ambient pressure can create positive or negative pressure breathing. These pressure differentials must be controlled to study their effects and to prevent complications such as barotrauma. The third problem stems from the depth related increase of gas density in accordance with Boyle's Law. As the gas density increases, the dynamic pressure drop for a given gas flow increases proportionally. This translates into greater breathing effort per unit volume. A final problem to consider relates to the measurement of ventilation, a parameter necessary for the calculation of $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$. The technique used must not be affected by pressure or gas composition.

Because the last decade has involved a shift in interest from the laboratory to the open-water, there must be an accompanying modification of physiological underwater data acquisition systems. The current lack of information concerning human physiology in the open water is partially attributed to the lack of adequate apparatus for physiological monitoring. A brief review of past methods and equipment illustrates the problems encountered in designing the equipment, and the advantages and disadvantages associated with each.

A number of researchers have estimated $\dot{V}_{O_2}$ and work stress by measuring heart rate and ventilatory response to work performed in the open sea [3,4,5]. However, the hardware technique used by Weltman and Egstrom [3] was disadvantageous because it used an umbilical line which required surface monitoring and limited the diver's mobility. An alternative is telemetry which provides real-time monitoring, does not require an umbilical line, but has the added problem of background noise which can interfere and obscure the signal. Dwyer [5] used measurements of heart rate and pulmonary ventilation for dry-land exercise to predict $\dot{V}_{O_2}$ from regression equations. He found that the equations underestimated $\dot{V}_{O_2}$ over most of the work range by 0.4 to 0.9 L/min when heart rate was used and resulted in errors of ±0.49 L/min or more of O_2 (for moderate work rates) when pulmonary ventilation was used. This led him to conclude that the accuracy of estimating oxygen consumption during underwater work from heart rate or ventilatory response, by general or depth specific regression equations, is insufficient to justify its use.

Other studies have employed diver-carried multi-channel recording systems which store the electrical analogue of various cardio-respiratory parameters on magnetic tape [6,7]. Although the use of this technique does not generate telemetry associated problems, it lacks the advantage of real-time monitoring. In terms of practicality however, this method allows full mobility, and permits the diver to carry out his normal activities unhindered by cables.

The systems described thus far represent considerable technological advances, but none of them are able to directly monitor $\dot{V}_{O_2}$. This downfall is attributed primarily to a lack of adequate oxygen and carbon dioxide sensors which can be built into the diver's breathing apparatus.

A number of experimenters have developed techniques and apparatus capable of safely measuring $\dot{V}_{O_2}$ underwater and at depth, but they are large, complicated and include parts unsuitable for actual open-water experiments [2,8,9].

Dywer and Pilmanis [10] developed an underwater respiratory gas sampling system from a standard double-hose SCUBA regulator. It consisted of a brass U-shaped manifold which interrupted the exhaust hose of a double-hose regulator. Ten sample flasks were connected along the manifold by valves. Gas was sampled at set times in the experiment. Inspiratory ventilation was determined by measuring tank pressure differentials, then correcting for temperature to determine the volume of gas used. Divers reported subjectively that the system did not noticeably affect the effort of exhalation. Although this system was a good solution to the problems encountered in measuring $\dot{V}_{O_2}$ underwater, and was an improvement over collecting bag techniques [2], it restricted hydrostatic pressure differentials and breathing resistance under study to those inherent in the apparatus. More work was required to develop a system which would accommodate a larger number of samples and offer adjustable breathing characteristics.

The forward trend in breathing equipment design continued when Thalman *et al.* [11] introduced the Low Resistance Breathing System (LRBS). The LRBS was set up inside a hyperbaric chamber. It consisted of a demand gas supply system as well as a bag-in-a-box breathing apparatus. Breathing resistance was minimized by using a specially designed mouthpiece connected to the gas supplies by 57.2 mm internal diameter (i.d.) hoses. Control of hydrostatic lung loads was accomplished by raising and lowering the diver's position in relation to a pressure reference. Ventilation was measured using both a spirometer inside the chamber and a dry gas meter outside the chamber. Gas could be continuously sampled and analyzed using a mass spectrometer. Overall, the apparatus developed by Thalman *et al.* [11] was a remarkable improvement over past systems but its size was a drawback.

The next step in designing a system was to reduce the size of the apparatus while preserving its ability to control hydrostatic pressure differentials and breathing resistance. On that premise, DCIEM developed the Underwater Metabolic Assessment System (UMAS). The UMAS is a compact version of its prototype, the Low Resistance Breathing Apparatus (LRBA), which used the LRBS low resistance bag-in-a-box technique. The prototype consisted of a $0.16m^3$ box housing a turbine volumemeter, a mixing box, and a Douglas bag. The subject inspired gas from the Douglas bag, which was kept inflated by a regulated and metered gas supply. One-way valves maintained a unidirectional gas flow. A turbine-type volumemeter measured the volume of the expired gas. The composition of the expired gas was measured by oxygen and carbon dioxide analyzers. The outputs from the ventilation meter and the gas analyzers were fed to a stripchart recorder. Following the successful verification of the prototype [12], work began on the design of the UMAS.

UMAS

The UMAS possesses a few features that neither the LRBS or LRBA offered. Most obvious is its size, which easily enables it to be worn on the diver's back. In addition, the apparatus is fully submersible. The breathing circuit consists of the subject inhaling gas from the counterlung through a smooth bore hose over the right shoulder and exhaling back into the housing through another hose over the left shoulder (Figure 1). The counterlung is supplied from an externally regulated and metered compressed gas supply. After entering the housing, the expired gas flows through the mixing box. A gas sample from the mixing chamber is analyzed for oxygen and carbon dioxide content. The volume of the expired gas is first measured by a turbine volumemeter as it leaves the mixing box. A thermistor measures the temperature of the gas flowing out of the volumemeter. Finally, the expired gas leaves the apparatus through a hose at the bottom of the housing and is expelled into the water through mushroom valves located in a regulator housing (not shown). The regulator maintains breathing system pressure. By altering the regulator's position in relation to the diver's respiratory tract, it is possible to examine the effects of positive and negative breathing. The features that potentially make the UMAS unique are its size, simplicity and adjustability, in particular, the small turbine volumemeter and ability to control respiratory hydrostatic loading by changing the position of the regulator.

The purpose of this study was to validate the on-land performance of the UMAS by comparing its results to those of a standard metabolic system. Measurements were made to determine oxygen consumption, carbon dioxide production, and ventilation during steady state and maximal exercise.

METHODS

Subjects

Table 1 presents the physical characteristics of the nine physically active male volunteers. Seven of the subjects were Canadian Forces clearance divers, the other two had no diving background. All subjects wore shorts, t-shirt, running shoes and a noseclip while exercising.

Apparatus

Since the aim of this study was on-land validation of the UMAS, the subject breathed room air through the inspiratory breathing hose. Therefore, the counterlung, the regulator, and the compressed air supply were not required. All other components of the UMAS were tested.

Table 1. Anthropometric Characteristics of Nine Subjects

Subject	Age (years)	Height (cm)	Weight (kg)
A	26	170	70.5
B	30	172	77.0
C	31	185	79.0
D	32	178	74.0
E	30	178	70.0
F	32	165	59.0
G	34	185	100.0
H	34	180	100.0
I	36	175	78.0
Mean	31.7	176.4	78.6
S.D.	2.92	6.69	13.53
Range	26-36	165-185	59-100

The UMAS consisted of a box with dimensions of 430 x 330 x 160 mm. The box housed a breathing bag, mixing box, turbine volumemeter and thermistor. All breathing hoses were smooth bore with 50 mm i.d. The inspiratory and expiratory hoses were 1.15 m in length and were connected to the mouthpiece by a plastic Y-pipe. Any backflow was prevented by two 57 mm one-way diaconical flapper valves (Scott Part No. 10005513) located at the inspiratory and expiratory junctions. The dead volume of the mouthpiece was about 160 mL.

On expiration, the gas passed through the mixing chamber (approximate volume = 8.0 L). A 0.5 L/min sample was taken from the mixing chamber, dried then pumped through a carbon dioxide analyzer (Beckman Medical Gas Analyzer, LB-2) and an oxygen analyzer (Applied Electrochemistry, S-3A). Following this the gas passed through the volumemeter (Alpha Technologies, Ventilation Measurement Module-2). A thermistor (YSI 44084) was used to measure gas temperature as it passed through the volumemeter. The electrical output from the carbon dioxide and oxygen analyzers and the volumemeter was passed to a stripchart recorder (Gould Recorder 2600). Finally, the expired gas was passed to a Standard Metabolic Cart (Jaeger Ergo-Oxyscreen) where it was analyzed for comparison purposes.

Procedures

Each subject performed both a steady state and a maximal exercise test on an electrically-braked cycle ergometer (W.E. Collins, Pedalmate). The subject began breathing on the system, then pedalled for two minutes at 50 watts. Following the warmup, the power setting was increased by 50 watts, and then in 50 watt increments every four minutes until 14 minutes had elapsed, thereby completing the steady state test. Once again, the subject pedalled gently for two minutes at 50 watts before commencing the maximal test. During the maximal test, the initial power setting was 200 watts. This was increased by 25 watt increments each minute until the subject was exhausted or the experimenter ended the trial.

Calculations

The expired oxygen and carbon dioxide fractions were determined from the strip-chart recording for the last two minutes at each steady state power output and for each minute of the maximal test. Ventilatory volumes were read from the ventilation measurement module each minute and corrected to BTPS. Oxygen consumption and carbon dioxide production were calculated [13] and reported for STPD conditions.

Data analysis

The mean and standard deviation of $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$, and $\dot{V}_E$ were determined for three power outputs performed during steady state exercise (100, 150 and 200 watts). For the maximal exercise trials, the highest power output attained by each individual was used to determine the average maximal power output and standard deviation for the group. The results for the UMAS and the Jaeger were plotted against the corresponding power output. In addition, normal $\dot{V}_{O_2}$ values from Åstrand and Rodahl [14] were plotted for comparison purposes.

The UMAS data for $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$, and $\dot{V}_E$ for each subject were plotted against the Jaeger Ergo-Oxyscreen values for the last two minutes of each power output during steady state exercise and for each minute of maximal exercise. A linear regression analysis was performed on the pooled individual data to compare the results of the UMAS to those of the Jaeger.

RESULTS AND DISCUSSION

The chart recordings in Figure 2 are typical examples of the oxygen (top), carbon dioxide (middle) and tidal volume (bottom) outputs for an individual during a maximal exercise trial. The smooth fractional gas outputs and consistent, normal ventilatory volumes indicate that the volume of the mixing box was sufficient to give a mixed expiratory sample. The jitter in the CO_2 trace was the baseline noise of the instrument.

Table 2. Correlation coefficients between metabolic parameters measured simultaneously with the UMAS and the Jaeger.

Condition	r
Steady state	
$\dot{V}_{O_2}$	0.948
$\dot{V}_{CO_2}$	0.956
$\dot{V}_E$	0.987
Maximal	
$\dot{V}_{O_2}$	0.913
$\dot{V}_{CO_2}$	0.978
$\dot{V}_E$	0.986

Note: All r-values significant ($p<0.01$).

The group mean oxygen consumption values and standard deviations for the UMAS, the Jaeger and the norm from Åstrand and Rodahl [14] are plotted in Figure 3. The steady state results (100, 150 and 200 watts) are comparable as evidenced by the small deviations seen between the results for the different apparatus. In addition, the results for the maximal trial are similar, particularily for the UMAS and the Jaeger. Figure 4 displays the corresponding results for carbon dioxide production for the UMAS and the Jaeger. Once again, the steady state results are close, with a small difference evident at the maximal power output. This difference was attributed to variations in individual fractional gas values. The ventilatory values for the UMAS and the Jaeger (Figure 5) are very similar for both the steady state and maximal trials with an average difference between the steady state results of only 0.5 L/min.

A more quantitative comparison can be seen in Figures 6 to 8. These figures display the individual data for steady state and maximal oxygen consumption, carbon dioxide production and ventilation in scatter plots of the UMAS versus the Jaeger. Table 2 shows that all of the relationships between the UMAS and the Jaeger were highly correlated and significant ($p<0.01$).

CONCLUSIONS

The UMAS measured metabolic parameters accurately and reliably on land. All of the relationships for $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$, and $\dot{V}_E$, between the UMAS and a standard metabolic cart were highly correlated and significant. The turbine volumemeter accurately measured ventilation and the mixing box provided adequate expired gas mixing during steady state and maximal exercise.

RECOMMENDATIONS

It is recommended that evaluation of the UMAS be continued using a controlled inspiratory gas supply, followed by validation underwater and at depth.

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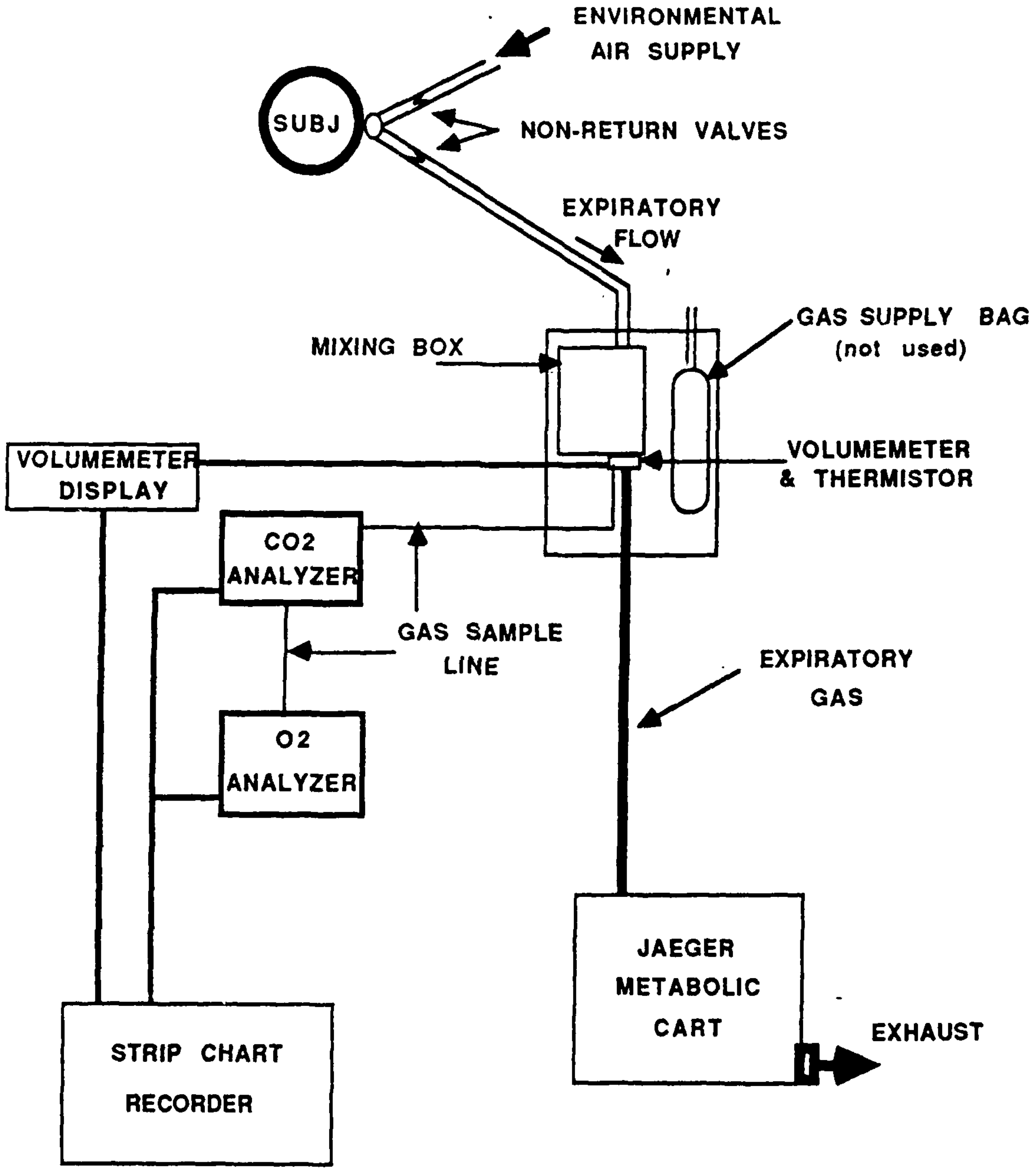


FIGURE 1. SCHEMATIC OF THE UMAS AND JAEGER SET-UP.

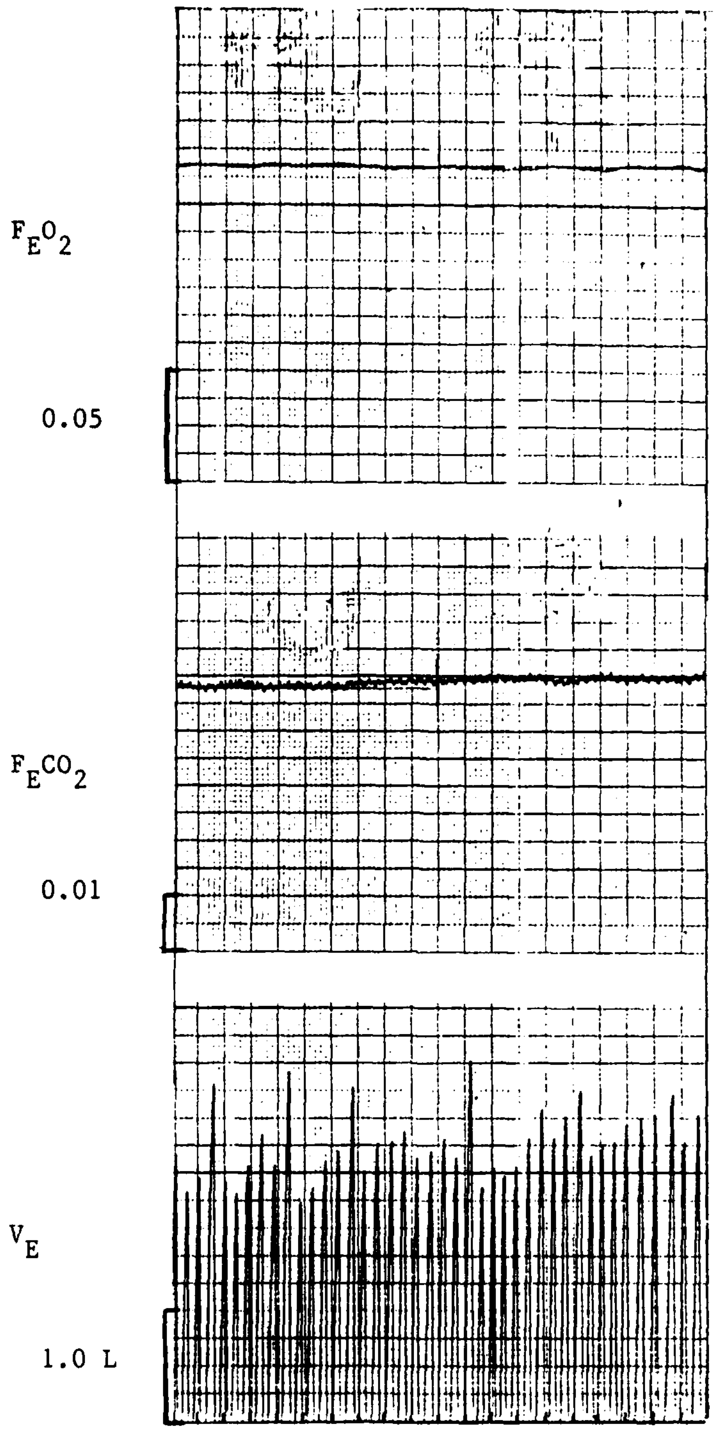


Figure 2. Sample trace of the oxygen, carbon dioxide and ventilation channels.

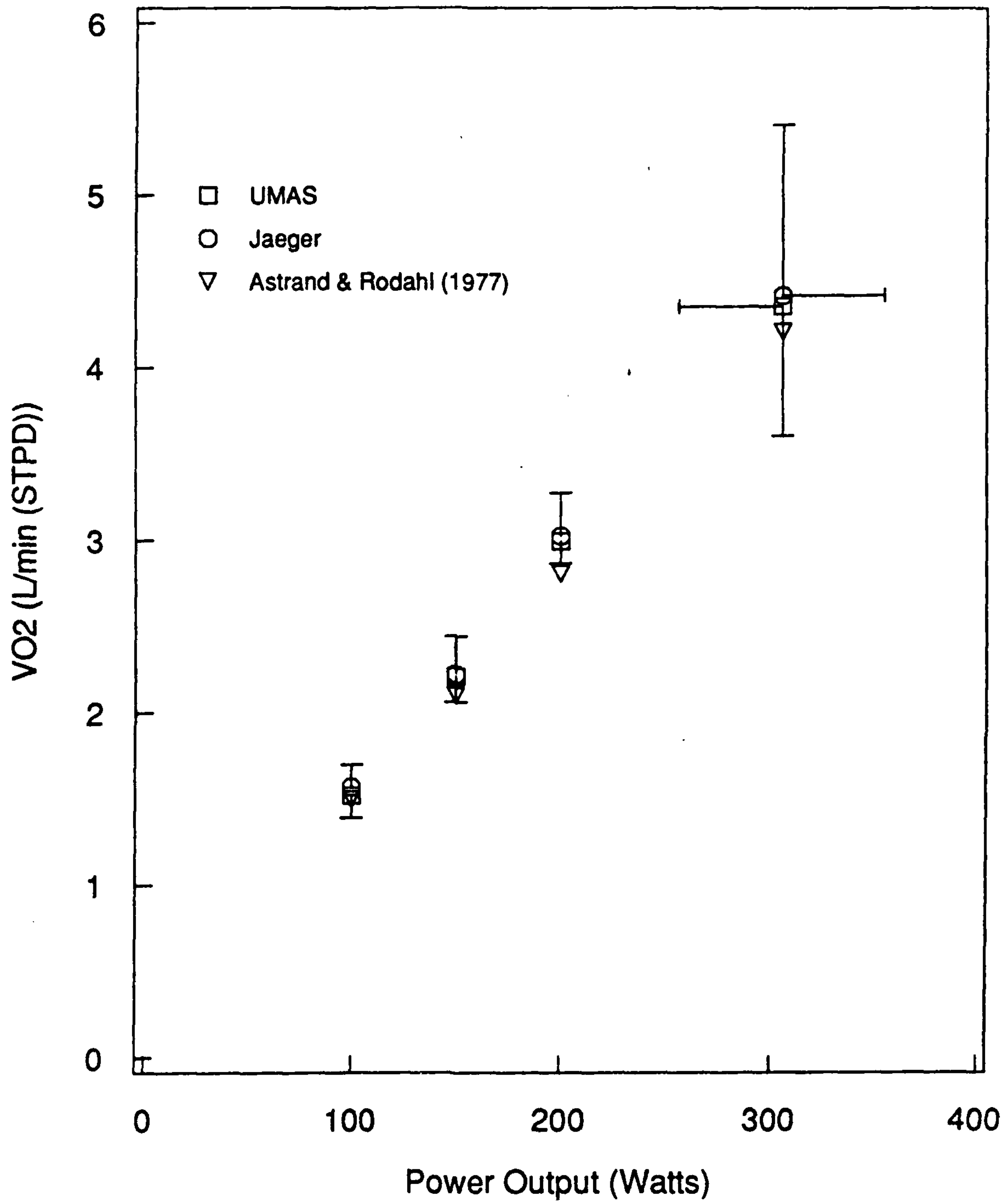


Figure 3. Comparison of oxygen consumption values recorded using the UMAS and the Jaeger metabolic systems with values from Astrand & Rodahl (1977).

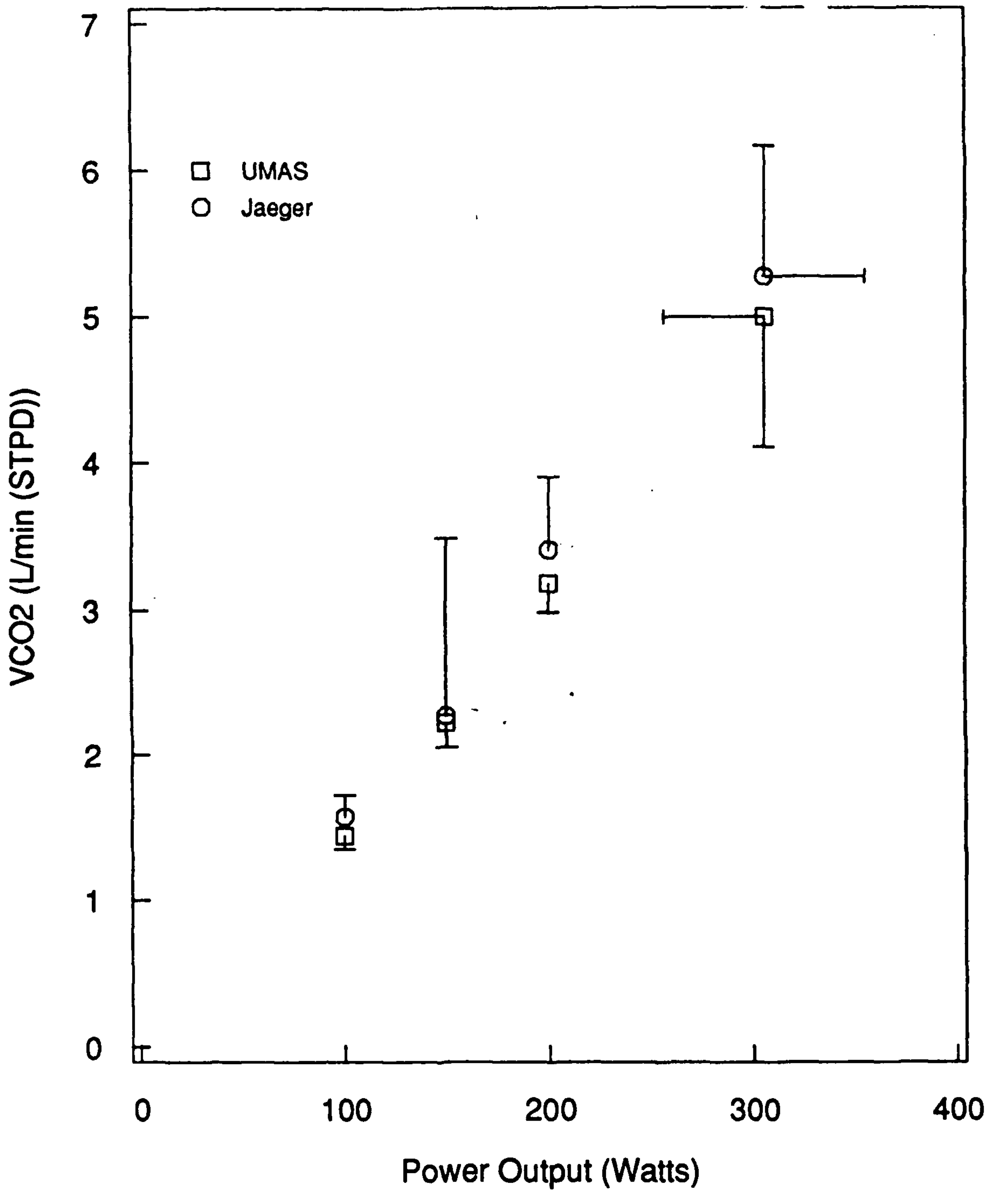


Figure 4. Comparison of carbon dioxide production values recorded using the UMAS and the Jaeger metabolic systems.

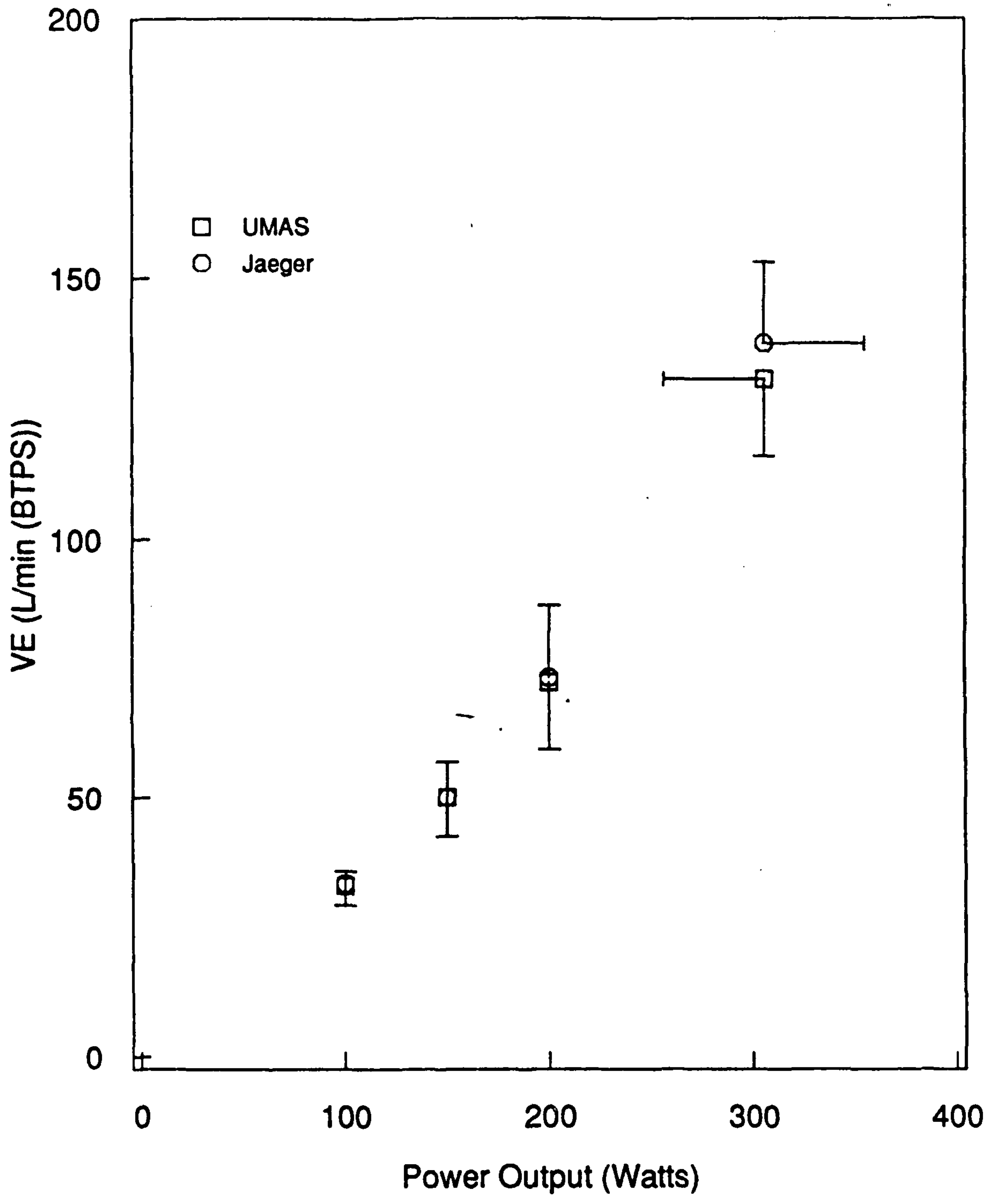
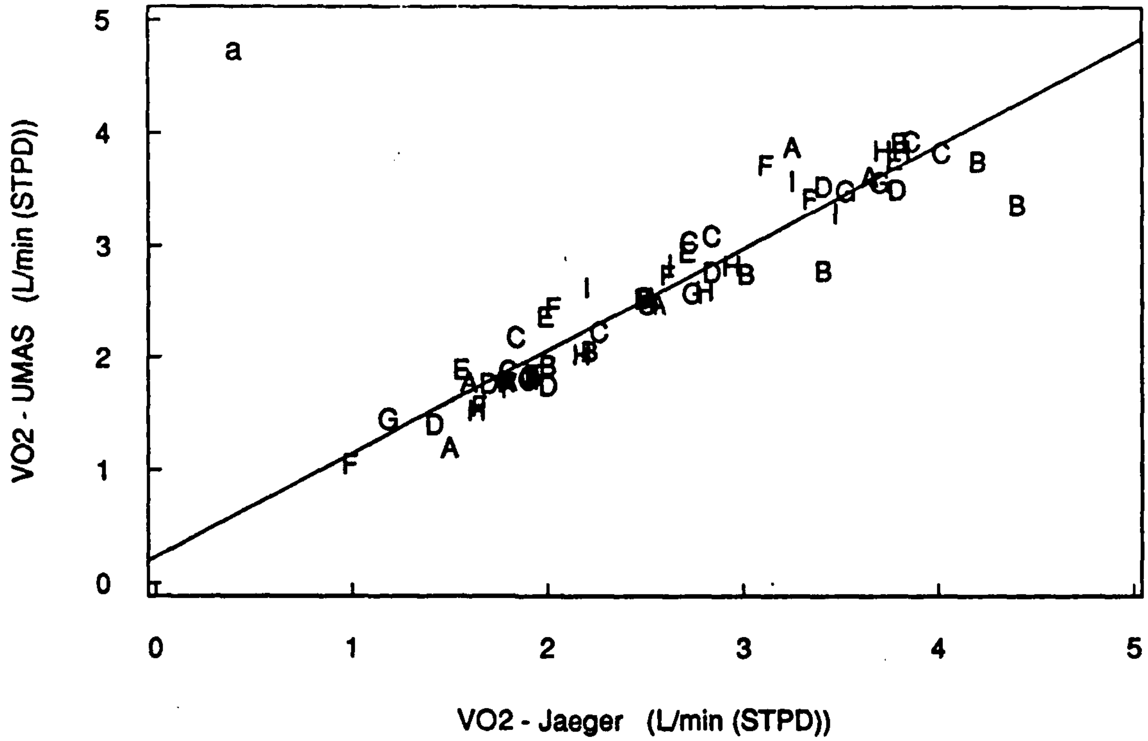
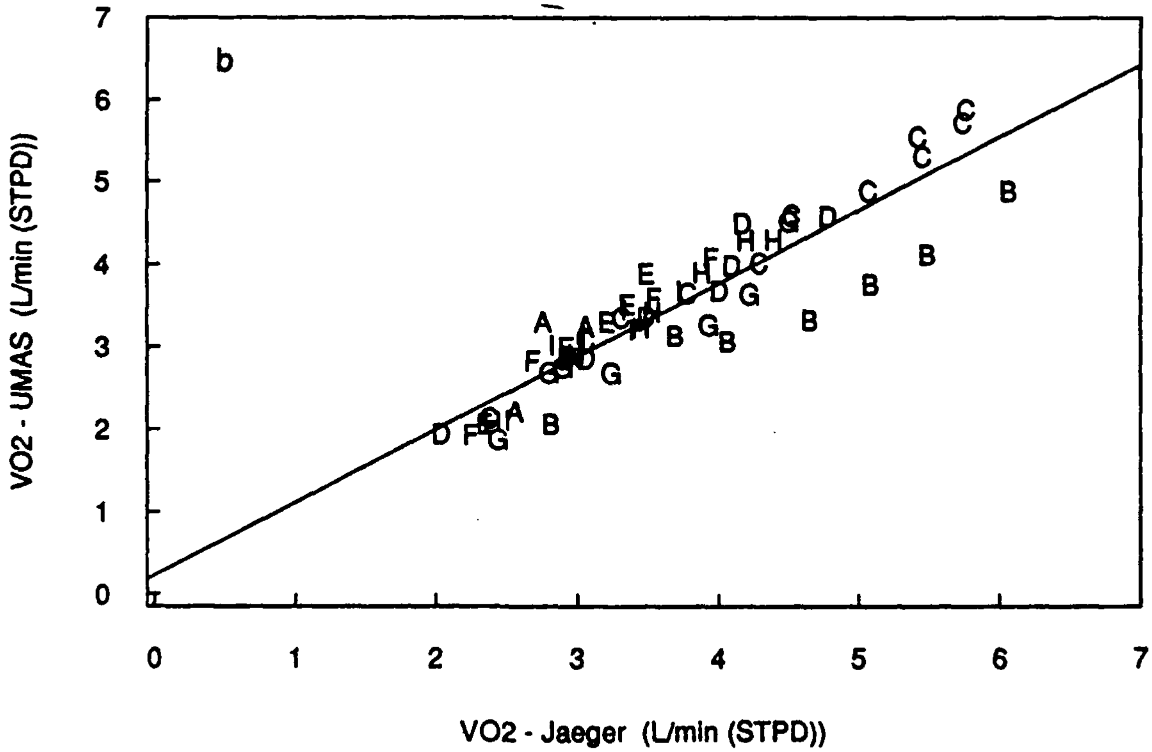
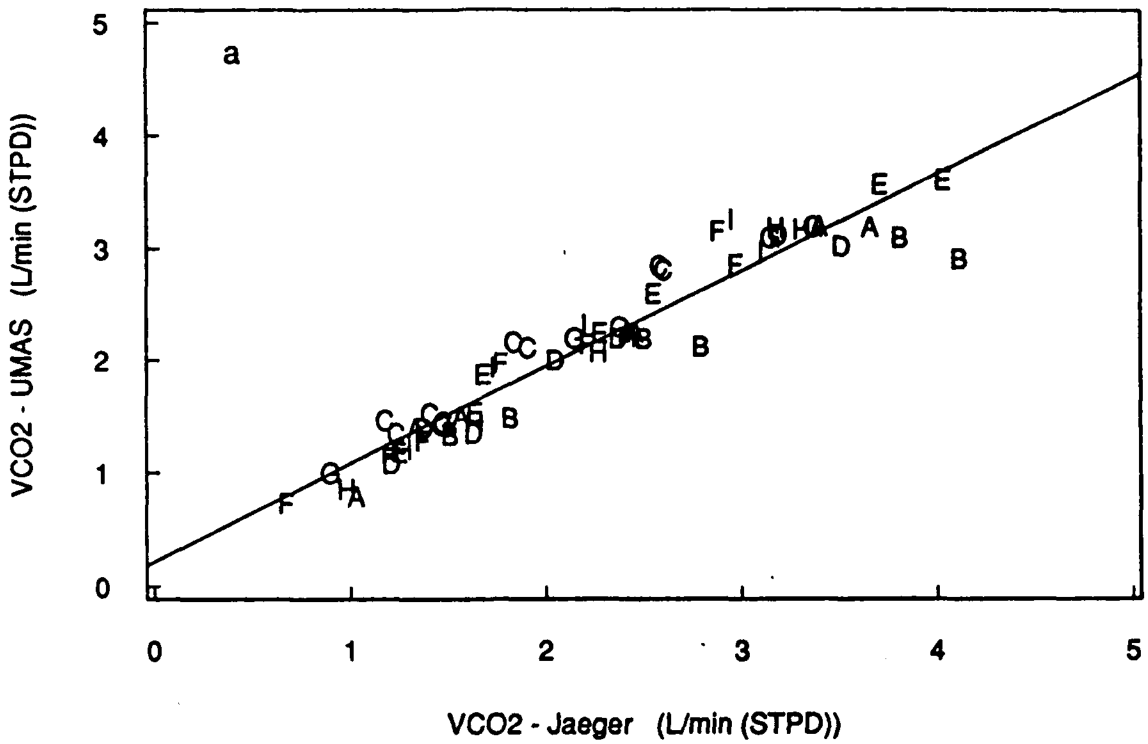


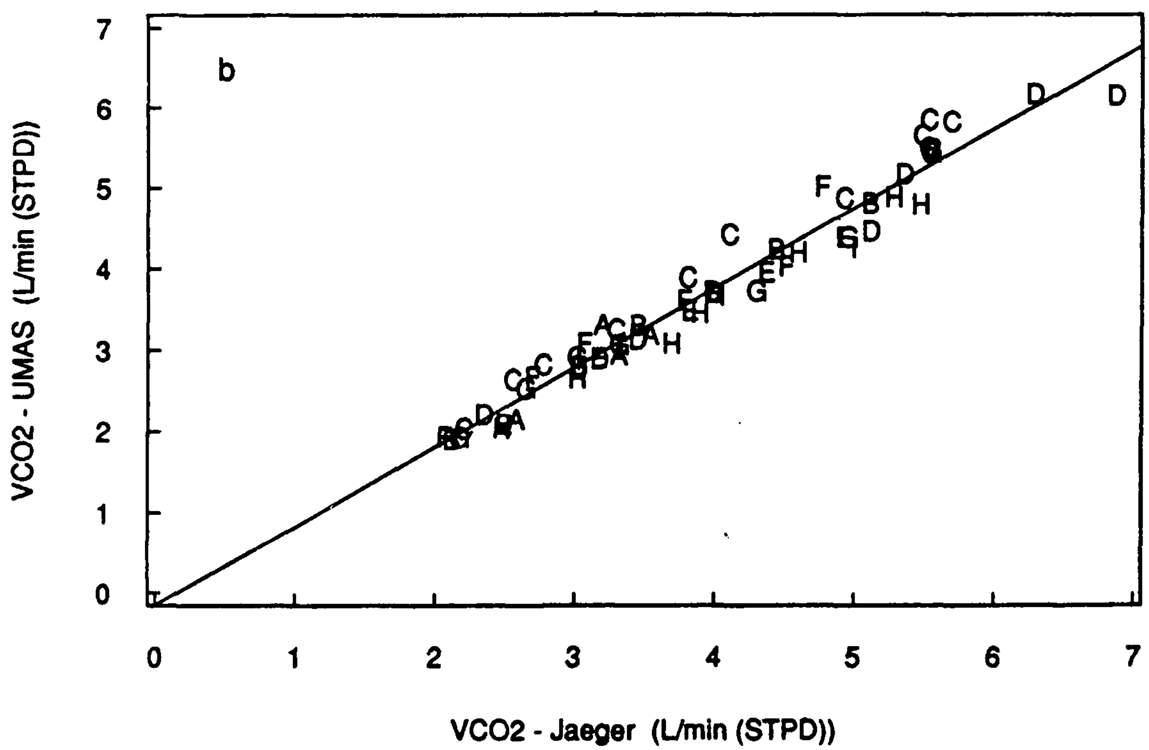
Figure 5. Comparison of ventilatory values recorded using the UMAS and the Jaeger metabolic systems.



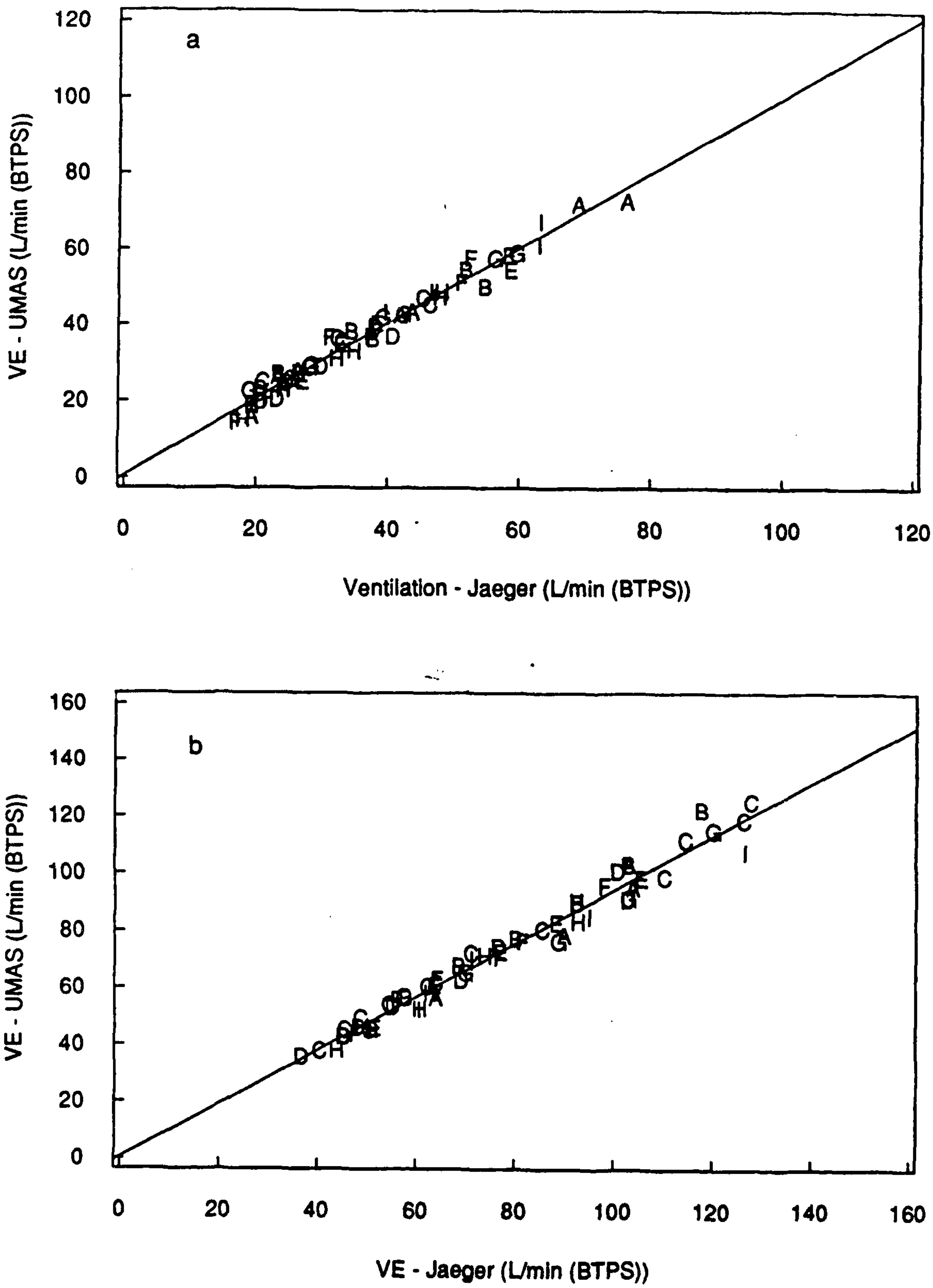


Figures 6. Comparison of the individual oxygen consumption values for the two systems during steady state (6a) and maximal (6b) exercise. Letters indicate individual subject data.





Figures 7. Comparison of the individual carbon dioxide production values for the two systems during steady state (7a) and maximal (7b) exercise. Letters indicate individual subject data.



Figures 8. Comparison of the individual ventilatory volumes for the two systems during steady state (8a) and maximal (8b) exercise. Letters indicate individual subject data.

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The recent increase in underwater research has produced an accompanying need for methods to assess energy and ventilatory requirements of diving activities. In response, DCIEM designed and built the Underwater Metabolic Assessment System (UMAS). It consisted of a low-resistance, open-circuit bag-in-box breathing apparatus. A small turbine volumemeter, the ability to control respiratory hydrostatic loading, and its size were the main advantages of the UMAS.

This study validate the on-land performance of the UMAS by comparing its results to those of a standard metabolic cart (Jaeger Ergo-Oxyscreen).

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