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Performance of a Demand Oxygen Saver System during Rest, Exercise, and Sleep in Hypoxemic Patients*

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Demand oxygen systems have been shown to be effective in treating hypoxemia during seated rest and during exercise, but the performance of these systems during sleep has not been previously studied. We compared the efficacy of a new demand oxygen saver system with that of continuous flow nasal oxygen during the usual activities of daily life including sleep, seated rest, and exercise. Six hypoxemic patients were studied. All six had chronic obstructive pulmonary disease, though one patient had kyphoscoliosis with mixed obstructive and restrictive lung disease. Patients were studied during each activity of daily life while receiving supplemental oxygen by continuous flow nasal cannula at 2 liters per minute and during use of the demand oxygen saver system. The demand oxygen system produced arterial oxygenation equivalent to continuous flow nasal cannula under all conditions while utilizing substantially less oxygen. When compared with administration of oxygen by continuous flow nasal cannula, the demand oxygen saver cannula utilized only 45 percent as much oxygen during seated rest, 44 percent as much oxygen during exercise, and 39 percent as much oxygen during sleep. Our data support the use of demand oxygen systems for treatment of hypoxemia in patients with chronic obstructive lung disease.

Administration of continuous supplemental oxygen to hypoxemic patients with chronic obstructive pulmonary disease has been demonstrated to increase survival and to decrease pulmonary hypertension.[1,2] In view of the significant expense associated with continuous oxygen use, there has been a concerted effort made to develop methods of oxygen delivery which will maintain adequate arterial oxygenation but utilize less oxygen than the continuous flow nasal cannula (CFNC). Among the devices which have previously been tested are reservoir nasal cannulas,[3-5] demand oxygen systems utilizing a sensor to identify negative pressure within the nares and triggering the administration of a pulse of oxygen,[6-11] and transtracheal catheters which are used to deliver oxygen directly into the distal trachea.[12]

Previous studies have demonstrated the effectiveness of demand oxygen systems in maintaining arterial oxygenation in hypoxemic patients at rest.[6-9] There has, however, been only limited study of these systems during exercise,[10,11] and the effectiveness of these systems during sleep has not been previously documented. Since widespread use of demand oxygen cannula systems will await the demonstration of their effectiveness during all conditions of normal living, we have studied six patients with hypoxemic chronic obstructive lung disease and have compared the effectiveness of oxygen delivery with a demand oxygen cannula system prototype with that by CFNC at rest, during exercise, and during sleep.

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Materials and Methods

Study Population

Six patients were selected for study. All had chronic lung disease with resultant hypoxemia, and all were judged clinically stable. All but one subject had a PaO_2 of 58 mm Hg or less breathing room air on the first day of study. The one exception, subject 1, had an initial PaO_2 measured at 62 mm Hg but was retained as a study subject because a second arterial sample drawn later the first study day did demonstrate a PaO_2 of less than 59 mm Hg. The two subjects with PaO_2 values during room air breathing of greater than 55 mm Hg both had clinical cor pulmonale and all subjects met Medicare criteria for supplemental oxygen administration. All subjects had PaO_2 values greater than 60 mm Hg on nasal O_2 at a flow rate of 2 liters per minute. The diagnosis in five of the six subjects was chronic obstructive pulmonary disease (COPD). The sixth subject had scoliosis with combined severe restrictive and mild obstructive lung disease. A summary of demographic data and arterial blood gas data for the six subjects may be found in Table 1.

Equipment

Testing was performed utilizing several different pieces of spirometry equipment, all of which met ATS criteria for accuracy and

Table 1—*Study Population*

Subject	Age/Sex	Po_2 (RA)	FEV_1, L	Diagnosis
1	76/M	57	0.82	COPD
2	67/F	53	0.66	COPD
3	76/F	50	0.54	COPD
4	50/F	45	0.65	COPD
5	60/M	56	1.15	COPD
6	59/F	41	0.89	COPD and kyphoscoliosis

reproducibility. Arterial blood was sampled via radial or brachial artery punctures; pH, P_{CO_2}, and P_{O_2} values were obtained using a blood gas analyzer, while oxyhemoglobin saturation was measured on a CO-oximeter. Ear oximetry was performed with a strip chart recorder. Oxygen flow to the patient was measured by a laminar flow element in the cannula for both continuous and demand flow.

Oxygen utilization data were obtained by monitoring the oxygen supply cylinder pressure readings upstream from the gas regulators and using an appropriate multiplier to determine the oxygen volume delivered. The companion oxygen saver (COS) utilized a standard nasal cannula for oxygen administration and delivered a pulse of oxygen in response to a negative pressure sensed within the cannula of -0.04 cm H_2O (Puritan-Bennett Corp, Overland Park, Ks). Total oxygen delivery per minute was determined by the prescribed oxygen flow rate. The volume of each oxygen pulse was continuously adjusted by the COS in response to the sensed trend in respiratory rates in such a way that total oxygen delivered to the patient each minute remained constant.

Three safety mechanisms were incorporated into the design of the COS. The first was intended to provide additional oxygen in the event the COS sensed a respiratory rate of less than eight breaths per minute. In that case, oxygen was delivered at the prescribed flow rate continuously for 7.5 seconds, followed by a seek interval of no more than 7.5 seconds. If no breaths were sensed during the seek interval, another 7.5 seconds of continuous flow followed, so that the subject received alternate 7.5 second periods of continuous O_2 with 7.5 seconds of no flow until negative pressure excursions were again sensed. The second safety mechanism was activated by sensed respiratory rates greater than 50 breaths per minute. Tachypnea of that magnitude produced a 7.5 second interval of continuous flow at the prescribed flow rate, followed by return to the usual demand mode. If the sensed respiratory rate was again over 50 breaths per minute, another 7.5 seconds of continuous flow was initiated. This mechanism thus produces nearly continuous oxygen flow in the event of marked tachypnea. The third safety feature allowed continuous oxygen flow at the prescribed flow rate in the event of power failure or failure of the sensing device.

Protocol

The study protocol was approved by the Research Medical Center Institutional Review Board and each subject signed an appropriate consent form. Spirometric data were obtained while patients were clinically stable and no longer than six months prior to participation in this study. Each subject was evaluated seated at rest, during walking exercise and during sleep. The seated resting portion of the study began with each subject seated in a comfortable chair breathing room air. Oxyhemoglobin saturation was monitored continuously using an ear oximeter. After 30 minutes, arterial blood was obtained for measurement of blood gases and oxyhemoglobin saturation. Oxygen was then administered at 2 liters per minute for one hour by either COS or CFNC system with the order of system usage varied randomly. Arterial blood gas studies were obtained at the conclusion of the hour. Subjects were then placed back on room air and had repeat room air arterial blood gas samples obtained after ear oximetry indicated a return to a stable room air oxyhemoglobin saturation. Oxygen was then administered for one hour using the alternative oxygen delivery system. Arterial blood gas sampling was again performed at the conclusion of the second oxygen delivery system study period. Arterial blood gas values and oxygen conservation were evaluated.

Each subject performed the exercise segment of the study twice, once using the CFNC and once with the COS. As with the seated resting studies, the order of oxygen delivery system usage was varied randomly. Exercise was performed on a treadmill set at zero grade. Treadmill speed was chosen for each subject during a one to two minute acclimation run during which oxygen was administered at 2 liters per minute by standard cannula. The treadmill speed chosen for testing was one at which pulse rate did not increase more than 20 percent from baseline, and one which the subject felt could be maintained comfortably for four to five minutes. Subjects rested between acclimation and the first study run, and again between exercise runs receiving standard cannula oxygen until oxyhemoglobin saturations and pulse rates returned to baseline. For each patient, measurements of oxyhemoglobin saturation were made at equivalent work rates and time durations for CFNC and COS. In addition to ear oximetry, all patients were monitored by ECG during exercise. Oxyhemoglobin saturation changes and oxygen conservation were compared for the two study runs on each subject.

Sleep studies were done at night in a darkened, well heated and ventilated room normally used for polysomnography at our medical center. Subjects began the sleep studies at their usual bedtime hour and were simply permitted to sleep according to their individual preferences for position in bed while wearing a standard nasal cannula. The oxygen delivery system was switched remotely at one hour intervals from CFNC to the COS, without changing the nasal cannula. The initial oxygen delivery system was randomly assigned. The nasal cannula was worn throughout the night and in no case did it come off the patient. Studies were performed during direct patient observation but without EEG quantitation of the period of time that patients actually slept. Patients appeared to sleep adequately, and no patient complained of sleeplessness.

Oxyhemoglobin saturation was monitored by ear oximetry, and oxygen used was evaluated as previously described during all three portions of the study. The oxygen used during administration by COS was expressed as a percentage of that used with CFNC by dividing oxygen utilized during administration by COS by oxygen utilized during administration by CFNC and multiplying by 100 percent.

RESULTS

Seated Rest

Table 2 lists the results of blood gas testing after one hour of seated rest on the two oxygen delivery systems and the percentage oxygen use with the COS. As Figure 1 illustrates, arterial P_{O_2} values achieved by the two systems fall very near the line of identity. Oxygen saturation data obtained from ear oximetry yielded very similar results, but the increased sensitivity of oxygen partial pressure measurements in the range of values observed lead us to emphasize blood gas data for this portion of the study. The safety features generating continuous flow when respiratory rate was less than eight breaths per minute occasionally activated in all patients. The high breath rate feature generating continuous flow for respiratory rate

Table 2—*Results of Seated Resting Study*

Subject	PaO_2 CFNC, mm Hg*	PaO_2 COS, mm Hg	$\frac{\text{COS } O_2 \text{ Used}}{\text{CFNC } O_2 \text{ Used}} \times 100\%$
1	69	64	51%
2	80	87	50%
3	73	68	33%
4	84	83	39%
5	95	83	50%
6	105	110	45%
Mean (±SD)	84 (14)	83 (16)	45% (7%)

*PaO_2 measured after one hour.

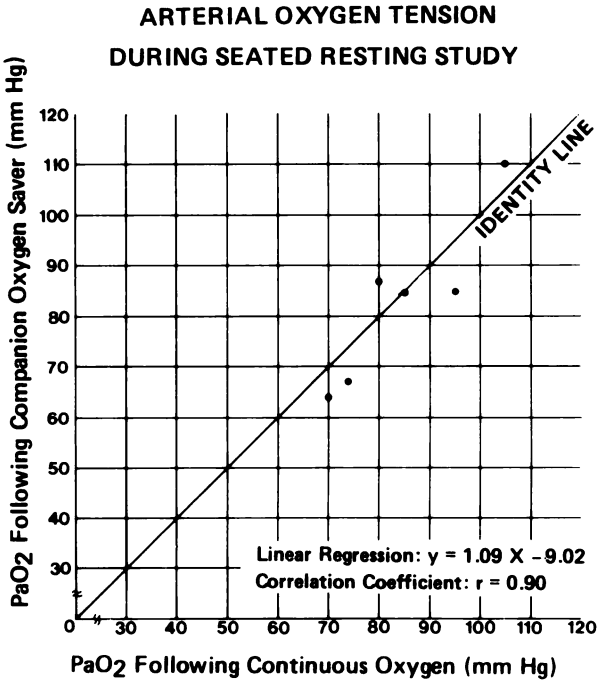

FIGURE 1. The arterial P_{O_2} during seated rest with oxygen delivered by continuous flow nasal cannula is plotted against the arterial P_{O_2} obtained utilizing the companion oxygen saver.

greater than 50 was activated in three of six patients. Both features were activated primarily by talking. Oxygen savings varied from subject to subject but the COS utilized an average of 45 percent of the oxygen utilized by CFNC.

Exercise Study

Table 3 displays average and low oxygen saturation results during continuous flow oxygen and with the COS. Average saturation was determined by averaging ear oximeter readings at one minute intervals. As with the seated resting portion of the study, there was no significant difference between the two oxygen delivery systems in their ability to maintain adequate oxygenation in our study subjects. The oxygen saving was similar to that in the resting study with the COS utilizing an average of 44 percent as much oxygen as CFNC. The safety mechanism generating continuous flow oxygen in response to respiratory rate greater than 50 breaths per minute was observed to be activated in two cases and in both cases it functioned appropriately.

Sleep Study

Table 4 displays arterial oxygen saturation and use of oxygen by the COS relative to CFNC during sleep. The average arterial oxygen saturation was determined by averaging ear oximeter readings obtained at 15-minute intervals. Arterial oxygenation was similar for the two systems and the COS utilized an average of 39 percent as much oxygen as the CFNC. The safety mechanism generating continuous flow oxygen when a respiratory rate of less than eight breaths per minute was sensed was activated in three patients and functioned appropriately.

DISCUSSION

The development of oxygen delivery systems designed to maintain adequate arterial oxygenation while utilizing less oxygen has been motivated by the desire to reduce the cost of oxygen administration and to provide patients with prolonged oxygen availability from portable oxygen sources. Although there has been increasing evidence that these goals can be achieved, the widespread use of oxygen conserving devices awaits demonstration that these devices are durable and will function reliably under all circumstances of daily life. Our data confirm previous observations concerning the efficacy of demand oxygen systems during seated rest and during exercise[6-11] and provide the first demonstration of their efficacy during sleep. When compared with CFNC, the COS required 45 percent as much oxygen during seated rest, 44 percent as much oxygen during exercise, and 39 percent as much oxygen during sleep.

The demonstration of efficacy of demand oxygen systems during sleep is of particular importance both because sleeping is an activity which occupies a significant percentage of time each day and because there has been concern that demand oxygen systems will fail to sense inspiratory pressure swings when sleeping patients breathe with open mouths. In three of six patients, we did observe episodes of opened

Table 3—*Results of Exercise Study*

Subject	CFNC, Avg Sat	CFNC, Low Sat	COS, Avg Sat	COS, Low Sat	$\frac{O_2 \text{ Utilized COS}}{O_2 \text{ Utilized CFNC}} \times 100\%$
1	94%	94%	94%	92%	47%
2	91%	87%	92%	89%	52%
3	92%	89%	91%	89%	23%
4	94%	91%	94%	91%	40%
5	94%	92%	97%	96%	45%
6	92%	83%	93%	88%	55%
Mean (± SD)	93% (5%)	89% (4%)	94% (2%)	91% (3%)	44% (11%)

Table 4—*Results of Sleep Study*

Subject	CFNC, Avg Sat	CFNC, Low Sat	COS, Avg Sat	COS, Low Sat	$\frac{O_2 \text{ Utilized COS}}{O_2 \text{ Utilized CFNC}} \times 100\%$
1	94%	91%	93%	90%	43%
2	94%	88%	93%	88%	64%
3	95%	88%	94%	87% (0.1 Min Below 88%)	22%
4	96%	89%	96%	87% (0.5 Min Below 88%)	28%
5	97%	91%	97%	91%	46%
6	93%	70% (20 Min Below 88%)	95%	82% (15 Min Below 88%)	29%
Mean (±SD)	95% (2%)	86% (8%)	95% (2%)	88% (3%)	39% (15%)

mouth breathing during which nasal pressure fluctuations did not activate synchronous pulse flow of oxygen, but under these circumstances, the seek-deliver safety feature of the COS activated continuous oxygen delivery according to previously described design features. There was, thus, no difference in the efficacy of the COS and CFNC in maintaining arterial oxygen saturation during sleep.

The oxygen savings reported by other investigators utilizing demand oxygen systems have been variable. Oxygen utilization relative to CFNC during seated rest has ranged from approximately 70 percent[7,8] to as little as 11 percent.[11] The cause for this variability is uncertain, though it is best accounted for by differences in design features of the demand systems. Oxygen savings in our study were very similar to those of Rinow and Saltzman[10] who used a device which was similar to ours.

Devices other than demand oxygen systems have been developed to conserve oxygen. The reservoir nasal cannula, for instance, has been demonstrated to provide oxygen savings of approximately 50 percent. This device has not gained widespread acceptance due in part to patient objections concerning its appearance, and this has led to the development of a less obtrusive pendant storage device.[5] Use of the transtracheal oxygen catheter has also been reported to reduce oxygen use by slightly more than 50 percent. This device is cosmetically very acceptable but requires surgical placement and involves the inconvenience of having to be removed and cleaned twice daily.[12]

Oxygen savings resulting from the use of demand oxygen systems will vary according to the severity of each patient's gas exchange abnormality and with the design characteristics of the system being used. Nonetheless, their use should result both in cost savings and increased duration of oxygen availability from portable systems for most patients. The demonstration that the COS can provide adequate nocturnal oxygenation, as well as adequate oxygenation during seated rest and during exercise, supports the further development of demand oxygen systems for use in the home and in institutional settings.

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