Papers and Originals**BEHAVIOUR OF APPARATUS FOR OXYGEN ADMINISTRATION**

BY

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Widespread recognition of the danger of producing carbon-dioxide narcosis by oxygen therapy in patients with acute respiratory failure has led to the development of apparatus designed to control the oxygen concentration given to these patients (Barach, 1950; Campbell, 1960a). This paper describes methods of determining the accuracy with which such apparatus controls the inspired-oxygen concentration. In particular, attention is drawn to the Venturi apparatus (Campbell, 1960b), but an analysis is also given of the behaviour of the Polymask, a blower system and a simple oxygen mask, both of our design.

Campbell (1960b) has pointed out that a convenient method of giving oxygen to patients with respiratory failure is to deliver an oxygen-enriched mixture through a loose-fitting mask at a high flow rate. The high-flow principle depends upon this delivery flow exceeding the peak inspiratory flow produced by the patient's breathing, so that all the inspired gas is taken from the apparatus and there is no dilution of the inspired gas by atmospheric air. The inspired-gas concentration can then be controlled independently of the patient's ventilation. If the respiratory air flow can be regarded as sinusoidal, it can be shown mathematically that the peak inspiratory flow is approximately three times the minute-volume. If the minute-volume is 10 litres per minute, or less, and if the apparatus delivers 30 l./min. or more, then the high-flow principle will apply. The Venturi mask and the blower system are intended to operate on this high-flow principle.

Description of the Devices Studied

1. The *Venturi apparatus* (Campbell, 1960b) consists of a light alloy cone, the wide end being supported loosely before the nose and lips by a perforated plastic facepiece. In the base of the cone are two orifices for the admission of oxygen, the central one being of narrow bore, through which oxygen emerges as a high-speed jet. The velocity of this jet is set by one of the calibrated gauges. By the Venturi principle this jet entrains atmospheric air through adjacent intake ports, and the resultant mixture of oxygen and air is delivered to the patient. It is claimed that an air flow of 50 l./min. is obtained when the jet is passing the calibrated 1.8 l./min. The additional wide-bore oxygen pipe in the base of the cone is used to add oxygen, which does not entrain any further air, in order to vary the oxygen concentration the patient receives. The apparatus used in these studies was supplied by Oxygenaire Ltd., and priced, with gauges, £22 1s.

2. The "*polymask*" (British Oxygen Company Ltd.) is a light polythene mask, designed to act as a reservoir of oxygen, which is fed in at one orifice at a selected flow rate. The plastic mask alone costs 2s. 3d.

3. The *blower system* was developed by us to deliver accurately known concentrations of oxygen to patients with respiratory failure (Hutchison, Flenley, and Donald, 1963). A 3-in. (7.5-cm.) four-bladed electrical axial blower directed atmospheric air into a metal box of 43 l. capacity (Fig. 1). A known flow rate of oxygen was delivered into one corner

of this box and the resultant mixture of oxygen and air was led to the patient by 1-in. (2.5-cm.) bore respiratory tubing. The mixture was delivered to the patient through one orifice of an aviator's oro-nasal mask, with two other orifices open to the atmosphere. A calibration graph was established by plotting the oxygen concentration in the exit pipe against the flow rate of oxygen entering the box, the mixture being delivered to the patient at approximately 30 l./min.

FIG. 1.—Diagram of authors' blower system.

4. The *authors' oxygen mask* consists of a loose-fitting plastic facepiece with a 2-in. (5-cm.) diameter orifice opening to the atmosphere (Fig. 2). Into the centre of this orifice projects an oxygen-delivery tube, which delivers the desired flow rate of oxygen at right angles to the air movement caused by the patient's ventilation. This mask is designed to ensure that the inspired-air stream from the atmosphere will dilute the administered flow of oxygen. The resulting inspired-oxygen concentration will therefore be dependent on the patient's minute-volume of ventilation. This concentration will rise as the ventilation falls if the administered oxygen flow rate remains constant. The mask, therefore, is *not designed to operate on the high-flow principle*. The oxygen delivery tube is not directed towards the subject's face but at right angles to the inspired-air stream, and by this means the mask is intended to provide an inspired-oxygen concentration which is relatively uninfluenced by the position of the mask on the subject. This mask is referred to throughout as the authors' mask.

FIG. 2.—Diagram of authors' oxygen mask.

Methods

Measurement of oxygen concentration was carried out with a Clark oxygen electrode (Bishop, 1960). The method

was calibrated against the Scholander (1947) method, and the results are displayed graphically in Fig. 3.

FIG. 3.—Calibration graph of the oxygen concentration determined polarographically against the Scholander method.

Experiments with Oxygen Apparatus

1. Sampling of Inspired Gas at Mouth

Sampling of the inspired gas at the mouth was carried out with each apparatus tested. A fine polythene catheter was taped to the cheek of the seated subject, the tip of the catheter lying close to the incisor teeth. Gas samples were taken into mercury tonometers as oxygen was given by the apparatus under test. About 4 ml. of gas was taken towards the end of each inspiration, and repeated over 16 to 20 successive breaths. Samples were taken over the third and sixth minutes after the oxygen flow rate was changed. The samples were analysed for oxygen with the Clark cell, and for carbon dioxide by the Scholander method.

2. Model of the Respiratory System

A model of the respiratory system was used to study the effects on the inspired oxygen concentration of changes in ventilation and in the position of the apparatus. The model (Fig. 4) consisted of a Starling sine-wave pump,

FIG. 4.—Diagram of the dynamic model of the respiratory system, showing the test position of the Venturi apparatus.

which "breathed" in and out of a "trachea" consisting of a tube 2.5 cm. wide and 15.4 cm. long. The trachea opened to the atmosphere at a circular "mouth" in a flat board. Gas samples were taken from the lower end of the "trachea," during inspiration only, over 15 to 20 successive cycles, as in the previous experiments. The "tidal volume" was changed by changing the stroke volume of the Starling pump, and the rate, or breathing frequency, was also independently variable.

In the case of the Venturi apparatus the plastic mask was removed and the alloy cone centred over the "mouth," leaving an annular gap of 0.8 cm. between the cone and the board. The annular gap was approximately equal in area to the holes in the mask when the Venturi apparatus was in position on a patient. It is stressed that the cone was fixed rigidly in this position.

The blower system, polymask, and authors' mask were studied by attaching the facepiece of the apparatus to a plasticene "face" which was built up on the flat board.

In the experiments with the Venturi apparatus the high-velocity jet was adjusted to 1.8 l. of oxygen per minute on the gauge provided, this being the recommended therapeutic setting. No oxygen was added through the second oxygen pipe, and according to the calibration marked on the gauge the apparatus should have given an inspired-oxygen concentration of 23% at these settings. The flow rate through the high-velocity jet was, in fact, found to be 2.1–2.3 l./min. when the gauge was set to 1.8 l./min. This flow-rate was measured on a Benedict-Roth spirometer, and was checked frequently throughout the experiments. The inspiratory "tracheal" oxygen concentration was measured at various levels of ventilation. In the case of the Venturi apparatus this ventilation change was at first produced by changing the stroke volume, with a constant rate, and then by changing the rate with a constant stroke volume. This latter procedure was used alone in the experiments with the blower system, polymask, and authors' mask.

The effects of moving the position of the apparatus with respect to the mouth was also studied with the Venturi apparatus. The stroke volume and rate were kept constant, and the cone was offset laterally by 0.5 cm. (position 2), 1 cm. (position 3), and 1.5 cm. (position 4), position 1 being when the cone was central. The annular gap, separating the edge of the cone and the board, was kept at 0.8 cm. "Tracheal" oxygen concentration was measured in the usual way.

Measurements were made of the tracheal oxygen concentration produced by closing the air-intake ports of the Venturi apparatus, at two stroke volumes (0.5 l. and 0.3 l.) and at a constant rate of 15/min.

A study of the effects of position on the tracheal oxygen concentration was made with the authors' mask. Comparisons with the central position were made when the mask was offset 4 cm. laterally, and in addition a leak of 4 sq. cm. in area was introduced between the mask and the plasticene face.

Steady-flow studies of the Venturi apparatus were undertaken, in order to determine the actual air flow entrained by the Venturi jet under optimal conditions. Two methods were used—one based on dilution, and one on direct measurements with a thermistor anemometer.

3. Dilution Method

The dilution method relied upon calculation of the entrained air flow from a mixing equation. The Venturi cone was closely sealed to one end of a 10-cm. iron pipe 180 cm. long. The rate of oxygen flow through the jet

was kept constant, and samples were taken from a tube projecting into the distal end of the pipe. Sampling was carried out after one hour from both the centre and the edge of the pipe, and was repeated until successive samples at 10-minute intervals showed identical concentrations. It was then assumed that an equilibrium was established, this being confirmed if the concentration in the edge and central samples was the same. A simple mixing equation then gave the air flow entrained for that particular oxygen flow through the jet.

4. Thermistor Anemometer

A thermistor anemometer was used to supplement the above measurements at low levels of oxygen flow through the jet, such as were recommended for therapeutic use. At these low levels complete mixing in the pipe did not occur, and the dilution method was invalid. A method of directly measuring the air flow across the Venturi intake ports was therefore devised, using a thermistor (Type M15, Standard Telephones and Cables Ltd.), which is a flat disk of 12.5 sq. mm. area. This disk is suspended in the plane of one of the four Venturi air-intake ports by means of the fine electrical leads. The area of one Venturi intake port is 95 sq. mm., and thus the thermistor disk occupies 3% of the total cross-sectional area available for air flow at all four ports. The anemometer is calibrated by drawing ambient air at a known rate through the air-intake ports, the position of the thermistor being unaltered. By this means the obstruction to air flow is the same under calibration conditions as during measurements (Fig. 5).

FIG. 5.—Venturi apparatus. Diagram of the method of calibrating the thermistor anemometer (see text).

The thermistor is used as one arm of a Wheatstone bridge, supplied by a stabilized 100 volts, D.C., the other bridge resistors being so chosen that enough current passes through the thermistor to raise its temperature. In still air the thermistor loses heat slowly, but in a moving air stream heat is lost more rapidly, and the temperature, and therefore the resistance, of the thermistor is a function of the linear velocity of the passing air stream. The bridge is so adjusted that the balancing galvanometer reads zero when the thermistor is in still air, but the galvanometer deflection is a function of the linear velocity of air flow past the thermistor. The large thermal time constant (11.4 sec.) of the thermistor chosen renders this instrument mainly an indicator of mean flow. The galvanometer reading was taken at each of several known flow rates of oxygen through the Venturi jet. Three different examples of the Venturi apparatus were tested, a calibration curve being set up for each one.

5. Authors' Oxygen Mask and Human Tonometry

A study of this oxygen mask by human tonometry was carried out to determine the inspired-oxygen concentrations

produced by this apparatus in practice. Eight patients (three emphysema, two primary polycythaemia, one congestive heart failure, one cirrhosis, one normal) were studied. They breathed air and then two known levels of oxygen delivered by the blower system previously described. Each oxygen mixture was given for a period of 20 minutes; an arterial blood sample was taken at the end of this period and the oxygen tension determined polarographically. By this means a graph of the inspired-oxygen concentration versus the arterial-oxygen tension was established for each patient. Immediately following on these "calibration" periods, oxygen was administered by the authors' mask, at a constant flow, for three 20-minute periods. Flows of 0.5, 1, and 2 l./min. were used, and the arterial-oxygen tension was measured at the end of each 20-minute period. These values of arterial-oxygen tension were then used to interpolate on the above graph, and the inspired-oxygen concentrations given by the authors' mask were thus determined.

Results

Sampling of the Inspired Gas at the Mouth

The results are shown in Tables I–IV. The scatter of the oxygen concentrations increased from a standard deviation of 0.7%–0.9% with the blower system, to 1.5%–2.8% with the Venturi apparatus, and to about 7% with the polymask and authors' mask.

1. *Venturi Apparatus*.—The data in Table I and in Fig. 6 show that the Venturi apparatus has a systematic error, as the gauge-setting at "23%" produced a mean concentration of 27.0% in the inspiratory samples taken from the mouth. When the gauge-settings were increased to "25%,"

TABLE I.—Venturi Mask. Mouth Sampling

Predicted O ₂ Concentration (%)	Observed O ₂ Concentration (%)		
	Mean	S.D.	No.
23	27.0	1.5	10
25	31.8	2.8	6
27	31.6	2.7	6
29	33.8	2.3	12
31	33.6	2.2	10
33	31.8		2

FIG. 6.—Venturi apparatus. O₂ concentration in inspiratory samples from the mouth at various predicted concentrations from the Venturi gauge (see text).

thereby adding some oxygen through the wide-bore orifice (which does not entrain any further air by the Venturi effect), the oxygen concentration increased to a mean of 31.8%, and there was no significant increase in oxygen concentration when the gauge settings were increased to "27%," "29%," "31%," and "33%." It therefore follows that the oxygen concentration of a sample taken from the mouth during inspiration, when using the model of the Venturi apparatus tested, is likely to be between 25% and 29%, if the gauge is set to 23%. A similar sample taken at any gauge-setting between "25%" and "33%" is likely to have an oxygen concentration anywhere between 29% and 35%. Carbon dioxide concentrations in these samples ranged from 0.2% to 0.6%, with a mean of 0.3%.

2. The *polymask* (Table II) provided a concentration of oxygen from 40.1% at 2 l. of oxygen per minute to 60.6% at 6 l./min., but this concentration had a large random variation of up to 7.5%.

TABLE II.—*Polymask. Mouth Sampling*

Oxygen Flow (l./min.)	Observed O ₂ Concentration (%)		
	Mean	S.D.	No.
2	40.1	6.4	8
4	54.6	7.5	8
6	60.6	7.2	8

3. The *blower system* can control the inspiratory oxygen concentration at the mouth to a predicted level within one standard deviation of 0.9%. This applies to the range 20.9% to 35% (Table III).

TABLE III.—*Blower System. Mouth Sampling*

Predicted O ₂ Concentration (%)	Oxygen Flow (l./min.)	Actual O ₂ Concentration (%)		
		Mean	S.D.	No.
25	5	24.5	0.7	15
30	12	29.8	0.7	15
35	19	35.1	0.9	10

4. The *authors' mask* produced a rise in oxygen concentration of these inspiratory samples from a mean of 23.4% at 0.5 l. of oxygen per minute, to a mean of 35.2% at 3 l./min. (Table IV). This can be contrasted with the

TABLE IV.—*Authors' Mask. Mouth Sampling*

Oxygen Flow (l./min.)	Actual O ₂ Concentration (%)		
	Mean	S.D.	No.
0.5	23.4	1.6	30
1.0	27.4	4.1	31
2.0	29.9	7.7	32
3.0	35.2	5.8	12

Venturi apparatus, where an increase in gauge-settings above "25%" did not significantly increase the oxygen concentration in mouth samples.

Studies with the Model of the Respiratory System

The effects of changes in ventilation, studied in this way, are shown in Tables V–IX, and in Fig. 7.

1. *Venturi Apparatus*.—In the first pair of experiments (Table V; Fig. 7), the minute-volume was altered by changing the stroke volume and keeping the rate constant. A decrease in the minute-volume from 7.5 l./min. (15 times 0.5 l./min.) to 3 l./min. (15 times 0.2 l./min.) led to a rise in the tracheal oxygen concentration from 31.0% to 34.0%, and from 34.5% to 37.4% in the duplicate experiment. In the second pair of experiments (Table VI; Fig. 7) the minute-volume was altered by changing the

TABLE V.—*Venturi Mask, Dynamic Model. Ventilation Change by Variation of Stroke Volume*

Oxygen Flow (l./min.)	Predicted Oxygen Conc. (%)	Pump			Tracheal O ₂ Conc. (%)		
		Stroke (l.)	Rate (cycles/min.)	Minute-vol. (l./min.)	Mean	S.D.	No.
2.1	23	0.2	15	3.0	34.0	0.7	4
	23	0.3	15	4.5	32.9	0.2	4
	23	0.5	15	7.5	31.0	0.5	4
2.2	23	0.2	15	3.0	37.4	0.2	4
	23	0.3	15	4.5	37.1	0.4	4
	23	0.5	15	7.5	34.5	1.2	4

FIG. 7.—Venturi apparatus. O₂ concentration in tracheal samples from the dynamic model at various stroke volumes (top) and rates of "breathing" (bottom) (see text).

TABLE VI.—*Venturi Mask, Dynamic Model. Ventilation Change by Variation of Rate*

Oxygen Flow (l./min.)	Predicted Oxygen Conc. (%)	Pump			Tracheal O ₂ Conc. (%)		
		Stroke (l.)	Rate (cycles/min.)	Minute-vol. (l./min.)	Mean	S.D.	No.
2.2	23	0.5	10	5.0	35.3	0.7	4
	23	0.5	15	7.5	34.9	0.5	4
	23	0.5	27	13.5	30.8	1.1	4
2.2	23	0.5	10	5.0	35.2	0.4	4
	23	0.5	15	7.5	33.5	0.9	4
	23	0.5	27	13.5	30.1	0.1	4

rate while the stroke volume remained constant. A decrease in minute-volume from 13.5 l./min. (27 times 0.5 l./min.) to 5 l./min. (10 times 0.5 l./min.) led to a rise in tracheal oxygen concentration from 30.8% to 35.3%, and 30.1% to 35.2% in the duplicate experiment. It will be noted that there was a difference in absolute oxygen concentration obtained in duplicate experiments. This probably arose from differences in position of the Venturi jet, which was set up afresh for each experiment. As shown later, the concentrations obtained with the Venturi apparatus were extremely sensitive to positional change. The results suggest that the Venturi apparatus does not operate on the high-flow principle under these conditions, for the oxygen concentration was influenced by changes in ventilation.

2. The *polymask* produced a high tracheal concentration (76.5%–79.9%), which was relatively insensitive to changes in ventilation from 3.8 to 5.3 l./min. (Table VII).

TABLE VII.—*Polymask, Dynamic Model. Ventilation Change*

Oxygen Flow (l./min.)	Pump			Tracheal O ₂ Conc. (%)	
	Rate (cycles/min.)	Tidal Vol. (l.)	Minute-vol. (l.)	Mean	No.
6	15	0.25	3.8	79.9	2
6	21	0.25	5.3	76.5	2

3. The blower system gave a tracheal oxygen concentration which changed by only 0.5% when the minute-volume increased from 3.8 to 8 l./min. (Table VIII). This confirms the suggestion that this apparatus does operate on the high-flow principle, within this range of ventilation.

TABLE VIII.—*Blower System, Dynamic Model. Ventilation Change*

Pre-dicted O ₂ Conc. (%)	Oxygen Flow (l./min.)	Pump			Tracheal O ₂ Conc. (%)		
		Rate (cycles/min.)	Tidal Vol. (l.)	Minute-vol. (l./min.)	Mean	S.D.	No.
30	12	15	0.25	3.8	29.2	0.2	4
30	12	22	0.25	5.5	29.1	0.1	4
30	12	32	0.25	8.0	28.7	0.0	4

4. Our own mask gave an oxygen concentration which was sensitive to ventilatory changes. A rise in ventilation from 2.5 to 6.8 l./min. caused a fall in tracheal oxygen concentration from 29.9% to 24.3% when an oxygen flow of 0.5 l./min. was given (Table IX). The same increase in

TABLE IX.—*Authors' Mask, Dynamic Model. Ventilation Change*

Oxygen Flow (l./min.)	Pump			Tracheal O ₂ Conc. (%)		
	Rate (cycles/min.)	Tidal Vol. (l.)	Minute-vol. (l./min.)	Mean	S.D.	No.
0.5	10	0.25	2.5	29.9	0.1	4
	18	0.25	4.5	26.2	0.1	4
	21	0.25	5.2	24.9	0.3	4
	27	0.25	6.8	24.3	0.1	4
1.0	10	0.25	2.5	36.2	0.8	4
	18	0.25	4.5	28.3	0.8	4
	21	0.25	5.2	27.8	0.3	4
	27	0.25	6.8	27.3	0.1	4
2.0	10	0.25	2.5	48.3	1.1	4
	18	0.25	4.5	35.5	0.4	4
	21	0.25	5.2	35.4	0.4	4
	27	0.25	6.8	33.4	1.1	4

ventilation when 2 l. of oxygen per minute was given lowered the tracheal oxygen concentration from 48.3% to 33.4%. These are significant differences.

5. The effects of changes in position of the Venturi apparatus and the authors' mask were also studied. The results with the Venturi apparatus are given in Table X and Fig. 8. A positional change of 0.5 cm. laterally lowered

TABLE X.—*Venturi Mask, Dynamic Model. Positional Change*

Oxygen Flow (l./min.)	Predicted Oxygen Conc. (%)	Pump Min. Vol. (l./min.)	Position of Cone with Respect to "Face"	Tracheal O ₂ Conc. (%)		
				Mean	S.D.	No.
2.2	23	7.5	1. Centred	30.4	0.5	4
	23	7.5	2. Offset 0.5 cm.	26.0	0.3	4
	23	7.5	3. " 1.0 "	24.1	0.1	4
	23	7.5	4. " 1.5 "	23.2	0.1	4
2.1	23	7.5	1. Centred	35.4	1.3	4
	23	7.5	2. Offset 0.5 cm.	34.8	1.0	4
	23	7.5	3. " 1.0 "	27.7	0.3	4
	23	7.5	4. " 1.5 "	26.3	0.1	4

the tracheal oxygen concentration from 30.4% to 26.0%—a significant difference. A lateral shift from 0.5 cm. to 1 cm. caused a fall in concentration from 34.8% to 27.7% in a duplicate experiment. The marked sensitivity to position shown by the Venturi apparatus may account for some of the scatter in inspiratory samples from the mouth, as it is impossible to position the mask on the face with an

accuracy of more than 1–2 cm., and this position inevitably changes during use.

The authors' mask gave a tracheal oxygen concentration which was less sensitive to positional change. With a fixed ventilation of 5.5 l./min. there was no significant difference in tracheal oxygen concentration when the mask was offset laterally by 4 cm. (Table XI). As the oxygen supply is

FIG. 8.—Venturi apparatus. O₂ concentration in tracheal samples from the dynamic model as the position of the mask was changed (see text). Ventilation, 7.5 l./min.

TABLE XI.—*Authors' Mask, Dynamic Model. Position and/or Leak*

Pump Min.-vol. (l./min.)	Position and Leak	Oxygen Flow (l./min.)	Tracheal O ₂ Conc. (%)		
			Mean	S.D.	No.
5.5	Central. No leak	0.5	24.9	0.3	4
		1.0	27.8	0.3	4
		2.0	35.4	0.4	4
		3.0	39.6	0.7	4
5.5	Central. Leak 4 sq. cm.	0.5	24.7	0.1	4
		1.0	27.1	0.7	4
		2.0	32.8	0.5	4
		3.0	39.3	0.4	4
5.5	Offset 4 cm. Leak 4 sq. cm.	0.5	24.2	0.4	4
		1.0	29.5	0.6	4
		2.0	35.8	0.5	4
		3.0	38.8	0.5	4

delivered at right angles to the inspiratory air stream, and is not directed towards the face as a high-velocity jet, as is the case with the Venturi apparatus, this lack of sensitivity to position can be predicted from the design.

Amount of Air Entrained by the Venturi Apparatus

The results presented so far suggest that the Venturi apparatus does not operate on the high-flow principle, in that the amount of gas delivered to the patient is not sufficient to maintain a constant oxygen concentration in the face of a changing air stream. This suggestion is supported by the results in Table XII, where it is seen that completely closing the air-intake ports caused a rise in tracheal oxygen concentration only from 32.4% to 34.1% at a ventilation of 4.5 l./min. and a rise from 32.5% to 34.3% at a ventila-

TABLE XII.—*Venturi Mask, Dynamic Model. Effect of Opening or Closing Air-intake Ports*

Min.-vol. (l./min.)	Tracheal O ₂ Conc. (%)					
	Ports Open			Ports Closed		
	Mean	S.D.	No.	Mean	S.D.	No.
4.5	32.4	0.4	4	34.1	0.6	4
	32.5	0.5	4	34.3	0.6	4

tion of 7.5 l./min. Although these differences are significant, the small amount of the increase suggests that air entrained through these intake ports, by the Venturi effect, plays only a small part in determining the inspired-oxygen concentration.

1. The dilution method gave results which support this view. Table XIII shows that when the flow of oxygen

TABLE XIII.—Venturi Mask. Steady-flow Study. Dilution Method

Jet Flow O ₂ (l. min.)	Entrained Air Flow (l. min.)	O ₂ Concentration (%)
3.2	18	32.8
3.7	21	32.9
4.3	24	33.1
5.4	29	33.4
5.7	31	33.2
6.0	31	34.1

through the Venturi jet was 3.2 l./min., 18 l./min. was entrained into the pipe, and this entrained flow rose to 31 l./min. when the jet flow was 6 l./min. These results were obtained with the third example (model 3) of the Venturi apparatus which was available for testing, and they are not applicable to the Venturi apparatus when used therapeutically, as the gauge is calibrated for a flow through the jet of only 1.8 l. of oxygen per minute. Higher velocities, in any case, become increasingly unpleasant for the patient.

2. The thermistor anemometer was used to measure the entrained flow produced by the lower rates of flow through the jet, of the order of those used therapeutically. Table XIV and Fig. 9 show the results of these measurements. At the recommended therapeutic flow rate of 1.8 l./min., the first model of the Venturi apparatus tested entrained about 3.5 l. of air per minute, the second model entrained about 6.8 l./min., and the third entrained 8.5 l./min. This last model was used in the dilution study. These measurements represent the maximal flow of entrained air

TABLE XIV.—Venturi Mask. Steady-flow Study. Thermistor Anemometer

Model 1		Model 2		Model 3	
Jet Flow O ₂ (l./min.)	Entrained Flow (l./min.)	Jet Flow O ₂ (l./min.)	Entrained Flow (l./min.)	Jet Flow O ₂ (l./min.)	Entrained Flow (l./min.)
1.2	2.6	1.1	3.8	0.9	4.4
1.3	2.7	1.5	4.2	1.2	5.3
				1.6	8.2
1.9	3.5	1.7	5.8	1.7	8.4
2.1	3.7	2.0	6.8	1.8	8.5
2.2	4.3	2.2	7.8		
2.4	4.5	2.5	8.0	1.9	9.5
2.6	6.2	3.0	11.0	1.9	10.7
3.3	6.8	4.0	14.2	2.0	11.5
3.4	8.0	4.1	14.6	2.1	12.8
5.2	10.5	4.6	16.6	2.2	13.0
6.1	13.0	5.2	19.0	2.9	15.5

FIG. 9.—Venturi apparatus. The entrained air flow at various rates of flow of oxygen through the high-velocity orifice, determined by the thermistor anemometer, and calibration curves for the anemometer (see text).

by these three examples of the Venturi apparatus, as the measurements were made without any obstruction to the jet stream. In practical use, the patient's face would provide some obstruction, and the device is stated to be very sensitive to such obstruction (Campbell, 1960b). The Venturi apparatus does not, therefore, operate on the high-flow principle, as three examples of the commercially available apparatus entrain less than 10 l. of air per minute under conditions where it is claimed to entrain 50 l./min. It therefore follows that at any ventilation rate above 3 l./min. the oxygen concentration delivered by the Venturi apparatus will be dependent upon the patient's ventilation.

Human Tonometry

The authors' mask was the only apparatus studied by this method. The results are shown in Table XV. For an

TABLE XV.—Authors' Mask. Human Tonometry

Oxygen Flow (l./min.)	Interpolated O ₂ Conc. (%)		
	Mean	S.D.	No.
0.5	23.8	1.6	8
1.0	26.3	2.0	8
2.0	28.8	1.8	5

oxygen flow rate of 0.5 l./min. the mean inspired oxygen concentration was 23.8%, rising to 26.3% at 1 l./min., and to 28.8% at 2 l./min. These results do not differ significantly from those obtained by sampling the inspiratory gas at the mouth (Table IV), although they show much less scatter about the mean. It therefore appears probable that if 0.5 l. of oxygen per minute is given by the authors' mask the inspired oxygen concentration will lie between 22% and 26%, that for 1 l. of oxygen per minute the concentration will be from 24% to 28%, and for 2 l. of oxygen per minute it will be between 27% and 31%.

Discussion

The methods employed will be discussed separately from the results obtained with the four types of apparatus.

Methods

Variations in the oxygen concentration of inspiratory samples from the mouth could presumably arise from two sources. In the first place the gas stream at this site could be incompletely mixed, and thus the measured concentration would not determine the true inspiratory concentration. In the second place, variations due to changes in ventilation and position cannot be assessed by this method. The increase in standard deviation of the concentrations, from 0.9% with the blower system to 2.8% with the Venturi apparatus, to 7.5% with the polymask, and to 7.7% with the authors' mask, suggests that the blower system provides a mixed gas stream at the mouth uninfluenced by ventilation, but that the Venturi apparatus gives a mouth concentration which is slightly sensitive to ventilation or position. However, these effects are much more marked with the polymask and authors' mask.

Kory *et al.* (1962) also found a wide scatter in the oxygen concentration of inspiratory samples taken from the region between the upper lip and the nose. These authors used end-expiratory samples to indicate alveolar gas tensions. In the present study it was not possible to take such samples without holding of the breath as the mask was removed, and this would have invalidated the results.

The model of the respiratory system was developed to study the effects of ventilatory changes and of position of

the apparatus. The model has no pretence to be an accurate substitute for the human respiratory system, for oxygen is not absorbed, carbon dioxide is not evolved, and there is no analogy to the capacity element of the lungs. It is not claimed that "tracheal" samples represent the actual inspired oxygen concentrations which would be obtained in a patient with the same ventilation. It is claimed, however, that the model does demonstrate how changes in ventilation and position of the apparatus will affect the inspired-oxygen concentration. Cooper (1960) used a sinusoidal air flow from a pump to measure the work of breathing with closed-circuit mine-rescue apparatus, and found very similar results with either the pump or the patient breathing through the apparatus.

The Venturi apparatus posed a specific problem in the measurements of the entrained air flow. The dilution method, where gas from the apparatus was directed into an iron pipe, was not applicable at low rates of oxygen flow, particularly at the therapeutic level of 1.8 l./min., since complete mixing did not occur. The thermistor anemometer enabled these low rates of air flow to be directly measured. The calibration was carried out with the ambient air flowing in the same direction, as in the actual measurements. This instrument measured the entrained flow under optimal conditions with no obstruction to the jet.

The method of human tonometry is tedious and requires arterial puncture. The method requires that the arterial oxygen tension at a given inspired oxygen concentration will remain constant during the study. This will occur if the total ventilation, the alveolar-arterial oxygen tension gradient, and the respiratory quotient (R.Q.) remain constant. The expired air could not be collected when the subject was using any of the apparatus investigated, and therefore the ventilation and R.Q. could not be measured. As the subjects were seated comfortably throughout the experimental period of two hours, and the studies were carried out at least one hour after a meal, it seems reasonable to assume that the ventilation and R.Q. remained relatively constant. The method will be most accurate in the normal subject, in whom the physiological venous admixture is small; for if this rises, as in emphysema, the arterial oxygen tension becomes less sensitive to changes in inspired-oxygen concentration.

Results of Tests of Oxygen Apparatus

The results obtained by inspiratory sampling from the mouth and with the model of the respiratory system both show that the Venturi apparatus gives a consistently higher oxygen concentration than the gauges indicate. This arises from the fact that the device does not entrain 50 l. of air per minute, as claimed by the makers, and in the description of the prototype (Campbell, 1960b). No information is given on how this flow rate was measured. The present results, using the thermistor anemometer, show that the three examples of the apparatus tested all entrained less than 10 litres of air per minute under optimal conditions.

It follows that the Venturi apparatus does not obey the "high-flow principle," and thus the inspired oxygen concentration increases as the ventilation falls. Minor variations in position of the apparatus, which would be inevitable in practice, produce striking changes in the inspired-oxygen concentration. This may be due to the high-velocity jet remaining as a discrete stream for some distance, as the velocity is not high enough to exceed Reynolds's number, and thus turbulent air flow and mixing is not produced.

It must therefore be concluded that the Venturi apparatus does not fulfil the maker's claim "to provide effective inspired-oxygen concentrations which can be accurately controlled to within $\pm 1\%$."

The polymask was shown to give high oxygen concentrations, and, not surprisingly, these are little influenced by ventilatory changes, as the mask has an oxygen reservoir. Catterall and Snow (1960) have shown that the concentration of oxygen from the polymask is very dependent upon correct positioning of the mask on the face. The apparatus is not therefore suitable for accurate control of the inspired-oxygen concentration. It may, in fact, fortuitously provide a low concentration of oxygen in patients with respiratory failure, as it is readily dislodged from the "correct" position in use.

The investigations of the blower system, by inspiratory sampling from the mouth or by using the respiratory model, show that it is capable of controlling the inspired-oxygen concentration within one standard deviation of 0.9%, independently of the patient's ventilation, provided this does not exceed 10 l./min. or thereabouts. The blower was silent enough to be used in a public ward at night, and as it was used with an aviator's mask and head harness the position of the mask was fairly constant. The device could be made less cumbersome by reducing the size of the mixing chamber (at present 43 l.).

The authors' mask is intended to cause the inspiratory breath to dilute a given flow of oxygen, and therefore the concentration delivered is dependent upon the size of this breath or, in other words, on the minute volume. In this respect the apparatus is similar to the Venturi apparatus, but wider variation in oxygen concentration (23%–40%) can be obtained by control of the amount of oxygen entering the mask. The lower concentrations in this range cannot be obtained with the Venturi apparatus with any certainty. The inspired-oxygen concentration obtained from the authors' mask is much less dependent on the position of the mask than is that produced by the Venturi apparatus. The mask appears capable of providing the same order of control of the inspired-oxygen concentration, and as no specialized gauges are required other than a simple rotameter, it should be much cheaper than the Venturi apparatus. It must be emphasized, however, that the authors' mask does produce an inspired-oxygen concentration which is sensitive to changes in ventilation.

The level of accuracy with which the inspired-oxygen concentration should be controlled in the treatment of acute respiratory failure is unknown. Campbell (1960a) suggests that the required level is $\pm 1\%$, but in a separate study (Hutchison, Flenley, and Donald, 1963) it is suggested that an accuracy of about 5% is required, in the range 21%–40%. Until further detailed studies of patients suffering from acute respiratory failure are available this matter will not be fully resolved.

Summary

The modern conservative management of respiratory failure depends upon control of the inspired-oxygen concentration. Methods are described for testing the performance of apparatus for this purpose. By using these methods the Venturi apparatus is found to be capable of controlling the inspired-oxygen concentration to within a standard deviation of 5%, in the range 21% to 35%. The reasons for this limit of control are discussed, and it is shown that the oxygen concentration from the Venturi apparatus is dependent on the patient's ventilation and on the position of the mask on the patient's face. The polymask is shown to give high inspired-oxygen concentrations, but is unsuit-

able for accurate control in the range 21%–40%. An electrical blower system is shown to be capable of controlling the inspired-oxygen concentration with one standard deviation of 0.9% if the ventilation is less than 10 litres per minute. A simple oxygen mask of our design (authors' mask) is described, and shown to be capable of controlling the inspired-oxygen concentration with the same accuracy as the Venturi apparatus. This authors' mask should be very much cheaper than the Venturi apparatus.

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EXPERIMENTAL CLINIC FOR PREVENTING CHRONIC BRONCHITIS

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"It is shameful to the health services of Britain that this disease should be so prominent as a cause of sickness and death, and that comparatively little should have been done to remedy matters" (*B.M.J.*, 1963).

In the past 30 years the pattern of mortality from pulmonary tuberculosis, pneumonia, and lung cancer has changed. However, every year chronic bronchitis has killed more than any of the above diseases (Registrar-General, 1962), and has been a major cause of morbidity and misery.

Clinical experience indicates the importance of both chronic irritation, by air pollution and cigarette smoke, and recurrent or chronic infection in causing disability in the bronchitic. Confirmatory evidence of this has been obtained from patients' histories in epidemiological surveys (Higgins, 1959; Olsen and Gilson, 1960), from the study of sickness-absence records (Fairbairn and Reid, 1958), and pathological studies (Reid, 1958). Disability, once established, is usually permanent and progressive.

In the management of patients with chronic bronchitis all practicable measures to reduce respiratory irritation and infection are usually undertaken, but these measures are seldom applied until irreversible disease is well advanced.

In October, 1960, an experimental clinic was established at the Pound Lane Health Centre, Willesden. It aimed to attract those in the earliest stages of chronic bronchitis and to attempt to stop or slow down the progress of the condition by the application of measures usually reserved for patients with advanced disease. The clinic had the active support of a local hospital, a chest clinic, the public health service, and a number of general practitioners. This paper describes its work and a follow-up of patients attending during the first two years. Ultimately the value of such a clinic can be measured only by a careful follow-up of those attending over many years. In the meantime the acceptability of the clinic by patients, the extent to which they act on the advice given, and the changes in symptoms over a short period give some indication of its potential value.

Description of Clinic

The principal aims of the clinic included attempts to (1) reduce irritation of the respiratory tract by helping patients to stop smoking and teaching them practical steps to reduce the damage done by air pollution; (2) combat

infection by the use of influenza vaccine and antibiotics; and (3) teach them to breathe better by daily exercises. At the same time general instruction and discussion on any matter relating to health were included.

For purposes of assessment the Medical Research Council (1960) Questionnaire on Respiratory Symptoms was completed on each patient and the forced expiratory volume (F.E.V.₁) measured. No physical examination was undertaken and no attempt made to take over the management of the individual patient.

The clinic differed in two important respects from the accepted pattern of general-practitioner consultation or hospital out-patient attendance. Changing of habits was considered more important than dispensing of drugs, and patients were not necessarily ill or disabled. The clinic therefore had to be run at a time, at a place, and in a manner that would attract the patients for whom it was designed.

The most suitable time was found to be from 7 to 9 p.m. The clinic was held in a new local authority health centre. The facilities were excellent, but the absence of a porter, receptionist, or telephonist on duty in the evenings sometimes made the management of the clinic difficult.

It was decided to see the patients as a group, of 10 to 20, rather than individually. In this way each patient was actively involved for the whole two hours on each evening, and advantage could be taken of the group situation to stimulate discussion. This in turn helped to disguise the educative function of the clinic by creating a social atmosphere. With some objectives, such as stopping smoking, competition between individuals could be usefully aroused.

On the first evening all patients were given an introductory talk on chronic bronchitis, its symptoms, natural history, and what is known of its aetiology, and breathing exercises were started. A questionnaire on respiratory symptoms was completed and F.E.V.₁ measured. Before leaving, the patients were given a bottle in which to bring a specimen of sputum on their next visit.

The routine for subsequent sessions was to start with three-quarters of an hour of physiotherapy. The aims were to mobilize the chest and shoulders, to encourage abdominal breathing with emphasis on expiration, and to improve posture and teach relaxation. Breathing exercises to develop both lower costal and diaphragmatic breathing