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Delivered Oxygen Concentrations Using Low-Flow and High-Flow Nasal Cannulas

Richard B Wettstein RRT, David C Shelledy PhD RRT, and Jay I Peters MD

INTRODUCTION: Nasal cannulas are commonly used to deliver oxygen in acute and chronic care settings; however, there are few data available on delivered fraction of inspired oxygen (F_{IO_2}). The purposes of this study were to determine the delivered F_{IO_2} on human subjects using low-flow and high-flow nasal cannulas, and to determine the effects of mouth-closed and mouth-open breathing on F_{IO_2} . **METHODS:** We measured the pharyngeal F_{IO_2} delivered by adult nasal cannulas at 1–6 L/min and high-flow nasal cannulas at 6–15 L/min consecutively in 10 normal subjects. Oxygen was initiated at 1 L/min, with the subject at rest, followed by a period of rapid breathing. Gas samples were aspirated from a nasal catheter positioned with the tip behind the uvula. This process was repeated at each liter flow. Mean, standard deviation, and range were calculated at each liter flow. F_{IO_2} during mouth-open and mouth-closed breathing were compared using the dependent t test for paired values, to determine if there were significant differences. **RESULTS:** The mean resting F_{IO_2} ranged from 0.26–0.54 at 1–6 L/min to 0.54–0.75 at 6–15 L/min. During rapid breathing the mean F_{IO_2} ranged from 0.24–0.45 at 1–6 L/min to 0.49–0.72 at 6–15 L/min. The mean F_{IO_2} increased with increasing flow rates. The standard deviation (± 0.04 – 0.15) and range were large, and F_{IO_2} varied widely within and between subjects. F_{IO_2} during mouth-open breathing was significantly ($p < 0.05$) greater than that during mouth-closed breathing. **CONCLUSIONS:** F_{IO_2} increased with increasing flow. Subjects who breathed with their mouths open attained a significantly higher F_{IO_2} , compared to those who breathed with their mouths closed. *Key words:* oxygen, nasal cannula, delivered oxygen concentration, F_{IO_2} . [Respir Care 2005;50(5):604–609. © 2005 Daedalus Enterprises]

Introduction

Low-flow nasal cannulas are commonly used in the acute and chronic care settings to deliver oxygen therapy. There is consensus that the nasal cannula is a low-flow device,

but disparities exist between published fraction of inspired oxygen (F_{IO_2}) ranges at specific liter flow settings.^{1–4}

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A review of the literature found little research on human subjects where the F_{IO_2} delivered by nasal cannula was measured. Kory et al⁵ measured nasopharyngeal oxygen concentrations at 4, 6, 8, and 10 L/min via nasal cannula. More recently, Bazuaye et al⁶ measured expired oxygen concentrations at 1 and 2 L/min on chronic obstructive

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Richard B Wettstein RRT presented a version of this report at the OPEN FORUM of the 49th International Respiratory Congress of the American Association for Respiratory Care, held December 8–11, 2003, in Las Vegas, Nevada.

The cannulas and bubble humidifiers were donated by Salter Labs Inc, Arvin, California.

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pulmonary disease patients, while Waldau et al⁷ measured fraction of expired oxygen (F_{EO_2}) and F_{IO_2} at 2, 4, and 6 L/min.

Recently a high-flow nasal cannula (Salter Labs, Arvin, California) has been released for which no published data were found. The utility of this device is in question, as Cairo and Pilbeam state, "oxygen flows higher than 6 L/min do not produce significantly higher F_{IO_2} ."¹

The literature is also unclear as to the effects breathing with the mouth open (oral breathing) versus with mouth closed (nasal breathing) has on the F_{IO_2} . Kory et al⁵ measured F_{IO_2} on 5 subjects on 6, 8, and 10 L/min while breathing with mouth open and mouth closed, and found no statistically significant differences, although they noted the "mouth-open position provided oxygen concentrations either equal to or greater than the mouth-closed position." Green⁸ reported no significant differences between mouth-open and mouth-closed breathing, but with only 2 subjects and 1 flow rate. By contrast, Poulton et al⁹ compared tracheal F_{IO_2} during mouth-open and mouth-closed breathing on nasal cannula at 1, 2, 4, 6, and 10 L/min. The authors reported a significantly higher ($p < 0.001$) F_{IO_2} with mouth-closed breathing; however, the study used only one healthy subject for the measurements. Dunlevy et al¹⁰ found similar results with 15 healthy subjects breathing at 2 L/min via nasal cannula.

The first objective of this study was to determine the delivered F_{IO_2} measured in healthy volunteers at each liter flow (1–6 L/min for low-flow nasal cannulas, 6–15 L/min for high-flow nasal cannulas), while at rest and during rapid breathing. The second objective of this study was to compare the effect of breathing with the mouth open versus with the mouth closed on F_{IO_2} while receiving oxygen via nasal cannula at each liter flow (1–6 L/min for low-flow nasal cannulas, 6–15 L/min for high-flow nasal cannulas).

Methods

Prior to collecting data, the accuracy of the oxygen analyzer used in the study was assessed by comparing the analyzed results of different F_{IO_2} delivered, by a Bird oxygen blender (Viasys Healthcare, Conshohocken, Pennsylvania). The comparison was made between the Hudson polarographic oxygen analyzer (Hudson RCI, Temecula, California) that was used in the study and the SensorMedics metabolic cart (SensorMedics, a division of Viasys, Yorba Linda, California). Before the comparison was performed, a 2-point (high/low) calibration was done on the metabolic cart, and a 1-point ($F_{IO_2} - 1.0$) calibration was done on the Hudson oxygen analyzer. Various F_{IO_2} settings were set on the Bird blender, and simultaneous readings were taken from the metabolic cart and the oxygen analyzer and recorded. The analyzer was determined to be accurate, as the variance of F_{IO_2} settings on the blender and

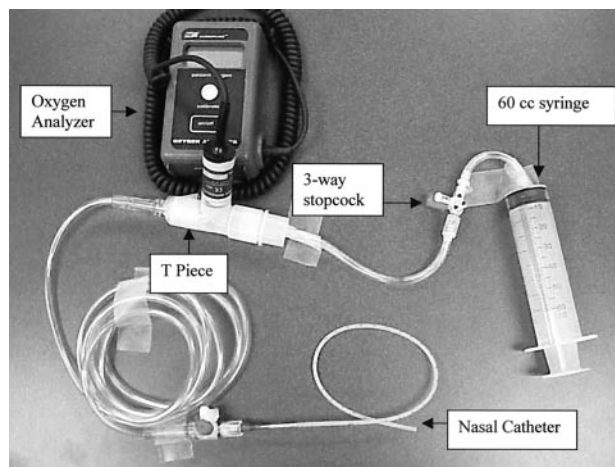


Fig. 1. Sampling system prior to nasal catheter insertion.

readings for the oxygen analyzer and the metabolic cart were never more than 0.01 for blended gas samples ranging from an F_{IO_2} of 0.21 to 1.0.

Ten healthy volunteers participated in the study, using a protocol approved by the institutional review board. Subjects were selected using the nonprobability method of convenience sampling. Volunteers who met the inclusion criteria of being normal, healthy individuals with no evidence of acute or chronic cardiopulmonary disease were enrolled in the study. After obtaining informed consent, the participants provided the following information: age, sex, height, weight, and history of reaction to lidocaine. Their ages ranged from 22 to 28 years old. Seven women and 3 men took part in the study.

Gas sampling for F_{IO_2} used the method described by Kory et al.⁵ Prior to beginning oxygen administration, each subject had a #8 French nasal catheter inserted through a nare, with the tip positioned immediately behind the uvula. The catheter was lubricated with 2% lidocaine jelly before insertion. Placement was confirmed by visualizing the tip of the catheter, using a penlight and having the subject open the mouth widely and say, "Ah." If required, a tongue depressor was also used. The nasal catheter's proximal end was connected to a syringe stopcock T-piece system with the oxygen analyzer in line (Fig. 1). Pulling back on the syringe plunger extracts a gas sample from the subject's pharynx, and exposes it to the oxygen analyzer at the T-piece. The 3-way stopcock allows the sample to be dumped to the atmosphere prior to the next sample being drawn.

Oxygen was administered via the low-flow nasal cannula (model Ref 1600, Salter Labs, Arvin, California) at flows of 1–6 L/min and via the high-flow nasal cannula (model Ref 1600HF, Salter Labs, Arvin, California) at flows of 6–15 L/min, consecutively. The nasal cannulas were attached to a high-flow bubble humidifier (model Ref 7900, Salter Labs, Arvin, California). Oxygen therapy

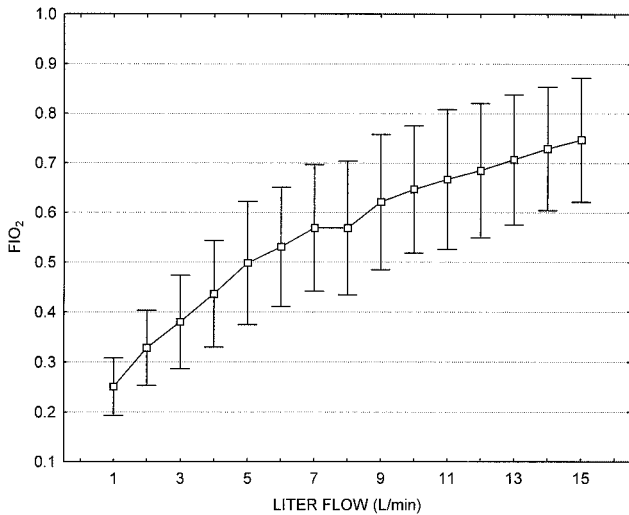


Fig. 2. Mean \pm SD for pharyngeal fraction of inspired oxygen (F_{IO_2}) at selected liter flows. Includes all values obtained (mouth open and mouth closed) during resting breathing.

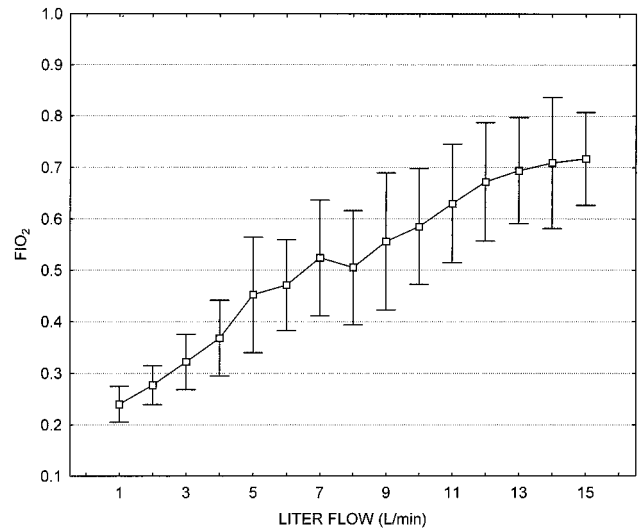


Fig. 3. Mean \pm SD for pharyngeal fraction of inspired oxygen (F_{IO_2}) at selected liter flows during rapid breathing.

was initiated on the low-flow nasal cannula at 1 L/min. Using the oxygen sampling system described above, gas samples (approximately 60 mL) were withdrawn from the pharynx during inspiration and directed to the oxygen analyzer for measurement of F_{IO_2} . Specifically, 3 samples were obtained while the subject breathed through the nose, with mouth closed. Next, subjects were instructed to breathe through their mouths. Three more samples were obtained while the subject breathed with the mouth open, and, lastly, one sample was obtained while the subject was asked to double his or her respiratory rate for a period of one minute. The same procedure was repeated at each liter flow setting on the low-flow nasal cannula and high-flow nasal cannula. Each sample was recorded as a data point, from which all ranges, means, and standard deviations were calculated. Each subject completed the study in approximately 90 min.

We compared the pharyngeal F_{IO_2} obtained while breathing with mouth closed and mouth open using the *t* test for dependent samples, with $p < 0.05$ being significant.

Results

Pharyngeal F_{IO_2}

The mean and standard deviation pharyngeal F_{IO_2} at each liter flow are displayed in Figure 2. At rest, the mean F_{IO_2} ranged from 0.26 to 0.75 at flow rates of 1–15 L/min. This figure includes the results of all gas samples. No discrimination was made between breathing with the mouth open or with mouth closed. As the set oxygen flow increased, there was a corresponding increase in the F_{IO_2} being delivered to the subject. The F_{IO_2} was lower (0.24–

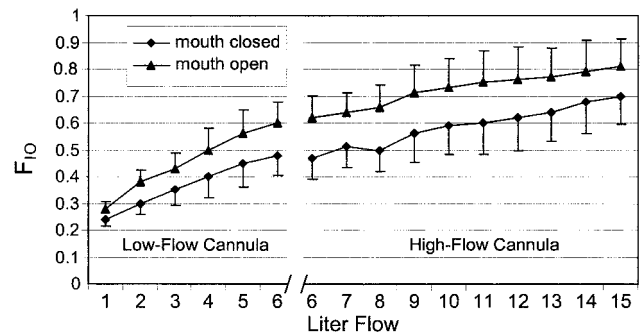


Fig. 4. Mean \pm SD for pharyngeal fraction of inspired oxygen (F_{IO_2}) at selected liter flows while breathing at a resting level with the mouth closed (lower data line) and open (upper data line).

0.72) with the higher inspiratory flow requirements associated with rapid breathing (Fig. 3).

Mouth-Open (Oral) Versus Mouth-Closed (Nasal) Breathing

Figure 4 displays the mean \pm SD analyzed pharyngeal F_{IO_2} on samples obtained for each flow setting while breathing with mouth closed and with mouth open. There were significant differences ($p < 0.05$) in F_{IO_2} between mouth-open and mouth-closed breathing at each liter flow, with mouth-open breathing resulting in a higher F_{IO_2} in each case (Table 1). In general, as the set oxygen flow increased, the F_{IO_2} increased in both groups, but both the mean and the high and low values of the range were higher at each liter flow, with one exception, while subjects were breathing with mouth open, compared to subjects breathing with their mouths closed.

Table 1. F_{IO_2} During Mouth-Closed and Mouth-Open Breathing

Flow (L/min)	Mean F_{IO_2}		p*
	Mouth Closed	Mouth Open	
Low Flow			
1	0.24	0.28	0.003
2	0.30	0.38	< 0.001
3	0.35	0.43	0.001
4	0.40	0.50	< 0.001
5	0.45	0.56	< 0.001
6	0.48	0.60	< 0.001
High Flow			
6	0.47	0.62	< 0.001
7	0.51	0.64	< 0.001
8	0.50	0.66	< 0.001
9	0.56	0.71	< 0.001
10	0.59	0.73	< 0.001
11	0.60	0.75	< 0.001
12	0.62	0.76	< 0.001
13	0.64	0.77	< 0.001
14	0.68	0.79	< 0.001
15	0.70	0.81	0.001

F_{IO_2} = fraction of inspired oxygen
 *All values were significant ($p > 0.003$)

Discussion

Pharyngeal F_{IO_2}

The results support the rule that F_{IO_2} increases with increasing flow, particularly on the low-flow or standard nasal cannula. In general, mean F_{IO_2} increased for each increase in liter flow during resting (increased on average 0.056) and rapid breathing (increased on average 0.042). It must be noted that the standard deviations and ranges were large, demonstrating the potential inaccuracy of correlating a liter flow with an estimated F_{IO_2} . The wide variation in delivered F_{IO_2} may reflect what is generally accepted (ie, that when using low-flow oxygen delivery devices, the F_{IO_2} varies unpredictably and is affected by many different factors). As the equipment used was consistent, these differences must occur because of subject-dependent variables, including tidal volume (V_T), respiratory rate, and inspiratory gas flow rate. Thus, when using nasal cannulas, the therapist must carefully monitor arterial blood gases or pulse oximetry trends to determine the best liter flow to maintain adequate oxygenation.

With the high-flow nasal cannula, the mean F_{IO_2} also rose fairly consistently with each increase in liter flow, although to a lesser degree than with the low-flow cannula (at-rest average rise/L 0.056 with the low-flow nasal cannula and 0.023 with the high-flow nasal cannula). With the high-flow cannula, trying to predict the F_{IO_2} based on the

liter flow will also potentially result in errors. The average range of F_{IO_2} on each liter flow on the high-flow cannula was 0.35, compared to a range of 0.20 on the low-flow cannula, so the likelihood of accurately predicting F_{IO_2} based on liter flow may be less with the high-flow nasal cannula.

In spite of the wide variance in device performance, it is apparent that the high-flow nasal cannula is capable of providing moderate to high F_{IO_2} . Given the increased patient comfort and compliance associated with the use of nasal cannulas, compared to that of oxygen mask devices, the high-flow cannula may provide an attractive and cost-efficient alternative for the delivery of moderate-to-high F_{IO_2} . Although there is a special high-flow bubble humidifier (model Ref 7900, Salter Labs, Arvin, California), which is recommended for usage with the high-flow nasal cannula, there may be issues related to adequate humidification and/or patient comfort with prolonged usage. We would recommend additional research to investigate these potential problems.

When subjects were asked to double their respiratory rate, we did not monitor their volumes or end-tidal carbon dioxide. Although some of our subjects volunteered that they felt symptoms of hyperventilation (dizziness or tingling sensation), we cannot quantify their alveolar ventilation. Thus, subjects' V_T may have increased, decreased, or stayed the same as during resting breathing. The number of samples drawn during rapid breathing was limited to one in order to minimize the symptoms of hyperventilation.

Our mean F_{IO_2} values were generally higher than those found in the literature. In 1998, Waldau et al⁷ used oxymetry and blood sampling to calculate F_{IO_2} , using a modification of the alveolar gas equation. They studied 10 normal subjects on 2, 4, and 6 L/min via nasal cannula, and published calculated F_{IO_2} values of 0.33, 0.4, and 0.48 associated with those liter flows. Our data showed a mean of 0.34, 0.45, and 0.54 on the same liter flows. This could be explained 2 ways. Our data for subjects breathing with mouth closed showed F_{IO_2} values of 0.30, 0.40, and 0.48 at 2, 4, and 6 L. These numbers are lower than or identical to those reported by Waldau et al. They did not specify whether their subjects were breathing with mouth open or mouth closed, so the subjects may have been breathing with mouth closed. In addition, their technique for calculating the F_{IO_2} may explain the difference from our measured results.

Open-Mouth (Oral) Versus Closed-Mouth (Nasal) Breathing

Our data indicated a higher delivered F_{IO_2} for subjects while breathing with the mouth open, as compared to breathing with the mouth closed. The results from both the low- and high-flow nasal cannula during mouth-open breathing

demonstrated significantly ($p < 0.05$) higher mean F_{IO_2} values at every liter flow, when compared to mouth-closed breathing. Note that the standard deviations and ranges were large for both groups, with considerable overlap between the 2 groups. Based on the raw data, of 480 mouth-open and 480 mouth-closed samples drawn, the F_{IO_2} during mouth-open breathing was higher than the F_{IO_2} during mouth-closed breathing for 94% (449/480) of the samples.

Other studies have found either no significant difference between mouth-open and mouth-closed breathing^{5,8} or a significantly higher F_{IO_2} during mouth-closed breathing, compared to mouth-open breathing.^{9,10} The number of studies that have been done is small, but they have developed all 3 possible outcomes: no significant difference between open-mouth and closed-mouth breathing on F_{IO_2} ; mouth-closed breathing provides a superior F_{IO_2} to mouth-open breathing; and our findings, in which mouth-open breathing provides a superior F_{IO_2} to mouth-closed breathing.

Our findings could be due to a number of different factors. First, they may be due to the reservoir effect of the nose, pharynx, and potentially the oral cavity. Breathing with the mouth open may provide a larger anatomic reservoir, by allowing oxygen to completely suffuse the nasal cavity during exhalation. With inhalation, the nasal oxygen is entrained and results in a higher F_{IO_2} . Studies looking at the effects of adding a mechanical reservoir, such as a mustache or pendant to the nasal cannula, have demonstrated an increase in the delivered oxygen and saturation by pulse oximetry.^{3,11,12} Therefore, increasing the anatomic reservoir could reasonably be expected to also increase the F_{IO_2} . During "nasal" breathing, gas is expelled through the nasal passageway during exhalation, limiting the reservoir effect of the nose and nasopharynx. Breathing with the mouth closed also reduces the volume of the oral cavity.

A second explanation may be that the higher F_{IO_2} associated with mouth-open breathing is an artifact of our sampling system. As the catheter tip is positioned in the nasopharynx, it may preferentially sample gas from this location. During mouth-open breathing, pure oxygen from the cannula may fill the nasal cavity and the nasopharynx. Thus, when drawing a sample from the catheter positioned in the nasopharynx, a higher F_{IO_2} may be obtained. Interestingly, the seminal study by Kory et al⁵ on the effects of mouth-open versus mouth-closed breathing used a catheter placement and measuring system similar to our study. Although they did not find statistically significant differences between the 2 breathing patterns, they noted that "the concentrations were either equal or greater during mouth-open breathing versus mouth closed."⁵ To quote Kory, "While we would not interpret our data as indicating that the mouth-open position is superior, our results provide strong evidence that the mouth-open position does not lessen the effectiveness of oxygen administration by either the nasal catheter or the nasal cannula."⁵ The raw

data for the 5 subjects on 6 L/min by nasal cannula showed a mean F_{IO_2} for mouth-open breathing of 0.44 versus 0.42 for breathing with the mouth closed.⁵ Three out of 5 samples were greater during mouth-open versus mouth-closed breathing, with the largest difference being an F_{IO_2} of 0.10.⁵ These findings are consistent with our study. Statistical significance may not have been attained by Kory et al, as this portion of their study only had 5 subjects and 3 measurements, one on each of 3 flow rates (6, 8, and 10 L/min).

We believe the results of the Dunlevy et al¹⁰ study, higher F_{IO_2} during mouth-closed breathing, may have been an artifact of their methodology. During "mouth closed" breathing, the subjects' mouths were actually open, but one-way valves allowed gas to enter only through the nose. Their subjects breathed in through their noses and out through their mouths. This is an artificial breathing pattern for normal or pulmonary subjects. Having subjects exhale through their mouths enhances the reservoir function of the nose by allowing 100% oxygen to accumulate in the nose and nasopharynx throughout exhalation. With the next inspiration, the gas accumulated in these anatomic reservoirs may significantly and artificially raise the measured F_{IO_2} . With our methodology, subjects breathing with their mouths closed will breathe in and out through their noses, thus removing the high oxygen concentration during exhalation, replacing it with gas with a lower F_{IO_2} .

The study by Poulton et al⁹ is unclear as to their methodology but does state that they used "intermittent spirometry and continuous inspection" of end-tidal carbon dioxide. This would suggest that their only subject was exhaling through his mouth, which, if true would then be affected by the same methodological artifact as the Dunlevy et al study.¹⁰

The study by Green⁸ found no significant difference between F_{IO_2} with mouth-open or mouth-closed breathing. However, that study included only 2 subjects, and at 1-L flow, which may not have provided a large enough sample to establish trends, let alone significance.

There were a number of limitations to our study. First, our subjects were young, healthy volunteers, which may limit the generalizability of our results. Another was the lack of tracheal gas samples, although in a study by Schacter et al,¹³ pharyngeal measurements reflected the same F_{IO_2} as tracheal measurements. The lack of V_T and inspiratory flow-rate measurements does not allow us to determine whether the wide variance in F_{IO_2} on the same liter flow was due to changes in these variables. We considered measuring V_T , but felt it would significantly alter the normal breathing pattern on nasal cannula, adding potential for further error. If subjects breathe out with the mouth open while not wearing nose clips, some gas may exit through the nose, providing inaccurate volume measurements. A further limitation is that the placement of the

catheter through the nasal cavity may have added resistance to oxygen flow from the nasal cannula.

Conclusions

At rest, the mean F_{IO_2} delivered by nasal cannula ranged from 0.26 to 0.75, and during rapid breathing from 0.24 to 0.72 at flow rates of 1–15 L/min. In general, increasing flow increased F_{IO_2} ; however, there was wide variation in delivered F_{IO_2} across subjects. In spite of the wide variance in device performance, it is apparent that high-flow nasal cannulas are capable of providing moderate-to-high F_{IO_2} values. In addition, subjects breathing with mouth open attained a significantly ($p < 0.05$) higher F_{IO_2} , compared to those breathing with mouth closed. When using nasal cannulas, clinicians should be aware of device limitations affecting the delivery of expected oxygen concentrations.

ACKNOWLEDGMENTS

We would like to thank Claudia Cantu, Jana Rodriguez, and Lizzette Benavidez for their work on data collection and compilation for this study. We would also like to express our appreciation to Carlos Garza, at the VA Hospital, for his contribution to the completion of this study, and the respiratory students at The University of Texas Health Science Center at San Antonio for volunteering to be study subjects.

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