

Work Performance when Using Closed-Circuit Oxygen Breathing Apparatus

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Abstract

The effects on performance of using closed-circuit oxygen breathing apparatus were studied under two protocols:

- 1) walking with increasing slope up to exhaustion, and
- 2) walking at a constant slope and at a speed equal to about 50% of maximum aerobic capacity. Two types of breathing apparatus (RE and BG) and a control situation were tested. The RE apparatus had a mass of 16.8 kg, a gas cooler, and relatively low breathing resistance. The BG apparatus had a mass of 14.2 kg and during the first 40 min the gas had low humidity but later had 100% humidity at temperatures above 50°C. Both apparatus reduced work capacity and endurance considerably, compared with the control situation, mainly owing to increased heat load induced by the mass of the apparatus and by heat transfer to the subject via ventilation. Gas inhaled at temperatures above 50°C was rated as very uncomfortable. Pressure variation in the facepiece from -0.8 kPa to + 1.2 kPa did not apparently influence performance. The physical stress caused an increase in plasma catecholamine concentrations (mainly noradrenaline).

Introduction

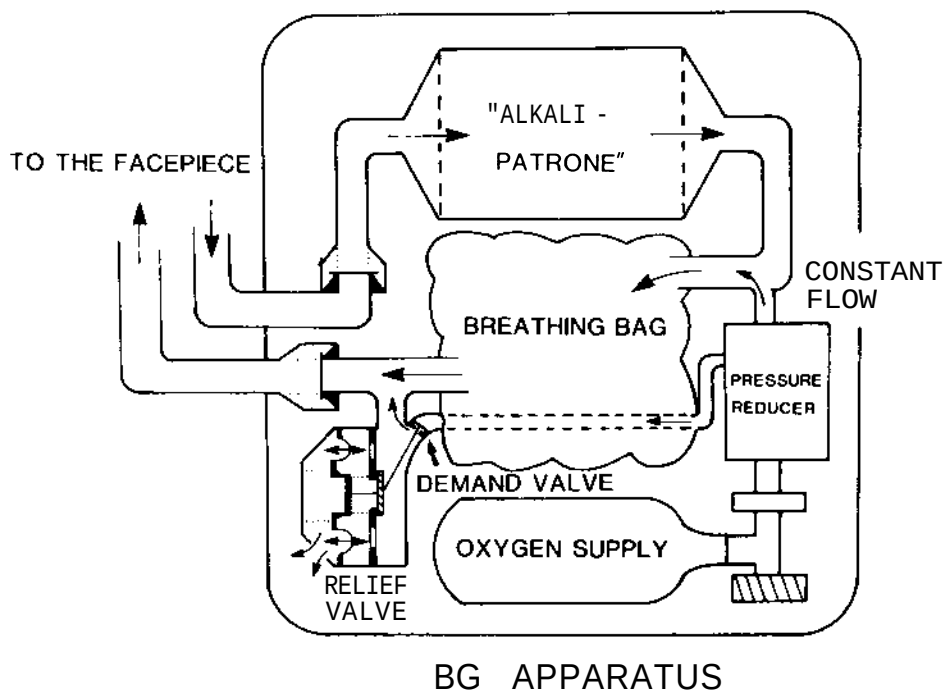
In many rescue operations, breathing apparatus must be used. Modern fire fighting equipment generally consists of a self-contained, compressed air breathing apparatus with a slight continuous positive pressure in the facepiece to eliminate inward leakage (Lundborg,1971). Such apparatus has a mass of 16 - 18 kg and has a duration of 30 - 60 min. In some operations, however, such as mine rescue work, the requirement is a duration of 2-4h. The only way to fulfil this requirement today is to use a closed-circuit oxygen breathing apparatus. There are several disadvantages with this type of equipment. In contrast to the compressed air breathing apparatus, the inhaled gas is often humidified to 100% at high temperatures (in other words,the gas has a high heat content), the breathing resistance is increased, the protection factor is lower, and the design is more complex. Reducing one or more of these factors will to some extent counteract reduction of other factors. For instance, the temperature of the inhaled gas can be kept down by an ice cooler, but this increases the mass. It is essential to establish the relative importance of the different factors concerning physical capacity and endurance.

The aim of our study was evaluating work performance with two types of closed-circuit oxygen breathing apparatus with different masses, different temperature characteristics of inhaled gas, and different breathing resistances, and comparing the appatatus to a control situation.

Materials and methods

Breathing apparatus

Most closed-circuit oxygen breathing apparatus as the ones in this study consist of a breathing circuit in which the gas is exhaled into a bag after passing through a carbon dioxide absorber (Figure 1). The gas in the bag is reinhaled and oxygen is automatically added to the circuit via both constant flow and a demand valve to compensate for oxygen consumed. The absorption of carbon dioxide is an exothermic reaction which raises the temperature and humidity of the gas.



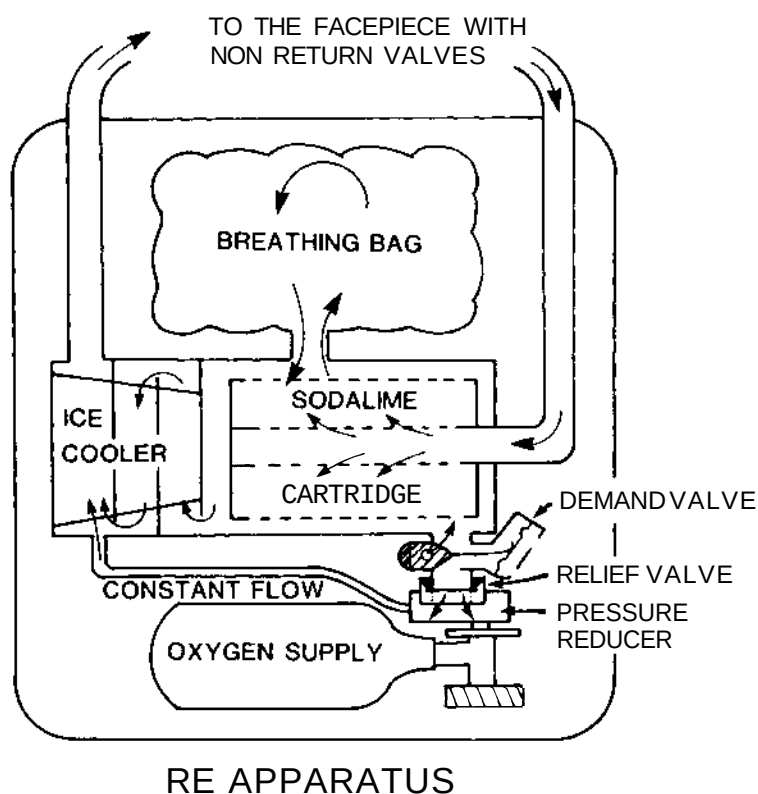


Figure 1. Schematic drawings of the closed-circuit oxygen breathing apparatus used in Studies A and B.

Two types of apparatus, BG and RE, were used. Type BG (Drager BG 174, Drager AG, Lübeck, West Germany) is a proven design used all over the world. Its carbon dioxide absorber, called "alkalipatrone", uses sodium hydroxide (NaOH) free from water. In the initial absorption phase it can thereby take up large amounts of water, thus keeping the inhaled gas relatively dry during the first 30 - 60 min. This implies that the heat content of the inhaled gas is low during this period. When the "alkalipatrone" can take up no more water the humidity will increase to about 100% and the heat content of the inhaled gas will become high.

The other type, RE (AGA Rescue, Interspiro AB, Lidingö, Sweden), is a prototype with low breathing resistance. The absorbent here is mainly calcium hydroxide - "sodalime" (Ca(OH)_2)- which takes up no water; in other words inhaled gas will be 100% humidified. Thus the heat content will be higher in the initial phase than with the BG apparatus, but the temperature will not rise as dramatically as with the "alkalipatrone". To reduce the heat content of inhaled gas, the RE is equipped with an ice cooler which makes it 18% heavier (16.8 kg compared with 14.2 kg for the BG-type, both masses including some measurement equipment).

In the control situation the subjects wore the same full-face mask as with the two breathing apparatus, but no apparatus was connected. The external dead space was thus equal (about 300 ml) in all 3 situations, but the total mass and the breathing resistance were much lower and the inhaled gas was at room conditions in the control situation.

Subjects

Five healthy, well-trained firemen from the Linköping Fire Brigade, were studied. Their mean age was 38 (33-53) years, mean mass 78 (69-88) kg and mean height 1.83 (1.76-1.91) m. Their experience of fire fighting ranged from 7 to 30 years, and 2 of them had previously used closed-circuit oxygen apparatus. All were healthy on clinical examination including determination of blood pressure, auscultation of lungs and heart, and a standard

exercise test with continuous recording of ECG. The maximum oxygen uptake was estimated from the results of the exercise test as described by Astrand and Rhyding (1954). Two were smokers. Each man took part in all 3 experiments, viz, the control test and tests with the 2 different apparatus. They gave their informed consent, and the protocol was approved by the ethics committee of the University Hospital, Linköping. During the experiments a light overall was worn.

Protocol

The general experimental set up is shown in Figure 2. Performance and endurance were tested by walking on a treadmill at constant speed (1.5 m/s) and varying slopes (0° to 12°) in accordance with 2 test protocols, A and B.

Study A was designed to simulate a rescue operation. It is probable that the rescueman will first have to walk with almost constant load for 40 to 50 min to reach the catastrophe area, and then to do some heavy rescue work up to his maximum performance. Thus, in Protocol A the slope was first kept constant at 0° for 40 min and then increased by 3° steps at 10th min intervals up to exhaustion. Three men were tested thus.

Study B was done to test performance and endurance throughout the period for which the apparatus was designed. The specified duration was 2 h for both apparatus, with a constant oxygen consumption of 2 l/min. This oxygen uptake corresponds to about 50%

of maximum working capacity of a well trained firemen. In the absence of external limiting factors a healthy man can sustain a relative work load of 50% for several hours. Using the results of study A and the formula given by Givoni and Goldman (1971) the slope was set at 4° , and was kept constant during the 3 trials. Two men were tested according to this protocol.

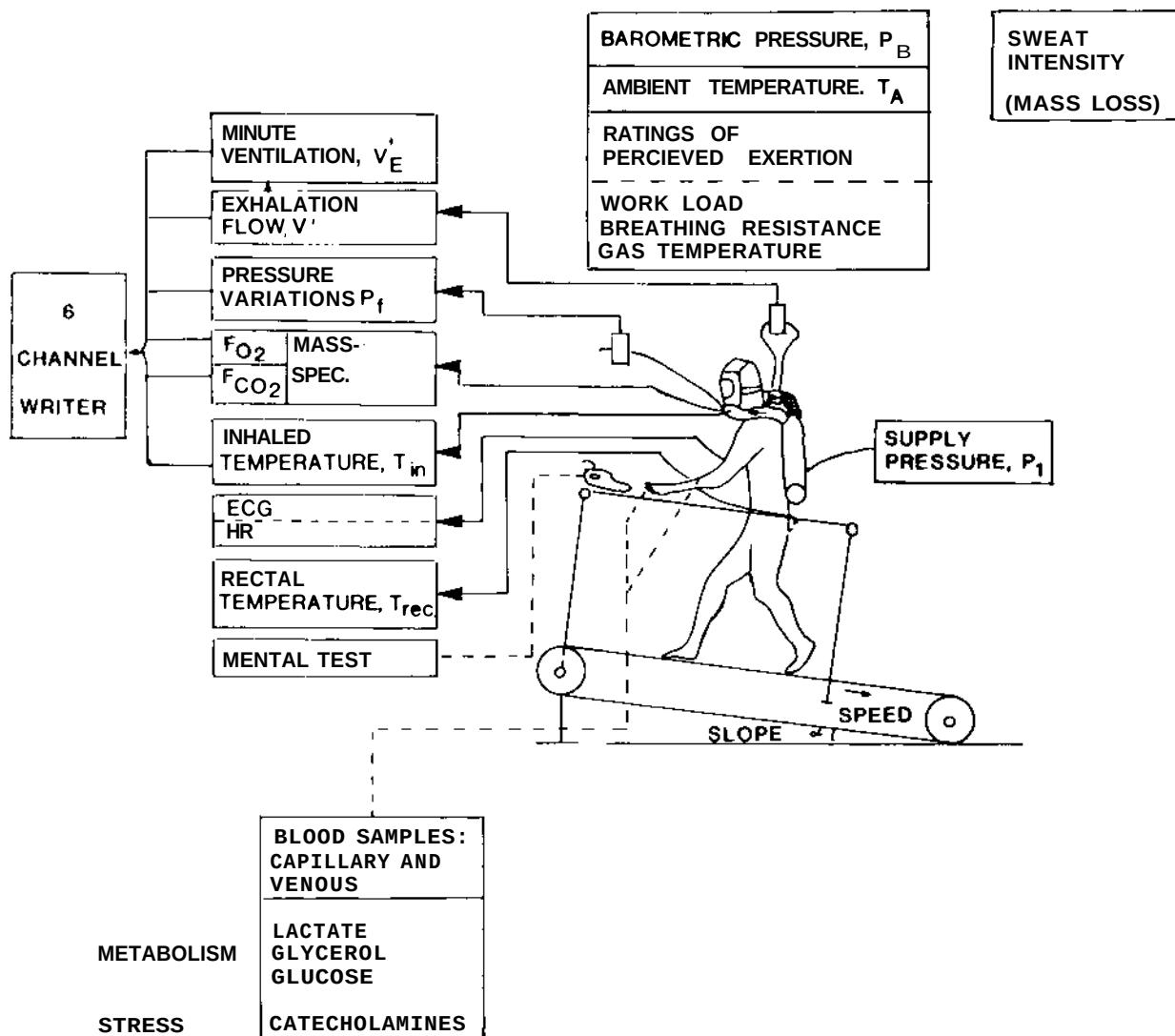


Figure 2. Experimental set up and recorded data. For details see text.

The following variables (see Figs 1 and 2) were continuously recorded on a 6-channel writer (Type 316, W+W Electronic Inc., Basel, Switzerland):

Exhaled flow ($\dot{V}'$) via a heated pneumotachograph (Fleisch no 4) situated in the exhalation tube, a differential pressure transducer (Validyne MP45, ± 0.2 kPa, Northridge, California), and an amplifier (Validyne CD 90).

Minute ventilation ($\dot{V}'_L$), using analogue integration of the flow signal (Validyne FV 156). The flow - and volume signals were calibrated before each test with a 2.3 L syringe. The results were corrected for the viscosity of the exhaled gas (Blais and Fanton, 1979), and are given at body temperature and pressure, saturated gas (BTP5).

Pressure variations (P_f) in the facepiece, using a differential pressure transducer (Validyne MP 45, ± 5 kPa) calibrated against a water manometer.

Carbon dioxide and oxygen fractions (FCO_2 and FO_2) in inhaled and exhaled gas, using a quadropole mass spectrometer (Centronics MGA 200, Croydon, England). The time constant was less than 100 ms, which means that we could follow breath-to-breath variations. Water vapour was excluded with an electronic circuit, so the fractions recorded represent values in dry gas.

Inhaled gas temperature ($T_{i,n}$), by means of a thermocouple in the inhalation tube about 200 mm upstream from the facepiece connector (DU3, ELLAB A/S, Copenhagen, Denmark).

The following variables were also continuously displayed and recorded at regular time intervals:

Heart rate (HR) and electrocardiogram (ECG), using a portable bedside monitor (Discope DS 521, Simonsen & Weal, Copenhagen, Denmark).

Rectal temperature (T_{IfcJL}), by means of a thermocouple placed in the rectum (DU 3, ELLAB A/S, Copenhagen, Denmark).

Pressure in the oxygen supply, measured with an electronic transducer (0-30 MPA, Bell & Howell Ltd, Basingstoke, England). The pressure drop was used to estimate the oxygen consumption while breathing with a closed system. The relationship between supply pressure and oxygen content was calibrated by weighing the supply cylinder on a precision balance with a resolution of 0.1 g (Mettler PC 4400, Zurich, Switzerland) while reducing the pressure. The oxygen consumption could thus be calculated with an accuracy of about 0.1 l/min, assuming that the temperature in the cylinder was constant.

Mental capacity was evaluated by means of a mental arithmetic test at regular time intervals. This test was programmed into a calculator (HP 97, Hewlett-Packard). At the start of the test the calculator displayed a random number with 3 digits. The subject had as fast as possible to subtract 3 from this number and then 3 from the result, and so on for 1 min. Every correct subtraction gave +1 point and every wrong one -1 point.

In the control situations in both studies oxygen consumption ($\dot{V}O_2$) and minute ventilation ($\dot{V}_L$) were measured by the Douglas bag method. In Study A the bags were collected after 30 min, and in Study B after 50 min and at the break point.

At about 10 min intervals and at break point a sample of arterialized capillary blood was taken for determination of blood lactate, glycerol, and glucose. A venous sample was also taken for determination of plasma catecholamine concentrations. After treatment the samples were stored at -80°C pending analysis with enzymatic techniques based on microfluorometry. After separation of the plasma the catecholamine samples were stored at -80°C until analysis by high performance liquid chromatography (Allenmark et al., 1980).

At about 10 min intervals and at break point the men were asked to give a rating of perceived exertion (RPE)(Borg, 1970) with regard to work load (RPEW), breathing resistance (RPEB), and in Study B also with regard to the temperature of the inhaled gas (RPET). The scales for RPE are shown in figure 3.

HOW DO YOU RATE WORK LOAD (RPEW)?	HOW DO YOU RATE BREATHING RESISTANCE (RPEB)?	IS THE GAS TEMPERATURE UNCOMFORTABLE (RPET)?
6	0	0
7 VERY, VERY LIGHT	1 VERY, VERY LOW	1 VERY, VERY LITTLE
8	2	2
9 VERY LIGHT	3 VERY LOW	3 VERY LITTLE
10	4	4
11 FAIRLY LIGHT	5 FAIRLY LOW	5 FAIRLY LITTLE
12	6	6
13 RATHER HEAVY	7 RATHER HIGH	7 RATHER UNCOMFORTABLE
14	8	8
15 HEAVY	9 HIGH	9 UNCOMFORTABLE
16	10	10
17 VERY HEAVY	11 VERY HIGH	11 VERY UNCOMFORTABLE
18	12	12
19 VERY, VERY HEAVY	13 VERY, VERY HIGH	13 VERY, VERY UNCOMFORTABLE
20	14	14

Figure 3. Scales for ratings of perceived exertion, regarding work load (RPEW), breathing resistance (RPEB), and inhaled gas temperature (RPET).

To estimate the water loss by sweating, the naked mass was measured with a resolution of 0.1 kg before each test and afterwards (dried with a towel).

The initial ambient temperature was 25°C, and rose to about 27°C. The relative humidity was about 40%. One man in Study B (LWa) was exposed to a temperature of 30°C and a relative humidity of about 40% in all 3 tests.

Evaluation of findings

In Study A the findings are presented as mean and SD. Owing to the smallness of the series no statistical tests were employed. Comments on differences between the experimental conditions are based on intra-individual comparisons, and are presented as tendencies. In Study B the main data from the 2 men are presented separately.

Results

Study A (Fig 4)

Here the slope was 0° for 40 min; it then increased 3° each 10th min. The total mass (man and equipment) was 83 +/-6 kg in the control test, 96 +/- 6 kg with the BG apparatus, and 99 +/-6 kg with the RE apparatus.

With either of the breathing apparatus all 3 men had to interrupt the exercise at a slope of only 6° or 9°, which was 6.2 +/-3.2 min earlier than in the control test. No differences were seen between BG and RE.

The oxygen uptake at 6° tended to be higher with the RE than with the BG apparatus (2.7 and 2.5 L/min, respectively).

The loss of mass including metabolic mass loss and water loss via respiration was 15 +/-10 g/min in the control test, 22 +/-4 g/min with the BG apparatus and 25 +/-6 g/min with the RE apparatus.

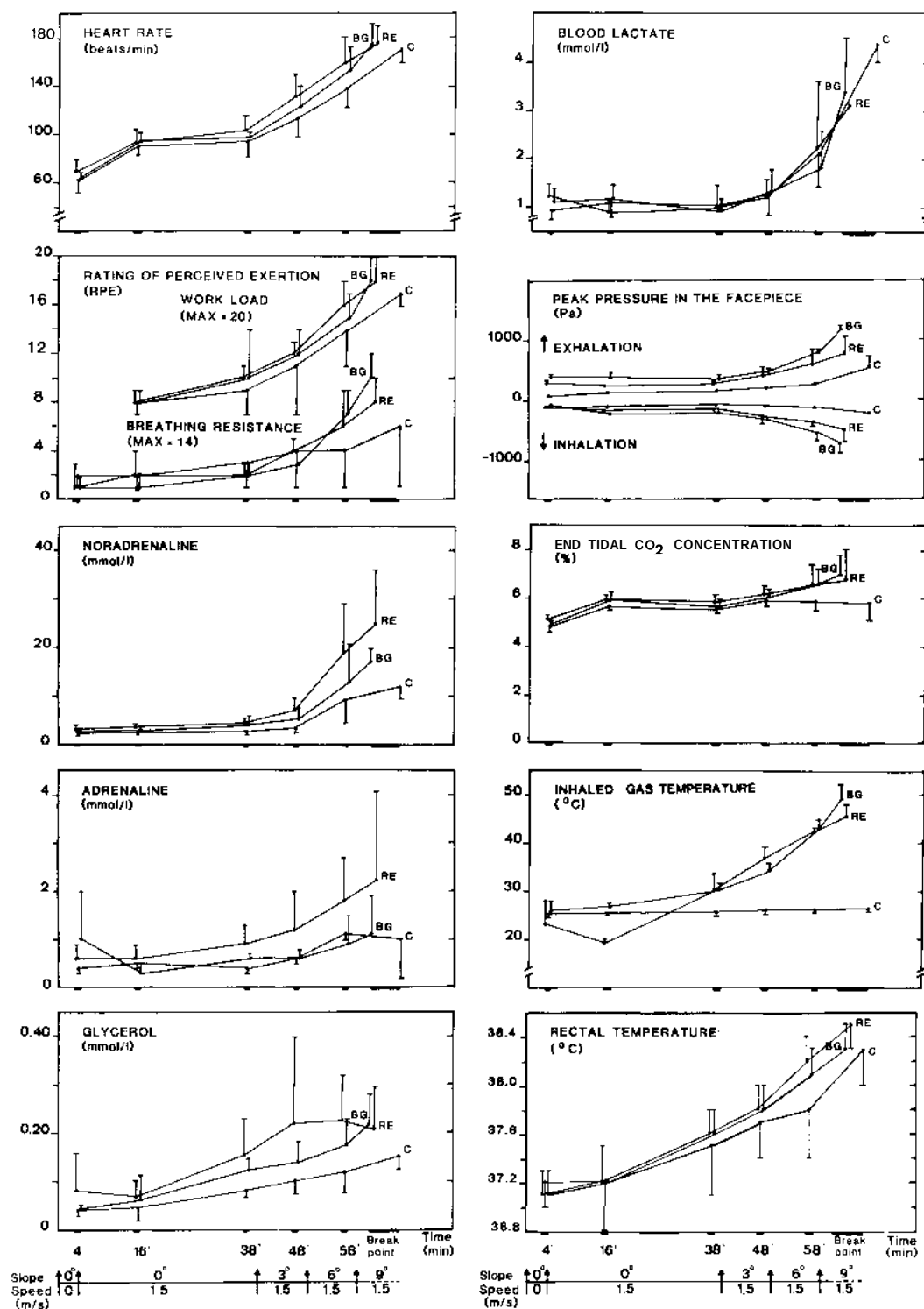


Figure 4. Diagrams showing mean values of recorded variables in 3 men in Study A. BG and RE indicate the different apparatus used, C is the control situation. The vertical bars indicate SD.

The values for mental capacity showed no obvious changes during the exercise period, and no clearcut differences between the different tests.

The minute ventilation at break point tended to be lower (10%) with a breathing apparatus than in the control situation (94 ± 17 L/min). No difference between the 2 apparatus was noted.

The HR before break point tended clearly to be higher using one of the apparatus, the highest values being recorded with the RE. The HR at break point was the same in all 3 tests, however.

The RPE for work load (RPEW) and plasma noradrenaline followed the same pattern as the HR except that the difference in noradrenaline concentration between the test using one of the apparatus and the control test persisted also at break point.

Plasma adrenaline was clearly higher when using the RE apparatus than with the BG apparatus or in the control situation. This difference persisted also at break point.

The blood glycerol followed the same pattern as the HR, RPEW, and plasma noradrenaline, in other words, the concentration were highest using the RE and lowest without an apparatus. At break point no difference was seen between the 2 apparatus, but the concentrations were still lower without an apparatus.

The blood lactate concentrations at the submaximum loads were almost identical in all 3 tests, but at break point the concent-

ration was higher (4.5 mmol/L) in the control situation when the men worked longer than in the apparatus tests. The blood lactate concentrations was 3.4 mmol/L with the BG apparatus and 3.1 mmol/L with the RE apparatus.

The peak pressures in the facepiece (absolute values) increased curvilinearly with increasing slopes and at the highest work load were about twice as high with the RE apparatus (-0.5 kPa to +0.8 kPa) and three times as high with the BG apparatus (-0.8 kPa to +1.2 kPa) compared to the control situation (-0.2 to +0.5 kPa).

The end tidal CO_2 concentration did not differ between slopes 0° and 3° . At break point, however, the end tidal CO_2 concentration was lower in the control situation (5.7%) than with the apparatus (6.9% with the BG apparatus and 6.7% with the RE apparatus). No obvious difference between the two types of apparatus was observed.

The rating of perceived exertion regarding breathing resistance (RPEB) also followed a curvilinear course similar to those of the peak pressures in the facepiece and of the end tidal CO_2 concentration.

The temperature of the inhaled gas showed no changes in the control condition when room air was inhaled. Using the RE apparatus a slight initial fall was observed owing to the effect of the ice cooler, but this was followed by an almost linear increase to 45°C at break point. The temperature in the BG

apparatus showed a curvilinear increase, and a maximum value of 49°C was reached at break point.

The rectal temperature at break point was 38.3°C in the control situation, 38.4°C with the BG-apparatus, and 38.5°C with the RE-apparatus.

Study B (Table 1)

In this study the slope was 4° throughout the exercise period, which in the control situation was interrupted after 120 min. Two men were studied, and the individual results are presented in Table 1. In the following the first figure represents RKi, and the second LWa, who was studied at a room temperature of 30°C . The total masses of man and equipment in the control test were 77 kg and 70 kg, with the BG apparatus 90 kg and 83 kg, and with the RE apparatus 93 kg and 86 kg, respectively. The men could not continue the exercise for more than 40 and 62 min using the RE apparatus, or for more than 43 and 79.5 min using the BG apparatus.

The oxygen uptake measured in the control test was 1.9 L/min for RKi, representing 57% of estimated $\dot{V}\text{O}_{2\text{max}}$, and 1.6 L/min for LWa, representing 32% of estimated $\dot{V}\text{O}_{2\text{max}}$.

The blood lactate concentrations were 1.0 mmol/L or less, in all men and all tests.

The calculated water loss was 25 and 23 g/min with the RE apparatus, 26 and 23 g/min with the BG apparatus, and 18 and 13 g/min in the control tests.

Table 1. Individual results for RKi and LWa from Study B, constant speed (1.5 m/s) and slope (4°)
(abbreviations as in text)

Recording time	20 min						40 min						Break point (min)					
	Control		BG		RE		Control		BG		RE		120	120	43	79.5	40	62
Experimental condition																		
Subject	RKi	LWa	RKi	LWa	RKi	LWa	RKi	LWa	RKi	LWa	RKi	LWa	RKi	LWa	RKi	LWa	RKi	LWa
HR (min^{-1})	115	96	126	100	131	107	120	103	140	109	152	122	141	118	142	138	152	139
RPEW (6-20)	9	11	11	13	11	13	11	13	13	15	13	15	16	15	13	17	13	19
RPEB (0-14)	3	3	5	4	6	5	4	3	9	5	8	6	7	3	9	9	8	5
RPET (0-14)	1	1	5	5	7	5	3	1	14	7	12	7	6	5	14	14	12	10
T_{in} ($^{\circ}\text{C}$)	25.2	31.0	33.5	39.5	33.0	35.0	25.4	30.5	48.6	43.5	43.0	39.0	26.2	30.5	49.5	51.0	43.0	39.5
T_{rect} ($^{\circ}\text{C}$)	37.3	37.4	37.7	37.7	37.2	37.8	38.1	37.8	38.5	38.1	38.2	38.2	38.8	38.3	38.7	38.9	38.2	38.7
V'_E (1 BTPS/min)	50	55	62	65	50	56	57	47	70	63	74	65	58	50	64	73	68	65

Both studies

Inhaled CO_2 concentration was always below 0.1% in the RE apparatus and below 0.3% in the BG apparatus.

By calculating the change in T_{rec} during 22 min and 20 min in both studies (16-38 min in study A and 20-40 min in study B) the following were found when comparing the apparatus situations with the control situation. Three of the 5 subjects had 0.2 to 0.3° greater increase in T_{rec} wearing the RE apparatus. Only 1 subject in study A had a greater increase with the BG apparatus (0.4°). No other comparison showed any difference.

Discussion

Two aspects of work performance are of particular interest, (i) physical capacity during a relatively brief exercise, and (ii) endurance. Endurance is particularly relevant with regard to oxygen apparatus, because these allow a longer duration than standard fire fighting equipments, which have poor gas economy. Also, the heat balance is of interest. The closed-circuit apparatus produces heat roughly in proportion to the amount of work performed, because the absorption of carbon dioxide is an exothermic reaction and heat transfer to the surroundings is limited.

Performance measured as endurance (time to break point) was reduced when using breathing apparatus, in both Studies A and B. The reduction was probably the result of a combined effect of, (1) increased physical load induced by the mass and torque of the apparatus, (2) raised temperature and increased heat content

of inhaled gas, (3) increased breathing resistance, and (4) the general irksomeness of carrying the equipment.

The mass of the apparatus influences work performance in two ways, directly, by increasing the physical load, and indirectly, by increasing the heat load.

In Study A the oxygen uptake at break point was less than 80% of the estimated maximum capacity. The corresponding figure in Study B was 63%. Thus in both studies the men were forced stop at a clear-cut submaximum work load.

The maximum relative work loads were so small that endurance would have been significantly longer if not factors other than the capacity of energy turnover had as limiting factor when using an apparatus.

The blood lactate concentrations were in keeping with the above relative work loads, and were not high enough to justify interrupting the exercise. In Study A, the blood lactate was lower at break point with apparatus than in the control situation. These results too indicated that the subjects broke off at submaximum work load.

When using closed-circuit breathing apparatus, the oxygen fraction in inspired gas is high. The loss of endurance caused by the factors discussed above may thus have been counteracted (Bannister and Cunningham, 1954; Ekblom et al., 1975). The high oxygen fraction in inspired gas may also have contributed to the

lower lactate concentrations at break point in Study A (Byrnes and Mullin, 1981).

A factor limiting endurance could have been the heat load. When carrying extra mass the metabolic heat production is increased. The mean $\dot{V}O_2$ measured in study B was 1.8 l/min, which is equivalent to a total power output of about 630 W. The external power when walking on the treadmill was 76 W, since the total mass was 74 kg, the speed was 1.5 m/s and the slope was 4°. Thus in this situation almost 90% of the total power became heat. By calculating the power output using the formula of Givoni and Goldman (1971) walking at a speed of 1.5 m/s and with a slope of 4° the total power requirement will be 600 W when the total mass is 74 kg (control), 706 W when the total mass is 87 kg (BG apparatus), and 730 W when the total mass is 90 kg (RE apparatus). Thus, implying that 90% was converted to heat as shown in the control situation, about 95 W (18%) more heat was added to the body with the BG apparatus than in the control situation, and about 117 W (22%) more heat with the RE apparatus than in the control situation.

The heat transfer from the body surface to the surroundings was limited by the clothing, which was the same under all 3 conditions. This limitation increases the demand on ventilation as a means of regulating the body heat storage. The respiratory heat transfer can be calculated from known thermodynamic equations.

Firstly the difference in heat content between inhaled and exhaled dry gas:

$$Q'_{\text{resp}} = \text{Lungvent.} * (\text{Amb. press}/(R*T)) * \\ * \text{Mol. mass} * \text{Spec. heat} * (T_{\text{in}} - T_{\text{ex}});$$

and, secondly, the heat transfer due to the condensation (or evaporation) of water:

$$Q'_{\text{cond}} = \\ \text{Lungvent.} * ((P_{\text{in}} \text{H}_2\text{O} - P_{\text{ex}} \text{H}_2\text{O})/(R*T)) * \\ * \text{Mol. mass of water} * \text{Cond. heat};$$

R (the gas constant) = 8.3143 J/(mol*K) and T = 310 K, which is the temperature in the lungs (37°C). T_{in} is the inhaled gas temperature and T_{ex} the exhaled gas temperature.

$P_{\text{in}} \text{H}_2\text{O}$ is the water vapor pressure (Pa) in inhaled gas and $P_{\text{ex}} \text{H}_2\text{O}$ in exhaled gas.

For estimating the respiratory heat transfer, mean values for minute ventilation and T_{in} from study B at 20 min and 40 min were used. T_{ex} was calculated from T_{in} according to a relationship between these variables found in a separate study, in which 4 subjects breathed 100% humidified gas tempered from 30°C to 50°C. This relationship, $T_{\text{ex}} = 20.79^\circ\text{C} + 0.425 \times T_{\text{in}}$, which was derived by linear regression analysis of the data points, gives slightly higher T_{ex} -values than the equation for hyperbaric conditions presented by Webb (1975), viz, $T_{\text{ex}} = 24^\circ\text{C} + 0.32 \times T_{\text{in}}$. The results for respiratory heat transfer show that in the control situation 54 W was removed by ventilation (mean $V'_L = 52 \pm 1$ BTPS/min,

relative humidity (RH)=40%, $T_{in} = 28^{\circ} \text{C}$, and $T_{ex} = 32.7^{\circ} \text{C}$). In contrast to this transfer from the body, small amounts of heat were delivered to the body with both apparatus. With the BG apparatus mean $\dot{V}_L$ was 65 l BTPS/min, RH was estimated to be 85% (Hartwell and Senneck, 1956), the mean T_{in} was 41°C , and T_{ex} was calculated to be 38.2°C . In this situation 2 W was added to the body via ventilation.

When carrying the RE apparatus the two men achieved after 20 - 24 min: a mean $\dot{V}_L$ of 61 l BTPS/min; an RH of 100%, a mean T_{in} of 37.5°C , and a T_{ex} of 36.7°C . In this situation the estimated heat transfer to the man by ventilation was 6 W.

Compared to the control situation the net effect of carrying an apparatus on the heat production within the body and the heat exchange by the ventilation is that the somewhat heavier RE apparatus with its ice cooler added 17% more heat ($117\text{W} + 6\text{W} + 54\text{W} = 177\text{W}$) to the body than did the BG apparatus ($95\text{W} + 2\text{W} + 54\text{W} = 151\text{W}$) with its "alkali patrone".

In accordance with the calculated data on heat balance, 3 subjects when looking at both studies showed a greater increase in T_{rec} with the RE apparatus than in the control situation. The tendency towards greater mass loss with the RE apparatus owing to a higher sweating rate is also an indication of greater heat load with this type.

How would a RE apparatus without cooler influence the body heat storage? The sodalime absorber will become quite hot and give the uncooled gas a temperature roughly 5°C higher, i.e. 42.5°C (c.f. Hartwell and Senneck, 1956). Thus under conditions like those with the RE apparatus this would mean that the ice cooler removes about 30 W, which is rather more than what the mass (about 3 kg) of the ice cooler will induce (about 20 W).

Our results indicate that the mass of a breathing apparatus is of great significance in reducing the physical and endurance capacities. However, this effect is probably not primarily due to the increased work load itself. Instead it seems to be caused by an increased heat load secondary to the increased energy expenditure. Also of importance for the heat balance is the fact that the rebreathing apparatus limits the heat loss from the body by ventilation. The effect on the heat balance of carrying the mass of an oxygen breathing apparatus is about twice as great as the influence of the apparatus on the heat loss by ventilation.

The high temperature of the inhaled gas influences physical performance not only by increasing the heat load but also by the discomfort felt in the mouth and throat. When the temperature of the inhaled gas exceeded 45°C with the BG apparatus the men in Study B rated the sensation of the gas temperature as 10, i.e. between "Uncomfortable" to "Very uncomfortable". In Study A this discomfort (T_{in} , ca. 50°C) probably helped to determine the break point.

In Study B, with a constant submaximum load, the main reason for RKi to break off was evidently the discomfort from the hot inhaled gas (49.5° C, BG; and 43° C, RE). He rated RPE for inhaled gas temperature "Very, very uncomfortable" (14) for both apparatus, the heart rate at the same time being moderate (142 to 152 beats/min) and the rating for work load only "Rather heavy" (13).

LWa broke off with the BG apparatus for the same reason. The HR was 138 beats/min, the RPE for work load was rated "Very heavy" (17), and RPE for inhaled gas temperature (51° C) was rated "Very, very uncomfortable" (14). Thus, if the temperature rises to 50°C or more it seems to be a directly limiting factor.

With the RE apparatus break point was probably defined by a combined effect of physical exhaustion, as RPE for work load was "Very, very heavy" (19) and RPE for gas temperature (39.5° C) was 10, i.e. between "Uncomfortable" and "Very uncomfortable".

Breathing resistance was probably secondary to physical load and inhaled gas temperature in causing the wearer to break off owing to a feeling of exhaustion. The pressure variations in the face-piece were quite moderate in Study A at break point (+1.2kPa to -0.8 kPa with the BG apparatus with the highest resistance). The men rated the resistance for this apparatus as between "High" and "Very high", as compared with "Rather high" to "High" for the RE apparatus at break point. The increased breathing resistance, however, caused some carbon dioxide (CO₂) retention.

At break point the end tidal CO₂-concentration with the BG

apparatus was 6.9% and with the RE apparatus 6.7%, as compared with 5.7% in the control situation. Deno et al (1981) showed a decrease of about 10% in endurance during exercising conditions similar to those of Study A, inducing breathing resistance up to ± 2.5 kPa in men wearing different masks. These pressure variations are almost twice those seen with the BG apparatus in the present study. In Deno's study the end tidal CO_2 -concentrations reached were also significantly higher, viz, 7.6 kPa.

Dahlbäck and Balldin (1984) showed that an external breathing resistance of about ± 1.2 kPa at exhaustion, which is similar to the resistance of the BG apparatus, caused slight CO_2 retention with end tidal CO_2 -concentrations of about 5.8% without influencing endurance.

In Study B both men rated the resistance for the BG apparatus as "High". For the RE apparatus the resistance was rated as "Fairly low" by LWa and between "Rather high" and "High" by RKi.

The tendency for blood catecholamine values to rise when using the apparatus is probably mainly an effect of the increased physical load (Euler and Hellner, 1952; Jansson et al., 1982), although the mental stress could have been partly responsible.

Increased catecholamine concentrations will increase lipolysis, which could partly explain the somewhat increased blood glycerol concentrations at break point. The tendency towards a raised adrenaline concentration at break point with the RE apparatus could be an indication of some kind of mental stress (Frankenhaeuser et al., 1969; Pierce et al., 1976).

Conclusions

Work capacity and endurance will be reduced when using a closed circuit oxygen breathing apparatus, mainly as a result of increased heat load.

The mass of the breathing apparatus is one of the most important factors reducing performance.

A gas cooler with a mass of about 3 kg should remove more than 20 W in order to compensate for its own mass.

Acknowledgments

The assistance of Elisabeth Forsström is gratefully acknowledged. This work was supported by the Swedish Work Environment Fund No. 80-309.

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