Thoracoabdominal asynchrony failed to grade airway obstructions in foals

CARRIE MILLER, ANDREW M. HOFFMAN, AND JANICE HUNTER
Department of Veterinary Clinical Sciences, Tufts University School of Veterinary Medicine, North Grafton, Massachusetts 01536

Miller, Carrie, Andrew M. Hoffman, and Janice Hunter. Thoracoabdominal asynchrony failed to grade airway obstructions in foals. J Appl Physiol 88: 2081–2087, 2000.—Respiratory inductive plethysmography (RIP) can be used to obtain a valid measure of tidal volume in humans. This device also compares the contributions to ventilation of the thorax and abdomen. Although thoracoabdominal asynchrony is a prominent clinical feature for patients with airway obstruction, the accuracy of the RIP device to assess the severity of obstruction is unclear. This study analyzes how well RIP variables reflect the degree of a fixed external inspiratory plus expiratory resistive load in foals. Foals were employed because the species and age group are commonly afflicted with respiratory disease. Eight conscious, sedated (xylazine 1.25 mg/kg body wt) foals were subjected to randomly ordered resistive loads at the airway opening and, on a separate day, to histamine aerosol challenge. During resistive loading, phase angle changed significantly, as did phase relation (P ≤ 0.05). However, no significant correlation was found between the degree of change in resistive load and the degree to which phase angle or relation was altered (r = 0.41 and 0.25, respectively). In addition, neither phase angle nor relation changed significantly with histamine challenge. We conclude that, although RIP variables changed significantly with fixed upper airway resistive loading, the degree to which they changed was erratic and therefore not useful for grading these obstructions. Furthermore, RIP variables were insensitive measures of histamine-induced bronchoconstriction.

phase angle; phase relation; respiratory inductance plethysmography; bronchoconstriction; resistive loading

Respiratory diseases are common in foals. To our knowledge, there is no objective, noninvasive monitoring system of lung mechanics in large animals. Impending respiratory failure must be assessed subjectively and by analysis of arterial blood gases. The most common etiologies of respiratory disease include bacterial pneumonia, premature birth with surfactant deficiency, chest trauma, or congenital heart disease (20, 26). As foals are prone to such respiratory diseases, yet highly ambulatory, we sought to find a noninvasive continuous monitoring system with potential accuracy for grading lung disease. Hence, foals were used as a model species to study the relationship between quantifiable RIP variables (i.e., phase angle and phase relation) and classical lung mechanics. We introduced graded resistive loads at the airway opening and, on a separate occasion, evoked bronchoconstriction by using histamine aerosol as provocative challenges.

MATERIALS AND METHODS

All procedures were approved by the Institutional Animal Care and Use Committee at Tufts University School of Veterinary Medicine.

Subjects. Eight healthy 2- to 4-mo-old mixed-breed foals (65–126 kg, mean 87.9 kg body wt) were used for this study. All foals were born at term and were obtained from a nurse mare farm within 2 wk after weaning, except for one foal (foal 8) that was kept with the mare throughout the length of the experiment. Foals were allowed to acclimate to their new environment for at least 2 days before any procedures were performed. Daily physical examinations were performed on each foal to ensure that it was free of clinical signs of disease.
(i.e., nasal discharge, abnormal lung sounds, cough, or fever). The orphan foals were stabled at night and were turned out each day into a grassy paddock for 6–8 h. They were fed a combination of mare’s milk replacer, grain, and hay. No vaccines were administered other than those given routinely to their mares 1 mo prior to parturition (equine influenza, rhinopneumonitis, Eastern and Western encephalitis, tetanus toxoid, and rabies).

RIP. Foals were sedated with xylazine (1.25 mg/kg body wt), and their heads were maintained in a horizontal position during measurements. Respitrace bands (4 cm wide, adult-size Resipbands; Ambulatory Monitoring Systems, Ardsley, NY) were placed on the foals, one at the 11th intercostal space and the other directly behind the 18th (last) rib. Measurements of thoracoabdominal asynchrony were obtained for all foals using calibrated RIP (oscillator unit, Ambulatory Monitoring Systems). The Respitrace bands were secured around the abdomen directly behind the eighteenth (i.e., last) rib, and the other around the rib cage at the eleventh intercostal space. The separate signals as well as the sum of the signals were digitized and recorded on a laptop computer. Phase angle and phase relation were determined by using a commercially available software package with a sampling rate of 50 Hz (RespiEvents version 4.2, Non-invasive Monitoring Systems, Miami Beach, FL). This system uses a qualitative diagnostic calibration (QDC) developed and described in detail by Sackner et al. (24). Basically, the QDC method is based on the isovolume maneuver equations but does not require subject cooperation or breathing through a pneumotachograph. It is carried out during a 5-min period of natural breathing during which time a baseline average is established such that the proportionality constant between the two compartments (abdomen and rib cage) is derived. The QDC has been shown to acceptably calibrate RIP for tidal volume in human adults (24) as well as newborns (2).

We used two indexes of thoracoabdominal asynchrony: phase angle and phase relation. The phase angle was calculated on a breath-by-breath basis from Lissajous curves according to principles first employed by Agostini and Maggioni (4) and later by Allen et al. (3). A minimum of 15 breaths was used to calculate each data point. This methodology assumes that breathing patterns exhibit a sinusoidal waveform and then \( \sin \phi = m/s \), where \( \phi \) is the phase angle, \( m \) is the line parallel to the abscissa on a rib cage-abdomen plot at one-half the distance between the maximal rib cage perpendicular intercept and the origin, and \( s \) is the length of a line from the maximal abdomen perpendicular intercept minus the origin. Unobstructed synchronous breathing results in a phase angle of close to 0°, increasing obstruction and subsequent asynchrony results in increasing phase angles for which 180° would be complete paradoxical motion of the rib cage and abdomen. Breathing patterns may assume a figure of eight pattern leading to erroneous phase angle measurements close to 0°. The phase relation is not subjected to this anomaly; rather, it provides an estimate of thoracoabdominal coordination that is independent of the shape of the waveforms. The phase relation is computed for each breath by using agreement and disagreement in derivative sign of the rib cage and abdomen compartments over the entire breath. It expresses the percentage agreement between the direction of rib cage and abdomen movements over the entire cycle of a breath. If both compartments move in the same direction throughout the breath a value of 0% is computed, whereas if both compartments move in the opposite direction a value of 100% is computed. Intermediate values are obtained as a function of the amount of agreement or disagreement. For example, a phase angle of 90° is equivalent to a phase relation of 43%. The deviation from the expected value of 50% reflects the error in phase angle due to the nonsinusoidal shape of the usual rib cage and abdomen waveforms (RespiEvents version 4.2, Non-invasive Monitoring Systems).

Conventional lung mechanics. The foals were fitted with a solid plastic facemask sealed 5–10 cm behind the external nares with a latex shroud, with ~80 ml of dead space. The nosepiece of the mask was attached to a pneumotachograph (Fleisch 2, OEM Medical, Lenoir, NC) connected to a differential pressure transducer (DP45-28, Validyne Engineering, Northridge, CA). The pneumotachograph was calibrated by using the electronic integration of flow introduced through the pneumotachograph with a precision syringe (3L syringe, Hans Rudolph, Kansas City, MO). Transpulmonary pressure (esophageal-mask pressure) was measured with an esophageal balloon catheter (length 10 cm, perimeter 3.8 cm, wall thickness 1 mm) sealed over the distal end of a polypropylene catheter (4 mm ID, 5 mm OD, length 100 cm). The esophageal balloon catheter was passed within the thoracic portion of the esophagus, the balloon was inflated with 2 ml of air, and when maximal negative pressure excursions were observed, the proximal end was exited through an airtight latex diaphragm in the mask, and the catheter was taped in place. End-expiratory pleural pressures ranged between ~2 and ~5 cmH2O. The esophageal balloon catheter was connected to a second differential pressure transducer (DP45-14, Validyne Engineering). The pressure transducer used for esophageal pressure measurements was calibrated statically with a water U-manometer. The signal derived was amplified, sampled at 30 Hz, and digitized for processing using pulmonary mechanics analyzer software (Buxco XA Biosystems, Buxco Electronics, Sharon, CT). Flow, tidal volume, and pleural pressure were recorded continuously and displayed by the computer on a breath-by-breath basis. These measurements were then used by the computer to yield a computation of total pulmonary resistance (Rt) by using the isovolume method of Amdur and Mead (5). Dynamic compliance (Cdyn) was computed as the change in volume divided by the change in transpulmonary pressure at two points of zero flow during the inspiratory portion of the breath. Five to ten breaths taken from each measurement period were averaged for each data point. No phase delay or signal attenuation of the pressure and flow sensors was observed up to 5 Hz.

Histamine bronchoprovocation. Histamine bronchoprovocation was performed after methods described for adult horses by Derksen et al. (10) and Klein and Deegen (17) and in foals by Hoffman et al. (14). In those studies, it was found that Cdyn reflected bronchoconstriction in a dose-dependent fashion more reliably than did Rt. Histamine aerosol was delivered to foals by use of a jet nebulizer (Pari LC JET, Pari, Paris, France), which produced fine particles (mass median diameter of 1.6 μm) at a flow rate of 0.35 ml/min using a high-pressure (30 psi) compressor (Compare, model NE-C08, Omron HealthCare, Vernon Hills, IL) with an output of 9 l/min. The order of challenges was as follows: normal saline solution (control) followed by histamine diphosphate (Sigma Chemical, St. Louis, MO) in saline solution at doubling concentrations (0.5, 1.0, 2.0, 4.0, 8.0, 16.0, and 32.0 mg/ml). Each solution was nebulized to the foal for a total of 2 min. Lung function measurements were resumed 20 s after the end of each nebulization period throughout the peak response and continued until there was a return of Cdyn to the postsaline baseline. Each dose of histamine or saline was separated by at least 5 min from the previous dose, which in humans has been shown to avoid a cumulative effect of histamine (16). Aerosol challenges were discontinued when Cdyn decreased to at least 35% of the postsaline challenge.
values, a dose of 32 mg/ml of histamine was used, or the foals showed signs of respiratory difficulty (i.e., accentuated abdominal lift, coughing, nostril flaring, or greater than a doubling of respiratory rate).

Upper airway resistive loads. This portion of the experiment was performed on a different day from the bronchoprovocation. The lung function testing systems were arranged as previously described, with the exception that the negative end of the pressure transducer used to measure pleural pressure was left open to atmosphere rather than connected to the facemask. A nasotracheal (NT) tube (Bivona, 10 mm OD, length 55 cm) was passed into the trachea of the foal. Lidocaine (0.3%) was administered into the trachea for local anesthesia, and the cuff was inflated. A tracheal catheter (polypropylene, 4 mm OD, length 60 cm) containing numerous distal side holes was passed so that the end of the catheter was distal to the NT tube for measurement of tracheal pressure. The proximal end of the NT tube was attached to a PVC ball valve (7/16 in. maximum ID, 7/16 in. OD, length 4 cm) that served as a controllable resistor. The valve was attached to the pneumotachograph. The loaded resistances induced were −150, 200, and 250% of baseline resistance (R150, R200, and R250, respectively) as determined by breath-by-breath monitoring of total respiratory system plus resistor resistance. Post hoc analysis of total resistance revealed that values at steady state did not correspond to exactly 150, 200, and 250% of baseline, so actual values were used for comparison with phase angle and phase relation during the same time segments. The order of the resistive loads was randomized after an initial baseline reading was obtained with the ball valve maximally opened in place. Next, lower airway lung resistance (RL) was measured by using tracheal and pleural pressures to discern whether resistive loading was affecting lower airway resistance as well and to better characterize our model. Each loading lasted 2 min and was followed by a capnographic reading (Multinex Datascope, Paramus, NJ).

Statistical analyses. ANOVA was used to compare the baseline value of phase angle and phase relation with the value at each histamine dose or resistive load. A Spearman rank correlation (r_s) test was performed to compare percent change in Cdyn to percent change in phase angle or phase relation after each dose of histamine or to test for a correlation between the percent change in Rt to the percent change in phase angle or phase relation (Statistix version 4.1, Analytical Software, Tallahassee, FL). A P value of 0.05 or less was considered significant.

RESULTS

Histamine bronchoprovocation. Coefficients of variation for respiratory frequency, tidal volume, maximum change in transpulmonary pressure, Cdyn, Rt, and phase angle during the baseline period of data collection were 5.9, 5.5, 2.9, 2.5, 4.4, and 13% respectively. Representative Lissajous figures are shown for foal 2 at baseline and after maximal bronchoconstriction (Fig. 1). There was no significant change in phase angle for foals as a group at maximal bronchoconstriction (range 6–62°, mean = 27.1, SD = 14.2, P = 0.35). Individual values for lung mechanics, phase angle, and phase relation are shown in Table 1. When comparing the percent change in Cdyn to the concomitant percent change in phase angle for each histamine dose administered (Fig. 2), no correlation was found (r_s = 0.02). Two of the eight foals showed a consistent decrease in phase angle with increasing bronchoconstriction. The other six foals showed phase angles that changed in both a positive and negative direction with increasing bronchoconstriction. The absolute percent change in Cdyn did not correlate with the absolute percent change in phase angle (r_s = 0.34).

There was no significant change in phase relation for all eight foals from baseline Cdyn to Cdyn after maximal bronchoconstriction (range 10.5–43.7%, mean = 26.7%, SD = 8.17%, P = 0.78). There was also no significant correlation between the percent change in Cdyn vs. the percent change in phase relation (Fig. 3). Two foals showed consistent decreases in phase relation with increasing bronchoconstriction, whereas five foals changed in both a negative and positive direction from the baseline phase relation. Phase relation data were not obtained from foal 3 due to technical problems with data acquisition in this foal. No correlation was found for the absolute percent change in Cdyn and the absolute percent change in phase relation (r_s = 0.40).

Upper airway resistive loading. There was no change in end-tidal CO2 during resistive loading. Individual values for the resistances measured during the experiment and the actual values determined after post hoc analysis are shown in Table 2. Although Rt increased slightly during resistive loading, this was not a significant change (baseline Rt mean = 2.58, SD = 2.8; Rt at 150% baseline Rt mean = 3.3, SD = 3.4, P = 0.23; Rt at 200% baseline Rt mean = 4.0, SD = 4.4, P = 0.12; Rt at 250% baseline Rt mean = 5.2, SD = 6.4, P = 0.12). The individual responses are shown in Table 2. Phase angle changed significantly at resistive loads of 150% and 250% Rt value (P < 0.05), and there was a strong trend (P = 0.09) toward a change at 200% Rt value. However, the correlation between percent change in resistance compared with percent change in phase angle was not significant (Fig. 4). Five of the eight foals showed an increase in phase angle with increasing Rt. Two foals showed decreasing phase angle with increasing Rt, and one foal changed in both a positive and negative direction relative to the induced resistance. The absolute percent change in Rt vs. the absolute percent change in phase angle showed a significant correlation
which indicated that there was a pattern to the change in thoracoabdominal synchrony, but it differed between foals. There was also a significant change in phase relation between baseline RT and 250% RT value (P = 0.05). However, between the percent change in RT and the percent change in phase relation, there was no significant correlation found (Fig. 5). Five of the eight foals showed an increase in phase relation with an increase in RT. Two of the foals showed a decrease in phase relation with an increase in RT, and one foal changed in both a positive and negative direction with increasing resistive load. There was a significant correlation with the absolute percent change in RT to the absolute percent change in phase relation (r = 0.67, P < 0.05), which indicated that there was a pattern to the change in thoracoabdominal synchrony, but it differed between foals. There was also a significant change in phase relation between baseline RT and 250% RT value (P < 0.05). However, between the percent change in RT and the percent change in phase relation, there was no significant correlation found (Fig. 5). Five of the eight foals showed an increase in phase relation with an increase in RT. Two of the foals showed a decrease in phase relation with an increase in RT, and one foal changed in both a positive and negative direction with increasing resistive load. There was a significant correlation with the absolute percent change in RT to the absolute percent change in phase relation (r = 0.66, P < 0.05), indicating that resistance affected phase angle, but not in the same direction in all foals.

**DISCUSSION**

Phase angle and relation were examined in this study because previous data demonstrated their relevance to detection of acute airway obstruction (13, 29). For phase angle or relation to have merit for gauging airway obstruction, they would need to correlate with classical measures of obstruction, but the data reported here do not support that conclusion. This is consistent with previous clinical data that have shown that there is wide variation in the degree of phase angle changes during upper airway obstruction (25).

**Table 1.** Lung mechanics during histamine bronchoprovocation in a group of normal foals

<table>
<thead>
<tr>
<th>Dose, mg/ml</th>
<th>RL, cmH₂O · l⁻¹ · s⁻¹</th>
<th>Cdyn, l/cmH₂O</th>
<th>PL, cmH₂O</th>
<th>VT, liters</th>
<th>f, breaths/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE</td>
<td>5.8</td>
<td>0.13</td>
<td>16</td>
<td>1.57</td>
<td>17.5</td>
</tr>
<tr>
<td>0</td>
<td>5.2</td>
<td>0.13</td>
<td>19.7</td>
<td>1.59</td>
<td>19.4</td>
</tr>
<tr>
<td>0.5</td>
<td>5.5</td>
<td>0.14</td>
<td>21.4</td>
<td>1.52</td>
<td>21.1</td>
</tr>
<tr>
<td>1</td>
<td>6.1</td>
<td>0.14</td>
<td>22.4</td>
<td>1.39</td>
<td>21.1</td>
</tr>
<tr>
<td>2</td>
<td>6.17</td>
<td>0.18</td>
<td>21.6</td>
<td>1.24</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>5.3</td>
<td>0.14</td>
<td>16.2</td>
<td>1.3</td>
<td>19.2</td>
</tr>
<tr>
<td>8</td>
<td>10.1</td>
<td>0.1</td>
<td>28</td>
<td>1.48</td>
<td>17.3</td>
</tr>
<tr>
<td>16</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>32</td>
<td>22.2</td>
<td>0.08</td>
<td>32.2</td>
<td>1.32</td>
<td>13.8</td>
</tr>
</tbody>
</table>

**Table 1.—Continued**

<table>
<thead>
<tr>
<th>Dose, mg/ml</th>
<th>RL, cmH₂O · l⁻¹ · s⁻¹</th>
<th>Cdyn, l/cmH₂O</th>
<th>PL, cmH₂O</th>
<th>VT, liters</th>
<th>f, breaths/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE</td>
<td>0.79</td>
<td>0.21</td>
<td>5.1</td>
<td>0.93</td>
<td>28.5</td>
</tr>
<tr>
<td>0</td>
<td>1.12</td>
<td>0.19</td>
<td>5.9</td>
<td>0.85</td>
<td>29.6</td>
</tr>
<tr>
<td>0.5</td>
<td>1.1</td>
<td>0.17</td>
<td>5.8</td>
<td>0.84</td>
<td>32.3</td>
</tr>
<tr>
<td>1</td>
<td>1.9</td>
<td>0.17</td>
<td>6.3</td>
<td>0.87</td>
<td>27.9</td>
</tr>
<tr>
<td>2</td>
<td>1.4</td>
<td>0.17</td>
<td>6.3</td>
<td>0.86</td>
<td>28.7</td>
</tr>
<tr>
<td>4</td>
<td>1.2</td>
<td>0.13</td>
<td>7.3</td>
<td>0.89</td>
<td>28.7</td>
</tr>
<tr>
<td>8</td>
<td>1.9</td>
<td>0.12</td>
<td>7.8</td>
<td>0.79</td>
<td>32.5</td>
</tr>
<tr>
<td>16</td>
<td>2.6</td>
<td>0.07</td>
<td>11.0</td>
<td>0.73</td>
<td>33</td>
</tr>
</tbody>
</table>

**Fig. 2.** Percent change in dynamic compliance (Cdyn) compared with concomitant percent change in phase angle in response to histamine aerosol challenge in foals (n = 8).

```
(r = 0.67, P < 0.05), which indicated that there was a pattern to the change in thoracoabdominal synchrony, but it differed between foals. There was also a significant change in phase relation between baseline RT and 250% RT value (P < 0.05). However, between the percent change in RT and the percent change in phase relation, there was no significant correlation found (Fig. 5). Five of the eight foals showed an increase in phase relation with an increase in RT. Two of the foals showed a decrease in phase relation with an increase in RT, and one foal changed in both a positive and negative direction with increasing resistive load. There was a significant correlation with the absolute percent change in RT to the absolute percent change in phase relation (r = 0.66, P < 0.05), indicating that resistance affected phase angle, but not in the same direction in all foals.

**DISCUSSION**

Phase angle and relation were examined in this study because previous data demonstrated their relevance to detection of acute airway obstruction (13, 29). For phase angle or relation to have merit for gauging airway obstruction, they would need to correlate with classical measures of obstruction, but the data reported here do not support that conclusion. This is consistent with previous clinical data that have shown that there is wide variation in the degree of phase angle changes during upper airway obstruction (25).

![Change in Phase Angle vs Cdyn](image_url)
We hypothesized that as the lower airways constrict during histamine challenge, the decrease in Cdyn would be associated with the recruitment of abdominal and other accessory muscles and this that might alter thoracoabdominal synchrony (22). This study, however, suggests that histamine-induced bronchoconstriction, to an extent that was clinically obvious, did not alter phase angle in a consistent fashion. Similarly, it has been shown in human infants that induced bronchoconstriction did not correlate linearly with a change in phase angle (22). This finding suggests several possibilities. The measurement of phase angle impinges on which compartment (i.e., thorax or abdomen) initiates inspiration and expiration. A change in the leading compartment during bronchoconstriction can obscure the measurement phase angle, despite an obvious change in breathing pattern (27). Moreover, Koterba et al. (18) demonstrated that adult horses breathe with a biphasic pattern (i.e., two separate inspiratory and expiratory efforts associated with each respiratory effort). This type of pattern may lead to a distorted Lissajous figure in equids, which would cause inaccurate phase angle measurements. We were concerned that phase angle may not have correlated with Cdyn or

Table 2. Lung mechanics and phase angle for individual foals subject to three levels of added fixed inspiratory and expiratory resistive loads

<table>
<thead>
<tr>
<th>%Ctl</th>
<th>Resistance, cmH₂O·l⁻¹·s⁻¹</th>
<th>Cdyn, l/cmH₂O</th>
<th>f, breaths/min</th>
<th>PETO₂, mmHg</th>
<th>PL, cmH₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>8</td>
<td>7.95</td>
<td>0.62</td>
<td>21</td>
<td>0.146</td>
</tr>
<tr>
<td>150</td>
<td>12</td>
<td>14.38</td>
<td>0.76</td>
<td>90</td>
<td>0.191</td>
</tr>
<tr>
<td>200</td>
<td>16</td>
<td>17.76</td>
<td>0.54</td>
<td>133</td>
<td>0.128</td>
</tr>
<tr>
<td>250</td>
<td>20</td>
<td>24.48</td>
<td>0.42</td>
<td>147</td>
<td>0.056</td>
</tr>
</tbody>
</table>

Key: %Ctl, percent baseline resistance; Rₜₛ is the total resistance recorded instantaneously at the time of the experiment; Rₜₛ and RL are actual total lung resistances measured after breaths were averaged (post hoc); ϕ, phase angle; PETO₂, end-tidal partial pressure of CO₂. Italic numbers refer to individual foals.

Fig. 3. Percent change in Cdyn compared with concomitant percent change in phase relation (n = 8 foals).

Fig. 4. Percent change in total respiratory resistance (RƩ) compared with the concurrent percent change in phase angle during fixed upper airway resistive loading in foals (n = 8).

Fig. 5. Comparison of percent change in RƩ to concomitant percent change in phase relation in foals during fixed resistive loading (n = 8).

We hypothesized that as the lower airways constrict during histamine challenge, the decrease in Cdyn would be associated with the recruitment of abdominal and other accessory muscles and this that might alter thoracoabdominal synchrony (22). This study, however, suggests that histamine-induced bronchoconstriction, to an extent that was clinically obvious, did not alter phase angle in a consistent fashion. Similarly, it has been shown in human infants that induced bronchoconstriction did not correlate linearly with a change in phase angle (22). This finding suggests several possibilities. The measurement of phase angle impinges on which compartment (i.e., thorax or abdomen) initiates inspiration and expiration. A change in the leading compartment during bronchoconstriction can obscure the measurement phase angle, despite an obvious change in breathing pattern (27). Moreover, Koterba et al. (18) demonstrated that adult horses breathe with a biphasic pattern (i.e., two separate inspiratory and expiratory efforts associated with each respiratory effort). This type of pattern may lead to a distorted Lissajous figure in equids, which would cause inaccurate phase angle measurements. We were concerned that phase angle may not have correlated with Cdyn or
angle. On that line, Newth et al. (19) found that phase
distinguished from normal individuals by using phase
a high degree of fixed upper airway resistance in which
sleep in humans. They postulated that individuals with
ity for detection of upper airway obstructions during
derived from RIP (sum) lacked sensitivity and specific-
the differences in results as well. Clark and co-workers
in the study by Hammer et al. (13), which may explain
they were significantly lower than the loads employed
resistive loads employed here were clinically evident,
the severity of upper airway loading. Although the
load evoked a significant change in phase angle but
found in nonhuman primates that a fixed inspiratory
responses during resistive loading. Hammer et al. (13)
investigate these factors. Other studies done in pri-
capacity or development of intrinsic positive end-
hyperinflation and an increase in functional residual
ance, physical maturity of breathing muscles, elastic
colloid pressures, or dynamic factors such as dynamic
hyperinflation and an increase in functional residual
capacity or development of intrinsic positive end-
expiratory pressure. Further studies are needed to
investigate these factors. Other studies done in pri-
mates have suggested similar variation in phase angle
responses during resistive loading. Hammer et al. (13)
found in nonhuman primates that a fixed inspiratory
load evoked a significant change in phase angle but
that the degree of change did not correlate linearly with
the severity of upper airway loading. Although the
resistive loads employed here were clinically evident,
they were significantly lower than the loads employed
in the study by Hammer et al. (13), which may explain
the differences in results as well. Clark and co-workers
(8) recently reported that the shape of the flow curve
derived from RIP (sum) lacked sensitivity and specific-
ity for detection of upper airway obstructions during
sleep in humans. They postulated that individuals with
a high degree of fixed upper airway resistance in which
pressure and flow are nearly linearly related cannot be
distinguished from normal individuals by using phase
angle. On that line, Newth et al. (19) found that phase
angle was logarithmically correlated with the product
of esophageal pressure and rate in anesthetized rhesus
monkeys with graded inspiratory loading. We speculate
that the fixed inspiratory and expiratory type of resis-
tive loading in this study might have affected the
outcome, and RIP may fare differently in the setting of
dynamic (e.g., inspiratory greater than expiratory)
resistive load.

This study does suggest that phase angle and phase
relation are more sensitive to upper airway loading
than to that during lower airway constriction, within
ranges that could be observed in clinical patients for
each perturbation. The lack of correlation between
phase angle or phase relation and conventional lung
mechanics indicates that these variables are not lin-
early correlated with traditional measures of fixed
upper or lower airway obstructions in foals. Further
studies are needed to determine the impact of dynamic
changes in airway caliber during measurements of
thoracoabdominal asynchrony.

We thank Brooke Yules, Nicole Manjerovic, and Seychelle Ricard
for technical assistance. We also thank Dr. Melissa Mazan and Dr.
Mary Rose Paradis for previewing this manuscript.

Address for reprint requests and other correspondence: A. M.
Hoffman, Large Animal Medicine, 200 Westboro Rd., North Grafton,
MA 01536 (E-mail: ahoffman@infonet.tufts.edu).

Received 16 March 1999; accepted in final form 11 February 2000.

REFERENCES

1. Abraham WM, Watson H, Schneider A, King M, Yerger L,
and Sackner MA. Noninvasive ventilatory monitoring by respi-
atory inductive plethysmography in conscious sheep. J Appl

MA. Tidal volume measurements in newborns using respiratory
1993.

3. Allen JL, Greenspan JS, Deoras KS, Keklikian E, Wolfson
MR, and Shaffer TH. Interaction between chest wall motion and
lung mechanics in normal infants and infants with BPD.

4. Agostoni E and Mogonni P. Deformation of the chest wall

5. Amidur MO and Mead J. Mechanics of respiration in unanesthe-

Goldman M. Accuracy of respiratory inductive plethysmogra-
phy during wakefulness and sleep in patients with obstructive

7. Chand N, Nolan K, Pillar J, Zomask M, Diamantis W, and
Sophia RD. Characterization of aeroallergen-induced dyspnea in
unrestrained guinea pigs by bias-flow ventilated whole body

JA. Assessment of inspiratory flow limitation invasively and
non-invasively during sleep. Am J Respir Crit Care Med 158:

9. Cohen KP, Panesuc D, Bookse J H, Webster J G, and Tomp-
kins WJ. Design of an inductive plethysmograph for ventilation

10. Derksen F J, Robinson NE, Armstrong P J, Stick J A, and
Slocombe RF. Airway reactivity in ponies with recurrent air-

11. Dorsch W, Waldherr U, and Rosmanith J. Continuous record-
ing of intrapulmonary “compressed air” as a sensitive noninva-