Efficiency of oxygen administration: Sequential gas delivery versus "flow into a cone" methods

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Objective: **F_{IO_2} values of a new oxygen mask that exploits efficiencies afforded by sequential gas delivery (SGD) were compared to those of a nonrebreathing mask (NRM) and a Venturi oxygen mask.**

Design: **Prospective, single-blinded, randomized study.**

Setting: **Laboratory study.**

Subjects: **Eight healthy male volunteers.**

Interventions: **Volunteers breathed through each of the masks at various minute ventilations ($\dot{V}_E$). Oxygen flows were 2, 4, and 8 L/min to the SGD mask but only 8 L/min to the other masks.**

Measurements and Main Results: **Net F_{IO_2} was calculated from end-tidal fractional concentrations of oxygen and CO_2 with the alveolar gas equation. Only the SGD mask at an oxygen flow of 8 L/min consistently provided both F_{IO_2} >0.95 (at resting $\dot{V}_E$) and higher F_{IO_2} than the other masks at all $\dot{V}_E$. The SGD mask delivered F_{IO_2} comparable to other masks at only a fraction of the oxygen flow and was characterized by a consistent relation between F_{IO_2} and oxygen flow for a given $\dot{V}_E$.**

Conclusion: **We conclude that SGD can be exploited to provide F_{IO_2} >0.95 with oxygen flows as low as 8 L/min, as well as accurate and efficient dosing of oxygen even in the presence of hyperpnea. (Crit Care Med 2006; 34:829–834)**

KEY WORDS: oxygen mask; inspired oxygen concentration; nonrebreathing mask; hypoxia; oxygen dosage; oxygen administration

Oxygen is by far the most commonly prescribed drug in the world, yet the dosage is rarely specified and, less commonly still, accurately dispensed (1). This is especially true with respect to higher oxygen concentrations required to treat hypoxemia due to large ventilation-perfusion mismatch (2), such as occurs with severe pneumonia, heart failure, and pulmonary embolization. Nevertheless, it is currently difficult to reliably provide F_{IO_2} >0.7 to spontaneously breathing patients (3). To do so, the oxygen flow into the mask, typically about 8 L/min, must match the patient's peak inspiratory flow (4), which may be in the range of 50–100 L/min in dyspneic patients (5). The nonrebreathing-type mask (NRM) has a vented hood cupping the mouth and nose and a reservoir that collects oxygen during exhalation, making it available during inhalation to meet peak inspiratory flow demands. However, there is also obligatory entrainment of air through the side vents of masks (4, 6) throughout inhalation, diluting the inhaled oxygen (5).

High F_{IO_2} values can be generated by measures that reduce the entrainment of air during inhalation, such as increasing the flow of source oxygen to match the peak inspiratory flow (5, 7) and modifying the side vents to minimize air entrainment (6, 7). Nevertheless, high oxygen flows are wasteful, are cumbersome to administer, and may not provide F_{IO_2} close to 1.0 (5), even with a second (5) or third (7) oxygen source set to maximum flows. Venturi masks were originally designed to limit the rise in F_{IO_2} in patients teetering on the verge of respiratory failure. They are prevented from providing a high F_{IO_2} by obligatory entrainment of air at a fixed ratio to oxygen flow as it enters the mask. Nevertheless, both the NRM and the Venturi mask are currently prescribed for many conditions—often inappropriately—simply because they are the only ones with which medical personnel are familiar (1).

A new approach to increasing the efficiency of oxygen administration is the sequential delivery of oxygen and air during inhalation (Fig. 1). The oxygen that enters the lungs first can be "washed down" to the alveoli by the remainder of the inspirate (Fig. 2). This should optimize oxygenation by ensuring the distribution of the oxygen predominantly to alveoli with a high ratio of alveolar ventilation to pulmonary blood flow ($\dot{V}_A/Q$) such as those at the lung bases, leaving the trailing gas (air) to be distributed predominantly to the remaining low $\dot{V}_A/Q$ alveoli and the anatomical dead space.

The package insert of the commercially available version of the sequential gas delivery (SGD) mask (Hi-Ox[80], VIASYS HealthCare, Yorba Linda, CA) states that an oxygen flow of 8 L/min results in an F_{IO_2} >0.8. However, the potential efficiencies of SGD suggest that the F_{IO_2} may remain high at much lower oxygen flows, especially when compared with the NRM and Venturi mask. Our aim was to investigate the efficiency of SGD by comparing the F_{IO_2} obtained by delivering oxygen via an SGD mask to that obtained

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The authors are co-inventors of sequential gas delivery method, have applied for patents and have licensed the technology to Viasys Healthcare of Yorba Linda California.

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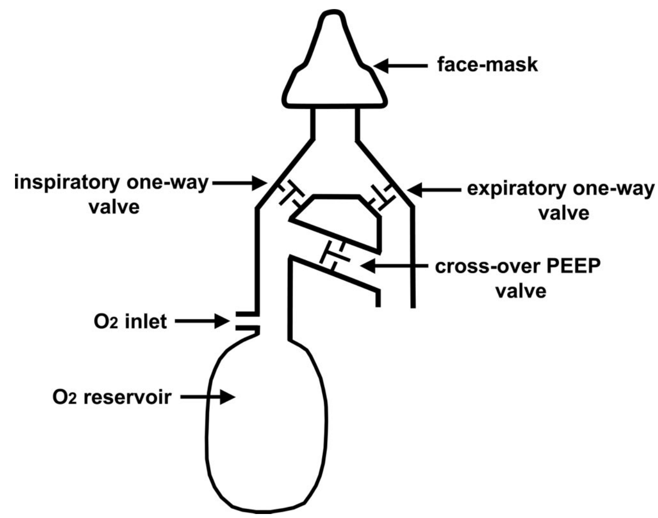

Figure 1. Schematic of a sequential gas delivery mask. The manifold attached to the mask is separated into inspiratory and expiratory limbs by one-way low-resistance valves. The two limbs are connected via a bypass limb with a one-way valve that has an opening pressure greater than that of the other two valves (crossover positive end-expiratory pressure [*PEEP*] valve). During exhalation, all the exhaled gas is directed out through the expiratory limb, while oxygen collects in the inspiratory reservoir. At the beginning of inhalation, oxygen is drawn from the oxygen source and the oxygen reservoir. Because there are no side vents in the facemask, the patient inhales undiluted oxygen. If minute ventilation exceeds oxygen flow during inhalation, all of the oxygen is drawn from the reservoir, the reservoir collapses, the crossover valve opens, and the balance of inhaled gas is drawn from the room air.

at the same oxygen flows delivered via an NRM and Venturi mask to subjects breathing over a region ventilations.

METHODS

After receiving institutional ethics research board approval, we obtained signed informed consent from eight healthy male volunteers (age, 34.9 ± 12.5 yrs; height, 182.3 ± 4.0 cm; weight, 79.9 ± 8.4 kg) with no history of respiratory disorders. Subjects were unaware of the specific objectives of the study. They were tested in the sitting position with each of the three masks. Adhesive tape (Tegaderm, 3M Health Care, St. Paul, MN) was used as necessary to ensure a good seal around each mask. The flow of oxygen to the masks was controlled by a calibrated electronic flow meter (Voltek Enterprises, Toronto, Canada). Gas was sampled continuously from the oropharynx via a small-bore, perforated catheter placed via the mouth. Gases were analyzed for CO_2 and oxygen (AS3, Datex, Helsinki, Finland). Results were digitized and recorded continuously with data acquisition software (Labview, National Instruments, Austin, TX).

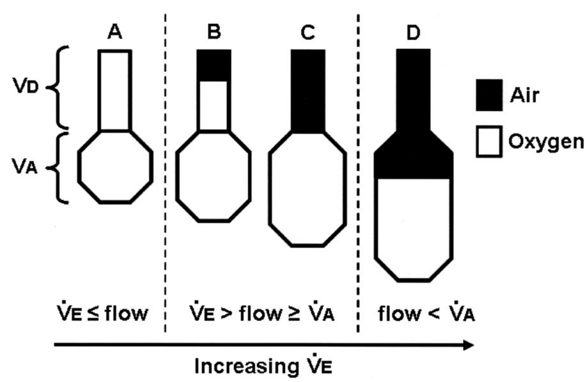

Figure 2. Explanation for the efficiency of oxygen delivery when a sequential gas delivery circuit is used. The lung is modeled as a unified anatomical dead space (V_D) in series with a gas-exchange volume (V_A). When minute ventilation ($\dot{V}_E$) is less than or equal to oxygen flow, only oxygen (clear space) enters the lung and the F_{IO_2} is close to 1.0 (*A*). If $\dot{V}_E$ is greater than oxygen flow, air will be drawn into the lung, "washing" the oxygen from the anatomical dead space into the gas-exchange region of the lung. At least some air will be retained in the anatomical dead space (shaded black) (*B* and *C*), displacing an equal volume of oxygen into the gas-exchange area of the lung. F_{IO_2} is reduced to the extent that air enters the gas-exchange region (*D*), where it mixes with and dilutes the oxygen. The effect of dilution is minimized because all of the oxygen enters the gas-exchange portion, whereas some of the air remains in the anatomical dead space and does not contribute to the dilution of the oxygen in the gas-exchange region.

Protocol

SGD Mask. An SGD mask (Hi-Ox[80]) was modified by placing a pneumotachometer (Universal Ventilation Meter, Vacu·Med, Ventura, CA) between the mask and the manifold (dead space ≈100 mL). Subjects breathed at a minute ventilation ($\dot{V}_E$) of 10, 14, 18, 24, and 30 L/min for 4 mins with a rest period of 5 mins between tests. Subjects synchronized respiratory frequency (*f*) to an electronic metronome and controlled tidal volume (V_T) according to visual feedback of $\dot{V}_E$ displayed on a computer monitor. Tests at each $\dot{V}_E$ were repeated for oxygen flows of 2, 4, and 8 L/min. Average $\dot{V}_E$, *f*, V_T, and fractional end-tidal CO_2 (F_{ETCO_2}) and oxygen (F_{ETO_2}) concentrations were calculated from the last 2 mins of recording of each test. Table 1 summarizes the ventilatory conditions used to test the SGD mask on all subjects. When oxygen flow to the SGD mask was set at 8 L/min, F_{ETCO_2} at each $\dot{V}_E$ was noted and used as the feedback parameter for the subject to set his $\dot{V}_E$ when breathing via the NRM and Venturi mask (a pneumotachometer cannot be used with these masks).

NRM and Venturi Mask. For the NRM (R-2450S, Respan Products, Erin, Canada) and "40% oxygen" Venturi mask, designed to provide a concentration of 40% oxygen into the mask (Percento$_2$, Allegiance Healthcare, McGaw Park, IL), oxygen flow was set to 8 L/min. Subjects again synchronized their *f* to a metronome and voluntarily adjusted their V_T to keep their F_{ETCO_2} within the target levels displayed graphically on a computer screen. Target F_{ETCO_2} values were those attained by each subject at each $\dot{V}_E$ when breathing via the SGD mask.

A peak detector algorithm from the data acquisition program selected F_{ETCO_2} and F_{ETO_2} for each breath. F_{IO_2} was calculated from F_{ETO_2} and F_{ETCO_2} by means of the alveolar gas equation (8),

$$F_IO_2 = \frac{(F_{ET}O_2 \times RQ + F_ACO_2)}{(RQ + F_ACO_2 \times (1 - RQ))}$$

where F_{ETCO_2} was substituted for fractional concentration of alveolar CO_2 (F_{ACO_2}) (8) and the respiratory quotient (RQ) was assumed to be 0.8. No correction was made for the small changes due to humidification of the gases.

Table 1. Ventilatory conditions used to test sequential gas delivery mask in all subjects

Condition	$\dot{V}_E$, L/min	f, breaths/min	V_T, mL
Rest	—[a]	—[a]	—[a]
1	10	10	1000
2	14	10	1400
3	18	15	1200
4	24	15	1600
5	30	15	2000

f, breathing frequency; V_T, tidal volume; $\dot{V}_E$, minute ventilation.

[a] $\dot{V}_E$, f, and V_T at rest differed between subjects. Subjects were asked to adjust their f to an electronic metronome and their V_T to a visual feedback of their $\dot{V}_E$, which was measured with a pneumotachometer.

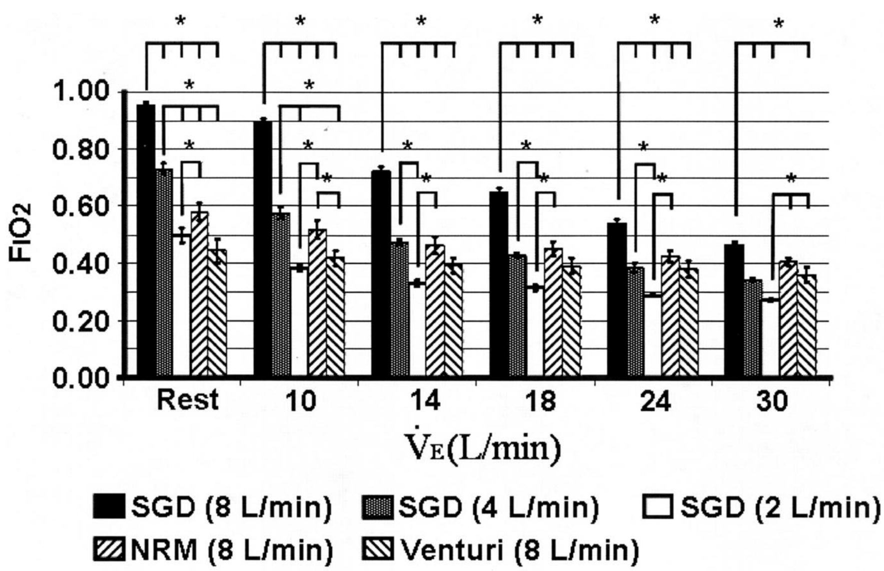

Figure 3. Data from all experimental conditions. Significant difference designations compare the values beneath the shorter ticks to those under the longer ticks. Minute ventilation ($\dot{V}_E$) is as defined in Table 1. Error bars are standard deviations (*SGD*, sequential gas delivery mask; *NRM*, nonrebreathing mask).

Statistical Analysis

Statistical analysis was performed with SigmaStat 2.03 (SPSS, Chicago, IL). Data are reported as mean ± SD. Repeated-measures analysis of variance (RMANOVA) was used with Tukey's least significant difference test, chosen for *post hoc* comparisons. Statistical significance was assumed when $p < .05$.

RESULTS

The SGD mask with oxygen flow set at 8 L/min delivered the highest F_{IO_2} under all experimental conditions (Fig. 3); at $\dot{V}_E$ of 30 L/min, the F_{IO_2} for the SGD mask did not reach statistical significance with respect to the NRM. F_{IO_2} fell as $\dot{V}_E$ increased. At $\dot{V}_E$ of 14 L/min, F_{IO_2} was <0.8. At $\dot{V}_E$ <10 L/min, F_{IO_2} was >0.95, and at an oxygen flow of 4 L/min, the F_{IO_2} (0.73 ± 0.06) was still higher than those with the NRM (0.58 ± 0.09) and the Venturi mask (0.44 ± 0.12; $p < .001$). With $\dot{V}_E$ at ≥10 L/min, the F_{IO_2} with the SGD at 4 L/min was equal to that with the NRM at an oxygen flow of 8 L/min. At an oxygen flow of only 2 L/min, the F_{IO_2} was the same as with the Venturi mask at all ventilations except for the highest. At resting ventilation, the F_{IO_2} with the SGD at 2 L/min (0.50 ± 0.07) would, in a clinical setting, be equivalent to that provided by NRM (0.58 ± 0.09; $p < .001$) and Venturi mask (0.44 ± 0.12; $p = .427$) with oxygen flow of 8 L/min. There was no significant difference in the F_{ETCO_2} among masks for each condition when ventilation was controlled. Subjects breathing to target ventilations maintained their F_{ETCO_2} within 0.003 (~2 mm Hg) (Table 2). Figure 4 summarizes the F_{IO_2} values with the SGD mask at oxygen flows of 2, 4, and 8 L/min at the various $\dot{V}_E$. Table 3 summarizes end-tidal oxygen concentrations attained by each subject at each testing condition.

DISCUSSION

The efficiency of the SGD mask in administering oxygen was manifested by its ability to deliver a higher F_{IO_2} for a given $\dot{V}_E$ than the other masks at a given oxygen flow. For an oxygen flow of 8 L/min, the SGD provided a higher F_{IO_2} than the NRM at all tested $\dot{V}_E$. At resting $\dot{V}_E$, the SGD was the only mask to provide F_{IO_2} >0.95 at oxygen flows of 8 L/min. The F_{IO_2} was still ~0.9 at $\dot{V}_E$ of about 10 L/min, which is 1.5 to 2 times the resting $\dot{V}_E$ in adults. We found that the manufacturer's claim that the SGD mask delivers F_{IO_2} >0.8 applies only up to $\dot{V}_E$ of about 14 L/min. Looking at things another way, we noted that the efficiency of the SGD mask in administering oxygen was also manifested by its ability to deliver F_{IO_2} similar to that of the other masks at a fraction of the oxygen flow, providing a potential means to extend oxygen supplies if they are limited. We also found a consistent relation between oxygen flow and F_{IO_2} at a given $\dot{V}_E$ ($F_{IO_2} = 0.495 + (0.0599 * O_2 \text{ flow}) - (0.0155 * \dot{V}_E)$; R = 0.937; $R^2 = 0.879$), suggesting that the SGD mask could function as a fixed-performance oxygen mask suitable for delivering precise F_{IO_2} even to hyperpneic patients. This would require clinical validation.

Basis for Efficiency of the SGD. The SGD facemask contains no vents; all gases enter and leave the mask via the manifold. The valve configuration of the manifold controls the sequence of presentation of oxygen and air to the lungs during inhalation. The benefit of sequential oxygen and air delivery is explained with reference to a model of the lung consisting of an anatomical dead space in series with the alveoli (Fig. 2*A*). The oxygen in the initial component of a breath arrives undiluted in the gas-exchange portion of the lung. When $\dot{V}_E$ exceeds oxygen flow, air enters the lung, initially displacing the oxygen in the anatomical dead space into the gas-exchange area (Fig. 2*B, C*) without diluting it. At rest, ventilation of the anatomical dead space can account for one third of $\dot{V}_E$ so that, theoretically, the oxygen flow need be only two thirds of $\dot{V}_E$ to sustain an F_{IO_2} of 1.0. In our subjects, however, oxygen flow

Table 2. End-tidal P_{CO_2} attained with each mask by all subjects at all testing conditions

		End-Tidal P_{CO_2} (mm Hg)					
		SGD		NRM		Venturi Mask	
Subject	Condition	Mean	SD	Mean	SD	Mean	SD
1	0	41.60	0.47	42.25	0.58	41.22	0.89
	10	39.15	0.64	39.30	0.44	38.72	0.68
	14	33.44	0.68	33.37	0.53	33.85	0.69
	18	29.07	0.65	28.12	0.48	29.14	0.43
	24	26.90	0.67	27.14	0.50	26.70	0.53
	30	24.39	0.47	24.86	0.47	24.62	0.57
2	0	41.78	1.28	41.91	0.67	37.12	0.82
	10	34.22	0.71	34.00	0.38	33.56	0.42
	14	27.67	0.55	27.62	0.53	27.28	0.91
	18	24.33	0.88	24.27	0.48	24.60	0.58
	24	22.22	0.75	21.22	0.71	22.07	1.00
	30	19.69	0.87	19.56	0.45	19.69	0.83
3	0	46.51	0.71	37.00	0.69	43.97	13.35
	10	43.03	0.83	39.51	2.63	43.06	1.90
	14	38.12	0.56	38.18	0.69	37.87	1.90
	18	34.56	1.00	34.29	0.65	34.43	1.00
	24	29.20	0.56	30.28	0.41	30.11	0.97
	30	24.49	0.95	25.17	0.88	25.88	0.56
4	0	39.53	1.26	36.84	0.79	35.31	1.05
	10	37.62	0.72	37.44	0.60	36.96	0.63
	14	30.39	1.09	29.66	1.46	29.61	0.57
	18	26.63	0.37	26.42	0.64	25.36	0.86
	24	23.71	0.73	23.23	0.62	23.00	0.78
	30	20.61	0.56	20.48	1.00	20.26	0.61
5	0	37.98	0.47	37.86	1.12	38.59	1.48
	10	32.77	0.57	31.68	0.95	31.57	1.07
	14	26.05	0.38	26.15	0.42	25.83	1.21
	18	23.27	0.60	23.13	0.36	22.35	0.64
	24	20.24	0.40	20.44	0.34	19.84	0.94
	30	17.77	0.42	17.46	0.26	16.19	1.55
6	0	41.65	0.64	41.19	0.44	36.37	1.57
	10	38.64	0.39	38.87	0.56	37.42	1.16
	14	32.65	0.38	32.58	0.49	33.16	0.99
	18	29.50	0.68	29.27	0.58	28.65	0.54
	24	23.54	0.60	23.50	0.61	23.72	0.70
	30	20.69	0.47	20.49	0.45	20.80	0.56
7	0	41.65	0.47	41.41	0.87	41.71	0.97
	10	37.04	0.93	36.95	1.00	36.10	0.54
	14	30.36	0.59	30.23	0.96	30.18	0.84
	18	26.62	0.46	26.84	0.63	25.24	0.76
	24	23.10	1.14	23.48	0.84	22.92	0.91
	30	19.00	1.52	20.29	0.72	19.51	0.78
8	0	42.00	0.87	42.77	4.12	46.01	0.97
	10	41.72	1.47	42.08	1.61	42.60	0.86
	14	35.89	1.08	36.47	1.38	35.97	1.33
	18	31.50	0.94	31.54	0.93	31.61	1.12
	24	29.04	1.11	28.28	1.36	29.52	0.80
	30	24.50	0.92	24.40	0.77	25.08	1.04

SGD, sequential gas delivery; NRM, nonrebreathing mask.
Condition 0 represents resting ventilation.

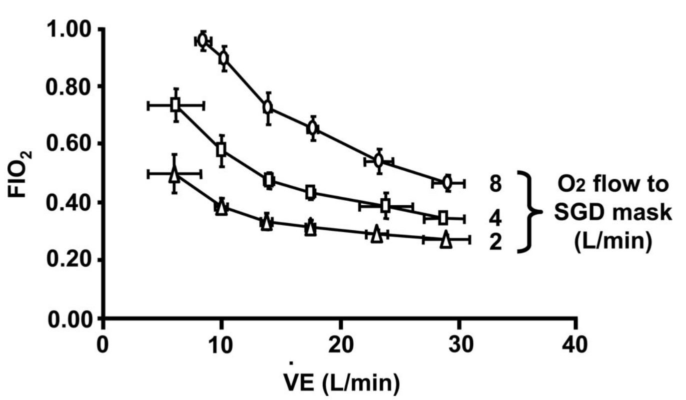

Figure 4. Inspired oxygen fraction (F_{IO_2}) with a sequential gas delivery (*SGD*) mask at different oxygen flows. The increase in resting minute ventilation ($\dot{V}_E$) at an oxygen flow of 8 L/min is consistent with hyperoxic ventilatory stimulation (21, 22). Error bars are standard deviations.

of 4 L/min provided an F_{IO_2} of only ~0.7, most likely reflecting resting $\dot{V}_E$ exceeding 6 L/min as well as some mixing and diffusion of gases in the manifold and anatomical dead space, which is inevitable. In contrast, the limitation on F_{IO_2} of the NRM stems from a variable extent of dilution of oxygen in the mask by air throughout inhalation (depending on the pattern of breathing and the oxygen flow), reducing the oxygen concentration before it even reaches the gas-exchange portion of the lung.

Determination of F_{IO_2}. In testing oxygen masks, one must account for patient factors such as $\dot{V}_E$ (5) and breathing pattern (especially as they relate to peak inspiratory flow (4)) which are major determinants of the F_{IO_2}. It is tempting to eliminate this source of variability when comparing masks by resorting to mechanical models to provide uniform test conditions. However, despite the consistent flow profiles, the calculation of F_{IO_2} may actually be more difficult. With mechanical models, as well as *in vivo*, the F_{IO_2} varies throughout inspiration and is not represented by the peak inspiratory oxygen concentration, as is sometimes reported (4, 9). In mechanical models, the *net* F_{IO_2} must be calculated as a flow- and time-averaged value of inspired concentrations (10)—a complex calculation (11) requiring synchronization and integration of flow and oxygen concentration signals. However, *in vivo*, net F_{IO_2} can be calculated from the expired oxygen and CO_2 concentrations by means of the alveolar gas equation as described in the Methods section above.

Value of F_{IO_2}. Endotracheal intubation, often the default method when the NRM (or noninvasive ventilation, if available) fails to provide adequate oxygenation (5), entails discomfort, risk, and increased intensity (and expense) of care. The maximum F_{IO_2} available from unmodified commercial oxygen masks (~0.7) (5) sets the degree of hypoxia that is the threshold indicating endotracheal intubation. Extraordinary measures taken to modify available masks (5–7) in order to raise the F_{IO_2} have sufficient drawbacks to make them unpopular. High oxygen flow delivered via tandem set-ups is uncomfortable for the patient and wastes oxygen. Occlusive masks such as those used for continuous positive airway pressure (CPAP) are efficacious (12) but require expensive machinery and are occasionally not well tolerated by distressed patients or

Table 3. End-tidal oxygen attained with each mask by all subjects at all testing conditions

		End-Tidal Oxygen (%)					
		SGD		NRM		Venturi Mask	
Subject	Condition	Mean	SD	Mean	SD	Mean	SD
1	0	87.38	1.50	54.59	1.28	32.84	0.34
	10	81.14	0.48	47.05	1.60	33.35	0.19
	14	66.19	0.92	39.77	1.36	32.92	0.30
	18	59.71	0.86	39.07	0.33	32.39	0.38
	24	49.67	0.62	39.04	0.53	32.91	0.44
	30	41.94	0.65	41.00	0.52	31.18	0.40
2	0	82.52	0.31	59.49	0.61	32.91	0.28
	10	79.75	0.71	48.07	1.00	33.01	0.51
	14	60.48	0.45	46.13	0.14	29.91	1.01
	18	58.16	0.86	47.36	0.36	30.16	1.02
	24	50.24	0.55	43.90	1.70	31.49	0.70
	30	44.27	0.38	40.74	2.17	28.38	1.07
3	0	89.14	1.17	62.30	1.61	45.43	24.90
	10	83.27	0.85	60.82	3.15	32.98	0.35
	14	66.84	0.80	58.24	1.91	32.05	0.64
	18	60.77	1.34	52.67	1.24	33.20	0.50
	24	48.16	0.73	49.44	1.30	31.97	0.38
	30	42.31	0.64	48.07	0.89	32.27	0.59
4	0	92.01	0.56	56.34	1.37	32.20	0.45
	10	89.93	0.77	51.36	1.43	32.15	0.16
	14	69.82	1.09	38.23	0.82	29.83	0.44
	18	63.12	1.00	36.94	0.92	31.98	0.33
	24	52.22	1.13	36.99	0.24	27.26	0.56
	30	44.99	0.58	40.64	0.72	27.54	0.62
5	0	93.61	0.11	53.82	1.53	34.10	0.80
	10	86.04	0.85	43.06	0.57	34.95	0.43
	14	68.26	1.13	41.73	0.89	33.62	0.51
	18	57.89	0.83	42.37	0.54	32.81	1.56
	24	49.12	0.67	39.54	0.37	32.86	0.66
	30	41.44	0.79	38.36	0.20	29.38	1.00
6	0	90.02	0.52	58.93	1.14	33.06	0.50
	10	87.44	0.82	58.34	1.18	34.13	0.22
	14	70.04	0.64	44.74	2.11	35.16	0.20
	18	61.33	1.07	44.11	2.26	35.63	0.15
	24	50.01	0.71	38.41	0.23	34.68	0.46
	30	42.81	0.43	38.97	0.37	34.70	0.46
7	0	91.00	0.33	56.56	1.35	32.83	0.43
	10	78.39	1.17	55.42	0.77	34.90	0.28
	14	62.25	0.86	60.11	0.93	32.92	0.66
	18	57.95	1.02	51.76	1.97	32.54	1.06
	24	44.65	0.56	49.06	2.21	31.46	0.94
	30	41.16	1.29	39.94	1.41	29.26	0.67
8	0	92.00	0.46	65.75	1.57	31.98	1.25
	10	87.07	1.06	54.85	1.52	33.46	0.29
	14	77.51	2.67	52.15	1.40	31.79	0.43
	18	69.55	3.06	52.93	0.66	32.00	1.06
	24	59.35	2.20	53.41	4.22	32.09	0.48
	30	49.18	3.05	50.42	1.48	29.63	1.01

SGD, sequential gas delivery; NRM, nonrebreathing mask.
Condition 0 represents resting ventilation.

for prolonged periods (13). Our study demonstrates that SGD is an effective strategy for raising F_{IO_2} to ~0.95 with a familiar soft facemask at oxygen flows currently used with conventional oxygen masks. An efficient means to administer high F_{IO_2} may reduce the number of hypoxic patients who require endotracheal intubation because of failed treatment with these conventional oxygen masks.

Efficiency. Efficient use of oxygen is important outside hospital settings or where oxygen supplies are limited, expensive, or dangerous to transport and store, as for example with prolonged ambulance transport, search and rescue operations, military combat, and natural and manmade disasters (14). In these situations the reduced oxygen flow required to generate a given F_{IO_2} with an SGD mask may be utilized to extend oxygen supplies.

Dosing. The F_{IO_2} with "variable performance devices" such as nasal prongs and simple vented masks varies with $\dot{V}_E$ and breathing pattern, particularly at low $\dot{V}_E$. Historically (as opposed to currently (15)), this was considered problematic in attempting to finely tune the F_{IO_2} to provide an "adequate" arterial P_{O_2} without abolishing what was considered hypoxic respiratory drive. Campbell (16) described masks administering oxygen based on the Bernoulli principle, in which the oxygen flow entering the mask entrains air at a fixed rate. As a result, gas enters the mask at a fixed FO_2, with total flow equal to the sum of oxygen flow and entrained air. The primary purpose of these masks was to "fix" the F_{IO_2} (i.e., to prevent a rise in F_{IO_2}) at a low $\dot{V}_E$ typical of patients with severe obstructive pulmonary disease. However, Venturi masks become "variable performance devices" when air entrainment is reduced in order to raise the F_{IO_2} above 0.4 (10, 17) or when $\dot{V}_E$ is increased above the total gas flow (5).

It is frequently unappreciated that replacing a "40% oxygen" Venturi mask with a "60% oxygen" Venturi mask does not raise the F_{IO_2}. The change only reduces the oxygen-to-air-entrainment ratio at the oxygen nozzle from 1:3 to 1:1; however, as long as the peak inspiratory flow exceeds total flow of oxygen and air entrained at the nozzle, the rest of the gas required to meet the demand of the peak flow comes from air drawn in from the side vents of the mask. As a result, the oxygen flow and total air entrained are unchanged, and so is the F_{IO_2}. Closed oxygen delivery systems such as CPAP devices can provide various F_{IO_2}, but they are expensive and occasionally not well tolerated. Our study indicates that the SGD mask may complement the current oxygen delivery systems by providing F_{IO_2} >0.9, even in the presence of moderate hyperpnea. However, the ability to extend the function of the SGD masks to hyperpneic patients and "fix" F_{IO_2} is limited by a lack of simple means to measure $\dot{V}_E$ in hyperpneic patients.

It may still be possible to titrate the oxygen flow to $Feto_2$ in the clinical setting, as is now done with other masks. This may be particularly important for patients with contagious respiratory illnesses (18, 19) in whom the SGD is used with a bacterial and viral filter to institute respiratory isolation (20).

Limitations. The power to detect statistical difference with our sample size of

Sequential gas delivery is a new and effective strategy to improve the efficiency of oxygen administration.

eight subjects was high, as the variability in results was small. The design of the SGD mask was such that it provided a good seal in most subjects. The seal about the face of the other masks was not as good, necessitating the use of adhesive tape in order to remove mask fit as a variable in the results. F_{IO_2} values with these masks may well be lower in clinical settings where tape is not used. Our aim was to compare the effects of the masks on alveolar P_{O_2}, which can be done by analysis of exhaled gas. To assess the effect of the masks on arterial P_{O_2} net of the $\dot{V}_A/Q$ ratio would have required arterial blood sampling. However, the effects of the masks on alveolar P_{O_2} can be assessed from end-tidal gas, as it is independent of the alveolar-arterial gradient. We measured $\dot{V}_E$ directly with the pneumotachometer in the SGD mask protocol only. In contrast, with the NRM and Venturi mask protocols we obtained $\dot{V}_E$ indirectly by means of matching of P_{ETCO_2}, which may have resulted in some discrepancy between assumed and actual $\dot{V}_E$.

CONCLUSION

SGD is a new and effective strategy to improve the efficiency of oxygen administration. This can be exploited to maximize F_{IO_2} for patients with large $\dot{V}_A/Q$ mismatch, such as in pneumonia, heart failure, and pulmonary embolism, or extend oxygen supplies beyond what is possible with the NRM and Venturi mask. It may also lead to "fixed performance" functionality for hyperpneic patients.

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