Scand J Work Environ Health 1983;9(6):471-477
https://doi.org/10.5271/sjweh.2389
Issue date: Dec 1983

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This article in PubMed: www.ncbi.nlm.nih.gov/pubmed/6369527

Print ISSN: 0355-3140 Electronic ISSN: 1795-990X

Scand j work environ health 9 (1983) 471–477

Cardiac output and gas exchange during heavy exercise with a positive pressure respiratory protective apparatus

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ARBORELIUS M JR, DAHLBÄCK GO, DATA P-G. Cardiac output and gas exchange during heavy exercise with a positive pressure respiratory protective apparatus. *Scand j work environ health* 9 (1983) 471–477. Continuous positive pressure breathing effectively prevents inward leakage of noxious agents into a breathing apparatus but may interfere with venous return and cardiorespiratory performance during heavy work. Cardiac output was therefore recorded with a dye dilution method, and ventilatory variables were measured from expired air, for seven well-trained firemen at a work load of 150 W. All the variables except the invasive ones were also measured during the maximal work load that each subject could sustain for 10 min. At random the subjects worked with a mouthpiece and a face mask with and without a positive pressure of 0.4 kPa. No variable deteriorated during positive pressure breathing, although the central venous oxygen pressure increased, an occurrence indicating higher cardiac output in relation to oxygen demand. Dead space ventilation decreased, an indication of increased ventilatory efficiency. Positive pressure breathing (0.4 kPa) thus does not deteriorate cardiopulmonary function during intermediate or maximal work loads.

Key terms: blood gas tensions, fireman, physical work capacity, positive pressure breathing, safety pressure, self-contained compressed air apparatus.

A breathing apparatus for use in contaminated environments must supply the wearer with clean gas in quantities large enough to maintain maximum physical work capacity. An apparatus that impairs performance might not be dangerous during moderate work but could jeopardize the wearer in a critical situation or make it impossible for him to perform the task required, eg, to rescue human life or property (1). Earlier research has shown that it is practically impossible to create a fullface mask that is completely leakproof on all people (12). Even though minor leakage might not seem harmful on isolated occasions, repeated exposure may have accumulative effects that could cause serious disease, especially with regard to the increasing toxicity of fumes and gases produced by chemicals and new materials such as plastics (13). The safety pressure mask is a design that prevents inward leakage by virtue of slight positive pressure (safety pressure) inside the facepiece throughout the breathing cycle (6).

The present study was designed to investigate whether slight positive pressure breathing of about +0.4 kPa in a safety pressure mask will influence cardiac output, gas exchange, and work capacity during heavy exercise.

Subjects and methods

The series consisted of seven healthy volunteers (firemen used to breathing

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apparatus) from the Malmö fire brigade. They were told only that this was an experiment concerning respiratory physiology during exercise, and thus they were unbiased regarding the positive pressure breathing. They were informed about the procedure and had consented to the invasive measures. (For details see table 1.)

The men arrived at the laboratory at 0900 after a light breakfast. With a percutaneous technique (14) PE 160 catheters were passed into the left brachial artery and into the right atrium from an antecubital vein. Cardiac output was measured with a dye dilution technique (15). Arterial and central venous pressures and pressure in the facepiece at the mouth were measured with capacitance manometers (Siemens-Elema AB, Solna, Sweden) and were recorded concomitantly with a chest-head electrocardiogram by means of an ink-jet recorder (Mingograph 81, Siemens-Elema AB, Solna, Sweden). The electrocardiogram was also used for the calculation of heart rate. Exhaled gas was collected in polylaminate plastic-aluminum bags from the exhaust side of the breathing apparatus using short, wide tubing (inner diameter 30 mm).

The gas analyses were done with the Scholander apparatus, and blood gas tensions were measured with conventional electrodes (Instrumentation Laboratories Inc, Boston, MA, the United States). Two sets of experiments were done on an electrically braked bicycle ergometer on different days, one with a work load of 150 W (900 kpm/min) [which has been shown to be usual during the heavy endurance work of firemen (16)] and one at the maximal work load the volunteers had been found to tolerate for 10 min when no breathing apparatus was worn.

The following outfits were tested:

1. The demand valve of a safety pressure mask (AGA Divator part no 331.190.174, AGA Spiro AB, Lidingö, Sweden) mounted with a mouthpiece but without positive pressure breathing applied. The breathing resistance and dead space during exercise proved not to exceed those of the low resistance valve commonly used at the laboratory. The values obtained were therefore taken as controls.

2. The same as the first, but with positive pressure applied.

3. The complete safety pressure mask, but without positive pressure.

4. The same as number 3, but with positive pressure.

During each part of an experiment the subject exercised with the relevant equipment for 10 min, and the physiological recordings were made during the last 5 min. Between the test periods the subject rested supine for 30 min. The order of the experiments was randomized (table 1). The influence exerted on the physiological variables by the preceding experiment was thus minimized. Repeated arterial catheterization after a brief interval was considered contraindicated, and the invasive measurements were therefore not made in the series with maximal work load, which was carried out one week after the first series. The maximal work load each subject could sustain for 10 min without a breathing apparatus was tested by cycle

Table 1. Physical data of the subjects.

Subject	Age (years)	Height (cm)	Weight (kg)	Maximum work capacity[a] (W)	Randomization[b]			
EJ	29	180	78	250	1	2	4	3
JM	38	180	80	200	4	3	1	2
BP	25	174	75	215	3	4	2	1
KF	27	180	73	200	2	1	3	4
RP	33	175	71	250	1	2	4	3
LS	37	175	70	200	4	3	1	2
RL	36	180	75	200	1	2	3	4

[a] Maximum work capacity was defined as the exercise level at which the subject became exhausted after 10 min after having reached a heart rate of above 180 beats/min in a previous test without breathing equipment.

[b] 1 = the demand valve mounted on a low resistance mouthpiece without positive pressure, 2 = the same situation as with 1 except with positive pressure, 3 = the complete fullface mask and demand valve without positive pressure, 4 = the same situation as in 3 except with positive pressure.

ergometry at least one week before the experiments started.

Statistical evaluation was made with Student's t-test on paired observations.

Results

Ventilatory variables and blood gas tensions with a work load of 150 watts

The minute ventilation showed no significant differences with the different sets of equipment (table 2). There was an increase in dead space (V_D) when the mask was used as compared to the use of the mouthpiece. However, the dead space tended to decrease with the mask when positive pressure was applied (0.70 to 0.63 l) and produced a small but significant decrease in V_D/V_T (V_T = tidal volume). The arterial carbon dioxide tension (P_aCO_2) rose to above the values at rest [P_aCO_2 at rest = 5.5 (SD 0.3) kPa] in all subjects irrespective of the equipment used, and the arterial oxygen tension (P_aO_2) fell to below the resting values [P_aO_2 at rest = 12.4 (SD 1.3) kPa]. Compared to the control values, central venous oxygen tension was significantly higher when the mask was used with positive pressure, a phenomenon indicating a slightly higher cardiac output in relation to oxygen consumption. The pressure at the mouth in the facepiece or mouthpiece was almost always slightly positive during the positive pressure breathing, but it occasionally approached zero, a value indicating an inspiratory flow close to 300 l/min (fig 1).

Hemodynamic variables during the submaximal work load

There were few significant differences in the hemodynamic variables at a work load of 150 W (table 3). The mean pressure in the right atrium during positive pressure breathing exceeded that recorded without by 0.45 kPa with the mouthpiece and by 0.27 kPa when the fullface mask was used. The change with the fullface mask was

Table 2. Ventilatory and blood gas tension variables of the seven subjects during work at 150 W. (PPB = positive pressure breathing)

Variable	1 Mouthpiece without PPB (control)		2 Mouthpiece with PPB		3 Fullface mask without PPB		4 Fullface mask with PPB	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Breathing rate (min^{-1})	17.1	6.7	16.6	5.9	17.6	4.4	18.1	5.5
Minute ventilation (l BTPS/min)[a]	46.8	10.6	45.4	7.6	49.6	5.2	48.4	8.4
Dead space (l BTPS)[a]	0.44	0.14	0.44	0.20	0.70	0.15	0.63	0.10
			(2–4,	$p < 0.025$)	(1–3,	$p < 0.001$)	(1–4,	$p < 0.005$)
Dead space/tidal volume	0.16	0.06	0.16	0.09	0.24	0.06	0.23	0.06
			(2–4,	$p < 0.05$)	(1–3,	$p < 0.001$)	(1–4,	$p < 0.01$)
Oxygen consumption (l STPD/min)[b]	2.26	0.16	2.27	0.25	2.31	0.16	2.22	0.10
Carbon dioxide production (l STPD/min)[b]	2.01	0.21	2.04	0.20	2.05	0.14	1.95	0.13
Arterial oxygen tension (kPa)	10.7	1.0	10.8	1.2	10.6	0.9	10.9	0.5
Arterial carbon dioxide tension (kPa)	6.0	0.6	6.2	0.5	6.3	0.3	6.1	0.3
Mixed venous oxygen tension (kPa)	4.5	0.3	4.8	0.4	4.7	0.3	4.9	0.4
							(1–4,	$p < 0.05$)
Mixed venous carbon dioxide tension (kPa)	7.7	0.3	7.1	0.5	7.4	0.3	7.2	0.2
					(1–3,	$p < 0.05$)	(1–4,	$p < 0.01$)
Alveolar-arterial oxygen tension difference (kPa)	2.5	0.8	2.3	0.8	2.3	0.7	2.1	0.7
Median minimal inspiratory pressure at the mouth (kPa)	−0.31	0.07	0.08	0.08	−0.26	0.13	0.09	0.10
Median minimal expiratory pressure at the mouth (kPa)	0.25	0.07	0.72	0.09	0.24	0.13	0.70	0.09

[a] BTPS = temperature 37°C, ambient pressure, saturated with water vapor at 37°C.

[b] STPD = temperature 0°C, pressure 760 mm Hg (101.3 kPa), dry (standard conditions).

slightly lower than the added positive pressure. The pressure variations in the right atrium were also slightly greater with the fullface mask. In spite of this increase in mean pressure in the right atrium, no significant changes in cardiac output or stroke volume were noted, although these variables tended to increase with positive pressure breathing. The alveolar-arterial oxygen differences were slightly lower during positive pressure breathing, both with the mouthpiece and with the fullface mask. These differences were not significant but may indicate better gas exchange during positive pressure breathing.

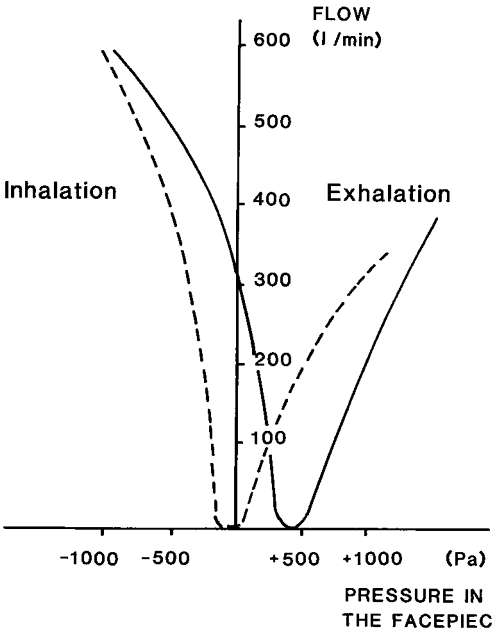

Fig 1. The curves define the pressure-flow relationship for the safety pressure mask during inhalation and exhalation. Positive pressure was maintained in the mask during inhalation at flow rates up to 300 l/min (5 l/s). (– – – = without safety pressure, ——— = with safety pressure).

Measurements during maximal work

Two subjects could sustain 250 W for 10 min, one tolerated 215 W, and three were able to continue at 200 W (table 1). The highest pulse rate registered was 208 beats/min, and the lowest was 170 beats/min, although the pulse rate exceeded 190/min in all subjects at some point during the experiment (table 4). All the subjects were exhausted at the end of each exercise period. The mean oxygen uptakes were as high as 3.26–3.35 l STPD [ie, conditions of 0°C, 760 mm Hg (101.3 kPa) dry]/min, with a maximum of 4.08 l STPD/min for one subject when working with the fullface mask without positive pressure (table 4). The breathing rate was slightly faster with the fullface mask and positive pressure than with the mouthpiece without positive pressure, although both values were within the normal range; tidal volume was also significantly lower. The heart rate was

Table 3. Hemodynamic variables of the seven subjects during work at 150 W. (PPB = positive pressure breathing)

Variable	1 Mouthpiece without PPB (control)		2 Mouthpiece with PPB		3 Fullface mask without PPB		4 Fullface mask with PPB	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Heart rate (min^{-1})	139	18	140	16	143	12	145	16
Cardiac output (l/min)	19.3	3.1	20.8	2.7	19.4	2.2	19.8	2.5
Stroke volume (ml)	141	33	149	19	126	17	137	16
Arteriovenous oxygen difference (ml/1)	120	20	111	18	120	16	114	16
Systolic arterial pressure (kPa)	29.1	1.9	30.9	2.0	30.3	2.5	30.0	2.4
Diastolic arterial pressure (kPa)	11.9	0.7	12.8	1.3	12.4	0.8	12.3	1.2
Mean arterial pressure (kPa)	16.3	0.8	17.6	1.6	16.4	1.2	16.8	0.9
Mean pressure in right atrium (kPa)	0.49	0.60	0.94	0.68	0.52	0.76	0.79	0.70
			(1–2, $p < 0.01$)		(3–4, $p < 0.01$)		(1–4, $p < 0.05$)	
Pressure variations in right atrium (kPa)[a]	0.95	0.28	1.13	0.41	1.28	0.50	1.31	0.28
							(1–4, $p < 0.05$)	

[a] Kilopascal values are converted to millimeters of mercury by multiplying by 7.5.

Table 4. Measurements made during maximum work, as seen in table 1. (PPB = positive pressure breathing)

Variable	1 Mouthpiece without PPB (control)		2 Mouthpiece with PPB		3 Fullface mask without PPB		4 Fullface mask with PPB	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Heart rate (min^{-1})	194	10	185	13	193	12	186	11
Breathing rate (min^{-1})	23.3	6.6	25.6	6.1	25.6	8	25.9 (1–4, $p < 0.05$)	7.4
Minute ventilation (l BTPS/min)[a]	84.2	19.2	82.9	9.0	86.1	15.2	85.7	16.2
Tidal volume (l BTPS)[a]	3.7	0.38	3.3	0.57	3.5	0.64	3.4 (1–4, $p < 0.025$)	0.52
Oxygen consumption (l STPD/min)[b]	3.35	0.20	3.26	0.31	3.33	0.42	3.32	0.38
Carbon dioxide production (l STPD/min)[b]	3.30	0.38	3.20	0.26	3.23	0.28	3.23	0.32

[a] BTPS = temperature 37°C, ambient pressure, saturated with water vapor at 37°C.
[b] STPD = temperature 0°C, pressure 760 mm Hg (101.3 kPa), dry (standard conditions).

somewhat slower with positive pressure than without, but the difference was not significant. The work capacity of each subject was constant irrespective of the experimental conditions.

Discussion

The normal variation in ventilatory response to exercise is quite large, both between subjects and for the same subject. Comparisons of these variables with different types of breathing equipment should therefore, if possible, be performed on the same subjects, and enough subjects should be studied. The ventilatory and circulatory response to exercise may also be influenced by earlier exercise periods (7), even though as long as 30 min has passed between the test periods and breathing and pulse rates have returned to the initial values within 10 min. Many contradictory results regarding the influence of breathing equipment on physiological variables may therefore be explained by such bias rather than by the influence of the type of apparatus.

The relatively large number of subjects used in the present series, the relatively long rest period between experiments, and the substantial number of variables that cannot be influenced voluntarily by the subjects, combined with randomization of the order of the tests, should support the validity of the results of our study. The positive pressure breathing influenced most variables very little, and the endurance of maximal work was not reduced. However, the very fact that the subjects, firemen trained to use breathing apparatus, started to use a breathing apparatus caused a decrease in ventilation. Instruction and/or experience had taught them to save air by working at increased alveolar-arterial carbon dioxide concentrations, low respiratory rates, and high tidal volumes. The same phenomenon occurs in trained scuba divers (10).

In the present study ventilatory minute volumes did not vary with the different breathing apparatus, although there was a tendency to increase with the increased dead space when the fullface mask was used. When positive pressure was applied with the mask, V_D/V_T was reduced. The reason for this phenomenon could be better air flow conditions in the mask, as similar improved ventilation with positive pressure has been noted in experiments testing the fullface mask on dummy heads in machine tests (9).

We did not note any negative effects of positive pressure breathing on circulation. Barach et al (2, 3) and Kilburn & Sieker (8) showed however that positive pressure breathing may reduce cardiac output. The positive pressure levels in their studies, performed during rest, were in the range of 2–3 kPa, with small variations during the breathing cycle. These levels are much higher than the positive pressure used in our study, in which it oscillated around 0.4 kPa at a moderate work load but was probably a little higher during a maximal work load. During inhalation, when the facepiece pressure was close to zero, there was no restriction of venous return, and, even with a positive mask pressure, intrathoracic pressure may be highly negative during inhalation beause of flow resistance in the airways.

Bjurstedt et al (4), who measured cardiac output with the dye dilution technique during positive pressure breathing, found that the 14 % reduction in cardiac output measured with 1.5 kPa of continuous positive pressure during rest was improved to an 8 % reduction during exercise at 50 % of the maximal work capacity. They concluded that "dynamic exercise counteracts deleterious effects of positive pressure breathing by normalizing respiratory function and by improving cardiac filling by activation of the leg muscle and the abdominal pump [p 212]."

Meyer et al (11) claimed that positive pressure breathing with a mean pressure of 0.64 kPa reduces left ventricular function, as judged from an indirect estimation of cardiac function using systolic time intervals. They concluded that "a fireman's physical performance seems to be reduced to 2000–2500 ml/min O_2 uptake [p 61]. Even disregarding the fact that their results were influenced by the experimental technique (no randomization and only 15 min between the tests), it is still difficult to find any significant differences that support their conclusions. Apart from the technical difficulties involved in measuring systolic time intervals during exercise, the pathological significance of small changes in these values in healthy subjects is unknown, and it has never been shown or even claimed that such changes would imply risk to a healthy subject.

In our experiments direct measurement showed cardiac output to be unchanged with a slight tendency to increase during heavy work (2.0–2.3 l of oxygen/min) with positive pressure breathing at about 0.4 (SD 0.3) kPa.

The slightly smaller arteriovenous oxygen differences noted with positive pressure breathing (in comparison to without) indicate improved rather than impaired circulation. At the maximal work load the subjects achieved oxygen uptakes of 2.81–4.08 l STPD/min, and positive pressure breathing caused no deterioration in any of the measured variables or in the time the subjects could work at a work load that exhausted them in 10 min without a breathing apparatus.

Our results support those of Dahlbäck & Balldin (5), who, using two types of positive pressure fullface masks, obtained no effect on ventilation, heart rate, blood lactate, oxygen saturation, physical performance, or subjective rating of perceived exertion in comparison with the corresponding values in the control situation. At the extreme work load one mask had a facepiece pressure of 0.5 (SD 0.5) kPa and the other mask had a corresponding value of 0.8 (SD 0.8) kPa. Dahlbäck & Balldin's control mouthpiece had a very low breathing resistance of 0.2 to 0.3 kPa at maximum ventilation under an extreme work load.

The conclusion from the work of Dahlbäck & Balldin and the present study must be that positive pressure breathing of about 0.4 kPa does not interfere with ventilation or with cardiac performance either at high submaximal work loads or at the maximal work load that could be sustained for 10 min and that gave a pulse rate of about 200 beats/min. The safety pressure system seems to offer a very high protection level in extremely toxic atmospheres without reducing the wearer's work capacity, cardiac output, or ventilatory efficiency.

Acknowledgments

Ms U Granqvist and the staff of the catheterization laboratory and blood-gas laboratory at the Department of Clinical Physiology, General Hospital, Malmö, gave invaluable assistance. The Malmö fire brigade furnished different AGA safety pressure apparatus from their stock for each experiment. The volunteers worked hard and suffered the inconvenience of arterial and venous catheterization solely out of interest in the function of their new equipment. We thank them all for their help.

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Received for publication: 5 July 1983