Oxygen Administration by Mask in a Pressure Chamber

D. G. McDowall, M.B. (Edin.), F.F.A.R.C.S., I. McA. Ledingham, M.B., Ch.B. (Glas.),† I. Jacobson, B.Sc., M.B. (Witwatersrand), F.R.C.S.E.,‡ J. N. Norman, Ph.D., M.D. (Glas.)§*

The mean end-expiratory oxygen concentration in nine volunteers breathing 100 per cent oxygen from a B.L.B. mask was only 61 per cent; furthermore there were wide differences in the efficiency of this mask between subjects. An alternative system of oxygen administration is described, consisting of a pilot's mask and a demand valve. The mean end-expiratory oxygen concentration attained with this system was 83 per cent and individual variations were small. This mask is more comfortable to wear than the B.L.B. and the inspiratory and expiratory pressures are very low.

This study was carried out at two atmospheres absolute in order to allow measurements of arterial oxygen tension to be made in some of these subjects. The arterial values obtained indicate that the arterial oxygen tension approaches closely the level predicted theoretically at this pressure. Hyperbaric oxygen therapy is therefore not impeded by the failure of the arterial blood to reach the expected oxygen tension provided that the oxygen administration system is efficient.

THE USE of hyperbaric chambers in medical therapy is dependent upon the efficient delivery of oxygen to the patient's lungs. The practice in many centers, including our own, has been to use the B.L.B. mask for this purpose. In the first part of the present study, it was found that this mask failed to provide the required alveolar oxygenation and led us to investigate a new method of oxygen administration. This report compares the two systems on the basis of measurements of alveolar oxygen partial pressure.

The volunteers were studied at two atmospheres absolute in order to make direct polarographic measurements of arterial oxygen tension in the range of supra-atmospheric pressures of oxygen used clinically.

Method

Part 1—The Study of the B.L.B. Mask. The full face model of the B.L.B. mask was used. The mask was carefully adjusted to fit each volunteer and connected to a B.O.C. rotameter which was set to an indicated flow of 10 liters/minute. This reading of the rotameter at 2 atmospheres absolute gives a true flow of 8 liters/minute.[1]

Nine volunteers were studied using the B.L.B. mask. The volunteers were patients admitted to a general surgical ward, and were selected according to the following criteria: (1) preoperative cases except for one patient who had undergone uncomplicated appendectomy six days previously, (2) under 45 years of age, (3) no history of cardiorespiratory disease, and (4) had consented to the procedure which had been fully explained to them.

Details of the individual patients are found in table 1.

The volunteers were brought to the pressure chamber on a trolley and remained recumbent throughout the procedure. They were allowed to rest in the chamber, breathing air, for one hour at normal pressure in order to accustom them to their surroundings. During this period they were given instructions on the method of supplying an alveolar air sample and several measurements of alveolar oxygen partial pressure were made in order to confirm that proper sampling was being achieved. The B.L.B. mask was then applied and connected

* Senior Lecturer in Anaesthetics, University of Glasgow.

† External Research Fellow of the Medical Research Council.

‡ Senior Registrar, Department of Surgical Neurology, Western General Hospital, Edinburgh.

§ Lecturer in Surgery, University of Aberdeen.

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TABLE 1

Volunteer	Age (years)	Sex	Surgical Condition	Operation
B.L.B. Series				
1	35	Male	Duodenal ulcer	No
2	26	Male	Inguinal hernia	No
3	39	Male	Varicose veins	No
4	38	Male	Ureteric calculus	No
5	35	Male	Peptic ulcer	No
6	29	Male	Appendicitis	Appendectomy six days previously
7	21	Male	Renal calculus	No
8	28	Male	Peptic ulcer	No
9	37	Male	? Abdominal T.B.	No
"Test" System				
1	42	Male	Duodenal ulcer	No
2	33	Male	? Appendicitis	No
3	36	Male	Ingiunal hernia	No
4	20	Male	Head injury	No
5	21	Male	Appendicitis	Appendectomy nine days previously
6	32	Female	Thrombo-angiitis obliterans	Below knee amputation six weeks previously
7	19	Male	Lingual angioma	No

to a cylinder of oxygen. The chamber was pressurized over 25 minutes to two atmospheres absolute. All samples were timed with reference to the time of reaching full pressure, although oxygen had also been administered during pressurization. The longest period of oxygen administration at two atmospheres was 65 minutes.

At least three alveolar samples were obtained, each separated by not less than five minutes and were analyzed for oxygen partial pressure. In 4 subjects between the penultimate and the final alveolar samples, 2 ml. of lignocaine were injected intradermally, subcutaneously and around one femoral artery and an arterial sample was withdrawn not less than 5 minutes after the last alveolar sample. In one further volunteer simultaneous arterial and alveolar sampling was carried out. The arterial blood samples were analyzed immediately for oxygen tension, *p*H and carbon dioxide tension.

The "alveolar" samples were end-expiratory samples collected into a Haldane-Priestley sampling apparatus. The patient was not warned that the time for sampling was near and the expiration used for sampling was performed from the normal end-inspiratory position. Immediately after the collection of the sample, the mask was reapplied so that there was no intervening air breathing.

Alveolar oxygen partial pressures and arterial oxygen tensions were determined in a few subjects with a Bishop [2] stirred electrode and a Severinghaus-Bradley amplifier [3] as modified for the pressure chamber by Jacobson.[4] However, most measurements were made with the oxygen electrode produced by Radiometer Limited. In both cases, calibration was carried out with nitrogen, air and 100 per cent oxygen, and both gas and tonometered water calibrations were performed.

Arterial *p*H and P_{CO_2} were measured by the technique of Sigaard Andersen *et al.*[5]

Part 2—The Study of the "Test" System. In view of the findings of part 1 of this study, the advice of the Institute of Aviation Medicine, Farnborough, Hants, England, was sought on the subject of oxygen masks. Squadron Leader J. Ernsting, advised an airline pilots mask used in conjunction with a tilt type demand valve (fig. 1). This soft-rubber, molded mask included a one-way expiratory valve. The tilt valve was attached to an oxygen cylinder through a reducing valve which was set to deliver oxygen at 20 pounds per square inch. When the patient made an inspiratory effort, the tilt valve opened and oxy-

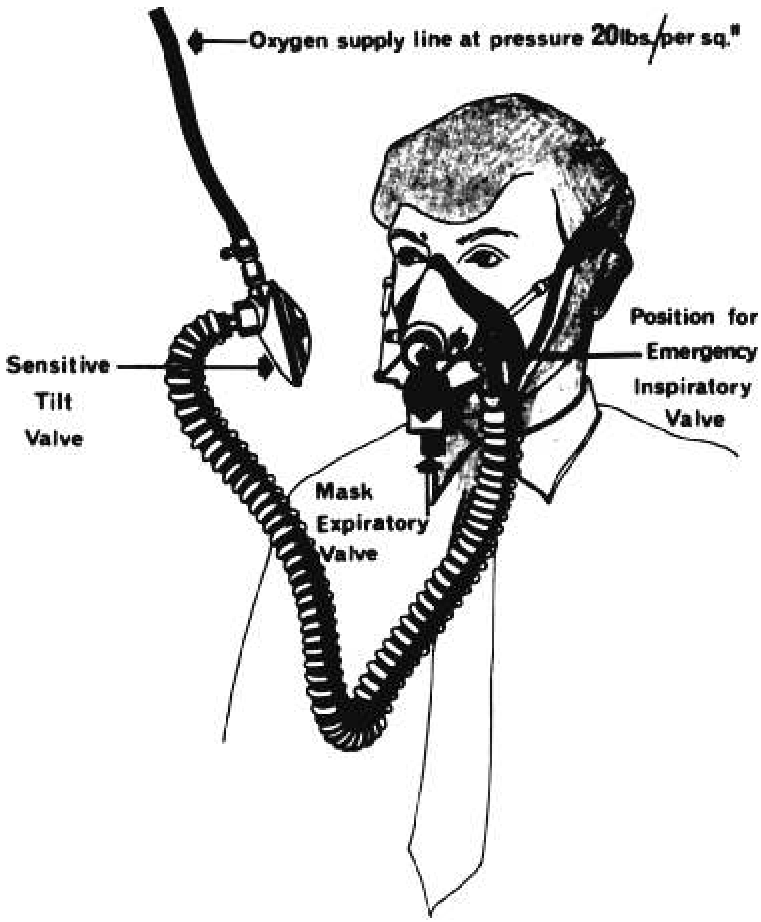

FIG. 1. The "test" system of oxygen administrations.

gen was delivered at a flow rate high enough to equal the peak inspiratory flow in any subject. Immediately inspiration ceased the valve closed and there was thus no wastage of oxygen during expiration. In a separate study, the pressures developed in this system were studied. A needle was introduced into the mask so that its tip lay near the volunteer's mouth and was connected to a pressure transducer, the output of which was fed to an ink-jet recorder. Inspiratory and expiratory pressures were measured at a number of settings of the oxygen supply pressure.

This system of administration was assessed in seven volunteers selected on the same criteria as in the B.L.B. study. All of them were preoperative patients except for one who had undergone uncomplicated appendectomy nine days previously and one who had had a below knee amputation performed six weeks previously. This last patient was the only female in this study. The methods used for obtaining alveolar and arterial samples were identical to those described in part 1. Arterial samples were measured in five of the volunteers in this group and the longest period of oxygen breathing at two atmospheres was 75 minutes.

Results

From table 1, it can be seen that the average age of the volunteers was 32 years in the B.L.B. group and 29 years in the "test" group; the oldest subject was 42 years of age.

Part 1—B.L.B. Mask. All measurements of alveolar P_{O_2} and of arterial P_{O_2}, *p*H and P_{CO_2} during oxygen breathing at two atmospheres with the B.L.B. mask are given in tables 2 and 4. The average alveolar oxygen concentration with this mask was 61 per cent and the average arterial value 56 per cent. It will be seen, however, that there were very large differences between the alveolar oxygen concentrations in different patients, ranging from 49 per cent to 80 per cent (table 4). The arterial oxygen tensions were in all cases within 100 mm. of mercury of the alveolar partial pressures but, as on only one occasion was simultaneous sampling carried out, it is not possible to define the mean alveolar-arterial differences for oxygen (especially with the swinging values obtained for alveolar P_{O_2} with the B.L.B. mask). On

TABLE 2. Results in 9 Patients Breathing Oxygen at Two Atmospheres Absolute from B.L.B. Mask

Patient	Time (minutes)	Alveolar P_{O_2} (mm. Hg)	Arterial P_{O_2} (mm. Hg)	Arterial pH	Arterial P_{CO_2} (mm. Hg)
1	+ 8	878			
	+ 19	815			
	+ 40	816	775	7.49	41
2	+ 11	1,214			
	+ 21	1,270			
	+ 31	1,170	—	—	—
3	+ 15	742			
	+ 35	678			
	+ 50	848			
	+ 60	—	661	7.43	—
4	+ 5	756			
	+ 30	820			
	+ 45	650	—	—	—
5	+ 5	892			
	+ 10	923			
	+ 15	947			
	+ 20	—	826	7.44	43
6	+ 5	756			
	+ 15	764			
	+ 20	813			
	+ 25	—	787	7.48	30
7	+ 5	958			
	+ 15	1,213			
	+ 30	1,148	—	—	—
8	+ 5	1,087			
	+ 20	1,117			
	+ 25	1,202			
	+ 65	—	1,176	7.42	45
9	+ 15	984			
	+ 20	834			
	—	864	—	—	—

TABLE 3. Results in 7 Patients Breathing Oxygen at Two Atmospheres Absolute from "Test" Mask

Patient	Time (minutes)	Alveolar P_{O_2} (mm. Hg)	Arterial P_{O_2} (mm. Hg)	Arterial pH	Arterial P_{CO_2} (mm. Hg)
1	+ 13	1,030			
	+ 23	1,270			
	+ 33	1,280			
	+ 38	1,315			
	+ 53	—	1,275	7.43	35
2	—	1,380			
	—	1,420			
	—	1,160			
	—	—	1,440	7.41	39
3	+ 10	1,231			
	+ 14	1,311			
	+ 20	1,353	—	—	—
4	+ 10	1,388			
	+ 15	1,409			
	+ 25	1,405	—	—	—
5	+ 25	1,260			
	+ 35	1,240			
	+ 42	1,180			
	+ 55	1,220			
	+ 59	1,240			
	+ 75	—	1,240	—	—
6	+ 10	1,030			
	+ 17	1,150			
	+ 27	1,130			
	+ 42	1,230			
	+ 52	—	1,260	7.43	36
7	+ 10	1,160			
	+ 30	1,260			
	+ 45	1,268			
	+ 60	—	1,240	7.24	35

the one occasion when simultaneous sampling was carried out the $A\text{–}aD_{O_2}$ was 41 mm. of mercury at an alveolar P_{O_2} of 816 mm. of mercury. This is in agreement with other measurements of the alveolar-arterial oxygen gradient at approximately this level of alveolar oxygen partial pressure.[6, 7]

Part 2—"Test" Mask. The individual results for the test mask are given in tables 3 and 5. It will be seen that both the alveolar and the arterial oxygen values using the "test" system were considerably higher than with the B.L.B. mask. The average alveolar oxygen concentration was 83 per cent, and the aver-

TABLE 4. Mean Values for Alveolar Oxygen Partial Pressure and Arterial Oxygen Tension Obtained with B.L.B. Mask

Patient	Mean Alveolar P_{O_2} (mm. Hg)	Alveolar Oxygen Concentration Percentage	Arterial P_{O_2} (mm. Hg)	Arterial Oxygen Percentage
1	836	55	775	51
2	1,218	80	—	—
3	756	50	661	44
4	742	49	—	—
5	921	61	826	54
6	778	51	787	52
7	1,106	73	—	—
8	1,135	75	1,176	77
9	894	59	—	—
Grand means	932 ± 179	61	845 ± 194	56

age arterial value 85 per cent. Furthermore, the values obtained with this system are very similar from patient to patient; varying only from 75 per cent to 92 per cent. The individual alveolar results are also consistent in any one patient with the exception of the third reading in patient 2. However, a close examination of the results shows that the alveolar oxygen values measured after 15 minutes or more of oxygen breathing at pressure were higher than those obtained at periods of less than 15 minutes. This observation suggests that significant washout of nitrogen continued throughout the 25 minutes of pressurization and for 10–15 minutes thereafter.

Table 6 summarizes the findings.

The pressures developed in the "test" mask in one subject at different oxygen supply pressures are shown in table 7. It will be seen that the higher the supply pressure, the greater the negative pressure that must be developed by the patient to "trigger" the inspiratory valve.

TABLE 5. Mean Values for Alveolar Oxygen Partial Pressure and Arterial Oxygen Tension with "Test" System of Oxygen Administration

Patient	Mean Alveolar P_{O_2} (mm. Hg)	Alveolar Oxygen Concentration Percentage	Arterial P_{O_2} (mm. Hg)	Arterial Oxygen Percentage
1	1,224	81	1,275	84
2	1,320	87	1,440	95
3	1,298	85	—	—
4	1,401	92	—	—
5	1,228	81	1,240	82
6	1,135	75	1,260	83
7	1,229	81	1,240	82
Grand means	1,262 ± 85	83	1,291 ± 85	85

At the supply pressure used for this investigation, *i.e.*, 20 pounds per square inch—the inspiratory pressure required was only 0.43 cm. of water. Similarly the expiratory pressures developed in this mask were very low, equaling only about a quarter of a centimeter of water.

Discussion

Validity of Techniques. End-expiratory sampling has been shown to give valid measurements of the composition of the alveolar air in healthy subjects,[8] provided that expiration starts from the normal end-inspiratory position. Care was taken in this study to ensure that the patient did not take a deep breath prior to sampling. The success of local anesthesia in avoiding hyperventilation in response to puncturing the femoral artery is demonstrated by the normal arterial carbon dioxide tensions in all subjects except number 6 of the B.L.B. series.

Mask Efficiencies. With the B.L.B. mask, the average alveolar oxygen concentration was 61 per cent; this is in close agreement with the 62 per cent value reported by Kory *et al.*[9] using the same fresh gas flow rate and method of alveolar sampling. They observed a range of alveolar oxygen concentrations of 45–79 per cent between individual subjects; our range was 49 to 80 per cent. Their results and ours are considerably below the values claimed for the B.L.B. mask by Boothby *et al.*[10] and by Card *et al.*[11] The efficiency of the B.L.B. mask in administering oxygen varies enormously from one patient to another. One standard deviation for the present series represents 19 per cent of the mean value. It follows, therefore, that the efficiency of oxygen therapy with the B.L.B. mask in any individual patient cannot be even roughly gauged without actual measurement.

The "test" oxygen administration system was much more efficient and the range of values obtained between different patients much smaller, *i.e.*, on average the alveolar oxygen concentration was 83 per cent and one standard deviation represented less than 7 per cent of this. Using this system for oxygen therapy, therefore, the concentration of oxygen received by the patient can be assumed, with reasonable accuracy, to be known without individual measurement. This is, of course, important in any assessment of the value of oxygen therapy, but is essential when the patient is receiving potentially toxic pressures of oxygen. This measured efficiency should be compared not only with the B.L.B. results, but also with the values reported in the literature for the other commonly used methods of oxygen administration. Kory *et al.*[9] reported the following alveolar oxygen concentrations: [redacted]eal [redacted]t; na[redacted]er ce[redacted] Christensen *et al.*[12] obtained a figure of 50 per cent for the nasopharyngeal catheter at the almost intolerable flow rate of 10 liters per minute. Poulton and Adams[13] quote 26–37 per cent for the nasopharyngeal catheter and 50 per cent for the nasal cannula at 8–10 liters per minute. Catterall and Snow[14] found that the Polymask will produce an inspired oxygen concentration of 77 per cent at a flow of 8 liters per minute, but only with "constant supervision," and if "the patient keeps still"; more usually, it delivers 33 per cent oxygen at this flow rate.

Arterial Oxygen Tensions. The values for arterial P_{O_2} obtained with the "test" system, although they cannot be used to compute an accurate $A\text{–}aD_{O_2}$, do show that in the conscious human subject, exposure to two atmospheres of oxygen can produce arterial oxygen tensions close to the expected values. The suggestion that an $A\text{–}aD_{O_2}$ of several hundred millimeters of mercury exists under these circumstances has therefore been demonstrated to be false at two atmospheres absolute for the period covered by our observations.

The mean value for arterial oxygen tension is slightly higher than the mean alveolar oxygen partial pressure with the test system because the arterial sample was taken after all the alveolar samples. As pointed out in the Results section, the earlier alveolar samples tended to give lower results than the later ones, presumably due to incomplete nitrogen washout and these earlier samples lowered the final mean alveolar value.

Other Considerations in Selecting a Mask for Oxygen Therapy. The acceptability of any particular mask to the patient is of as much importance as is its efficiency. None of the volunteers in this study wore both masks, but all those who wore the mask of the "test" system said that it was comfortable and that they would be prepared to wear it for longer periods of time. On the other hand, several of the B.L.B. subjects remarked at the end of the experiment that the mask had begun to hurt at the points of maximum pressure. It is well known that the B.L.B. mask represents one of the least comfortable methods of giving oxygen,[9, 15] and, at worst, the new mask is an improvement on this.

The inspiratory pressures required to trigger the "tilt" valve are low, and so the work of ventilation is not significantly increased. In practice it has been found that the system works well at an oxygen supply pressure of 20 pounds per square inch because, at this value, both the inspiratory and expiratory pressures are low while the peak flow rate is more than adequate.

Another attribute often demanded of a clinical mask is that it should require only a minimum of supervision. The B.L.B. mask is often said to fulfil this condition, but in the present series, it was found that unless considerable and continuous attention was paid to mask fit, the efficiency of the mask became very low indeed. The "test" mask requires a little

TABLE 6. Summary of Main Results

	B.L.B.	Test System	Significance of Observed Difference
Mean alveolar oxygen partial pressure	932 mm. Hg (61%)	1,262 mm. Hg (83%)	$P < 0.001$
Mean arterial oxygen tension	845 mm. Hg (56%)	1,291 mm. Hg (85%)	$P < 0.005$

TABLE 7. Pressures Developed in the Mask During Normal Respiration with the "Test" System

Supply Line Pressure (lb./sq.in.)	10	20	30	40	50	100
Mask inspiratory pressure (cm. H_2O)	0.29	0.43	0.58	0.77	0.96	1.55
Mask expiratory pressure (cm. H_2O)	0.29	0.19	0.24	0.24	0.29	0.33

care when first applied, but thereafter it maintains a good face fit with minimal attention. An emergency spring loaded inspiratory valve can be obtained from the mask manufacturers and can be fitted to the front of the mask. With this valve in place, the patient is able to breathe air should the oxygen supply fail. The opening pressure of this valve is 1.2 to 1.6 cm. of water, and therefore, under normal circumstances, the oxygen tilt valve opens first and no dilution of oxygen by air occurs. This has been confirmed in tests carried out using a Beckman paramagnetic oxygen analyzer.

Conclusions

In this study, the efficiency of the B.L.B. mask has been found to be relatively low, in agreement with the work of Kory *et al.*[9] Therefore to attain any required arterial oxygen tension with the B.L.B. mask in a pressure chamber, the ambient pressure has to be raised excessively.

The "test" system of oxygen administration described here is not only markedly more efficient but is in practice more comfortable than is the B.L.B. mask. This "test" mask has now been in continuous clinical use in the pressure chamber in Glasgow over a period of 18 months. During this time many patients with circulatory failure, including several being treated for severe myocardial infarction, have received hyperbaric oxygen therapy by this means. Because of the very low inspiratory and expiratory pressures required, efficient oxygen administration has been achieved in these patients without in any way compromising circulatory function.

From the measurements of arterial oxygen tension, it is now clear that the use of hyperbaric oxygen at two atmospheres pressure for medical treatment is not hampered by the occurrence of a large alveolar-arterial gradient for oxygen.

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The inspiratory tilt valve can be obtained from Messrs. Normalair, Ltd., Yeovil, Somerset. The mask can be obtained from Airmed Ltd., Edinburgh Way, Harlow, Essex.

References

1. McDowall, D. G.: Anaesthesia in a pressure chamber, Anaesthesia 19: 321, 1964.
2. Bishop, J. M.: Measurement of blood oxygen tension, Proc. Roy. Soc. Med. 53: 177, 1960.
3. Severinghaus, J. W., and Bradley, A. F.: Electrodes for blood P_{O_2} and P_{CO_2} determination, J. Appl. Physiol. 13: 515, 1958.
4. Jacobson, I.: Personal Communication, 1963.
5. Sigaard-Andersen, O., Engel, K., Jorgensen, K., and Astrup, P.: A micro method for determination of *p*H, carbon dioxide tension, base excess and standard bicarbonate in capillary blood, Scand. J. Clin. Lab. Invest. 12: 172, 1960.
6. Said, S. I., and Banerjee, C. M.: Venous admixture to the pulmonary circulation in human subjects breathing 100% oxygen, J. Clin. Invest. 42: 507, 1963.
7. Ayres, S. M., Criscitiello, A., and Grabovsky, E.: Components of alveolar-arterial oxygen difference in normal man, J. Appl. Physiol. 19: 43, 1964.
8. Schmidt, C. F.: The Respiration, *In:* Medical Physiology, ed. 10, Edited by P. Bard. St. Louis, C. V. Mosby Co., 1956, p. 296.
9. Kory, R. C., Bergmann, J. C., Sweet, R. D., and Smith, J. R.: Comparative evaluation of oxygen therapy techniques, J. Amer. Med. Assoc. 179: 767, 1962.
10. Boothby, W. M., Lovelace, W. R., and Bulbulian, A. H.: Series of papers introducing B.L.B. mask, Proc. Mayo Clin. 13: 641, 1938.
11. Card, W. I., Smith, J. F., Griffiths, W. J., McSwiney, B. A., and Savage, B.: The B.L.B. mask for administering oxygen, Lancet 1: 398, 1940.
12. Christensen, E. M., Urry, A. G., and Cullen, S. C.: Alveolar and arterial oxygen contents during oropharyngeal oxygen therapy, ANESTHESIOLOGY 7: 399, 1946.
13. Poulton, E. P., and Adams, T. W.: Oxygen tents and nasal catheters, Brit. Med. J. 1: 567, 1936.
14. Catterall, M., and Snow, M.: The Polymask as a means of administering oxygen, Brit. Med. J. 1: 1254, 1960.
15. Ball, J. A. C.: Techniques of oxygen administration, Brit. J. Anaesth. 35: 441, 1963.