Noncontact Monitoring of Respiration by Dynamic Air-Pressure Sensor

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We have previously reported that a dynamic air-pressure sensor system allows respiratory status to be visually monitored for patients in minimally clothed condition. The dynamic air-pressure sensor measures vital information using changes in air pressure. To utilize this device in the field, we must clarify the influence of clothing conditions on measurement. The present study evaluated use of the dynamic air-pressure sensor system as a respiratory monitor that can reliably detect change in breathing patterns irrespective of clothing. Twelve healthy volunteers reclined on a dental chair positioned horizontally with the sensor pad for measuring air-pressure signals corresponding to respiration placed on the seat back of the dental chair in the central lumbar region. Respiratory measurements were taken under 2 conditions: (a) thinly clothed (subject lying directly on the sensor pad); and (b) thickly clothed (subject lying on the sensor pad covered with a pressure-reducing sheet). Air-pressure signals were recorded and time integration values for air pressure during each expiration were calculated. This information was compared with expiratory tidal volume measured simultaneously by a respirometer connected to the subject via face mask. The dynamic air-pressure sensor was able to receive the signal corresponding to respiration regardless of clothing conditions. A strong correlation was identified between expiratory tidal volume and time integration values for air pressure during each expiration for all subjects under both clothing conditions (0.840–0.988 for the thinly clothed condition and 0.867–0.992 for the thickly clothed condition). These results show that the dynamic air-pressure sensor is useful for monitoring respiratory physiology irrespective of clothing.

Key Words: Air-pressure sensor; Respiratory; Monitor; Nonrestrictively; Sedation.

Management of patient fear and anxiety during surgical procedures is a primary concern of dental practitioners. Sedation is increasingly being used to improve patient comfort by relieving anxiety, elevating the pain threshold, rendering the patient compliant, and inducing amnesia.¹ However, many drugs used for sedation are central nervous system and respiratory

depressants that can result in decreased ventilatory response to CO₂, attenuated tidal volume, and decreased respiratory rate.^{2–5} Accordingly, respiratory monitoring during sedative procedures is crucial for early detection of adverse side effects. Many techniques and devices are available to assist in monitoring respiratory function during sedation. However, these methods require attachment of sensors directly to the patient's body, which may cause discomfort and influence the depth of sedation. Development of noncontact monitoring for respiratory status is thus needed to achieve comfortable sedation in clinical practice.

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Figure 1. Dynamic air pressure sensor.

We have already reported that dynamic air pressure enables visual monitoring of respiration.⁶ A dynamic air-pressure sensor system allows the measurement of pressure fluctuations induced by respiration without the use of a harness or sensor on the subject's body. However, in our previous report, subjects were minimally clothed. To utilize this device in the field, we must clarify the influences of clothing conditions on respiratory measurements.

The purpose of this study was to assess the ability of the dynamic air-pressure sensor to monitor respiratory status in clothed patients. Accordingly, the present study was designed to test whether the dynamic air-pressure

sensor, placed under the lumbar area of the subject, could be used for respiratory monitoring under different clothing conditions, compared with other physiological signals such as tidal volume measured by pneumotachography.

METHODS

Subjects

After we obtained approval from the institutional ethics committee and written informed consent, 12 adult volunteers were studied. Volunteers had not been taking any regular medication and were free of respiratory disease and other significant medical problems.

Measurement by Dynamic Air-Pressure Sensor

A dynamic air-pressure sensor (Body Movement Sensor BMS 21; Advance, Tokyo, Japan) was used to convert body-weight shifts due to respiratory movements into pressure fluctuations. This sensor comprised a sensor pad (dynamic air-pressure generator) enclosing a sponge to obtain an air layer of $25 \times 25 \times 4$ mm, polyvinyl chloride tubing to transmit air pressure, and a dynamic air-pressure detector comprising a piezoelectric device (air-pressure sensor), variable gain amplifier, and converter (Figures 1 and 2).

Figure 2. Structure of the dynamic air-pressure detector.

Table 1. Demographic Data

Variable	Mean (SD)	Range
Age, y	30 (6)	23–44
Weight, kg	62 (9)	43–73
Height, cm	169 (9)	148–179
Body mass index, kg/m ²	21.4 (2.0)	19.0–25.3

The sensor pad was placed on the back seat of the dental chair positioned under the central lumbar area of the subject. The obtained analog air-pressure signals showing total activity of the body were amplified and transmitted to a personal computer at a sampling rate of 1 kHz. Transmitted data had an output sensitivity of 1 mV/kPa in the frequency range of 0.1–1000 Hz.

The signal corresponding to respiration (respiratory air-pressure signal) was extracted from combined signals in the frequency range of 0.15–0.47 Hz. Furthermore, the respiratory air-pressure signal was integrated to yield volume using Chart software (AD Instruments, Bella Vista, Australia).

Measurement by Respirometry

A Wright respirometer (Ferraris Respiratory, Herford, UK) was used to measure expiration volume simultaneously for comparison with the respiratory information measured by the dynamic air-pressure sensor. Subjects breathed through a tight-fitting face mask connected to the respirometer, and the device was videotaped for analysis of expiratory tidal volume (TV_{exp}).

Procedure

Subjects wore thin cotton 2-piece clothing and reclined on a dental chair positioned horizontally. The sensor pad and the mask connected to the respirometer were set in place.

Respiratory measurements were taken under 2 conditions: (a) thinly clothed (subject lying directly on the sensor pad); and (b) thickly clothed (subject lying on the sensor pad covered with a pressure-reducing sheet made of 100% polyester with a cut pile face 30 mm in height (75 × 100 cm, Fleecy Sheet; Smithsmedical Japan, Tokyo, Japan) spread from the buttocks to the shoulders of the subject).

First, under the thinly clothed condition, subjects were instructed to breathe in a continuous pattern using 3 types of breathing: 2 deep breaths, approximately 10 natural breaths, and 5 breaths that gradually became deeper. Next, under the thickly clothed condition,

subjects were instructed to breathe the same as for the thinly clothed condition.

Data Analysis

Sequential respiratory data were obtained from 2 deep breaths, approximately 10 natural breaths, and 4 breaths gradually becoming deeper. A fifth breath after the final 4 was excluded because, in the subject's enthusiasm to make the final deepest breath, excessive body movements created an unreliable noise signal that could not be analyzed. The respiratory air-pressure signal was integrated and the time integration value of respiratory air pressure for each expiration ($\int P_{exp}$) was calculated to yield a volume measurement. TV_{exp} for each expiration was measured by the regeneration screen on the respirometer. The relationship between TV_{exp} and $\int P_{exp}$ for each clothing condition and subject was assessed according to the Pearson correlation coefficient.

Statistical Analysis

Statistical analyses were performed using StatView for Windows version 5.0 software (SAS Institute, Cary, NC). Statistical differences were considered significant for values of $P < .05$.

RESULTS

Demographic data are shown in Table 1. Respiratory air-pressure signals and TV_{exp} were recorded and analyzed for each subject under each clothing condition.

Figure 3 shows a representative respiratory air-pressure waveform and the integral waveform. The dynamic air-pressure sensor was able to receive the signal corresponding to respiration regardless of whether the subject was thinly or thickly clothed. However, comparing pressure fluctuations between the 2 conditions, the amplitude of the air-pressure signal was smaller in the thickly clothed condition than in the thinly clothed condition.

Figure 4 and Table 2 show the relationships between TV_{exp} and $\int P_{exp}$. Pearson correlation coefficients ranged from 0.840 to 0.988 for the thinly clothed condition and 0.867 to 0.992 for the thickly clothed condition. Strong correlations between TV_{exp} and $\int P_{exp}$ were observed for all subjects under both clothing conditions. However, the $\int P_{exp}$ value was smaller in thinly clothed subjects than in thickly clothed subjects with the same TV_{exp} value.

Figure 3. A representative respiratory air-pressure waveform obtained from the dynamic air pressure sensor (top) and the integral waveform (bottom) under thinly clothed (left) and thickly clothed (right) conditions.

DISCUSSION

The present study assessed the ability of the dynamic air-pressure sensor to monitor respiratory activity in clothed patients. We compared $\int P_{\text{exp}}$ extracted from respiratory movements by the dynamic air-pressure sensor to TV_{exp} for each expiration under thinly and thickly clothed conditions, revealing a strong linear correlation between $\int P_{\text{exp}}$ and TV_{exp} . These results showed that using dynamic air pressure, an observer can visually monitor respiratory status irrespective of the clothing worn by the patient.

Respiratory impairment is the most frequently reported major adverse event associated with sedation. Numerous techniques and devices are thus utilized to monitor and assess respiratory function during sedation. Traditional methods have included careful visual assessment of skin color, airway patency, and chest movements and auscultation of breath sound using a stethoscope, and electronic methods have included

capnography and pulse oximetry.⁷ However, observing chest wall movements and skin color is impractical during surgical procedures, because the patient is covered with a hospital blanket that prevents the clinician from observing chest wall movements and skin color. Conversely, a stethoscope can still be used by the clinician to monitor respiratory function, as the technique involves auditory assessment. However, the stethoscope head secured by tape to either the precordial or pretracheal region on the chest of the patient can be uncomfortable.

Recently, electronic instruments such as the pulse oximeter and capnograph have proven to be quite acceptable for monitoring respiratory status in sedated patients.^{8–13} However, measurements require attachment of sensors directly to the patient's body. An improved system is needed if respiratory monitoring is to be applied more widely in clinical settings by practitioners.

Dynamic air-pressure sensor systems allow the measurement of respiration and heartbeat movements without using a harness or sensor on the patient's body, and are beginning to see use in the research field of sleep apnea syndrome.¹⁴ Respiratory status can be monitored without attaching a sensor directly to the patient's body, allowing natural respiratory conditions.

However, noncontact monitoring systems have their own specific disadvantages, such as the influence that interposition, in other words, clothing between the patient's body and the sensor, exerts on measurement. Our results showed that amplitude of air-pressure signals under thickly clothed conditions was smaller than that under thinly clothed conditions, but the respiratory pattern remained clearly recognizable. Furthermore, the correlation between TV_{exp} and $\int P_{\text{exp}}$ was strong for all subjects regardless of clothing conditions. During inspiration, the sensor received positive pressure and the respiratory air-pressure signal waveform showed positive

Table 2. Pearson's Correlation Coefficient Between Expiratory Tidal Volume and Time Integration Values for Air Pressure for Each Subject Under Both Clothing Conditions

Subject	Thinly Clothed Condition			Thickly Clothed Condition		
	Pearson's r	n	P	Pearson's r	n	P
A	0.987	15	<.0001	0.93	13	<.0001
B	0.98	19	<.0001	0.974	13	<.0001
C	0.985	21	<.0001	0.881	22	<.0001
D	0.938	12	<.0001	0.974	13	<.0001
E	0.971	14	<.0001	0.978	15	<.0001
F	0.979	18	<.0001	0.956	19	<.0001
G	0.979	15	<.0001	0.905	12	<.0001
H	0.988	16	<.0001	0.992	14	<.0001
I	0.98	17	<.0001	0.946	16	<.0001
J	0.985	15	<.0001	0.898	14	<.0001
K	0.84	11	.0005	0.93	12	<.0001
L	0.947	14	<.0001	0.867	12	<.0001

Figure 4. Relationship between expiratory tidal volume (TV_{exp}) and time integration values for air pressure ($\int P_{exp}$) for each subject under each clothing condition. Open circles indicate data measured under thinly clothed condition; closed circles, data measured under thickly clothed condition.

deflection. Conversely, the waveform showed negative deflection during expiration. In the respiratory pressure-time integral waveform, the rising part of the wave represented an inspiration phase and the descending part represented an expiration phase. Furthermore, amplitude showed respiratory volume. An observer could thus visually monitor the breathing pattern and perceive relative changes in the amount of breath by means of the respiratory pressure-time integral waveform.

During sedative procedures, the most important side effect is respiratory depression. This depression manifests as decreased respiratory drive and, more importantly, the inability to maintain a patent upper airway, and this can lead to life-threatening hypoxemia.¹⁵ Because upper airway obstruction causes the paradoxical breathing, 2 sensor pads positioned under the central lumbar and chest area, as for respiratory inductive plethysmography,¹⁶ may make it possible to

differentiate between the chest/body movements associated with a spontaneously breathing patient with total upper airway obstruction and a spontaneously breathing patient who is adequately breathing because there is no upper airway obstruction.

CONCLUSION

Our results demonstrate that the respiratory pressure–time integral waveform from the dynamic air-pressure sensor is useful in visually monitoring respiratory physiology regardless of clothing conditions. We believe that in the future, this device will be useful for monitoring the respiratory status of clothed patients during sedative procedures.

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