PHYSIOLOGICAL MEASUREMENT DURING VARIABLE PHYSICAL WORK DEMAND ACTIVITY

II. The Validity of Mixing Chamber Sampling for Expired Gas Fraction Analyses

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Introduction

The work of Åstrand and Saltin (1961) and Shephard et al (1968) has established maximum oxygen uptake ($\dot{V}O_2$ maximum) as the reference standard for cardio-respiratory fitness. Prediction of physical work ability from $\dot{V}O_2$ maximum is exemplified by Taylor (1944), (1945), Rowell (1964), Brooke and Knowles (1974) and prediction from the lung gas extraction fraction ($F_{I}O_2\% - F_{E}O_2\%$) by Brooke (1970).

The accurate determination of the percentage of oxygen in expired air samples ($F_{E}O_2\%$) is an essential in both methods of prediction. Traditionally expired air collection by Douglas Bags for subsequent analysis using the Haldane apparatus as described by Consolazio et al (1963) has been practised.

The development of electronic analysers such as the Pauling Type paramagnetic oxygen analyser and the infra red carbon dioxide analyser have created the opportunity to establish on-line systems for the continuous sampling and analysis of expired lung gases. Such systems are based upon the use of a mixing chamber from which the samples can be withdrawn. A mixing chamber is necessary to overcome breath-by-breath and intra-breath fluctuations.

Consolazio et al (1963) and Davies and Shirling (1967) showed that the very small differences between duplicate samples analysed for O_2 content by the Haldane apparatus and by paramagnetic analysers were of little significance. Campney and Pleasants (1965) and Davies and Shirling (op. cit) have also established the validity of expired air sampling using a 5 litre mixing chamber by comparison with the Douglas Bag method.

However, the work tasks in the previous studies mentioned have been characterized by constant load or constantly increasing loads. In field conditions it is clear that energy expenditure fluctuates during most sports and physical education activities. As the electronic speed control system of the Jaeger 'Laufergotest' Treadmill provides the possibility for designing 'specific' laboratory tests which mirror the fluctuations encountered in the field, the validation of the use of an on-line sampling chamber system incorporating direct measurement of expired air gas volumes and continuous withdrawal of gas samples from a mixing chamber for

oxygen content analysis was felt to be worthwhile. It has the advantage of increased laboratory efficiency in terms of subject throughput, reduction in technical assistance and reduced chances of accidental Douglas Bag leakage.

The Problems

1. The problem was to establish the comparability of the $F_{E}O_2$ analyses by sampling from an on-line system versus one by Douglas Bag collection in work conditions where physiological variability has been minimized, i.e. steady state.
2. The problem was then to determine the validity of these techniques for determination of $F_{E}O_2$ in tests where energy expenditure fluctuates.

Method

Section 1: Reliability of the gas sampling and O_2 analysis

Fig. 1 shows the arrangement of the apparatus in the on-line system. The Servomex paramagnetic oxygen analyser (Type OA 134) was calibrated before and after testing using a series of prepared reference gases supplied with calibration certificates by B.O.C. Special Gases Division and also checked periodically by use of the Haldane apparatus. The mixing chamber was a 5 litre Pyrex glass aspirator close coupled to the gas meter. It was fitted with a Max Planck Institute low resistance respiratory valve sealed and modified in order to allow gases to be exhausted from the mixing chamber. A 7.5mm bore polythene sampling tube extending to the approximate centre of the chamber was coupled to a low flow sealed pump which withdrew a continuous sample of expired air for passage via a silica gel drying cell to the O_2 analyser. A direct reading of the analyser, using the expanded scale calibrated in 1% O_2 divisions and allowing estimates to 0.1% O_2 , was made at the end of each work minute. (It should be noted that Fig. 1 shows the coupling of the O_2 analyser to a recorder but this facility was not used in this study). All the visual readings were made by the same researcher to the nearest estimated 0.1% O_2 .

Douglas Bags were attached to the mixing chamber exhaust valve at the beginning of each work minute and removed at the end. Although there was a few seconds delay at each change over, bags of expired air were

AN ON-LINE SYSTEM FOR MEASUREMENT OF EXPIRED AIR VOLUMES (V_E) AND CONTINUOUS SAMPLING OF OXYGEN AND CARBON DIOXIDE FOR $\%F\text{ECo}_2$

DIAGRAM 1

PARKINSON-COWAN
CD4 GASMETER

5 LITRE MIXING CHAMBER
(PYREX ASPIRATOR)

AIR FLOW
EXHAUST VALVE
(MODIFIED MAX PLANCK VALVE)

SAMPLING TUBES
(7.5m/m BORE POLYTHENE)

LOW FLOW PUMP

SILICA GEL
DRYING CELL

CO₂ ANALYSER
HARTMANN & BRAUN
(BUILT IN PUMP)

O₂ ANALYSER
SERVOMEX TYPE

A.E.I. 8 CHANNEL
POLYGRAPH

VENTILATION
TRACE

TEMPERATURE
PROBE

THERMISTOR THERMOMETER
(3 GID LIGHT LABORATORIES)

POTENTIOMETER
COUPLING

MAX PLANCK
LOW RESISTANCE
RESPIRATORY VALVE

AIR FLOW

FACE MASK

FALCONIA TUBING
(EXPANDABLE)
(1 1/2" DIA.)

HONEYWELL ELEKTRONIK 194
2 PEN RECORDER

considered to contain a representative sample of the air expired from the lungs during the minute. The bags were Plysu type polythene, of 200 litre volume and fitted with 2-way spigots. All bags were checked for leaks, filled with expired air squeezed empty and numbered in sequence as they were used.

A single subject exercised on the Müller cycle ergometer at a constant 90 r.p.m. and a power output of 60 watts for 21 minutes. During the last 11 minutes O₂ analyser readings were taken at the end of each minute and Douglas Bag samples were collected for each work minute according to the methods previously stated. At the end of the test the Douglas Bag expired air contents were sampled by connection of the side arm to the pump sampling tube and a steady reading from the analyser was assumed to be representative of the O₂ content of the bag.

The data obtained by direct analysis of samples from the mixing chamber were arranged in data pairs as follows:-

% O₂ minute 0 — % O₂ minute 1
 % O₂ minute 1 — % O₂ minute 2
 etc. etc.
 % O₂ minute 10 — % O₂ minute 11.

Resulting in data pairs $n = 10$.

Within Trial Reliability was then tested by two way analysis of variance applying the formula:-

$$rel = \frac{V_I \times V_I \times T}{V_I + (k-1)V_I \times T}$$

after the manner of Brooke et al (1970).

Standard errors of measurement were determined by applying the formula:-

$$Se = S\sqrt{1 - r_{11}}, \text{ Thorndike (1951),}$$

and the 95% confident limits for the error of measurement were determined by $\pm tSe$.

Identical procedures were applied to the data obtained from the analysis of the expired air contained in the Douglas Bags.

Within Trial comparability of the direct sampling and O₂ analysis was tested by data pairing of the direct analysis with the Douglas Bag analysis at each work minute. This gave 11 data pairs. Thereafter statistical procedures were identical with those given previously.

Section 2: FEO₂ % determinations by direct sampling from a mixing chamber and by the Douglas Bag method

in a fluctuating speed Treadmill test.

The on-line system previously described was used in conjunction with Douglas Bags connected to the mixing chamber exhaust valve. Minute by minute direct analysis and Douglas Bag collection of expired air samples for subsequent analysis was conducted in the same manner as before.

The subjects, $n = 12$, well trained male soccer players (age $\bar{x} = 24$) all performed an identical pre-test Treadmill run followed by a horizontal Treadmill work test to exhaustion which required increasing numbers of 5 second bursts of speed as described in this journal, Brooke & Knowles "Validity of 10 beat measure".

Reliability coefficients, standard errors of measurement and 95% confidence limits were established for subjects at each work level and over all work levels by using the statistical methods outlined in the previous sections.

Results

Descriptive statistics, standard errors of measurement and the 95% confidence limits for measurement error are given in Table I for one subject tested according to the procedures shown in the Method, of our other paper.

Table I

Within Trial Reliability of FEO₂ measures obtained from a single subject in steady state conditions.

	n	$\bar{x}$	S.D.	Se	$\pm tSe$ for 95% confidence limits for standard error of measurement $\pm \% O_2$
Consecutive minute samples on-line vs on-line	10	16.09	0.09	0.076	$\pm 0.17 \% O_2$
Consecutive minute samples D. Bag vs D. Bag	10	16.16	0.08	0.067	$\pm 0.15 \% O_2$
Simultaneous minute samples on-line vs D. Bag	11	16.12	0.10	0.05	$\pm 0.11 \% O_2$

Table II

Means and standard deviations for the two methods of FEO₂ determination overall and at each minute of the

variable load, increasing intensity work task

Time	No. of Subjects	$\bar{x}$ Douglas Bag	S.D.	$\bar{x}$ on-line	S.D.
0-1	11	17.15	0.73	17.01	0.66
1-2	11	16.87	0.63	16.74	0.65
2-3	11	16.90	0.49	16.75	0.64
3-4	11	17.04	0.60	16.84	0.63
4-5	7	17.31	0.63	17.20	0.62
5-6	10	17.35	0.58	17.16	0.64
6-7	6	17.68	0.46	17.53	0.54
7-8	9	17.72	0.44	17.58	0.50
8-9	9	17.88	0.45	17.71	0.44
9-10	8	17.94	0.26	17.91	0.44
10-11	7	18.29	0.35	18.11	0.36
overall	100	17.38	0.67	17.24	0.69

Table III

Replicability coefficients, standard error of measurement and 95% confidence limits overall and minute by minute for $F_{E}O_2$ % measurement using the two methods of air sampling in a variable load, increasing intensity work task.

Time	No. of Subjects	r_{11}	S.D.	Se	$\pm tSe$ for 95% confidence limits for standard error of measurement, $\pm \% O_2$
0-1	11	0.970	0.68	0.118	0.26
1-2	11	0.965	0.63	0.118	0.26
2-3	11	0.944	0.56	0.132	0.29
3-4	11	0.968	0.61	0.109	0.24
4-5	7	0.998	0.60	0.027	0.07
5-6	10	0.975	0.60	0.073	0.16
6-7	6	0.962	0.48	0.093	0.23
7-8	9	0.971	0.46	0.078	0.17
8-9	9	0.923	0.44	0.122	0.28
9-10	8	0.704	0.35	0.19	0.44
10-11	7	0.978	0.36	0.530	0.12
Overall	100	0.961	0.68	0.134	0.26

Descriptive statistics relating to each minute of exercise for twelve subjects performing a variable load, increasing intensity, work task according to the procedures outlined in the Method, Section 2, are given in Table II. Replicability coefficients, standard error of measurement and 95% confidence limits for $F_{E}O_2$ measurement in this test are given minute by minute and overall in Table III.

It should be noted that, although 12 subjects were tested, the number of subjects from which data was

available at each minute varies due to the fact that:-

1. A leaking bag was discovered and results obtained from its use were discarded.
2. Some subjects became exhausted before the eleventh minute of testing.

Discussion

The procedures adopted in Method, of our previous paper, establish the reliability of the $F_{E}O_2$ % measure for a single subject during steady state. Table I shows that the 95% confidence limits for the standard error of measurement between analyses of samples taken from the mixing chamber of the on-line system and samples collected simultaneously by Douglas Bag are approximately $\pm 0.11\% O_2$. In reading the results of the analyses from the Servomex analyser, estimates were made to the nearest $0.1\% O_2$, therefore, it can be seen that the calculated error of measurement at the 95% confidence level is close to the nearest estimate in reading from the meter scale. The error of measurement is slightly increased when results of analysis from consecutive minutes by both on-line and Douglas Bag methods are used, but the error is of the same order in both methods $\pm 0.17\%$ and $\pm 0.15\%$. This small error in measurement comparing between minutes taken in conjunction with the even smaller error for within minute sampling establishes the validity of this on-line system as a satisfactory system for determination of $F_{E}O_2$ %. Davies and Shirling (op. cit) found that the difference between duplicate samples analysed by Haldane and Beckman paramagnetic O_2 analysers to be $\pm 0.15\% O_2$ for 80% of 200 samples. (This is the equivalent of $\pm 0.23\%$ for a population at the 95% confidence level). The present calculated error falls comfortably within the error they found when engaged in a similar exercise.

During the fluctuating speed and increasing number of speed bursts test on the treadmill the common pattern of $F_{E}O_2$ % with increasing intensity of exercise can be seen in Table II. That is with low intensity high values are seen; these decrease as intensity increases with later increases to high values at exhaustion. The trend of the standard deviations to decrease minute by minute with increased intensity of exercise is also clearly established in the results shown in Tables II and III. In general, this has led to the decline in the standard error of measurement as subjects have approached exhaustion, though reduced reliability coefficients in minutes 8 – 9 and 9 – 10 produce exceptions. The high reliability coefficients for each work minute and overall establishes the reliability of the $F_{E}O_2$ % determinations from samples drawn from the mixing chamber of the on-line system. The fact that standard deviations and standard error of measurement is higher than in the 'steady state'

test reflects the fact that there is within minute fluctuation in physiological response commensurate with the fluctuations in physical work demand. Samples withdrawn from the Douglas Bag reflect a partialling out of this response whilst the mixing chamber samples may be more reflective of the changes occurring within the minute. Since even with 'steady state' an error of $\pm 0.11\% \text{ O}_2$ exists at the 95% level of significance, the increase in error overall with variable load of a further $0.15\% \text{ O}_2$ is only slight. It would therefore appear that in conditions of fluctuating physical work demand there is loss of accuracy with an on-line system when samples for F_{EO_2} determination are withdrawn from a mixing chamber, but this increased error is small.

Conclusions

1. An on-line system employing a mixing chamber is a reliable system for provision of samples for F_{EO_2} determination during steady state conditions.
2. This method, when employed with fluctuating physiological load conditions, provides reliable $\text{F}_{\text{EO}_2}\%$ determinations with increased error not likely to exceed $\pm 0.15\% \text{ O}_2$.
3. The greater the physiological load the greater the accuracy of the $\text{F}_{\text{EO}_2}\%$ determinations with such a system.

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