Calibration of the Respiratory Inductive Plethysmograph with the Single Position Graphic Technique*

Accuracy in Different Behavior States in Lambs


Respiratory inductive plethysmography (RIP) can measure breathing patterns noninvasively. Calibration is required for rib cage and abdomen transducers utilizing breaths with different compartment contribution correlated with tidal volume measured by integrated pneumotachography (PNT). This study was performed to determine if RIP remains accurate during sleep states following calibration in the quietly awake state. We used our single position graphic calibration technique (SPG) to calculate gain factors in seven tracheostomized lambs. Validation of gain factors was accomplished by comparing tidal volume obtained simultaneously by RIP and PNT during quiet wakefulness (QW), quiet sleep (QS) and active sleep (AS). Results of the study showed that RIP was accurately calibrated during QW. Accuracy was decreased during QS and AS.

In the past decade, advances have taken place in the development of techniques to assess breathing pattern without physical airway connections.1-3 Following accurate calibration, respiratory inductive plethysmography (RIP) can measure tidal volume (VT) noninvasively, avoiding an increase in VT and decrease in respiratory frequency that may occur during mask or mouthpiece breathing.4,5 We have previously shown that RIP can be accurately calibrated using the single position graphic (SPG) technique for assessment of breathing pattern during quiet wakefulness in neonates.6,7 However, we do not know if this calibration technique will prove applicable for collection of breathing pattern data during sleep, because of the relatively large changes that occur—particularly in active sleep—in contribution of the diaphragm and rib cage to tidal volume.8

The present study was designed to determine if RIP can provide accurate VT measurement in quiet sleep and active sleep following calibration using the SPG technique during quiet wakefulness in lambs.

Materials and Methods

Animals

Seven lambs ranging in age from 13 to 21 days and in weight from 3.2 to 7.4 kg were studied. Each lamb was separated from its ewe one to two days after birth and was housed in our laboratory in a Plexiglas cage with continuous access to milk (Lamb Milk Replacer, Land O'Lakes, Inc., Fort Dodge, IA).

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Each lamb underwent one operation prior to study. For surgery, each lamb was given atropine sulfate (0.2 mg/kg subcutaneously) and ketamine hydrochloride (10 mg/kg intramuscularly) and their tracheas were intubated with a cuffed endotracheal tube. The cuff was inflated to a gas tight fit and anesthesia was maintained by ventilating the lamb's lungs with 0.5 percent to 1.0 percent halothane (Fluothane) in oxygen and nitrous oxide (3:1). An electrocardiogram and the rectal temperature were monitored during surgery; body temperature was kept as near 39°C as possible with a heating pad. The operation was done between ten and 18 days of age when electrodes for the following recordings were implanted: electrocor-ticogram (recorded from electrodes placed through burr holes to lie over the parietal cortex), electrooculogram (recorded from electrodes placed at the inner and outer canthus of the right eye), nuchal electromyogram (recorded from electrodes placed in the dorsal cervical muscle), and diaphragm electromyogram (recorded from electrodes placed transabdominally into the muscle fibers adjacent to the lateral margin of the central tendon of the right hemidiaphragm). A reference wire was sutured into the subcutaneous tissue of the scalp. The proximal end of each wire was bared and soldered to the appropriate pin of an 18-pin electrical plug which was interfaced with a backpack preamplifier during a study.

A tracheotomy also was performed and a fenestrated tracheostomy tube (Shiley, Inc, Irvine, CA) placed in the trachea. This tracheostomy tube allowed the lamb to breathe entirely through the opening of the tracheostomy tube (cuff inflated, inner cannula in place) or entirely through its upper airway (cuff inflated, decannulation cannula in place). Following surgery, the decannulation cannula was inserted into the tracheostomy tube so that air flow during tidal breathing would be through the upper airway. The lambs were allowed to recover in a Shor-Line intensive care unit for small animals (Schroer Manufacturing Company, Kansas City, MO) and were then placed in a Plexiglas study cage in our sleep laboratory but were not studied before the third postoperative day. The lambs received antibiotics (procaine penicillin G, 100,000 U/kg, gentamycin sulfate, 2 mg/kg) for five days beginning on the day of surgery.

Apparatus

Descriptions of the respiratory inductive plethysmograph (Respiritrace, Non-Invasive Monitoring System, Inc, Ardsley, NY) have been published.9,10 Briefly, the device consists of two coils of Teflon-insulated wire sewn into elastic bands which are placed about the...
rib cage (RC) and abdomen (AB) and are connected to an oscillator module (Fig 1). Changes in the cross-sectional areas of the RC and AB compartments alter the self-inductance of the wires and the frequency of their oscillations. The change in inductance is converted into a proportional direct current voltage that can be amplified and recorded. The RC band is placed around the chest with the upper border just below the axillae and the AB band is placed at the umbilical level with the upper border just below the rib cage.

During calibration and validation, tidal volume is measured using a Fleisch type-O pneumotachograph (Godart model 17212, Gould, Inc, Bilthoven, the Netherlands) attached to the inner cannula of the Shiley fenestrated tracheostomy tube. Analog signals from the calibrator-demodulator and PNT are passed through an analog to digital converter and recorded on a Z-80 based microprocessor system (Respicomp, Non-invasive Monitoring Systems, Inc, Ardsley, NY) which samples data at 20 points per second. The rib cage and abdomen signals from the calibrator-demodulator are zeroed and referenced to 1 V representing 50 ml in the calibrate mode, thus establishing the voltage-to-volume relationship. Following calibration, gain factors for the RC and AB channels are manually entered into the calibrator-demodulator.

Calibration Technique

Calibration by the SPG is based on the assumption that the respiratory system can be regarded as a simple physical system with two independent moving parts, the rib cage and abdomen. The sum of displacement of the rib cage and abdomen due to breathing, determined by inductance changes of the RC and AB bands, is then equal to the volume measured by integrated pneumotachography. Over one 20-s breath collection period, the trough-to-peak values of RC and AB displacements are measured at the same points in time as the PNT signal and the RC/PNT and AB/PNT ratios are calculated. Two breaths are selected with different RC/PNT and AB/PNT values representing different RC and AB compartment contributions. A line drawn between the two selected breaths as shown in Figure 2 and the reciprocals of the intercept of that line with the RC/PNT and AB/PNT axes are taken as gain factors for the RC and AB respectively.

Experimental Protocol

During a study, the electrophysiologic and Respitrace signals were recorded on a Grass Model 7 polygraph (Grass Medical Instruments, Quincy, MA) and the lambs were monitored on a closed circuit video system. Once the animals were laying down, the Respitrace was calibrated during quiet wakefulness using the SPG technique and the gain factors for RC and AB entered into the calibrator-demodulator. The gain factors were then validated during quiet wakefulness (QW) by comparing VT measured by RIP with VT measured by pneumotachography. The percentage of deviation from the PNT obtained volume was calculated as ([RIP volume—PNT volume] + PNT volume) x 100. If the deviation was less than 10 percent, the gain factors were validated during an epoch of quiet sleep (QS) and during an epoch of active sleep (AS). The following criteria were used to define behavioral state once the animal was laying down. During QW, the electrocorticogram shows a fast wave, low voltage pattern; there are occasional eye movements and there is tonic activity on the nuchal electromyogram. During QS, the electrocorticogram shows a slow wave-high voltage pattern; there are no eye movements and there is tonic activity on the nuchal electromyogram. During AS, the electrocorticogram shows a fast wave-low voltage pattern; there are rapid-eye movements and there is no activity on the nuchal electromyogram.

RESULTS

Rib cage and abdominal gain factors obtained during QW were 0.70±0.36 (mean ± SD) and 0.95±0.43 (mean ± SD), respectively. Volume differences between the two selected breaths used for gain calculation ranged between 0 and 6 ml (2.4±2.1, mean ± SD). Validation runs consisted of 15 consecutive breaths. Tidal volume differences of validation breaths measured simultaneously by RIP and PNT during QW, QS, and AS are listed in Table 1. Mean VT measured by RIP (36±14 ml, M ± SD) correlated well (r = 1.0) with mean VT measured by PNT (36±15 ml, mean ± SD) on seven validation runs during quiet wakefulness. Mean VT measured by RIP (35±13 ml, mean ± SD) correlated well (r = 0.97) with mean VT measured by PNT (35±14 ml, mean ± SD) on seven validation runs during quiet sleep. Poor correlation (r = 0.47)
20 s Breath Collection on Lamb # 3

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<tr>
<th>Breath #</th>
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<th>RC</th>
<th>AB/PNT</th>
<th>RC/PNT</th>
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<tr>
<td>1</td>
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<td>2</td>
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<td>3</td>
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<td>0.312</td>
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<tr>
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<td>18.1</td>
<td>10.9</td>
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<td>0.501</td>
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<td>9</td>
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<td>23.2</td>
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<td>24.3</td>
<td>9.34</td>
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2 Selected Breaths

<table>
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<tr>
<th>Breath #</th>
<th>PNT</th>
<th>AB</th>
<th>RC</th>
<th>AB/PNT</th>
<th>RC/PNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>23.2</td>
<td>18.1</td>
<td>10.9</td>
<td>0.810</td>
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<tr>
<td>10</td>
<td>24.7</td>
<td>23.2</td>
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<td>0.912</td>
<td>0.345</td>
</tr>
</tbody>
</table>

**Figure 2.** Over one 20-s breath collection period on lamb 3, the trough-to-peak values of rib cage (RC) and abdominal (AB) displacements are measured at the same points in time as the integrated pneumotachography (PNT) signal and ratios of RC/PNT and AB/PNT were calculated. Two breaths were selected, No. 8 and 10. A line was drawn between the two selected breaths. Gains were derived from the reciprocals of the intercepts of that line with the RC/PNT and AB/PNT axes.

was demonstrated between mean Vt measured by RIP (21 ± 8 ml, mean ± SD) and PNT (25 ± 11 ml, mean ± SD) on seven validation runs during active sleep. The mean percentage of deviation of RIP and PNT on seven validation runs during quiet wakefulness, quiet sleep, and active sleep was 3.1 ± 3.1 percent (mean ± SD), 8.4 ± 5.7 percent (mean ± SD), and 38.1 ± 13.1 percent (mean ± SD) respectively.

Mean Vt on seven subjects measured by PNT during quiet wakefulness correlated well (r = 0.99) with mean Vt during quiet sleep and poorly (r = 0.46) with mean Vt during active sleep. The mean and standard deviation of AB compartment contribution to Vt following calibration on seven animals was 18.1 ± 6.4 ml and 20.1 ± 11.7 ml for quiet wakefulness and quiet sleep, respectively. During active sleep the AB contribution to Vt was 20.3 ± 13.6 ml; the RC contribution to Vt was 6.6 ± 8.4 ml. Rib cage compartment contribution to Vt during quiet wakefulness was 15.1 ± 12.2 ml and 15.7 ± 14.4 ml during quiet sleep. The mean and standard deviation of respiratory frequency was 40.3 ± 12.7 breaths per minute in quiet wakefulness, 41.2 ± 15.1 breaths per minute in quiet sleep and 44.5 ± 10.7 breaths per minute in active sleep. Time required for gain calculation and validation during quiet wakefulness ranged between five and ten minutes. Subsequent validations during quiet sleep and active sleep were performed in less than one minute.

**DISCUSSION**

This study evaluated the accuracy of RIP during quiet and active sleep using gain factors calculated in the quietly awake state by our SPG calibration technique. We suspected inaccuracy of RIP during sleep states in our previous studies on human infants where the SPG technique for obtaining gain factors was utilized.

In previous studies by Tabachnik et al. and Tepper et al. gain factors for RIP were calculated using various calibration techniques on awake pediatric patients. Evidence of accuracy of RIP was not presented in quiet or active sleep states during which their ventilatory measurements were made. Dolfin et al. obtained gain factors for RIP utilizing two separate periods of quiet sleep, active sleep, or a combination of the two sleep states in 36 normal infants. Only 62
(59 percent) of 106 calibration calculations were accurate, regardless of sleep state. No evaluation of accuracy was documented during quiet wakefulness.

Our results show that gain factors obtained during quiet wakefulness with the SPG calibration technique were accurate during that behavioral state when compared with simultaneous pneumotachography but were less accurate during quiet sleep and inaccurate during active sleep (Table 1). Previous investigations of infants in the same behavioral state demonstrated wide changes in tidal volumes with maintenance of RIP accuracy.\(^7\)\(^1\) Therefore, it is our conclusion that wide changes in volume alone are not responsible for the loss of accuracy but rather the variations of the RC and AB contributions outside of those that are present during the actual validation run. This is especially significant during the RC and AB asynchrony which occurs during active sleep.

The SPG calibration technique for RIP was developed with specific objectives in mind. First, a time-efficient means of calibration was considered necessary for RIP to have clinical application. Second, the data collection periods were to be short-term and immediately following the calibration-validation procedure. Third, for intermittent data collection, the SPG technique would allow for a rapid check of gain factors prior to another data collection period with recalibration able to be accomplished within an acceptable period of time. These requirements would not allow RIP, using the present SPG calibration technique, to be an acceptable method for long-term continuous data collection which would carry the obvious potential of changes in behavioral state associated with wide variations in RC and AB contributions to tidal volume. Therefore, documentation of accuracy of RIP, through validation of the set gain factors, in behavioral states other than the state in which gain factors were calculated is necessary to have confidence in the resultant breathing pattern data when the SPG calibration method, as presently developed, is used. Determination that the gain factors are accurate should precede data collection in each behavior state studied in order to ensure accuracy of breathing pattern data.

### Table 1—Tidal Volume Differences of Breaths Measured Simultaneously by RIP and PNT During Validation of Calculated Gains*

<table>
<thead>
<tr>
<th>Vt</th>
<th>0 ± 10%</th>
<th>0 ± 20%</th>
<th>0 ± 30%</th>
<th>&gt;30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaths in quiet wakefulness (%)</td>
<td>91 (87%)</td>
<td>104 (99%)</td>
<td>105 (100%)</td>
<td></td>
</tr>
<tr>
<td>Breaths in quiet sleep (%)</td>
<td>61 (58%)</td>
<td>95 (93%)</td>
<td>105 (100%)</td>
<td></td>
</tr>
<tr>
<td>Breaths in active sleep (%)</td>
<td>1 (1%)</td>
<td>11 (11%)</td>
<td>15 (14%)</td>
<td>105 (100%)</td>
</tr>
</tbody>
</table>

*RIP, respiratory inductive plethysmography; PNT, integrated pneumotachography.

REFERENCES


Calibration of Respiratory Inductive Plethysmograph (Warren, Fewell, Alderson)