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Effects of Elevated Inhaled Oxygen and Carbon Dioxide Concentrations on Respiration and Metabolism During Moderate Exercise

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Abstract

Thirteen healthy subjects performed bicycle-ergometer cycling at approximately 50% of their maximum working capacity while inhaling four different gas compositions: 1) Normoxia and Normocapnia (room air); 2) Hyperoxia (40%O₂); 3) Hypercapnia (3%CO₂); 4) Hyperoxia and Hypercapnia (40%O₂ and 3%CO₂). Hyperoxia decreased the ventilation rate about 7% with normocapnia and about 6% with hypercapnia. It also decreased the carbon dioxide output rate about 5% under both normocapnia and hypercapnia. Hyperoxia had no significant effect on the oxygen uptake rate. Hypercapnia increased the ventilation rate approximately 40% compared to normocapnia, but it did not change the rates of oxygen uptake or carbon dioxide output significantly.

Introduction

Closed-circuit breathing apparatuses (CCBAs) are very important tools for rescue or escape in an irrespirable atmosphere, but their inhaled gases contain super-ambient levels of oxygen and carbon dioxide (e.g. Kyriazi *et al.* 1983). One of the most important safety considerations for CCBAs is the effect of abnormal inhaled gas concentrations on respiration and metabolism (Rosenberg *et al.* 1991; Johnson *et al.* 1992). The expected metabolic rate of the user is important to know for determining the necessary oxygen supply and carbon dioxide absorbent capacity. Most of the present data used for designing CCBAs were obtained by measuring the metabolic rate while subjects breathed ambient air since there are technical difficulties with such measurement if the components of the inhaled gas

differed from that of normal ambient air (Kamon *et al.* 1983; Turner *et al.* 1995). Recent physiological studies have documented the effects of hyperoxia on metabolism (Welch *et al.* 1981; Adams *et al.* 1986; Plet *et al.* 1992; Hughson and Kowalchuk 1995; Walsh and Banister 1995), but the combined effect of hyperoxia and hypercapnia on the metabolic rate during exercise is also needed. In addition, the effect of hyperoxia and/or hypercapnia on ventilation rate is also very important, because a higher ventilation rate is a greater physiological stress on the body (Demedts and Anthonisen 1973; Poon 1987; Babb *et al.* 1989). This study was designed to evaluate the effects of hyperoxia and hypercapnia on respiration and metabolism during moderate exercise and to evaluate the safety of CCBAs.

Methods

Thirteen healthy subjects ranging in age from 28 to 46 yr (twelve males and one female) volunteered to participate in the tests with knowledge of the possible risks. Their average height was about 170 cm and the average weight was about 67kg.

Figure 1 is a schematic diagram of the system which continuously measures the subject's ventilation rate, oxygen uptake rate and carbon dioxide output rate breath-by-breath. A subject wore a half-mask, inhaling gas from the conditioning chamber through the inhalation tube. A blower delivered ambient air to the chamber where carbon dioxide and oxygen were mixed if needed for a particular condition. Exhaled gas passed through the exhalation tube to the mixing chamber. Gas analyzers (AIC Co., RAS-31/41) measured the amount of oxygen and carbon dioxide in the gases in the conditioning chamber and the mixing chamber. The analyzers were calibrated with precision-analyzed gas mixtures before and after each test. A pneumotachometer

(Nihon-Koden Co., VT-112T) measured the volume of the gas flow in the inhalation tube. The coefficient of the viscosity of the inhaled air, which was needed for determining the volume, was calculated from the composition of the gas and the ambient temperature. A pressure sensitive diode (Toyota-Koki Co., PD104K) measured the pressure level inside the mask. Signals from these devices underwent analog to digital conversion and were processed with a personal computer for the determinations of minute ventilation (BTPS), oxygen uptake and carbon dioxide output rate (STPD). The accuracy of these data was evaluated with a lung simulator and by comparison with the Douglas bag method. The errors in measured data were determined to be within 2%.

The arterial hemoglobin oxygen saturation measured at the index fingers of 6 subjects was monitored throughout the tests by a pulse oximeter (Nihon-Koden Co., OLV-1100).

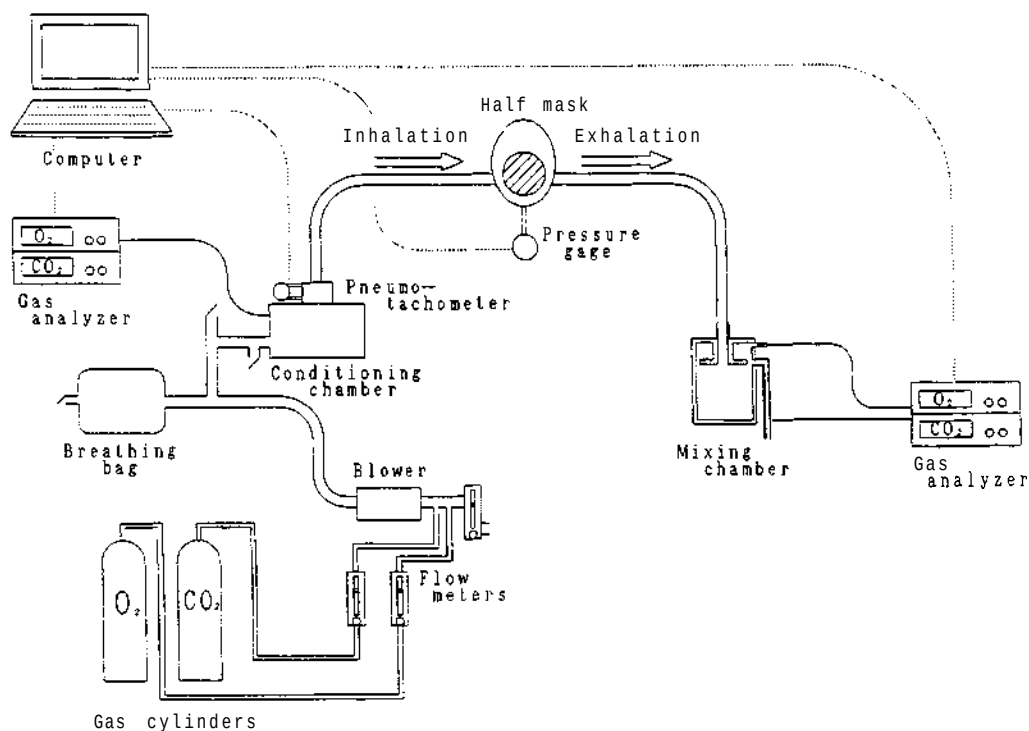


Figure 1. Schematic drawing of the measuring system.

Table 1 shows the four breathing gas test conditions. The 3% carbon dioxide level was chosen since it is the permissible limit in the Japan Industrial Standard (JIS) for CCBAs, and the 40% oxygen level was chosen as the lowest level of inhaled oxygen exhibited by CCBAs that were tested at the author's laboratory. All human subject tests were conducted in random sequence with sufficient rest between each test.

After initial familiarization with inhaled gas conditions, data acquisition was started. A subject

breathed through the mask at rest for 2 minutes on a bicycle ergometer, and started exercising by rotating the pedals at 60 rpm with a 20 W work load. Following 1 min of cycling at this initial exercise load, the power output was increased every minute by 20 W until it reached approximately 50% of the maximum working capacity of the subject determined by heart rate. The subject continued the test for at least 3 minutes at the last work load.

Results

Figures 2–4 show the ventilation rate, oxygen uptake rate and carbon dioxide output rate, respectively, of one subject while breathing the gases of each test condition. It is clear that the ventilation rate while breathing 3% carbon dioxide (hypercapnia) was much higher than that for breathing ambient air (normocapnia). The ventilation rate while breathing 40% oxygen (hyperoxia), however, tended to be a little lower than that of breathing ambient air (normoxia). However, the effects of hyperoxia and hypercapnia were less obvious, in these figures, on oxygen uptake and carbon dioxide output rate.

Table 2 and Figures 5–8 show the effects on ventilatory rate, oxygen uptake rate, carbon dioxide output rate and arterial oxygen saturation during moderate exercise in all subjects. The values for each subject were 1-min averages taken after becoming stable at approximately 50% of their maximum working capacity. The effects of change in inhaled

oxygen and carbon dioxide concentration were statistically evaluated by the Student's t-test.

Inhalation of three-percent carbon dioxide increased the ventilation rate more than 35% both for normoxia and hyperoxia. Increasing inhaled oxygen to 40% decreased the ventilation rate a little, but statistically significantly, with and without the 3% inhaled carbon dioxide. The increase in inhaled oxygen and carbon dioxide concentration had no significant effect on oxygen uptake rate during moderate exercise. Increased levels of inhaled carbon dioxide did not significantly affect the carbon dioxide output rate, but hyperoxia statistically significantly decreased the value compared to normoxia with and without hypercapnia. Hyperoxia significantly elevated the level of arterial oxygen saturation while hypercapnia increased the level only with normoxia.

Discussion

The present study examined the effects of increased inhaled oxygen and carbon dioxide concentrations on respiratory and metabolic variables

during moderate exercise. It has been demonstrated that an increase in inhaled oxygen concentration during exercise reduced the ventilation rate and did

Table 1. Breathing conditions for the tests.

Test	Inhaled gas concentration*	
	O ₂ (%)	CO ₂ (%)
a	21	trace
b	21	3
c	40	trace
d	40	3

* The residual component was mainly nitrogen.

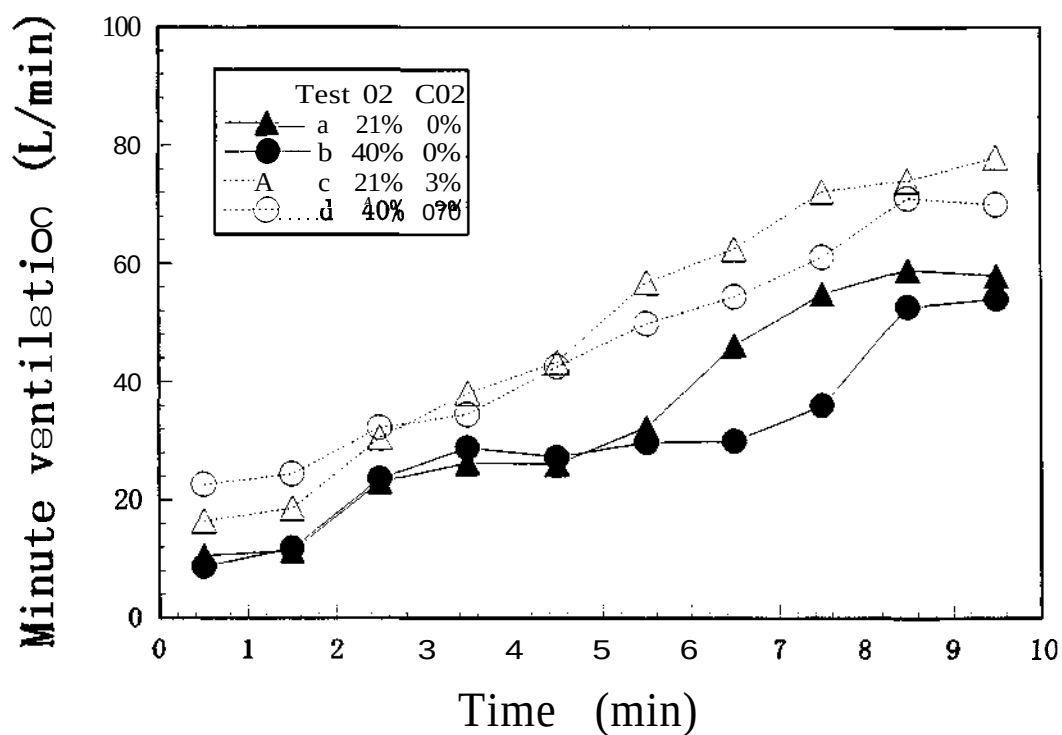


Figure 2. Minute ventilation during incremental and subsequently steady-state exercise under varied breathing gas conditions in a subject.

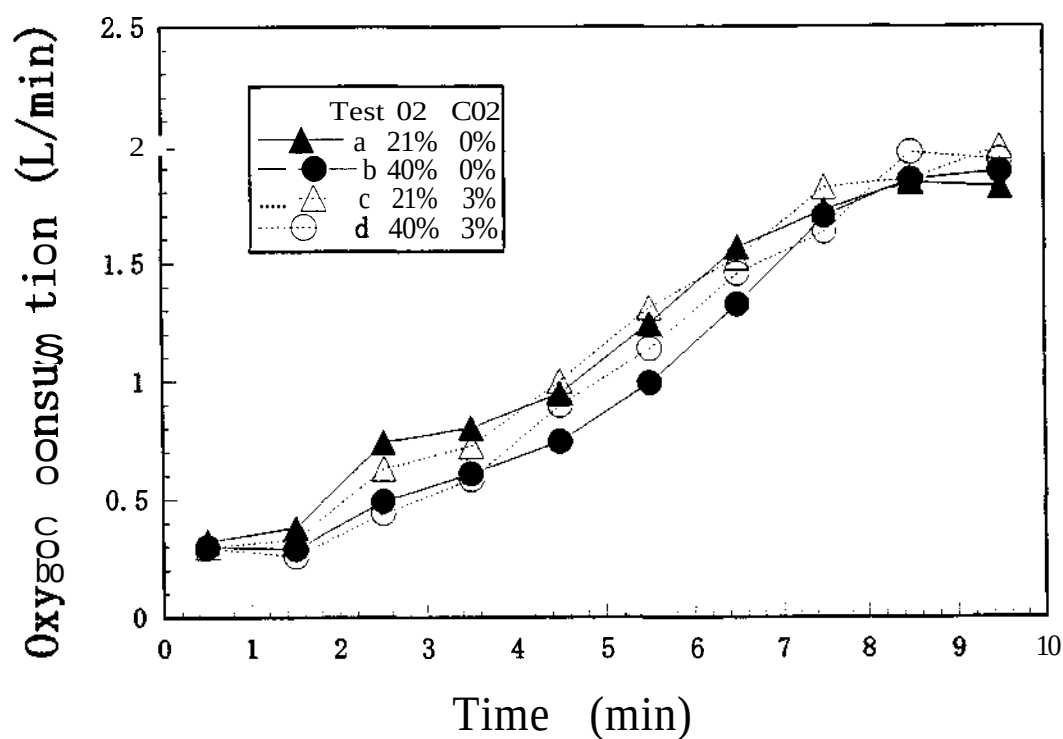


Figure 3. Oxygen consumption in the subject.

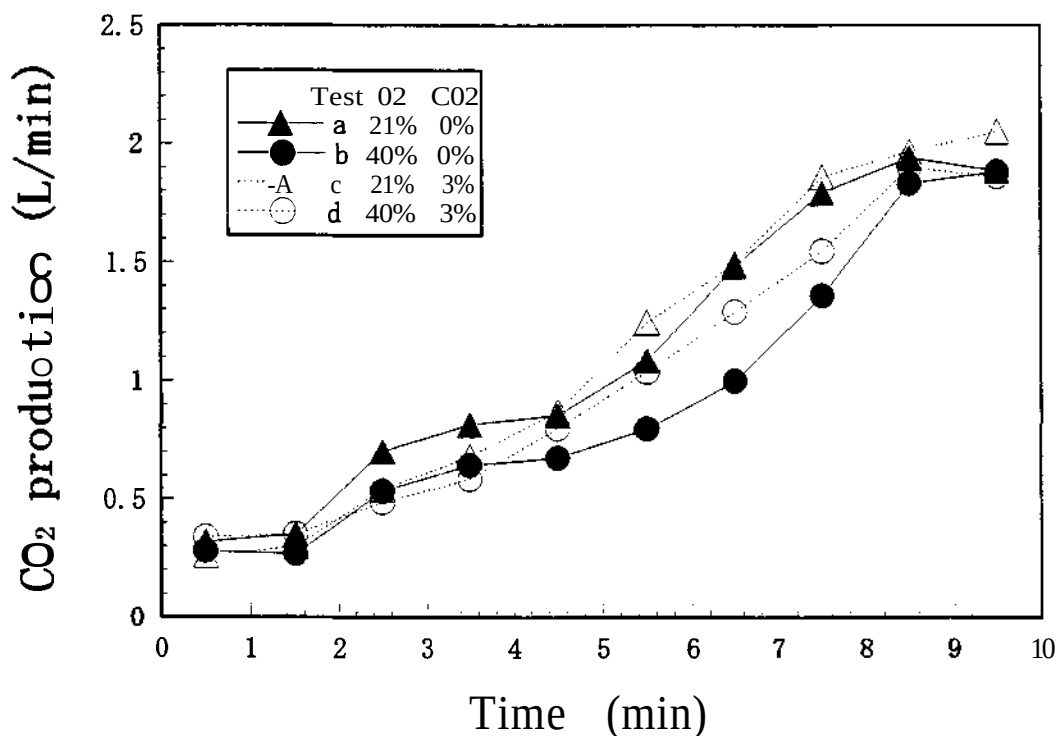


Figure 4. Carbon dioxide production in the subject.

not significantly change the oxygen uptake rate. But for consideration of the safety of CCBA, we need more information about the effect of change in inhaled gas content, especially the combined effect of hyperoxia and hypercapnia. Change in ventilation rate and metabolism affect the performance of CCBA so the effects of hyperoxia and hypercapnia on ventilation and metabolism are of interest to CCBA designers and government certifying agencies.

The effect on ventilation rate is a very important factor for consideration of the safety of the apparatus, since the increase in ventilation rate enlarges the pressure fluctuations in the respiratory circuit with breathing resistances and causes a physiological stress. Carbon dioxide stimulates the ventilation and 3% of carbon dioxide increased the minute ventilation by more than 35%. We can expect the effect of hyperoxia to decrease the ventilation rate, but the effect is not enough to compensate the effect of elevated carbon dioxide concentration. Three-percent of inhaled carbon dioxide is defined as the permissible level of CCBA by some criteria such as JIS. This value should be reduced to a much lower level to decrease the physiological stress induced by using the apparatus while working.

The breathing circuits of CCBA is closed systems, so the oxygen supply must accommodate the oxygen uptake rate of the user. If the supply is less than the demand, there will be an oxygen deficit; if the demand is less than the supply, gas leaves the circuit from a relief valve and oxygen is wasted. Most of the fundamental physiological data used for designing CCBA were obtained using human subjects breathing ambient air at field tests (Kamon *et al.* 1983; Turner *et al.* 1995). This is because it is practically impossible to measure the metabolic values under inhaled gas conditions different from ambient air in the field, such as an underground mine. Earlier research reported that the oxygen uptake rate was higher while breathing hyperoxic gases than under normoxic conditions (Ekblom *et al.* 1975, Wilson *et al.* 1975), but Welch (1981) showed that under hyperoxic conditions, the conventional Douglas bag technique tends to overestimate oxygen uptake rate because of the contamination of the bag with ambient air. We used the mixing chamber method and did not find any significant difference in oxygen uptake rate between normoxia and hyperoxia; this finding supports the results of Welch (1981), Adams (1986) and Hughson (1995). Neither did the addition of hypercapnia to the hyperoxia

Table 2. Minute ventilation, oxygen consumption, carbon dioxide production, respiratory quotient, and arterial oxygen saturation in 13 subjects during approximately 50% $\text{VO}_{2\text{max}}$ exercise at different concentrations of inhaled oxygen and carbon dioxide.

CO_2	Sub	21% O_2					40% O_2				
		VE L/min	VO_2 L/min	VCO_2 L/min	R	SaO_2 %	VE L/min	VO_2 L/min	VCO_2 L/min	R	SaO_2 %
trace	A	60.5	2.05	2.08	1.01	96	54.3	2.12	1.97	0.92	97
	B	58.8	1.91	1.90	0.99	96	55.7	1.97	1.88	0.95	99
	C	45.3	1.59	1.58	0.99	96	41.2	1.62	1.49	0.92	99
	D	39.4	1.86	1.81	0.97	96	37.1	1.78	1.59	0.89	100
	E	43.0	1.58	1.68	1.06	95	36.4	1.57	1.49	0.94	98
	F	21.5	0.99	0.89	0.89	93	19.4	0.94	0.81	0.86	100
	G	45.3	2.06	2.08	1.01	—	38.0	2.10	1.78	0.84	—
	H	46.1	1.77	1.76	0.99	—	41.9	1.82	1.62	0.88	—
	I	24.4	1.03	0.93	0.90	—	23.8	1.06	0.90	0.85	—
	J	47.1	1.89	1.82	0.95	—	46.0	1.96	1.86	0.95	—
	K	53.6	2.01	1.92	0.95	—	53.47	2.12	2.01	0.95	—
	L	41.9	1.18	1.26	1.06	—	40.0	1.28	1.25	0.98	—
	M	30.7	1.40	1.43	1.02	—	29.2	1.41	1.30	0.92	—
Ave		42.9	1.64	1.63	0.98	95.3	39.8	1.68	1.54	0.92	98.8
SD		11.8	0.38	0.39	0.05	1.2	11.17	0.40	0.38	0.04	1.2
t-test O_2		—	—	—	—	—	**	—	**	**	**
3%	A	91.2	2.09	2.16	1.03	96	82.1	2.17	1.98	0.91	98
	B	78.9	1.99	2.16	1.08	97	72.0	1.98	1.99	1.00	99
	C	68.2	1.63	1.76	1.08	98	64.4	1.65	1.69	1.02	100
	D	55.8	1.80	1.85	1.02	97	48.9	1.73	1.66	0.96	100
	E	57.7	1.46	1.70	1.16	97	46.9	1.48	1.56	1.05	98
	F	29.4	0.97	0.95	0.97	96	27.2	0.97	0.90	0.92	99
	G	52.7	1.91	1.85	0.96	—	50.8	2.04	1.76	0.86	—
	H	60.7	1.70	1.71	1.00	—	56.8	1.79	1.62	0.90	—
	I	39.4	1.13	1.06	0.93	—	34.7	1.11	0.92	0.82	—
	J	61.0	2.08	1.82	0.87	—	62.7	2.04	1.73	0.85	—
	K	84.5	2.09	2.02	0.96	—	84.1	2.43	2.02	0.83	—
	L	44.5	1.25	1.25	1.00	—	44.1	1.20	1.28	1.06	—
	M	36.5	1.37	1.27	0.92	—	39.5	1.44	1.37	0.95	—
Ave		58.5	1.65	1.66	1.00	96.8	54.9	1.69	1.58	0.93	99.0
SD		18.7	0.38	0.40	0.07	0.8	17.5	0.44	0.36	0.08	0.9
t-test O_2		—	—	—	—	—	**	—	**	**	**
t-test CO_2		**	—	—	—	**	**	—	—	—	—

CO_2 , inhaled carbon dioxide concentration; Sub, subject; VE, minute ventilation; VO_2 , oxygen consumption; VCO_2 , carbon dioxide production; R, respiratory exchange ratio; SaO_2 , arterial oxygen saturation at finger; Ave, average; SD, standard deviation; t-test O_2 , significant difference between 21% and 40% of inhaled oxygen by paired t-test (** $p < 0.01$); t-test CO_2 , significant difference between trace (<0.04%) and 3% inhaled carbon dioxide.

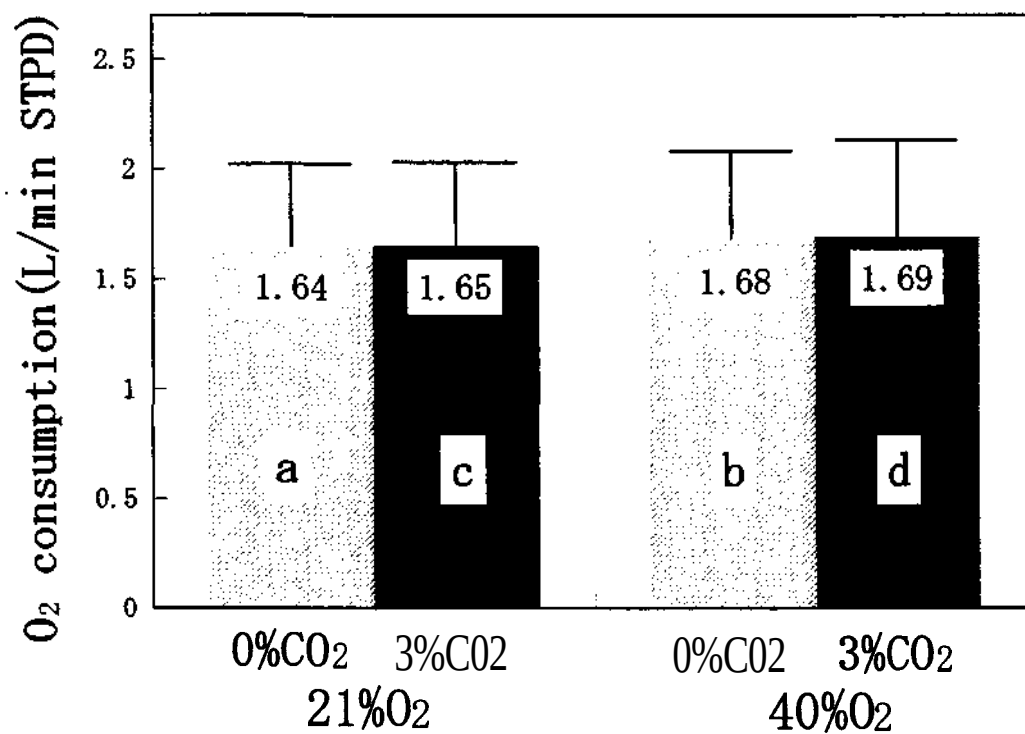


Figure 5. Minute ventilation at 4 different test conditions. The asterisk shows that the difference between the two conditions which are indicated by broken line is statistically significant (**:p<0.01).

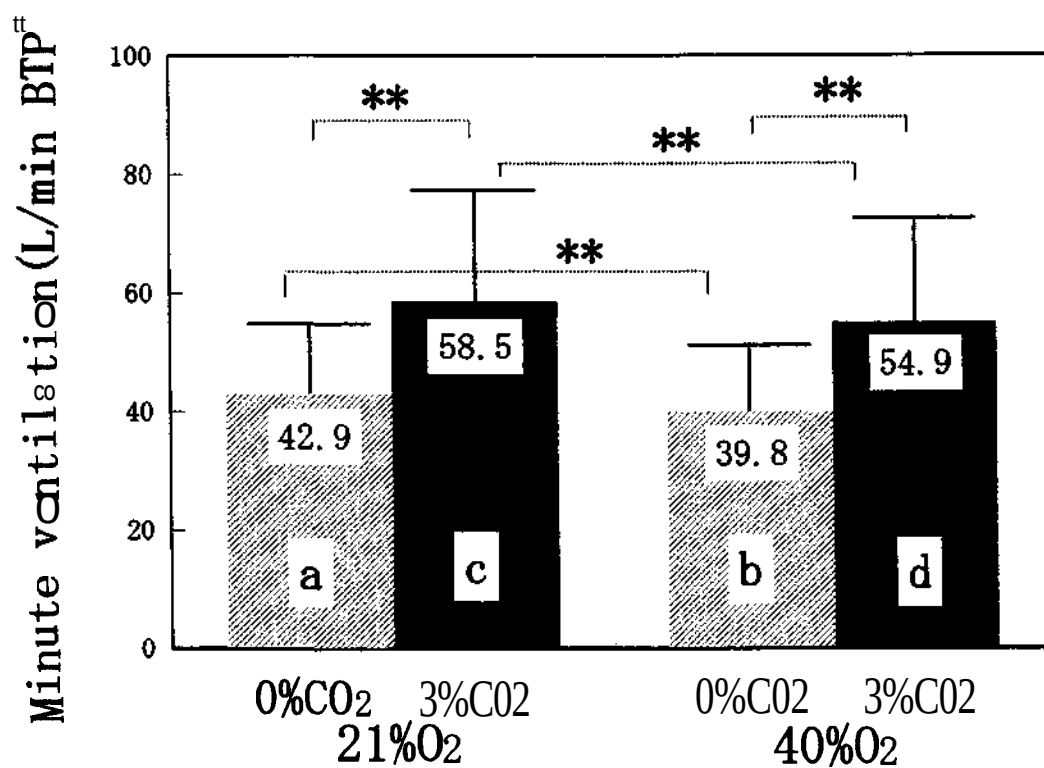


Figure 6. Oxygen consumption at 4 different test conditions.

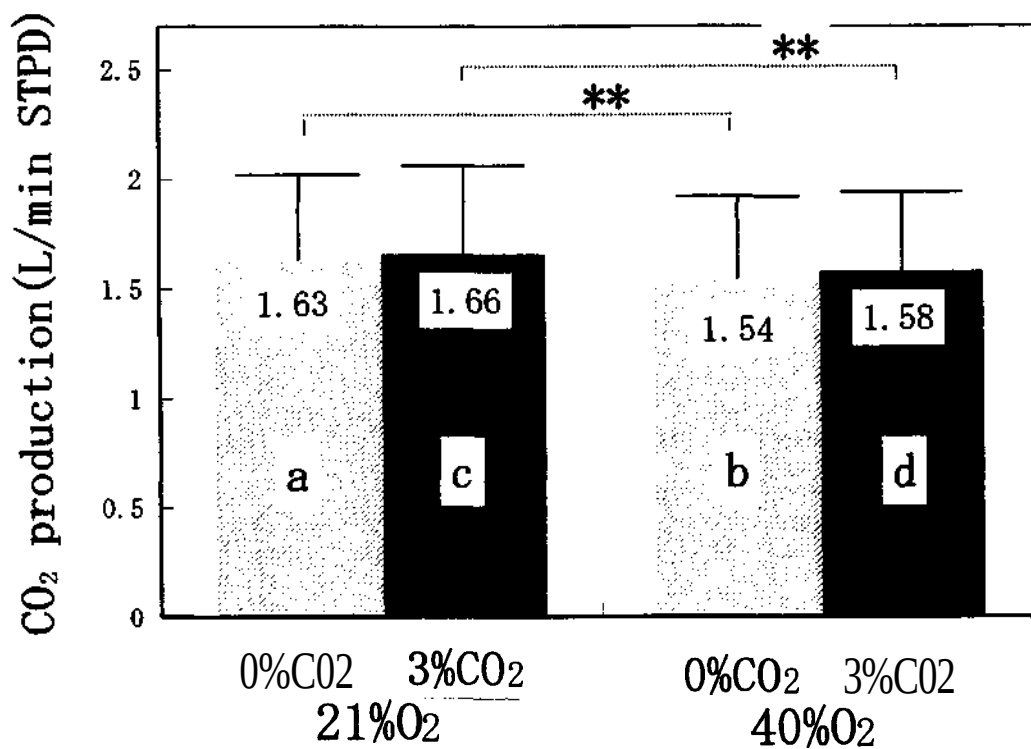


Figure 7. CO₂ production at 4 different test conditions.

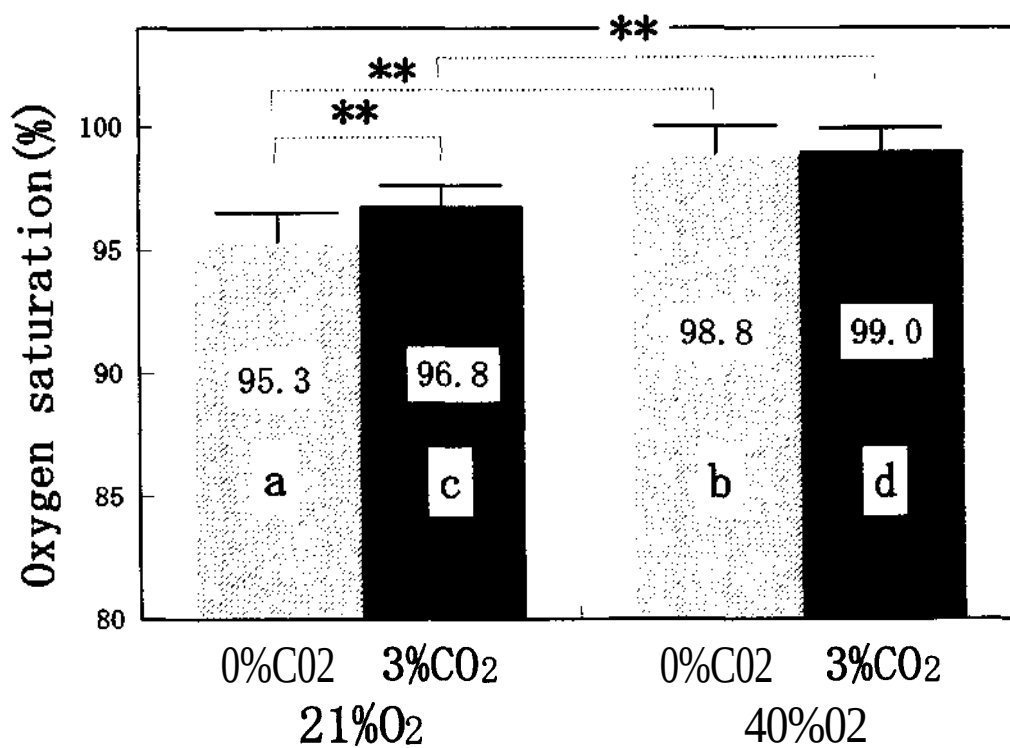


Figure 8. Arterial oxygen saturation at 4 different test conditions.

change the oxygen uptake rate. Therefore, the sizing of the oxygen supply of an apparatus at its expected work load can rely on data acquired while breathing air at ambient rather than at conditions simulating CCBA breathing circuits (hyperoxic and hypercapnic), which would make data acquisition more difficult.

The effect of increased oxygen and carbon dioxide concentration on carbon dioxide output rate is also very important for designing CCBA, because it determines the required carbon dioxide absorbent capacity of the apparatus. Too little absorbent will result in elevated carbon dioxide levels causing serious physiological stress. Menn (1970), Ehram (1982) and Kaminski (1982) reported that hypercapnia decreased the carbon dioxide output rate, but we found that 3% carbon dioxide had no such significant effect. Welch (1981) and Adams (1986) demonstrated that hyperoxia tended to decrease carbon dioxide output rate during exercise. We confirmed the same effect of hyperoxia under both normocapnia and hypercapnia conditions. So, sizing the carbon dioxide absorbent capacity for CCBA's can also rely on physiological data acquired while breathing

ambient air at field tests because a decrease in the carbon dioxide output rate with hyperoxia works on the safe side by prolonging the life time of the absorbent.

Breathing hyperoxic gas decreases the respiratory exchange ratio because of the decrease in the carbon dioxide output rate with no change in the oxygen uptake rate. Welch (1981) also demonstrated the existence of this effect on the exchange ratio and attributed it to a substrate shift toward an increased use of fatty acids.

Considering the effect of hypercapnia on metabolism, Ehram (1982) demonstrated that severe acidosis induced by breathing 5% carbon dioxide during exercise reduced the respiratory exchange ratio because of the plausible effect on metabolism, especially glycogenolysis. But we did not confirm any effect of hypercapnia on metabolism from the respiratory exchange ratio data. Inhalation of less than 3% carbon dioxide during moderate exercise, therefore, will probably not result in such strong acidosis that it would affect metabolism.

Conclusions

The effects of elevated inhaled oxygen and carbon dioxide concentrations on respiration and metabolism during moderate exercise were studied in thirteen healthy subjects. Hyperoxia decreased the minute ventilation about 7% with normocapnia and about 6% with hypercapnia. It also decreased the carbon dioxide production about 5% under both

normocapnia and hypercapnia. Hyperoxia had no significant effect on the oxygen consumption. Hypercapnia increased the minute ventilation approximately 40% compared to normocapnia, but it did not change the rates of oxygen uptake or carbon dioxide output significantly.

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References

- Adams R. P., Cashman P. A., Young J. C. Effect of hyperoxia on substrate utilization during intense submaximal exercise. / *Appl. Physiol.* 61: 523-529, (1986).
- Babb T., Turner N., Staupe K., Pawelczyk J. Physical performance during combinations of hypercapnic, resistive, and hot air breathing. *Am. Ind. Hyg. Assoc. J.*, 50: 105-111, (1989).
- Demedts M., Anthonisen N. R. Effects of increased external airway resistance during steady-state exercise. / *Appl. Physiol* 35: 361-366, (1973).

- Ekblom B., Huot R., Stein E. M., Thorstensson A. Effect of changes in arterial oxygen content on circulation and physical performance. */ Appl. Physiol.* 39: 71-75, (1975).
- Ehrsam R. E., Heigenhauser G. J. F., Jones N. L. Effect of respiratory acidosis on metabolism in exercise. */ Appl. Physiol.* 53: 63-69, (1982).
- Hughson R. L., Kowalchuk J. M. Kinetics of oxygen uptake for submaximal exercise in hyperoxia, normoxia and hypoxia. *Ca. / Appl. Physiol.* 20: 198-210, (1995).
- Johnson A. T., Weiss R. A., Grove C. Respirator performance rating table for mask design. *Am. Ind. Hyg. Assoc. J.* 53: 193-202, (1992).
- Kaminski R. P., Forster H. V., Klein J. P., Pan L. G. Effect of elevated PICO_2 on metabolic rate in humans and ponies. *J. Appl. Physiol.* 52: 1623-1628, (1982).
- Kamon E., Doyle D., Kovac J. The oxygen cost of an escape from an underground coal mine. *Am. Ind. Hyg. Assoc. J.* 44: 552-555, (1983).
- Kyriazi N., Kovac J., Duerr W., Shubilla J. Laboratory testing of compressed-oxygen self-rescuers for ruggedness and reliability. Bureau of Mines Report of Investigations RI-8839, (1983).
- Menn S. J., Sinclair R. D., Welch B. E. Effect of inspired PCO_2 up to 30 mmHg on response of normal man to exercise. */ Appl. Physiol.* 28: 663-671, (1970).
- Plet J., Pedersen P. K., Jensen F. B., Hansen J. K. Increased working capacity with hyperoxia in humans. *Eur. / Appl. Physiol.* 65: 171-177, (1992).
- Poon C.-S. Ventilatory control in hypercapnia and exercise: optimization hypothesis. */ Appl. Physiol.* 62: 2447-2459, (1987).
- Rosenberg B. S., White M. K. Human factors related to the testing of self-contained breathing apparatus: a review. */ ISRP9* : 6-25, (1991).
- Turner N., Beeckman D., Hodous T. Evaluation of proposed methods to update human testing of self-contained breathing apparatus. *Am. Ind. Hyg. Assoc. J.* 56: 1195-2000, (1995).
- Walsh M. L., Banister E. W. The influence of inspired oxygen on the oxygen uptake response to ramp exercise. *Eur. / Appl. Physiol.* 72: 71-75, (1995).
- Welch H. G., Pedersen P. K. Measurement of metabolic rate in hyperoxia. */ Appl. Physiol.* 51: 725-731, (1981).
- Wilson B. A., Welch H. G., Liles J. N. Effects of hyperoxic gas mixtures on energy metabolism during prolonged work. */ Appl. Physiol.* 39: 267-271, (1975).