

Comparison of Respiratory Event Detection by a Polyvinylidene Fluoride Film Airflow Sensor and a Pneumotachograph in Sleep Apnea Patients*

Richard B. Berry, MD; Gary L. Koch; Steven Trautz; and Mary H. Wagner, MD

Study objectives: Compare the ability of a polyvinylidene fluoride (PVDF) thermal sensor and a pneumotachograph to detect respiratory events in patients with obstructive sleep apnea.

Design: Single night of monitoring, single blinded scorer.

Setting: Veterans Affairs medical center.

Patients: Ten male subjects with obstructive sleep apnea.

Interventions: Nasal-oral airflow was simultaneously detected by a PVDF thermal sensor attached to the upper lip and a pneumotachograph in a mask over the nose and mouth.

Measurements: Events were scored from display views showing only the airflow tracings of the sensor in question and the events scored from that sensor. The apnea-hypopnea index was computed using two definitions for hypopnea. Hypopnea-1 was defined as a 50% reduction in flow for ≥ 10 s in duration. Hypopnea-2 was defined as any reduction in airflow for ≥ 10 s associated with a 3% drop in the arterial oxygen saturation or followed by an arousal. The level of agreement (κ) for the sensors was determined by comparing whether or not they identified candidate events determined by a second blinded scorer.

Results: For the apnea-hypopnea-1 index (mean \pm SD), the event rate for the pneumotachograph (26.0 ± 27.9 events/h) was slightly greater than that for the PVDF sensor (20.1 ± 27.1 events/h; $p < 0.05$). For the apnea-hypopnea-2 index, the event rate for the pneumotachograph (29.4 ± 26.8 events/h) and for that of the PVDF sensor (26.4 ± 25.9 events/h) were similar (difference not significant). The mean ± 2 SD difference was 3.0 ± 8.5 events/h. The level of agreement between the sensors was in the "good range," whereby $\kappa = 0.69$. For 20 randomly selected breaths per patient, the maximum deflections of the PVDF sensor varied linearly with pneumotachograph airflow deflections.

Conclusion: The PVDF sensor compared favorably with a "gold standard" method of detecting respiratory events during sleep in patients with obstructive sleep apnea.

(CHEST 2005; 128:1331-1338)

Key words: airflow; pneumotachograph; sleep apnea

Abbreviations: AHI = apnea-hypopnea index; hypopnea-1 = 50% reduction in flow for ≥ 10 s; hypopnea-2 = any reduction in airflow for ≥ 10 s that was associated with a 3% drop in arterial oxygen saturation or was followed by an arousal; PVDF = polyvinylidene fluoride; RERA = respiratory effort-related arousal

The traditional heat-sensitive devices that have been used to detect airflow during sleep studies (thermocouples and thermistors) are limited by slow response times and signal changes that are not

linearly proportional to changes in flow. These devices are generally satisfactory for the detection of apnea but are not as accurate for detecting hypopneas (reduction in airflow) when compared with accurate measures of airflow.¹⁻³ The monitoring of nasal pressure has gained popularity as a method for detecting respiratory events during sleep studies.^{4,5} The nasal pressure signal is proportional to the flow squared.⁶ The change in the shape of the nasal pressure signal (inspiratory flattening) is also useful for detecting airflow limitation and increased upper airway resistance.^{5,7} This method is more sensitive than traditional thermal devices for detecting hypop-

*From the Departments of Medicine (Dr. Berry, Mr. Koch, and Mr. Trautz) and Pediatrics (Dr. Wagner), University of Florida, Gainesville, FL.

This study was supported by a grant from Dymedix. Manuscript received September 27, 2004; revision accepted January 11, 2005.

Reproduction of this article is prohibited without written permission from the American College of Chest Physicians (www.chestjournal.org/misc/reprints.shtml).

Correspondence to: Richard B. Berry, MD, Box 100225 HSC, University of Florida, Gainesville, FL 32610; e-mail: sleep_doc@msn.com

neas.^{4,8} However, in patients who breathe mainly through the mouth, the signal may not always be satisfactory.

A new type of thermal sensor using polyvinylidene fluoride (PVDF) film has been developed with a faster response time than those of traditional thermal devices. Sensors based on this technology appear to produce signals that more accurately estimate changes in airflow. The PVDF signal is proportional to the difference in temperature between the two sides of the film. A single PVDF device can detect both nasal and oral airflow. The purpose of this study was to compare the ability of a PVDF sensor (Dy-medix Corp; Minneapolis, MN) and a pneumotachograph placed in a mask over the nose and mouth to detect respiratory events in patients with obstructive sleep apnea.

MATERIALS AND METHODS

Ten male patients with a mean (\pm SD) age of 54.8 ± 11.1 years and a mean body weight of 217.4 ± 53.8 lb with known obstructive sleep apnea were studied on a single night. The patients had undergone testing showing an apnea-hypopnea index (AHI) > 5 events/h during the previous year. Three were using continuous positive airway pressure treatment at the time of the study. The subjects signed an informed consent form before participating in the study. The project was approved by the Human Studies Subcommittee of the Malcom Randall Veterans Affairs Medical Center and the Institutional Review Board of the University of Florida.

Digital polysomnography was performed (Aurora System; Grass-Telefactor; Warwick, RI). A central and occipital EEG, right and left electrooculograms, a chin electromyogram, and ECG tracings were recorded. Sleep was manually staged in 30-s epochs using standard criteria.⁹ Arousals were defined by American Academy of Sleep Medicine criteria.¹⁰ A PVDF sensor was placed on the upper lip to sense nasal and oral flow. The PVDF devices used in this study were disposable airflow sensors (model 2002; Dymedix Corp). The devices supplied to us were off-the-shelf and were not specifically made for the study.

A tight-fitting mask over the nose and mouth with a pneumotachograph (Hans Rudolph; Kansas City, MO) in the mask opening was also used to detect airflow. The pneumotachograph was connected to a sensitive pressure transducer (Hans Rudolph) and calibrated with a rotometer. A low amount of bias flow was added to the mask to prevent heat and moisture buildup. After giving subjects a topical anesthesia of the nose and throat, a fluid-filled esophageal catheter was placed with the tip between 34 and 36 cm from the nares. The catheter was attached to a transducer and a pressurized fluid system to maintain catheter patency.¹¹ The transducer was calibrated by a U-tube manometer. Chest and abdominal movements were detected by piezoelectric bands. Arterial oxygen saturation was continuously monitored by pulse oximetry. The subjects were continuously observed by the sleep technologist using a low-light video-monitoring system but were not restrained to sleeping in any particular posture. The gain setting on the PVDF channel was adjusted so that the deflections during quiet breathing were roughly equivalent to those of the pneumotachograph.

Event Definitions

The digital scoring system (Gamma Reviewer; Grass-Telefactor) allowed the construction of multiple displayed views and a separate scoring file for each view. First, sleep was staged, and arousals were scored. Respiratory events were then determined on three separate passes each using one of three custom display views. These included a PVDF scoring view (with no pneumotachograph or esophageal pressure tracings visible), a pneumotachograph flow view (with no PVDF sensor or esophageal pressure tracings visible), and an esophageal pressure pass (with no PVDF sensor or pneumotachograph tracings visible). EEG, electrooculogram, electromyogram, ECG, chest and abdominal tracings, arterial oxygen saturation, sleep stage, and marked arousals were also visible on each custom view. The scoring was performed by the same individual who was blind to events marked in other views (scoring passes). Each scoring view had a separate scoring file, so that the results of other scoring passes were not available to the scorer. The passes were scored in random order.

An apnea was defined based on either PVDF sensor tracings or pneumotachograph flow tracings (apnea-PVDF or apnea-pneumotachograph) as fluctuations of $< 10\%$ from baseline tracings for ≥ 10 s in duration. Hypopnea-1 was defined as a 50% reduction in flow for ≥ 10 s. Hypopnea-2 was defined as any reduction in airflow for ≥ 10 s that was associated with a 3% drop in arterial oxygen saturation or was followed by an arousal.¹² Using these definitions and the PVDF sensor or pneumotachograph views, hypopnea-1 PVDF and hypopnea-2 PVDF events or hypopnea-1 pneumotachograph and hypopnea-2 pneumotachograph events were scored. AHIs (in number of events per hour of sleep) were computed for the PVDF and pneumotachograph views and for both hypopnea definitions (apnea-PVDF-hypopnea-1-PVDF, apnea-PVDF-hypopnea-2-PVDF, apnea-pneumotachograph-hypopnea-1-pneumotachograph, and apnea-pneumotachograph-hypopnea-2-pneumotachograph).

Respiratory Arousals

Esophageal pressure-effort arousals were defined as arousals occurring after a crescendo increase in the esophageal pressure deflections over ≥ 10 s or high-pressure deflections (> 15 cm H₂O) followed by an arousal. In both conditions, an abrupt decrease in esophageal pressure deflection after arousal had to be present. Respiratory arousals for the PVDF and pneumotachograph sensors were defined as arousals associated with a PVDF sensor, pneumotachograph apnea or hypopnea-2. The respiratory arousal indexes for the PVDF and pneumotachograph sensors were compared with the esophageal pressure-effort arousal index.

Agreement Analysis

An analysis of the level of agreement (κ) was also performed.¹³ Candidate events were identified by an independent scorer who was blinded to any event scoring. Candidate events were defined as discernable changes in airflow lasting ≥ 5 s on either the PVDF sensor or pneumotachograph tracings. The number of candidate events identified as apneas or hypopnea-2 events by both sensors, the PVDF sensor but not pneumotachograph, the pneumotachograph but not PVDF sensor, and neither sensor were identified. The scorer of respiratory events was blind to the placement of candidate events. A 2×2 table was constructed, and the κ was calculated.

PVDF Flow vs Pneumotach Flow Relationship

We compared the values of maximum peak-to-peak deflections in the pneumotachograph flow and PVDF flow signal magnitude for a series of 20 breaths that were randomly chosen over a range of flow rates for each patient (200 pairs total). The magnitude of the PVDF signal was normalized for each patient by finding a factor that made the mean of the 20 breath magnitudes for the PVDF sensor and the pneumotachograph equal. For example, if the pneumotachograph flows were 2, 4, and 6 (mean, 4), and the PVDF breaths were 10, 20, and 30 (mean, 20), then each PVDF breath was multiplied by 0.2. The signal magnitudes at different times during the same breath were not compared because of phase differences in the signal. It was thought that the maximum deflection is the main magnitude variable used to score events on thermal sensors.

Data Analysis

Variables for the PVDF sensor and the pneumotachograph were compared by the paired *t* test. In addition, a Bland-Altman plot was constructed by plotting the difference in the values of the two sensors vs the average value for each subject.¹³ The number of respiratory arousals detected by PVDF sensor, pneumotachograph, and esophageal catheter were compared using analysis of variance. A *p* value of < 0.05 was considered to be statistically significant. The 200 pairs of PVDF and pneumotachograph deflections were analyzed by plotting the two against each other and determining the correlation coefficient. Statistical analysis was performed using a computer program (SigmaStat; Systat Software Inc; Richmond, CA).

RESULTS

A sample tracing of a hypopnea with visible PVDF sensor, pneumotachograph, and esophageal pressure tracings is shown in Figure 1. In this example, there is a > 50% reduction in both the

pneumotachograph and PVDF signals. In Figure 2, an event qualifying as an hypopnea-2 (but not an hypopnea-1) is illustrated. Finally, an obstructive apnea is shown in Figure 3. The mean (\pm SEM) values of the total sleep time and amount of rapid eye movement sleep were 269 ± 17.3 and 23.9 ± 5.9 min, respectively. The AHI results are displayed in Table 1. The subjects had moderate obstructive sleep apnea, as determined by the frequency of events (*ie*, AHI). The mean arterial oxygen desaturation index (*ie*, drops in arterial oxygen saturation of $\geq 4\%$ per hour of sleep) was 6.3 ± 4.9 events/h. For apneas, the mean value detected by the PVDF sensor was lower, but the mean difference was only about three events per hour. For the apnea-hypopnea-1 index, the mean value detected by the PVDF sensor was significantly lower than the value detected by the pneumotachograph (Table 1). The correlation of the corresponding values was very high, and the mean (± 2 SDs) difference between the values for the PVDF and pneumotachograph sensors for the subjects was 6.1 ± 14.8 events/h.

For the apnea-hypopnea-2 index, the mean values for the group using the two types of sensors did not differ statistically (Table 1) with a mean (± 2 SDs) difference of 3.0 ± 8.5 events/h. The correlation of the values obtained from the two types of sensors was also high. A Bland-Altman plot of the mean difference vs the average value of the apnea-hypopnea-2 index is shown in Figure 4. In all but one subject, the pneumotachograph apnea-hypopnea-2 index value was higher.

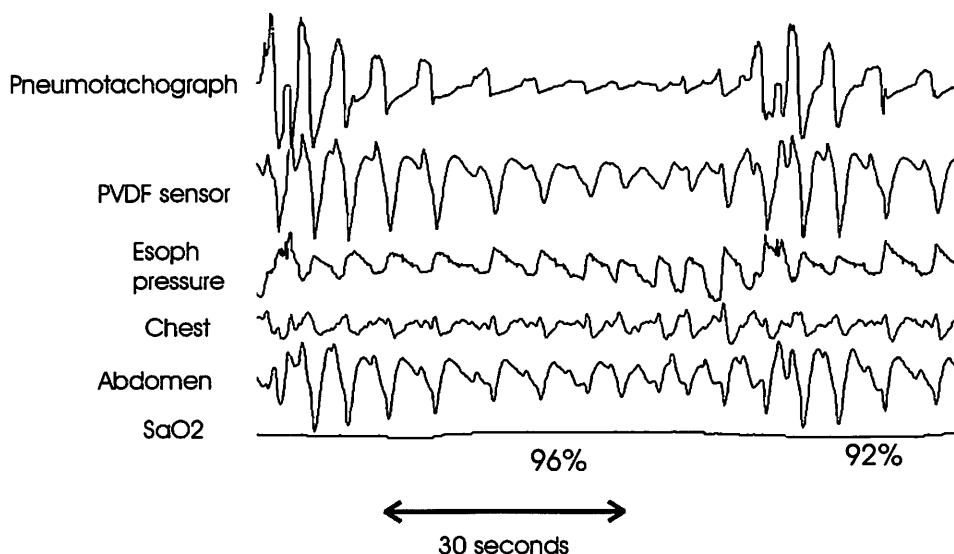


FIGURE 1. An example of a hypopnea with PVDF sensor, pneumotachograph, and esophageal pressure tracings is shown. This hypopnea would qualify as either a hypopnea-1 or hypopnea-2. This view is presented for comparison but was not used for scoring events (see "Materials and Methods" section).

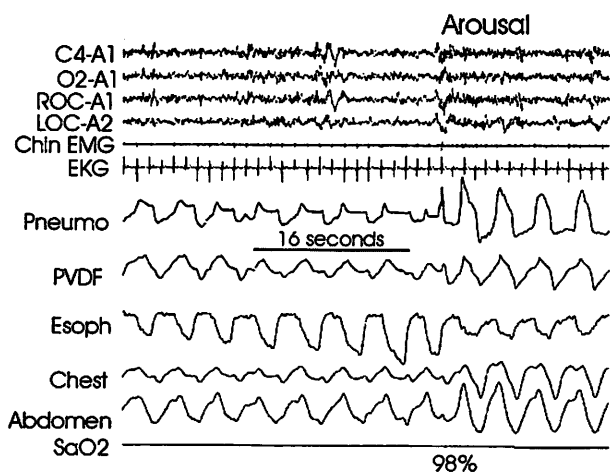


FIGURE 2. An example of an hypopnea with PVDF sensor, pneumotachograph, and esophageal pressure tracings is shown. This hypopnea would qualify as a hypopnea-2, because the flow reduction was $< 50\%$, but the respiratory event is followed by an arousal. This view is presented for comparison but was not used for scoring events (see "Materials and Methods" section).

Sensor Agreement, Respiratory Arousal Index, and Esophageal Pressure Measurements

The 2×2 agreement table for all of the events with any discernable change in flow is shown in Table 2. The κ value computed from Table 2 is 0.69, which demonstrates good agreement. Of note, the range of κ values for good agreement is 0.61 to 0.80, and for very good agreement it is from 0.81 to 1.0.¹³ The values for use of the two sensors and for esophageal pressure monitoring were also compared for the ability to detect respiratory arousals (Table 3). The three values of the respiratory arousal index were similar and did not differ statistically.

The esophageal pressure deflections for hypopnea-2 events that did not qualify as hypopnea-1 events or have an associated drop in the arterial

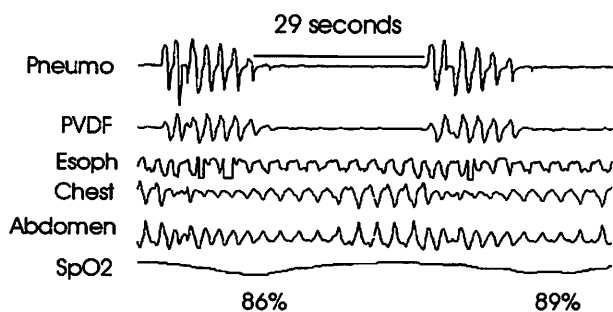


FIGURE 3. An example of an obstructive apnea with PVDF sensor, pneumotachograph (Pneumo), and esophageal (Esoph) pressure tracings is shown. This view is presented for comparison but was not used for scoring events (see "Materials and Methods" section).

oxygen desaturation were analyzed. These events were characterized by a more subtle reduction in flow (a $\leq 50\%$ reduction) that was followed by an arousal. The mean (\pm SEM) esophageal pressure deflections for the PVDF events and pneumotachograph events were 16.5 ± 2.7 and 16.8 ± 3.0 cm H₂O, respectively (difference not significant).

Flow Deflections for the PVDF Sensor and Pneumotachograph

An analysis for the group using 20 pairs (PVDF deflection and pneumotachograph deflection) for each of the 10 subjects (200 total pairs) showed a correlation coefficient of 0.84 ($p < 0.001$). A plot of the pairs is shown in Figure 5. The regression line and the line of identity are shown. Although there was some scatter, the deflections from the two sensors were proportional to each other. The line of identity and the regression line are very similar. In Figure 6, examples of pneumotachographs vs PVDF sensor tracings from four patients are shown during periods of variability in airflow.

DISCUSSION

The main finding of this study was that the PVDF sensor accurately detected respiratory events compared with the "gold standard" of a pneumotachograph-mask system. The PVDF sensor gave slightly smaller AHI values, with the magnitude of the difference depending on the definition of hypopnea. Using the apnea-hypopnea-2 definition, the mean difference in event detection between the sensors was only three events per hour. The hypopnea-1 definition, requiring a 50% reduction in airflow, gave a greater difference in the AHI values, suggesting that the fall in flow during hypopneic events was somewhat greater with the pneumotachograph than with the PVDF sensor or that the pneumotachograph sensor changes were easier to identify secondary to the flattened airflow profile. However, in either case the difference would not be clinically significant except in patients with the mildest change in flow.

The signal produced by the PVDF film is 150,000 times stronger than the signal produced by a thermocouple. In contrast to thermistors and thermocouples, the PVDF sensor responds linearly and nearly instantaneously to changes in temperature.¹⁴ Thermocouples have a response time of around 1 s, whereas the PVDF response time is on the order of 0.005 s.¹⁴ In this study, we did not compare the PVDF sensor to a traditional thermal airflow sensor (*ie*, thermistor or thermocouples). Rather, we compared the PVDF sensor to a "gold standard" mea-

Table 1—Respiratory Events by the Two Methods of Detecting Airflow*

Variable	PVDF Sensor	Pneumotachograph	PVDF vs Pneumotachograph	Correlation Coefficient
Apnea index, /h	8.85 ± 7.2	11.9 ± 8.8	p = 0.07	0.99 (p < 0.05)
Apnea + hypopnea-1 index, /h	20.1 ± 27.1	26.0 ± 27.9	p < 0.05	0.96 (p < 0.05)
Apnea + hypopnea-2 index, /h	26.4 ± 25.9	29.4 ± 26.8/h	p = NS	0.98 (p < 0.05)

*Values given as mean ± SD unless otherwise indicated.

surement of airflow (pneumotachograph). Berg et al² compared thermistors, nasal pressure, and summed respiratory inductance plethysmography to airflow determined using a head-out-of-box body plethysmograph during simulated hypoventilation in awake subjects. The analysis compared the different devices as the percentage of baseline flow. The thermal devices correlated least well with the body plethysmograph (coefficient range, 0.42 to 0.63). Norman et al,⁴ using either “usual” or “liberal” criteria, found that a thermistor detected either 30.1% or 78.6% of events detected by nasal pressure, respectively. The usual criteria required a 50% drop in flow, whereas the liberal criteria required any drop in flow. Hernández et al⁸ compared nasal pressure and thermistor airflow monitoring in 12 patients with suspected sleep apnea. The AHI determined by nasal pressure monitoring was significantly higher than that determined by thermistor (37.1 vs 27.1 events/h, respectively). The definition of hypopnea was equivalent to our definition of hypopnea-2.

The current study also compared the deflections of signals from the PVDF sensor and a pneumotachograph. We found that the PVDF signal deflections varied linearly with pneumotachograph flow deflections over a wide range of flow rates. Farré et al¹ compared a traditional thermistor signal to pneu-

motachograph flow rates using a respiratory nose model and flow generator (sinusoidal and square wave patterns). They found the signal from the thermistor to be nonlinear compared with the pneumotachograph signal. For example, a 50% reduction in pneumotachograph flow resulted in only an 18% reduction in thermistor flow signal. In addition, the thermistor signal was strongly dependent on the size of the nares and the distance of the sensor from the nose. We found a linear relationship between the flows detected by the PVDF sensor and those detected by the pneumotachograph (Fig 5). Thus, the PVDF sensor appears to be superior to thermistors and thermocouples with regard to the relationship of the signal to the actual flow. There was some variability in the relationship of the PVDF signal and pneumotachograph flow (Fig 5). This may have been related to different nasal orifice sizes and/or the distance of the PVDF sensor from the nose in individual subjects. Of note, although the PVDF sensor signal tracks changes in flow magnitude, it does not show the flattening seen in the pneumotachograph signal (Fig 6).

A number of limitations in our study must be mentioned. First, we used disposable sensors. It is possible that the behavior of sensors could vary from batch to batch. However, the same possibility could be present in multiple-use devices. Second, there is always the possibility that the sensor response varied over a night of use. To determine whether there was any evidence of performance variability over the night, we performed the following analysis. The sleep period time was divided into equal parts. The apnea-hypopnea-2 index value for each period was determined by both the PVDF sensor and pneumotachograph. The ratio of the values of the PVDF

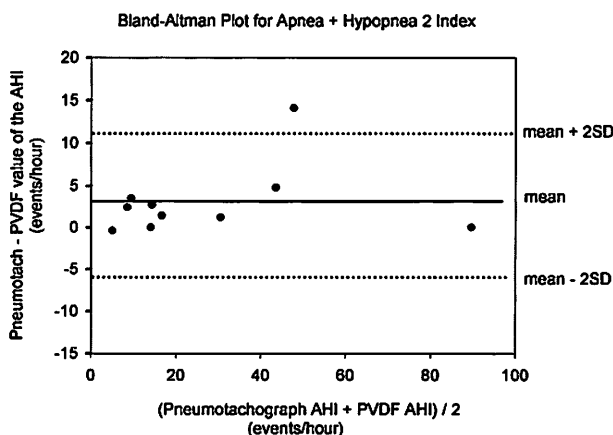


FIGURE 4. A Bland-Altman plot of the difference in the apnea-hypopnea-2 indexes for each subject (pneumotachograph-PVDF) plotted against the average of the pneumotachograph AHI and PVDF AHI using the hypopnea-2 definition.

Table 2—Apnea or Hypopnea-2 Events From Candidate Events*

	Pneumotachographs	
	Yes	No
Yes	1065	90
No	186	554

*Candidate events defined by any discernable drop in flow by either sensor for ≥ 5 s.

Table 3—Respiratory Arousal Index*

Variables	Respiratory Arousal Index, Events/h
PVDF sensor	13.4 ± 19.6
Pneumotachograph	13.9 ± 20.1
Esophageal pressure	12.4 ± 21.3

*Values given as mean ± SD unless otherwise indicated. For the pneumotachograph and PVDF sensor, a respiratory arousal is one following an apnea or hypopnea-2 event.

sensor to those of the pneumotachograph ratio was determined for each subject. For the first part of the night, the mean ratio was 0.88 ± 0.05 , and for the second part of the night it was 0.89 ± 0.05 (difference not significant). Thus, the ability to detect events over the course of the night did not vary.

A third possible concern is that, because there was some heating of air inside the mask, it is possible that the thermal device functioned differently when a mask was in place than when no mask in place. The PVDF sensor responds to differences in temperature between the two sides of the film rather than the absolute temperature. We measured the temperature inside our mask set-up worn by a subject at the bias flow used in the study. The air temperature in the mask increased from room temperature (22°C) to about 27°C and then stabilized. The temperature of the side of the film facing away from the airflow is difficult to estimate, given the constant change in temperature of the other side of the film secondary to inhalation of air at mask temperature and exhalation of air at body temperature. Given this uncer-

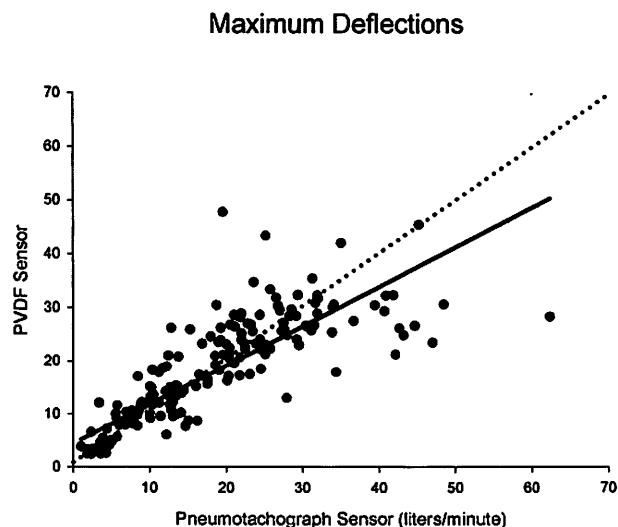


FIGURE 5. The corresponding maximum peak-to-peak deflections of 20 randomly chosen breaths over a range of flow rates for each subject for the pneumotachograph and PVDF sensors are shown. The dotted line is the line of identity. The solid line is the regression line ($r = 0.84$; $p < 0.001$).

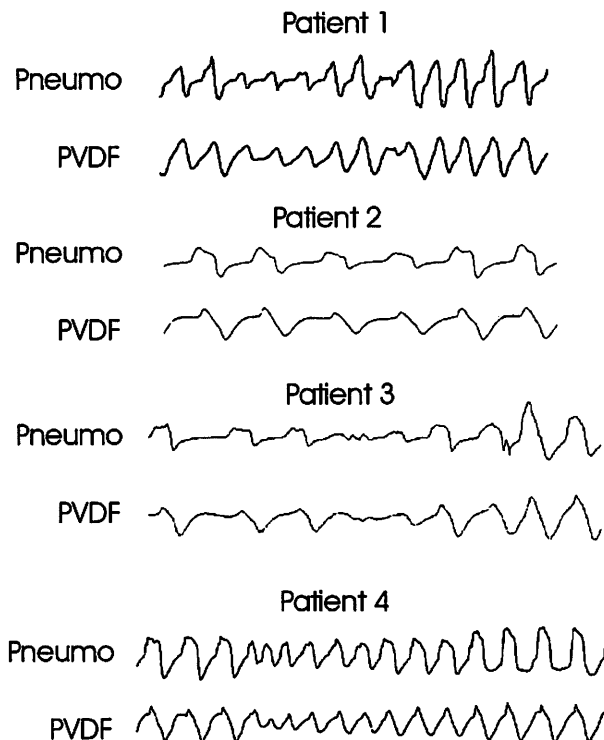


FIGURE 6. Tracings from the pneumotachograph (pneumo) and PVDF sensors are shown for four patients during periods of variable airflow. As seen from the tracing, the PVDF signal gives a good picture of changes in the magnitude of airflow. The PVDF signal shape does not show the flattening seen in the pneumotachograph signal.

tainty, it still seems likely that an air temperature higher than room temperature inside the mask would reduce the PVDF signal for a given amount of airflow. However, respiratory events are determined by changes from the baseline PVDF signal rather than the absolute magnitude of the signal. This should minimize any effects of mask temperature on the identification of respiratory events. To substantiate this contention, we measured the pneumotachograph signal and PVDF signal in a subject immediately after placing a mask and then when the mask temperature had increased to 27°C. The subject varied the pattern of breathing, and the relationship between the pneumotachograph and the PVDF signal was determined as in Figure 5. The pneumotachograph-PVDF sensor relationship for two mask temperatures was very similar (Fig 7), with a slightly higher signal for a given flow at the lower mask temperature (as predicted). The slopes of the regression lines are nearly parallel. Therefore, we do not think that using a mask changed the ability of the PVDF sensor to detect respiratory events.

Thermal sensors have the advantage of not requiring sensitive pressure transducers. Thermal sensors may also give a more reliable signal in patients who

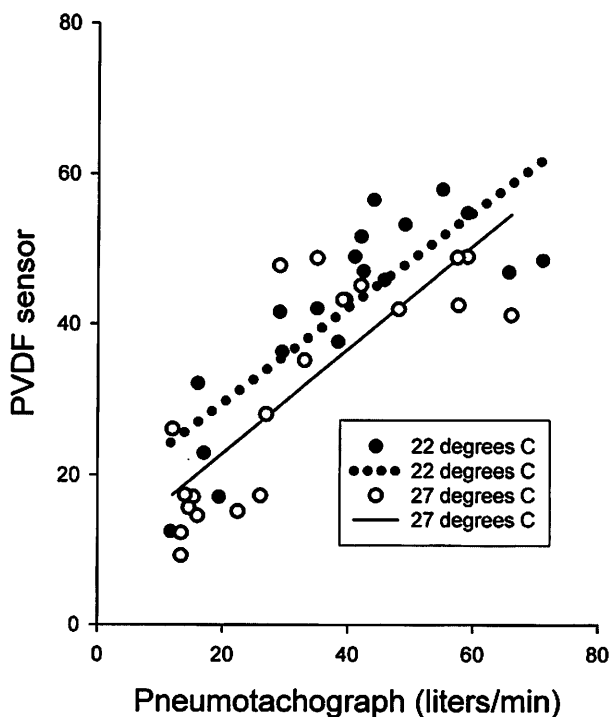


FIGURE 7. The corresponding maximum peak-to-peak deflections of randomly chosen breaths over a range of flow rates for the same subject for the pneumotachograph and PVDF sensor are shown at a temperature of 22°C and 27°C inside the mask. The regression lines are nearly parallel, although the one for the lower temperature is slightly shifted upward.

primarily breathe through the mouth. Whereas some deflection in the nasal pressure signal may occur during mouth breathing,⁸ the relationship of nasal pressure and flow is altered with the signal no longer proportional to the flow squared. Some sleep centers use a nasal-oral thermal device in conjunction with a pressure monitor and find the signals to provide complimentary information.¹⁵ In studies comparing thermal devices and nasal pressure, the results could vary with the relative amount of nasal and oral flow.¹⁶ In our study, the relative amount of nasal or oral breathing would not be expected to affect the pneumotachograph flow.

A potential advantage of nasal pressure monitoring over monitoring with thermal devices is the ability of the former to detect airflow limitation and respiratory effort-related arousals (RERAs).¹⁷ The “gold standard” for RERA detection is esophageal pressure monitoring.³ A RERA is defined as a sequence of breaths that is characterized by increasing respiratory effort leading to an arousal from sleep that does not meet the criteria for an apnea or hypopnea. The events must meet the following two criteria: a duration of ≥ 10 s; and a pattern of progressively more negative esophageal pressure terminated by a sudden change in pressure to a less negative level and an

arousal. One study¹⁷ found that respiratory arousal detection by esophageal pressure and flow-limitation arousals by nasal pressure were very similar in the patients studied. Flow-limitation arousals were defined as periods of flattening of the nasal pressure signal, followed by an arousal and the restoration of a round shape to the signal. The main goal of our study was to compare AHI values. However, depending on the definition of hypopnea that is used, a given event may be either a hypopnea or a RERA. We compared the total respiratory arousal index (defined as arousals after apnea or hypopnea-2 events per hour of sleep). Thus, arousals after any detectable (by PVDF or pneumotachograph sensor) change in airflow from baseline followed by a desaturation or arousal were compared with arousals after changes in esophageal pressure (*ie*, esophageal pressure arousals). Using this hypopnea definition, there were essentially no airflow events of ≥ 10 s in duration followed by an arousal that would not be called *hypopneas*. For this reason, we did not separately evaluate RERAs. However, because the arterial oxygen desaturation index was only 6.3 events/h and the apnea index values were about 9 and 12 events/h (Table 1), most events detected by both sensors could be considered RERAs if a 4% oxygen desaturation was required as part of the hypopnea criteria.¹⁸ Thus, whereas the PVDF sensor did not show a flow plateau identifying flow limitation, it was sensitive enough to identify changes in flow preceding the majority of respiratory arousals (identified by esophageal pressure deflections).

In summary, the PVDF sensor accurately detected respiratory events and changes in airflow preceding respiratory arousals compared with the detection accuracy of the “gold standard” mask pneumotachograph in a group of patients with a varying severity of obstructive sleep apnea. The deflections in the PVDF sensor vary linearly with flow as measured by the pneumotachograph. This result differs from previously published data¹ on the relationship of the thermistor signal and flow. Whereas this study did not directly compare the PVDF sensor and a traditional thermistor, the results suggest that the PVDF sensor is likely to be a more sensitive instrument for detecting changes in airflow during sleep compared with traditional thermal devices. The PVDF sensor does not show flow plateaus during airflow limitation. However, easily identifiable changes in the PVDF signal did precede nearly all of the respiratory arousals identified by the pneumotachograph or esophageal pressure. Thus, the PVDF sensor provides a useful alternative to the other sensors used to detect respiratory events in patients with obstructive sleep apnea.

ACKNOWLEDGMENT: We thank Dymedix Corporation for their support.

REFERENCES

- 1 Farré R, Montserrat JM, Rotger M, et al. Accuracy of thermistors and thermocouples as flow-measuring devices for detecting hypopneas. *Eur Respir J* 1998; 11:179–182
- 2 Berg S, Haight JS, Yap V, et al. Comparison of direct and indirect measurements of respiratory airflow: implications for hypopneas. *Sleep* 1997; 20:60–64
- 3 American Academy of Sleep Medicine Task Force. Sleep-related breathing disorders in adults: recommendation for syndrome definition and measurement techniques in clinical research. *Sleep* 1999; 22:667–689
- 4 Norman RG, Ahmed MM, Walsleben JA, et al. Detection of respiratory events during NPSG: nasal cannula/pressure sensor versus thermistor. *Sleep* 1997; 20:1175–1184
- 5 Hosselet J, Norman RC, Ayappa I, et al. Detection of flow limitation with nasal cannula/pressure transducer system. *Am J Respir Crit Care Med* 1998; 157:1461–1467
- 6 Montserrat JM, Farré R, Ballester E, et al. Evaluation of nasal prongs for estimating nasal flow. *Am J Respir Crit Care Med* 1997; 155:211–215
- 7 Clark SA, Wilson CR, Satoh M, et al. Assessment of inspiratory flow limitation invasively and non-invasively during sleep. *Am J Respir Crit Care Med* 1998; 158:713–722
- 8 Hernández L, Ballester E, Farré R et al. Performance of nasal prongs in sleep studies. *Chest* 2001; 119:442–450
- 9 Rechtschaffen A, Kales A, eds. A manual of standardized terminology techniques and scoring system for sleep stages of human sleep. Los Angeles, CA: Brain Information Service/Brain Research Institute, University of California Los Angeles, 1968
- 10 American Sleep Disorders Association. EEG arousals: scoring rules and examples; a preliminary report from the Sleep Disorders Atlas Task Force of the American Sleep Disorders Association. *Sleep* 1992; 15:173–184
- 11 Flemale A, Gillard C, Dierckx JP. Comparison of central venous, oesophageal and mouth occlusion pressure with water filled catheters for estimating pleural pressure changes in healthy adults. *Eur Respir J* 1988; 1:51–57
- 12 American Academy of Sleep Medicine Task Force. Sleep-related breathing disorders in adults: recommendation for syndrome definition and measurement techniques in clinical research. *Sleep* 1999; 22:667–689
- 13 Altman DG. Practical statistics for medical research. New York, NY: Chapman Hall, 1999; 403–407
- 14 Alfini S. Data on file. Minneapolis, MN: Dymedix Corporation
- 15 Farré R, Rigau J, Montserrat JM, et al. Relevance of linearizing nasal prongs for assessing hypopnea and flow limitation during sleep. *Am J Respir Crit Care Med* 2001; 163:494–497
- 16 Heitman SJ, Atkar RS, Jajduk EA, et al. Validation of nasal pressure for the identification of apneas/hypopneas during sleep. *Am J Respir Crit Care Med* 2001; 166:386–391
- 17 Ayappa I, Norman RG, Krieger AC, et al. Non-invasive detection on respiratory effort related arousals (RERAs) by nasal cannula/pressure transducer system. *Sleep* 2000; 23:763–771
- 18 Meoli AL, Casey KR, Clark RW. Hypopnea in sleep disordered breathing in adults. *Sleep* 2001; 24:469–470