Actual Tracheal Oxygen Concentrations with Commonly Used Oxygen Equipment

ROBERT L. GIBSON, M.D.,* PAUL B. COMER, M.D.,* RICHARD W. BECKHAM, B.S.,† C. P. MCGRAW, PH.D.‡

Supplemental oxygen is administered to spontaneously breathing patients by various techniques. Some methods, such as nasal prongs attached to a flowmeter, are simple. Clearly, under these circumstances the $F_{I_{O_2}}$ can only be crudely estimated, although numerous textbooks[1-5] offer speculations about the actual values.

Other methods are more complicated. For example, Venturi-type masks or nebulizers are designed to deliver a known concentration of O_2 to the patient. It is not always appreciated that with such devices the percentage of O_2 being inspired may not be the same as that being delivered. In other words, actual tracheal concentrations achieved by the spontaneously breathing patient may be considerably lower than the mask or nebulizer settings.

In this study, we measured the highest concentrations of O_2 actually reaching the trachea during the inspiratory phase of ventilation with commonly used equipment, and assessed the effects of different patterns of breathing on those concentrations.

METHODS

A sensing catheter was placed percutaneously via the cricothyroid membrane into the trachea of each of two healthy, trained subjects. While each breathed spontaneously, absolute tracheal O_2 concentrations were measured with a mass spectrometer§ that samples at a rate of 2 ml/sec and discriminates with less than a ±2 per cent error within the calibrated range (0–100 per cent for O_2, 0–10 per cent for CO_2). The output signals were recorded on a Grass Polygraph.¶

A Gaensler-Collins Double Spirometer** was used intermittently to record tidal volumes ($\bar{V}_T$), respiratory frequency (f), and minute ventilation ($\dot{V}_E$), and to calculate peak inspiratory flow rates ($\dot{V}_I$). Standard wall O_2 flowmeters and Ohio Deluxe Nebulizers†† were used as required. Nasal prongs, nasopharyngeal catheters, ordinary and Venturi-type face masks, face tents, and various combinations of these devices were tested with various O_2 flowmeter settings.

In addition, two or three different breathing patterns were simulated with each type of device. These patterns were given the following arbitrary designations: 1) "quiet": $\bar{V}_T$ = 400 ml, f = 16, $\dot{V}_E$ = 6.4 l/min, $\dot{V}_I$ = 21 l/min; 2) "normal": $\bar{V}_T$ = 690 ml, f = 17, $\dot{V}_E$ = 11 l/min, $\dot{V}_I$ = 37 l/min; 3) "hyperventilation," simulating mild dyspnea: $\bar{V}_T$ = 1,400 ml, f = 14, $\dot{V}_E$ = 19.5 l/min, $\dot{V}_I$ = 63 l/min.

That the trained subjects were maintaining the same general respiratory pattern throughout each period was confirmed by intermittent spirometric comparisons and a fairly steady state of end-tidal CO_2 percentage recordings during each equipment test run. The highest absolute tracheal O_2 percentages achieved during inspiration were measured on the polygraph tracing, averaged, and tabulated.

RESULTS

In interpreting these data, several points should be kept in mind. 1) The O_2 concentrations reported here are the highest inspiratory concentrations for any given breath. They do not reflect mean inspiratory O_2 concentrations, which might be even lower. 2) There is a ±2 per cent error in the mass spectrom-

* Assistant Professor, Department of Anesthesia.
† Allied Health Division—Respiratory Therapy Training Program.
‡ Assistant Professor, Department of Neurology.
Received from the Departments of Anesthesia and Neurology, The Bowman Gray School of Medicine of Wake Forest University, Winston-Salem, North Carolina. Accepted for publication August 3, 1975. Presented in part at the Fourth Annual Meeting of the Society of Critical Care Medicine, Anaheim, California, February 17–19, 1975.
Address reprint requests to Dr. Gibson: Department of Anesthesia, Bowman Gray School of Medicine, Winston-Salem, North Carolina 27103.

§ MMS-8 Scientific Research Instruments, Inc., Baltimore, Md.

¶ Model 7, Grass Instrument Company, Quincy, Massachusetts.

** Warren E. Collins, Inc., Braintree, Massachusetts.

†† Ohio Medical Products, Madison, Wisconsin.

TABLE 1. Highest Absolute Inspired Tracheal O_2 Concentrations Attained with Nasal Prongs

Flowmeter (l/min)	Per Cent O_2 in Trachea		
	"Quiet" Breathing	"Normal" Breathing	"Hyperventilation"
1	22.0	—	—
2	21.1	22.0	20.0
3	22.4	23.6	22.7
5	23.8	25.4	25.2
10	46.2	35.2	30.5
15	60.9	44.0	36.2

TABLE 2. Highest Absolute Inspired Tracheal O_2 Concentrations Attained with Nasal Catheter

Flowmeter (l/min)	Per Cent O_2 in Trachea		
	"Quiet" Breathing	"Normal" Breathing	"Hyperventilation"
1	—	—	—
2	—	20.6	19.8
3	—	22.7	21.6
5	—	24.4	23.4
10	—	30.7	27.1
15	—	44.5	40.1

eter for absolute O_2 concentrations. 3) The inspired gases measured in these absolute concentrations in these subjects were diluted by water vapor from the nasopharynx and trachea. Thus, on occasion, particularly where low-flow O_2 was used, the absolute tracheal O_2 concentration was lower than ambient O_2.

As expected, the use of nasal prongs for the administration of low-flow O_2 resulted in only slight increases in tracheal O_2 concentration. Interestingly, substantial increases were found only at high rates of delivery, and the air dilutional effect of "hyperventilation" was evidenced by lower tracheal fractions as compared with those of "normal" or "quiet" breathing (table 1). Oxygen delivery by nasopharyngeal catheters resulted in similar findings (table 2).

A commonly used Venturi-type nebulizer, connected in-line with a wall O_2 flowmeter, delivered to a face mask O_2 percentages that were always higher than the actual intratracheal peak concentrations (table 3). Again, the air dilutional effect of higher levels of ventilation tended to magnify this effect. Remarkably high tracheal concentrations prevailed when a face tent was used; Venturi masks consistently failed to produce the advertised concentrations within the trachea (table 3).

Very high $F_{I_{O_2}}$'s were produced by the simultaneous use of nasal prongs and a face mask with "normal" and "quiet" breathing but not with "hyperventilation" (table 4). However, the highest tracheal O_2 concentrations were obtained when the following apparatus was used: a face mask with one-way valve flaps covering the expiratory ports connected to a one-way valve and then a 3-liter anesthesia bag joined by a simple "Y"-connector to two nebulizers set on 100 per cent with flowmeters set at 15 l/min. The importance of the one-way flap valves in minimizing air dilution is illustrated in table 4. Even with this apparatus, some dilution of inspired O_2 occurred.

Discussion

The data obtained suggest that the actual inspired percentage of O_2 reaching the trachea is never as high in spontaneously breathing patients as that measured in masks or tubing systems external to the patient. This discrepancy is due to air dilution. Factors that tend to magnify this discrepancy include large tidal volumes and high peak inspiratory flow rates, such as may develop in dyspneic or physiologically stressed patients. Factors that tend to minimize it include reservoir capacity and a high delivered flow rate. With the latter set of factors, the administered O_2-enriched gases are delivered at flows and volumes that more nearly match the patients' efforts, and dilution with air inflow is minimal.

These observations have practical merit. For example: 1) Face tents, with their larger area around the face, gave higher tracheal O_2 concentrations than the smaller face masks set on comparable O_2 concentrations and flow rates. 2) Venturi-type masks apparently cannot always be counted upon to deliver the O_2 percentage indicated. 3) A wall nebulizer primed with a 10 l/min O_2 flow and set on the 100 per cent mode may deliver to the trachea no more oxygen than when changed to the 60 per cent mode. In this instance, total delivered flow is doubled via the Venturi mechanism on the 60 per cent mode and there is less air dilution by the patient. 4) Nasal prongs providing

TABLE 3. Comparison of O_2 Concentrations "Delivered" by Various Types of Apparatus with Actual Concentrations of O_2 Delivered to the Trachea

Apparatus	Per Cent O_2 "Delivered"	Per Cent O_2 in Trachea		
		"Quiet" Breathing	"Normal" Breathing	"Hyper-ventilation"
Face mask with Ohio Deluxe nebulizer at 10 l/min	44	39.5	32.7	26.0
	60	53.4	50.3	41.0
	100	62.7	52.0	42.0
Face mask with Ohio Deluxe nebulizer at 15 l/min	44	41.1	34.2	29.1
	60	52.5	46.1	40.1
	100	68.1	54.0	50.2
Face tent at 15 l/min	100	—	88	82
Venturi mask at 4 l/min	24	23.1	22.0	21.0
	28	24.2	23.0	21.4
Venturi mask at 8 l/min	35	32.3	30.0	26.2
	40	36.4	33.1	29.4

TABLE 4. Comparison of O_2 Concentrations "Delivered" by Various Combinations of Anesthesia Apparatus with Actual Concentrations of O_2 Delivered to the Trachea

Apparatus	Per Cent O_2 in Trachea		
	"Quiet" Breathing	"Normal" Breathing	"Hyper-ventilation"
Nasal prongs at 15 l/min and face mask with humidifier–nebulizer on 100 per cent setting at 15 l/min	86.2	84.1	66.0
Face mask with interposed 3-liter anesthesia bag and two humidifier–nebulizers on 100 per cent setting at 15 l/min flow each (total flow = 30 l/min)	61.4	50.1	36.2
Above set-up with mask holes occluded by one-way flap valves	98.2	96.1	94.2

relatively low flow rates are not necessarily associated with the inhaled concentrations reported by standard textbooks of respiratory care.[1–5]

The highest absolute tracheal O_2 concentrations delivered in this study, and the ones most nearly approximating those in the apparatus, were delivered through a set-up that has, on occasion, been indicated clinically: a face mask with one-way flap valves covering the expiratory ports connected in line with a one-way valve, a reservoir bag, and two nebulizers set to provide a high flow of 100 per cent O_2.

These findings re-emphasize the necessity of obtaining serial arterial blood gases when O_2 is given, since the complex interactions of equipment and patient variables strongly influence the amount of O_2 actually delivered to the patient's trachea.

REFERENCES

1. Egan DF: Fundamentals of Respiratory Therapy. St. Louis, C. V. Mosby, 1973, pp 278–294
2. Bendixen HH, Egbert LD, Hedley-Whyte J, et al: Respiratory Care. St. Louis, C. V. Mosby, 1965, pp 133–136
3. Young JA, Crocker D: Principles and Practice of Inhalation Therapy. Chicago, Year Book Medical Publishers, 1970, pp 80–84
4. Heironimus TW: Mechanical Artificial Ventilation. Second edition. Springfield, Charles C Thomas, 1972, pp 105–106
5. Winchell SW: Inhalation of oxygen, Respiratory Therapy. Edited by P Safar, Philadelphia, F. A. Davis, 1965, pp 153–159