Effects of tension of the girth strap on respiratory system mechanics in horses at rest and during hyperpnea induced by administration of lobeline hydrochloride

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Objective—To determine whether tension of the girth strap of a saddle would sufficiently affect rib motion and reduce lung volume to alter pulmonary resistance in horses.

Animals—10 healthy adult horses.

Procedure—We used classical techniques to measure the effects of tightening a girth strap (15 kg of tension) on pulmonary dynamics during eupnea and hyperpnea in horses. Respiratory impedance was evaluated by use of oscillometry, and resistance and reactance data were partitioned into lung and chest wall components. Rib cage and abdominal contributions to tidal volume and minute ventilation were measured by use of respiratory inductance plethysmography. Effects of strap tension on functional residual capacity (FRC) were measured during eupnea by use of a helium-dilution technique. In a subgroup of 6 horses, we also measured transdiaphragmatic pressures during eupnea and hyperpnea induced by administration of lobeline hydrochloride (0.2 mg/kg, IV).

Results—Pulmonary resistance measured by use of oscillometry but not by use of classical methods was significantly increased by the tension of the girth strap. However, the increase in pulmonary resistance could not be explained by a decrease in FRC. Motion of the rib cage was significantly reduced during eupnea and hyperpnea. However, ventilatory variables (tidal volume, minute ventilation, and peak flows), FRC, and transdiaphragmatic pressures were unaltered by strap tension.

Conclusions and Clinical Relevance—Although tension of the girth strap caused measurable changes in respiratory mechanics (loss of rib motion and increased pulmonary resistance), there was no evidence that ventilation was limited. (*Am J Vet Res* 2005;66:1167–1174)

The girth strap has been used for millennia to stabilize the position of a saddle and rider in horses; yet, the restrictive effects of strap tension on respiration have received little scientific attention. The girth strap is positioned at the center of the lungs; therefore, restrictions of the chest wall, lungs, or mediastinal structures may be important consequences. An initial study[1] on exercise consequences of strap tension conducted on Thoroughbreds at racetracks disclosed a wide range of strap tensions, with a mean of 13 kg. There were notable inconsistencies in tension of the girth straps among horses, days, and people (males vs females) who tightened the straps. The investigators applied their observed range of tensions to Thoroughbreds in exercise experiments and discovered that increased strap tension was associated with fatigue.[2] In humans, inelastic restriction of the external chest wall evokes a substantial (> 25%) decrease in static lung volumes and is associated with loss of exercise capacity and a sensation of inspiratory dyspnea[3,4]; however, the mechanisms for these effects are unclear.

Changes in respiratory mechanics in response to restriction of the external chest wall include an increase in **static recoil pressure (Pst)** of the lungs and maximum expiratory flow rates at low lung volumes.[5-9] The increase in Pst can be simulated by voluntary breathing (ie, low-volume breathing).[10] The mechanism of increased Pst in either situation (ie, restriction of the external chest wall or low-volume breathing) is unknown, although it does not appear to be related to atelectasis[11] or airway closure.[12] Because those studies involved restriction of the entire thorax, we do not know whether the findings can be extrapolated to tightening of a girth strap, which is a more localized application of force. Because of the relatively low compliance of the chest wall in horses,[13] it is plausible that local forces are transmitted to a larger area of the chest wall in this species, compared with forces transmitted in humans.

We hypothesized that tightening of a girth strap acts to reduce rib motion during respiration, thus contributing to reduced lung volume or ventilation during quiet breathing or hyperpnea. We also examined the effects of tension of a girth strap on pulmonary dynamics because the loss of lung volume, when evident, may be associated with increased airway resistance in horses. Any of these changes could help explain the decrease in exercise capacity with increased strap tension in horses and ultimately lead to ways of addressing this problem.

Materials and Methods

Animals—Ten healthy equids (5 Standardbreds, 3 Thoroughbreds, 1 Quarter Horse, and 1 pony) were used in the study. Body weight ranged from 314 to 506 kg (mean ± SEM, 428 ± 26 kg). The experiments were conducted at Tufts University and the University of New

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Hampshire. All experiments received prior approval from the Massachusetts School of Veterinary Medicine at Tufts University and the University of New Hampshire Institutional Animal Care and Use Committees.

Experimental design—The study was performed at 4 time points (experiments 1 to 4, respectively). For each experiment, we applied a single inelastic leather girth strap (11 cm wide × 4 mm thick) and English saddle to all animals. A single investigator (HK) applied the saddle in each experiment. The girth strap was positioned behind the most dorsal point of the shoulders (ie, withers) in a standard manner and tightened to the extent that was appropriate for the sport of dressage. Preliminary studies revealed that the tension for these equids was approximately 15 kg. Hence, we locked the girth strap at the closest point that generated 15 kg of nominal tension at end expiration, as measured by use of an in-line linear digital spring scale.[a] The linear spring scale was removed before the girth strap was locked. The horses were given at least 3 minutes of tidal breathing to acclimate prior to obtaining measurements; a similar 3-minute period of tidal breathing was allowed after removal of the girth strap before any additional measurements were obtained.

Experiment 1—Experiment 1 was designed to measure the effect of strap tension on flow-derived variables, **pulmonary resistance (R_{Ldyn})**, and **dynamic compliance (C_{dyn})**. Dynamic mechanics were measured in the 10 equids by use of classical (ie, esophageal pressure or flow) techniques for conditions of a girth strap or no girth strap. A crossover design was used, with the order of girth strap versus no girth strap randomized.

Pulmonary mechanics were measured as described elsewhere.[14] Briefly, an esophageal balloon catheter (120 cm in length) was inserted to the region of the midthorax and positioned at a point where there were maximal changes in pleural pressures, and oscillations attributable to cardiac activity were negligible. Animals were fitted with a polyurethane facemask that provided a low volume of dead space and had a stretched rubber seal that prevented leakage of air. The balloon catheter was inserted through a sealed hole in the facemask and connected to 1 pole of a pressure transducer[b] that had a range of ± 66 cm H_2O. The balloon (10 × 3 cm) consisted of a condom[c] filled with 3 mL of air.[15] The opposite pole of the transducer was connected to the lumen of the facemask to enable us to obtain transpulmonary pressure. A pneumotachograph[d] that was linear for a static flow from 0 to 35 L/s and differential pressure transducer[e] that had a range of ± 2.25 cm H_2O were used to measure nasal flow. **Tidal volume (V_T)** was obtained from the electronic integration of flow. The pressure sensor was calibrated by use of a water U-manometer. Pressure and flow sensors were found to be in phase up to 10 Hz. Flow and pressure signals were amplified[f] and digitized (30 Hz), and waveforms were analyzed by use of commercial software[g] to compute frequency, V_T, **minute volume (VM)**, R_{Ldyn}, C_{dyn}, **maximum change in transpulmonary pressure ($dPPl_{max}$)**, **peak inspiratory flow (PIF)**, **peak expiratory flow (PEF)**, **inspiratory time (T_i)**, and **expiratory time (T_e)**. Values were based on the mean for 10 breaths (except for values calculated during induced hyperpnea, when we determined the mean for 5 breaths during the peak response) free from swallowing artifacts.

Respiratory inductance plethysmography (RIP) was used to measure rib and abdominal motion, as described elsewhere.[16] Bands[h] were placed in the 11th intercostal space (ie, rib sensor) and caudal to the 18th rib (ie, abdominal sensor) for measurement of rib cage and abdomen motion (change in cross-sectional area), respectively. The bands were connected to an oscillator[i] that also provided a volumetric output signal that was digitized[j] (30 Hz) for display and analysis. Gains (ie, sensitivity to stretch) for the rib and abdominal sensors were adjusted to be equivalent. Gain of the sum (rib sensor plus abdominal sensor) was adjusted during quiet breathing to equal V_T measured with the pneumotachograph during a 1-minute period by overlapping the volumetric waveforms visually and confirming their equivalence by use of digital calipers.[k]

Baseline measurements were collected for at least 2 minutes. After 2 minutes, lobeline hydrochloride[l] was administered (0.2 mg/kg, IV). Hyperpnea ensued within 60 seconds after injection, which was followed by a brief period of apnea, as described elsewhere.[14,17] Measurements of lung function continued throughout hyperpnea and into the ensuing period of apnea.

Experiment 2—Experiment 2 was designed to measure the effect of strap tension on forced oscillatory mechanics of the respiratory system, lungs, and chest wall. It was performed 1 to 2 months after the conclusion of experiment 1 and used the same 10 animals. Again, the experiment was conducted as a crossover design with the application of treatments (girth strap or no girth strap) randomized.

Forced oscillatory mechanics were applied for measurement of respiratory impedance, as originally described elsewhere.[18] Briefly, a pneumatic 3-port proportional valve[m] supplied with compressed air (55.2 kPa) was used to generate sinusoidal flow of desired frequencies at the airway opening. The oscillatory flow was applied to each animal's respiratory system by use of a rigid, plastic, T-shaped piece that was fitted to the facemask. The T-shaped piece contained a side port fitted with a resistor of approximately 2 cm H_2O/L/s. Values for the facemask relative to atmospheric pressure (ie, to measure **impedance of the respiratory system [Z_{RS}]**) or esophageal pressure (ie, to measure **impedance of the lungs [Z_L]**) were measured by use of a differential pressure transducer[b] that had a range of ± 66 cm H_2O. Flow at the airway opening was measured by use of a pneumotachograph[n] and differential pressure transducer[e] that had a range of ± 2.25 cm H_2O. Data were collected for 10 seconds at each input frequency. Amplified pressure and flow signals were digitized (25.6 Hz), band-pass filtered (width, 0.4 Hz; stopband attenuation, 80 dB), and divided into 2 consecutive 5-second data segments with 50% overlap from which Z_{RS} was calculated by use of a computer and commercial software.[o] The apparatus was calibrated daily by attaching the T-shaped piece to a solid polyvinyl chloride pipe (inside diameter, 52.3 mm; length, 6.215 m) with known impedance; the value for known impedance was then compared with the measured impedance. A correction factor was then generated from this comparison by use of the following equation:

$$k = Z_{ref}/Z_M,$$

where k is the correction factor, Z_{ref} is the known impedance, and Z_M is the measured impedance. Corrected impedance measurements for each equid (ie, Z_{corr}) were then obtained by use of the following equation: $Z_{corr} = k \times Z_{RS}$. Resistances and reactances were computed from the impedance spectra, as described elsewhere.[19]

The respiratory system was oscillated from 1 to 5 Hz at 1-Hz intervals. Measurements were made in duplicate, and mean values were calculated. Four series of duplicate recordings were obtained for determination of **resistance of the respiratory system (R_{RS})** and **reactance of the respiratory system (X_{RS})** by use of airway opening pressure with no girth strap, **resistance of the lungs measured by use of oscillometry (R_{Losc})** and **reactance of the lungs (X_L)** by use of transpulmonary pressure and no girth strap, R_{RS} and X_{RS} by use of airway opening pressure and application of a girth strap, and R_{Losc} and X_L by use of transpulmonary pressure and application of a girth strap. All horses were measured with and without application of the girth strap (in random order) and provided both lung and respiratory system measurements. The order of respiratory system and lung measurements was also randomized. An acceptable coherence value for entrance into the analysis portion of this study was ≥ 0.9. Data for the chest wall (ie, **resistance of the chest wall [R_w]** and **reactance of the chest wall [X_w]**) were computed by subtracting the values for the lungs from the values for the respiratory system (eg, $R_w = R_{RS} - R_{Losc}$).

Experiment 3—Experiment 3 was designed to measure the effect of strap tension on **functional residual capacity (FRC)**. This experiment used 10 healthy horses (7 geldings and 3 mares, comprising 3 Morgans, 4 Thoroughbred crossbreds, 2 Thoroughbreds, and 1 Quarter Horse crossbred); these 10 horses included 4 horses from experiment 1. Body weight ranged from 385 to 578 kg (mean ± SEM, 489 ± 18.5 kg) and was determined by use of a weight tape, the precision (within 5% of actual body weight) of which was verified by weighing 4 horses on a digital scale. Experiment 3 was performed > 6 months after experiment 2, and FRC was measured by use of a crossover design, with or without application of a girth strap applied in random order.

Food was withheld from horses overnight prior to collection of data. The FRC was measured by use of a helium-dilution technique.[20] A nondiffusible gas collection bag was filled (6 L) with test gas (10% helium, 0.3% carbon monoxide, 21% oxygen, and 68.7% nitrogen) and attached to a 3-way stopcock[p] (internal diameter, 5 cm) that was in the closed position. The stopcock was attached to the proximal port of the facemask. **Dead space (V_{DS})** in the facemask varied slightly among horses, but the value we measured for the facemask and stopcock by use of water displacement for a representative horse was 0.65 L.

Each horse initially breathed air (15 L) from a second bag, which allowed us to visually determine the end of expiration (ie, peak fill). When the second bag was full, we turned the stopcock to the open position, which allowed the horse to breath the test gas. The horse rebreathed this test gas for 45 to 55 seconds, which was sufficient for equilibration. The stopcock was then closed at the end of expiration after the rebreathing (equilibration) period. Gas within the test bag after rebreathing was measured for helium content, and FRC was calculated by use of the following equation:

$$FRC = ([6 \times \{He_i/He_f\}] - 6) - 0.65,$$

where He_i is the initial concentration of helium, He_f is the final concentration of helium, 6 represents the volume (in liters) in the bag at the start, and 0.65 equals the volume (in liters) of V_{DS}. Measurements for each treatment (girth strap or no girth strap) were made in duplicate, and the mean was calculated.

Experiment 4—Experiment 4 was designed to measure the effect of strap tension on **transdiaphragmatic pressures (Pdi_{max})**. It was performed 6 months after completion of experiment 3. The experiment used 6 healthy horses that ranged in body weight from 344 to 487 kg (mean ± SEM, 421 ± 22 kg). These 6 horses had been used in experiments 1 to 3.

Food was withheld from horses for ≥ 12 hours prior to insertion of instruments, as described elsewhere.[21] Two identical esophageal balloon catheters (10 cm) were inserted in tandem to enable us to obtain measurements of Pdi_{max}. The catheters were lashed together with suture to reduce the chance of either catheter kinking; they were inserted such that the tip of 1 catheter was positioned at the midthorax (pleural pressure catheter), whereas the tip of the other catheter was positioned within the lumen of the stomach (gastric pressure catheter). The location of the catheter tips was verified by examining polarity of the waveform (during inspiration; negative for pleural pressure and positive for gastric pressure) and by obtaining the maximal amplitude of each signal during quiet breathing. These catheters were phase-matched up to 7 Hz. None of the horses had respiratory rates > 1 Hz during the study. The position of the balloon catheters was secured by taping them to the muzzle.

We used RIP to measure V_T ($V_{T\text{-}RIP}$ = rib sensor + abdominal sensor) and VM ($VM_{RIP} = V_{T\text{-}RIP} \times$ frequency). The RIP sensors were calibrated as described for experiment 1. The objective for use of RIP was to verify that effects of administration of lobeline during application of a girth strap were equivalent to those when the girth strap was not applied. Each horse was allowed at least 3 minutes for acclimation after insertion of the balloon catheters before recording was initiated. After 5 minutes of quiet tidal breathing, lobeline was administered (0.2 mg/kg, IV), and we continued recording continuously throughout the period of hyperpnea and into the subsequent period of apnea. The recordings were evaluated later by use of commercial software.[q] Maximum change in Pdi_{max} was derived from the mean of 5 consecutive breaths that were representative of eupnea and maximal hyperpnea. The latter was determined by observing the maximum plethysmographic V_T; once maximum V_T was reached, 5 subsequent breaths free of artifact were used to calculate the mean and obtain the Pdi_{max} during hyperpnea.

Statistical analysis—Periods of eupnea and hyperpnea were analyzed separately. Paired *t* tests (2-tailed) were used to test the effects of a girth strap on pulmonary dynamics (experiment 1), FRC (experiment 3), and Pdi_{max} and associated flow-derived variables (experiment 4) during periods of eupnea or hyperpnea. General linear model univariate analyses[r] were used to examine the effects of a girth strap and frequency and their interaction term on resistance and reactance values (experiment 2). We also performed separate post hoc evaluations of frequency dependence of resistance and reactance data for girth strap versus no girth strap. All data were expressed as mean ± SEM, and values of $P < 0.05$ were considered significant.

Results

Experiment 1—Application of a girth strap did not have a significant effect on flow-derived variables during eupnea. Administration of lobeline induced significant ($P < 0.001$) increases in frequency, V_T, PEF, and PIF and decreases in T_i and T_e, but there was no discernable effect of tension from the girth strap on these variables. Mean V_T for the rib compartment was significantly decreased by application of the girth strap during eupnea ($P = 0.04$) and hyperpnea ($P = 0.002$; **Figure 1**). Additionally, VM_{RIP} of the rib compartment was significantly ($P = 0.006$) reduced by the girth strap. The VM_{RIP} of the abdominal compartment increased but not significantly. In 1 horse, we were unable to obtain acceptable esophageal pressure measurements. In the remaining 9 animals, $dPPl_{max}$ and R_{Ldyn} were significantly increased as a result of hyperpnea, but there were no significant effects of the girth strap on these variables **(Figure 2)**. Finally, application of the girth strap or administration of lobeline did not significantly affect C_{dyn}.

Experiment 2—Application of the girth strap caused a significant ($P = 0.004$) increase in R_{Losc} and a decrease that was not significant ($P = 0.08$) in R_w

(**Figures 3–5**). We made 50 measurements (ie, 5 input frequencies in 10 horses) for each of the respiratory system, lung, and chest wall resistances. One set of measurements (at a frequency of 1 Hz) was excluded because of unacceptably low coherence (< 0.9). Of the remaining 49 measurements of R_{Losc}, 39 (80%) were increased by application of the girth strap. Mean ± SEM change for all horses at all frequencies was 17.0 ± 7.1%, with increases of 21.0%, 8.8%, 22.0%, 16.2%, and 12.3% for frequencies of 1 to 5 Hz, respectively. There were no significant ($P > 0.1$) effects of the girth strap on R_{RS}, X_{RS}, X_L, or X_w (**Figures 6–8**). Overall, both R_{Losc} and R_{RS} were significantly ($P < 0.001$) affected by frequency dependence. When variables were examined for frequency dependence within treatment groups (girth strap vs no girth strap), the frequency effect was found to be unchanged for R_{Losc} ($P = 0.045$ before and $P = 0.064$ after application of the girth strap) but changed significantly for R_{RS} ($P = 0.071$ before and $P = 0.003$ after application of the girth strap), with values for R_{RS} at frequencies of 4 and 5 Hz

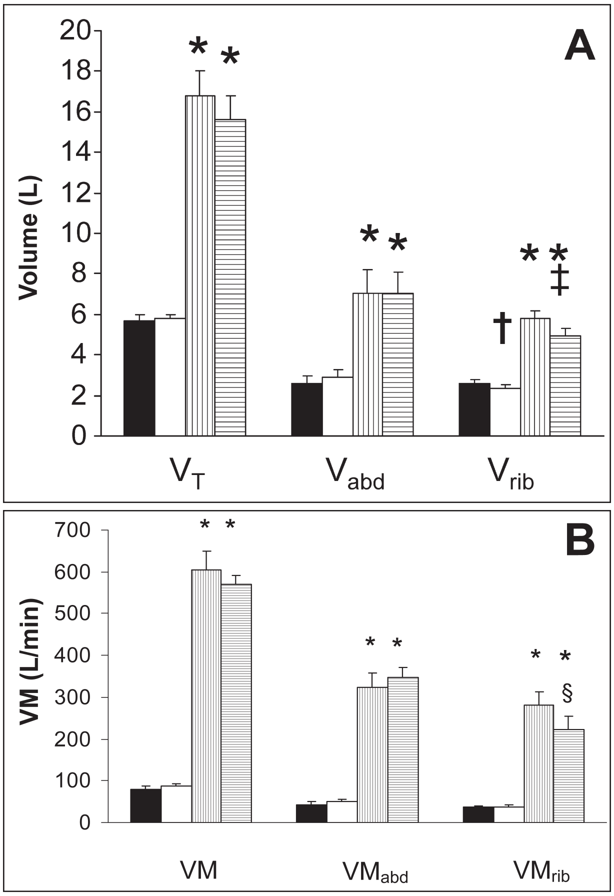

Figure 1—Mean ± SEM tidal volume (V_T; A) and minute volume (VM; B) measured by use of a pneumotachograph (V_T or VM) or calibrated values for volume of the rib compartment (V_{rib}), volume of the abdominal compartment (V_{abd}), and VM of the rib (VM_{rib}) or abdominal (VM_{abd}) compartments determined by use of respiratory inductance plethysmography in 10 equids. Periods included eupnea without application of a girth strap (black bars), eupnea with application of a girth strap (white bars), hyperpnea without application of a girth strap (vertical stripes), and hyperpnea with application of a girth strap (horizontal stripes). Lobeline hydrochloride was injected IV to induce hyperpnea. *Within each variable on the x-axis, the value differs significantly ($P < 0.001$) from the corresponding value for eupnea. †,‡,§Within a variable on the x-axis, the value differs significantly (†$P = 0.04$, ‡$P = 0.002$, and §$P = 0.006$) from the corresponding value without application of a girth strap.

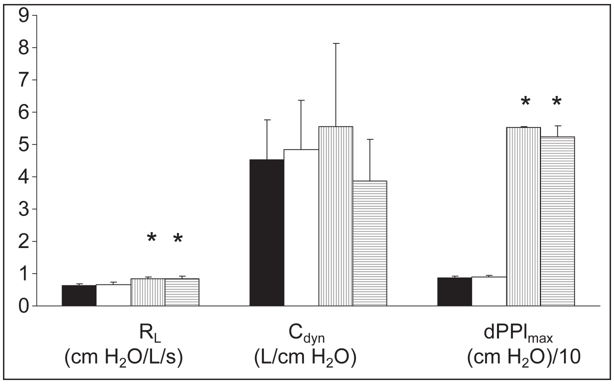

Figure 2—Mean ± SEM values for pulmonary resistance (R_L), dynamic compliance (C_{dyn}), and maximum change in transpulmonary pressure ($dPPl_{max}$) measured during eupnea and hyperpnea with and without application of a girth strap in 9 horses. Notice that application of a girth strap did not have a significant effect on pulmonary dynamics during eupnea or hyperpnea. *See* Figure 1 for key.

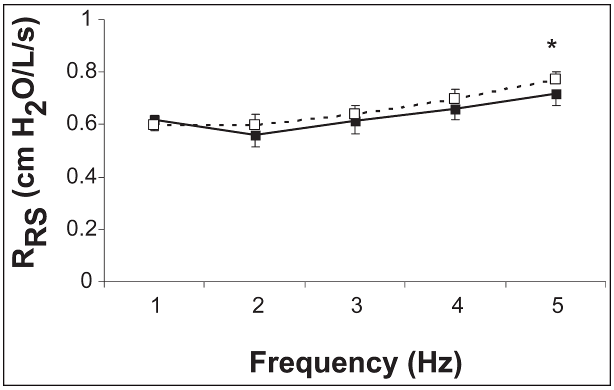

Figure 3—Mean ± SEM resistance of the respiratory system (R_{RS}) measured by use of oscillometry at input frequencies ranging from 1 to 5 Hz in 10 equids with (white squares and dashed line) and without (black squares and solid line) application of a girth strap. There was no significant effect attributable to application of the girth strap. *Mean value for R_{RS} with the girth strap differs significantly ($P < 0.05$) from mean values for 1 and 2 Hz (ie, frequency dependence).

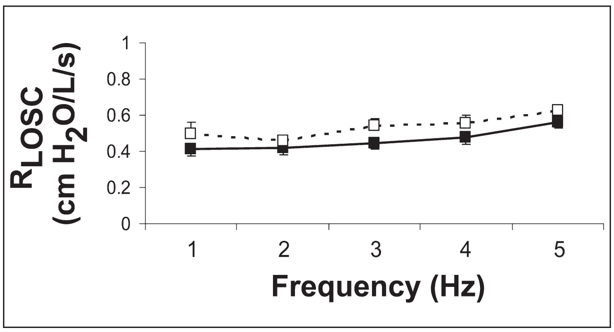

Figure 4—Mean ± SEM pulmonary resistance (R_{Losc}) measured by use of oscillometry at input frequencies ranging from 1 to 5 Hz in 10 equids with (white squares and dashed line) and without (black squares and solid line) application of a girth strap. Overall, there was a significant ($P = 0.004$) increase in R_{Losc} attributable to application of the girth strap. There was a significant ($P = 0.045$) effect of frequency on R_{Losc} without application of the girth strap, but this effect was not significant ($P = 0.064$) with application of the girth strap.

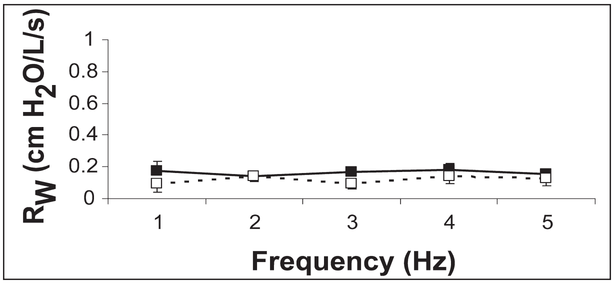

Figure 5—Mean ± SEM resistance of the chest wall (R_w) measured by use of oscillometry at input frequencies ranging from 1 to 5 Hz in 10 equids with (white squares and dashed line) and without (black squares and solid line) application of a girth strap. Values for R_w decreased but not significantly (P = 0.082) with application of the girth strap.

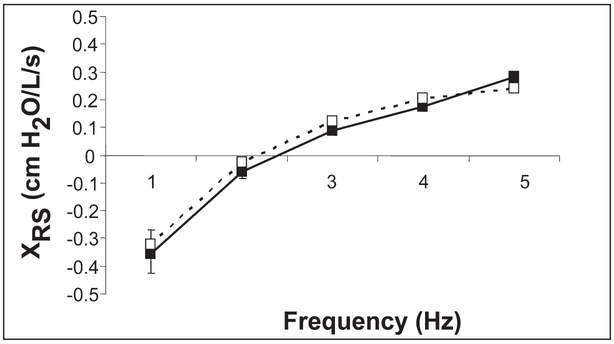

Figure 6—Mean ± SEM reactance of the respiratory system (X_{RS}) measured by use of oscillometry at input frequencies ranging from 1 to 5 Hz in 10 equids with (white squares and dashed line) and without (black squares and solid line) application of a girth strap. There was no significant effect attributable to application of the girth strap. Values differ significantly (P < 0.001) among frequencies within strap status (ie, frequency dependence).

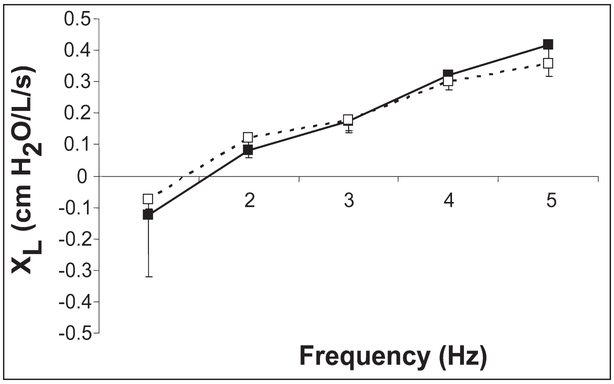

Figure 7—Mean ± SEM reactance of the lungs (X_L) measured by use of oscillometry at input frequencies ranging from 1 to 5 Hz in 10 equids with (white squares and dashed line) and without (black squares and solid line) application of a girth strap. There was no significant effect attributable to application of the girth strap. Values differ significantly (P < 0.001) among frequencies within strap status (ie, frequency dependence).

significantly different from values for the other frequencies (1 to 3 Hz). All measurements of reactance (X_{RS}, X_L, and X_w from 1 to 5 Hz) were frequency dependent (P = 0.005). There was no significant girth strap × frequency interaction for any variable.

Experiment 3—Measurements of FRC were highly repeatable, with a mean ± SEM difference between

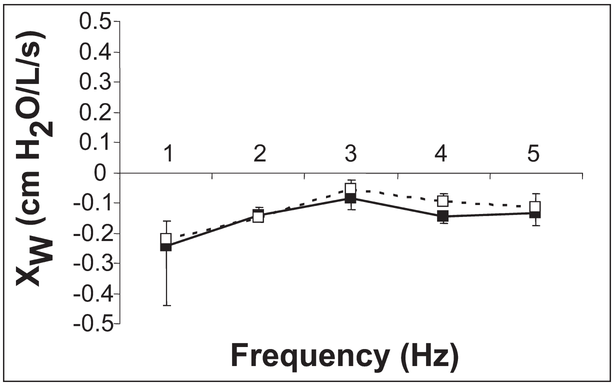

Figure 8—Mean ± SEM reactance of the chest wall (X_w) measured by use of oscillometry at input frequencies ranging from 1 to 5 Hz in 10 equids with (white squares and dashed line) and without (black squares and solid line) application of a girth strap. There was no significant effect attributable to application of the girth strap.

measurements 1 and 2 (within treatment group) of 3.3 ± 1.6%. There was a significant correlation (r, 0.77; $P < 0.05$) between FRC and body weight as determined by use of the weight tape method. There was no effect of application of a girth strap on FRC. Mean FRC before application of the girth strap was 21.6 ± 1.4 L (ie, 44.0 ± 2.1 mL/kg), which did not differ significantly compared with 22.2 ± 1.7 L (ie, 45.0 ± 2.5 mL/kg) after application of the girth strap.

Experiment 4—We detected a significant (P < 0.001) increase in Pdi_{max} during the first 60 seconds after IV injection of lobeline. We were unable to measure a significant effect of the girth strap on Pdi_{max} during eupnea or hyperpnea induced by injection of lobeline. Mean ± SEM Pdi_{max} was 4.0 ± 2.9 cm H_2O, 4.4 ± 2.6 cm H_2O, 40.5 ± 8.4 cm H_2O, and 39.2 ± 8.3 cm H_2O for conditions of eupnea without application of a girth strap, eupnea with application of a girth strap, hyperpnea without application of a girth strap, and hyperpnea with application of a girth strap, respectively.

Discussion

Analysis of the study reported here provides the first insights into the alteration of respiratory system mechanics attributable to application of a saddle girth strap in horses. The lack of information on effects of a girth strap left open the distinct possibility that strap tension contributes to mechanical constraints on breathing at rest or during hyperpnea. We emphasize that this study was not performed during exercise, so the results cannot be directly extrapolated to exercise settings. However, these data lead to new questions concerning these effects.

We found that the effects of a girth strap in horses differ markedly from external chest restriction in humans. These differences are likely attributable to the more local application of external forces by the girth strap, in contrast to the extensive restriction on the chest wall in humans.[3-5,7-11,22-25]

We did not detect significant decreases in flow-derived variables (frequency, V_T, VM, PEF, and PIF) during eupnea or hyperpnea. In humans with external restriction, there is a significant change in breathing pattern with more shallow, rapid breathing to preserve VM.[4] This would suggest that horses are able to compensate for restriction attributable to the girth strap by augmentation of muscular force. Such compensation could be conscious, even anticipatory, or involuntary, as in the case of lobeline-induced stimulation.

The $V_{T\text{-}RIP}$ and VM_{RIP} measured at the thorax (rib volume) by use of inductance plethysmography decreased significantly with application of the girth strap during eupnea and hyperpnea (Figure 1). The greater decrease in **volume of the rib compartment (V_{rib})** during hyperpnea, compared with the volume during rest, may have resulted from greater inelasticity of the girth strap at higher lung volumes, similar to the situation reported in humans.[26] Because the maximal changes in V_T, $dPPl_{max}$, and Pdi_{max} were unaffected by the girth strap, we could interpret the decreases in rib motion as a manifestation of decreased passive or active rib cage compliance.[24] The ratio of compliances for the abdominal compartment and rib compartment was proportional to their volumetric ratio as follows:

$$\text{compliance of abdomen/compliance of rib cage} = (dV_{abd}/dV_{rib}) \times K,$$

where dV_{abd} is the change in volume of the abdominal compartment, dV_{rib} is the change in V_{rib}, and K is an undeterminable constant for the study. On the basis of this estimate, rib cage compliance would have decreased from 0.48 × K to 0.42 × K (ie, –12.5%) at rest and to 0.39 × K (ie, –18.8%) during hyperpnea. A similar interpretation is that there was a significant change in thoracic shape during application of the girth strap. Distortion of the chest as a result of restriction of the rib cage was observed in another study.[8] In that study, lung height was increased and cranial-caudal diameter was reduced. The extent to which the chest changed shape in the equids of our study was not determined.The impedance evaluations did not disclose a significant change in the mean value or frequency dependence of R_w, although there was a pattern of a decrease in R_w with application of the girth strap. Moreover, the study reported here did provide some novel physiologic data concerning this variable in horses, compared with responses in humans. We documented that R_w in horses (without a girth strap) was approximately 27% of R_{RS} at 4 Hz and, typically, 13% of R_{RS} for all frequencies. In comparison, investigators in 1 study[26] found that R_w in humans was 22% and 13% of R_{RS} at 4 and 20 Hz, respectively. In another study,[25] it was found that R_w and X_w (5 Hz) were between 40% and 50% of R_{RS} in humans with an unrestricted chest state. Despite the stiffer chest wall in horses, the contribution of R_w to R_{RS} is still lower than in humans. This may be the reason, in addition to the variability posed by the awake state, that changes in R_w were not measured.

The data for the study reported here were in agreement with those in studies[25,26] in humans in that X_w was negative at all frequencies studied. Dynamic chest wall compliance can be roughly computed[25] from reactance (X_w) as –0.5 × frequency × C_{dyn}. At the lowest frequency (1 Hz), mean chest wall compliance (without a girth strap) was X_w/–0.5 (ie, –0.199/[–0.5 × 1] or 0.4 ± 0.03 L/cm H_2O), which is comparable to published[27] values (0.44 ± 0.01 cm H_2O) for static chest wall compliance in anesthetized 1-year-old horses. This suggests that, at the lowest frequency used for our study (1 Hz), the dynamic measure of static chest wall compliance closely approximated the value for static chest wall compliance; yet, it was determined in awake, standing subjects.

We measured Pdi_{max} at rest and during hyperpnea with the belief that diaphragm motion may be compensating for the observed loss of rib motion. This would support the assertion made in 1 study[21] that the role of the diaphragm may be accentuated by the saddle girth strap in exercising horses. Our experiment on a subgroup of 6 horses revealed that there was no significant change in Pdi_{max} during eupnea or hyperpnea with the girth strap. In another study,[24] investigators also found no change in Pdi_{max}, despite severe constriction of the chest wall, but they were able to detect an increase in electromyographic activity. Therefore, we cannot rule out the possibility that, although Pdi_{max} was unchanged, diaphragmatic electromyographic activity or contractility may have been altered.

The fact that R_{Ldyn} increased as a function of hyperpnea corroborates data collected in other studies during lobeline-induced hyperpnea[14,17,28] and during exercise (ie, running at 8 to 12 m/s).[29] Application of the girth strap did not accentuate this change. The degree of hyperpnea induced in the study reported here was similar to that reported with moderate exercise on a treadmill.[21] However, shortcomings of our experiment to simulate exercise conditions with hyperpneic challenge were the lack of an abdominal piston effect, the lack of locomotor-impact effects on rib cage motion, and the apparent cranial-caudal lengthening (rather than progressive lateral expansion) of the chest during exercise-induced hyperpnea.[30] These phenomena may cause the effects of a girth strap on R_{Ldyn} to differ (increase or decrease) during exercise, compared with changes during hyperpnea. Two weaknesses of our study concerning the precise measurements of R_{Ldyn} and C_{dyn} relate to volume history and absolute lung volume, neither of which was controlled for in our study. Furthermore, pleural pressure measurements restricted to 1 location in the esophagus, as were performed in our study, may result in dismissing important changes that result from a formation of pressure gradients in the pleural cavity. For example, investigators in 1 study[8] found that there was an increase in pleural pressure in the proximal portion of the esophagus that was not evident in the distal portion of the esophagus during chest restriction. Additional studies are warranted to determine how these experimental variables may influence the observed effects attributable to application of a girth strap, although these would not be expected to qualitatively change the findings reported here.

In contrast to the measurement of R_{Ldyn} by use of classical methods, our measurements of R_{Losc} were increased significantly after application of the girth strap (Figures 3 and 4). Similarly, investigators in 1 study[25] reported an increase in R_{Losc} during application of a chest strap in humans. They speculated that the increase in R_{Losc} represented an increase in tissue resistance because concurrent plethysmographic measurements of airway resistance failed to reveal an effect of application of the chest strap. The increase in R_{Losc} that they observed was not relieved by restoring lung volume. Because of a lack of changes in frequency dependence, the increase in R_{Losc} we observed was most likely attributable to changes in airway resistance rather than tissue resistance, which would tend to increase low-frequency values for R_{Losc}.[31] Analysis of our data suggested that airway resistance increased (ie, there was an increase of pulmonary resistance among frequencies). The increase in airway resistance may have been the result of indirect constriction of large airways resulting from inward forces applied at the body surface. Alternatively, lengthening of the thorax may have altered airway resistance. An increase in R_{Losc} could also be explained by a decrease in lung volume, but our FRC data did not support that notion. Indeed, our data for FRC (no girth strap, 21.6 ± 1.4 L; girth strap, 22.2 ± 1.7 L) were almost identical to data (21.5 ± 4.2 L) measured by use of helium-dilution techniques in another study[20] for similar-sized horses. The fact that R_{Ldyn} did not change but R_{Losc} did change with the application of a girth strap may relate to the relative insensitivity of R_{Ldyn}. In 1 study,[32] the isovolume method of measuring pulmonary resistance was significantly less sensitive than the oscillometry method for measurement of added resistance in humans. The use of oscillometry may enhance the detection of obstruction because of the sinusoidal nature of input flow and evaluation of multiple frequencies.

Analysis of our data suggested that application of a saddle girth strap to horses caused a small but significant decrease in rib cage motion and an increase in R_{Ldyn}. The importance of these observations with regard to loss of exercise capacity cannot be estimated from the study reported here, but questions have been raised concerning these effects. Additional studies are needed with precisely controlled conditions of lung volume and volume history and during exercise to understand the importance of restriction attributable to a girth strap on the physiologic aspects of respiration in horses.

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a. Digital fish scale (29.5 kg), Berkley, Spirit Lake, Iowa.
b. DP45-28, Validyne Engineering, Northridge, Calif.
c. Trojan, CWI Carters, New York, NY.
d. Fleisch No. 5, OEM Medical, Lenoir, NC.
e. DP45-14, Validyne Engineering, Northridge, Calif.
f. Max2215, Buxco Electronics, Sharon, Conn.
g. XA Biosystem, version 2.0, Buxco Electronics, Sharon, Conn.
h. Respitrace, Ambulatory Monitoring Inc, Ardsley, NY.
i. Respitrace Interface, Ambulatory Monitoring Inc, Ardsley, NY.
j. ADAPC, Buxco Electronics, Sharon, Conn.
k. XA Biosystem, Buxco Electronics, Sharon, Conn.
l. Lobeline hydrochloride (98%), Aldrich Chemical Co, Gillingham, UK.
m. No. 602 00001, Joucomatic, Rueil, France.
n. Fleisch No. 4, OEM Medical, Lenoir, NC.
o. On The Nose 2.0, Scientific Solutions, Eden Mills, ON, Canada.
p. 120°-angle stopcock, Hans Rudolph, Kansas City, Kan.
q. Acknowledge, version 3.7, Biopac Systems, Goleta, Calif.
r. SPSS, version 12.0, SPSS Inc, Chicago, Ill.

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