Spectrum analysis of respiratory sounds in exercising horses with experimentally induced laryngeal hemiplegia or dorsal displacement of the soft palate

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Objective—To record respiratory sounds in exercising horses and determine whether spectrum analysis could be used to identify sounds specific for laryngeal hemiplegia (LH) and dorsal displacement of the soft palate (DDSP).

Animals—5 Standardbred horses.

Procedure—Respiratory sounds were recorded and pharyngeal pressure and stride frequency were measured while horses exercised at speeds corresponding to maximum heart rate, before and after induction of LH and DDSP.

Results—When airway function was normal, expiratory sounds predominated and lasted throughout exhalation. After induction of LH, expiratory sounds were unaffected; however, all horses produced inspiratory sounds characterized by 3 frequency bands centered at approximately 0.3, 1.6, and 3.8 kHz. After induction of DDSP, inspiratory sounds were unaffected, but a broad-frequency expiratory sound, characterized by rapid periodicity (rattling) was heard throughout expiration. This sound was not consistently detected in all horses.

Conclusions and Clinical Relevance—The technique used to record respiratory sounds was well tolerated by the horses, easy, and inexpensive. Spectrum analysis of respiratory sounds from exercising horses after experimental induction of LH or DDSP revealed unique sound patterns. If other conditions causing airway obstruction are also associated with unique sound patterns, spectrum analysis of respiratory sounds may prove to be useful in the diagnosis of airway abnormalities in horses. (Am J Vet Res 2001;62:659–664)

Upper airway obstructions are common in horses and often associated with exercise intolerance and abnormal respiratory noise.1-3 In racehorses, exercise intolerance associated with upper airway obstruction is the primary concern, whereas in show horses, respiratory noise is the most important problem, as excessive respiratory noise may be a cause for dismissal in some types of competition. Respiratory sounds in exercising horses are difficult to evaluate, because observers cannot always be in an optimal location and respiratory sounds may be obscured by extraneous noises, such as hoof beats, wind noise, or sounds associated with treadmill operation.

Idiopathic laryngeal hemiplegia (ILH) and dorsal displacement of the soft palate (DDSP) are among the most common upper airway obstructions of horses and have been studied most intensively. Idiopathic laryngeal hemiplegia occurs in 3 to 8% of horses and is caused by neuropathy of the left recurrent laryngeal nerve.14 In this condition, airway obstruction occurs during the inspiratory portion of the respiratory cycle.15 Little is known about the prevalence of DDSP, as the condition is usually not apparent in resting horses and, in most instances, occurs only during exercise. A definitive diagnosis of DDSP requires endoscopy during high-speed exercise. In horses evaluated for poor performance on a treadmill, DDSP is the most commonly diagnosed upper airway abnormality.16 Experimentally, DDSP can be produced by blockade of the pharyngeal branch of the vagus nerve and causes an expiratory upper airway obstruction.17

In human medicine, spectrum analysis of speech is a recognized field of study, and practical applications of spectrum analysis, including speech therapy and voice recognition, are now commonplace.8 Spectrum analysis has also been used to characterize the sounds produced by many species, including song birds10 and marine mammals.11 Attenburrow et al12 recorded respiratory sounds of horses, using a radiostethoscope, and analyzed these sounds using spectrum analysis. However, respiratory sounds recorded using a radiostethoscope placed over the trachea do not directly relate to the respiratory sounds of exercising horses discerned by an examiner.

It is possible that respiratory sounds associated with ILH and DDSP are unique to these conditions. If this is the case, analysis of respiratory sound could be useful as a field test for the diagnosis of these and, possibly, other airway obstructions in exercising horses. The purpose of the study reported here was to develop a method for recording respiratory sounds in exercising horses and to determine whether spectrogram analysis could be used to identify sounds specific for laryngeal hemiplegia (LH) and DDSP.

Materials and Methods

Experimental animals—5 Standardbred horses, 3 geldings and 2 mares, 2 to 7 years old, and weighing between 400 and 427 kg were used in the study. The experimental proto-
col was approved by the All-University Committee on Animal Use and Care. All horses were vaccinated against tetanus, equine influenza, rhinopneumonitis, eastern and western encephalitis, and *Streptococcus equi* infection. Physical examination of horses and endoscopy of the pharynx and nasopharynx at rest and during high-speed treadmill exercise failed to reveal any abnormalities. All horses were trained to run on the treadmill prior to the study. Maximum heart rate (HR$_{max}$) was determined by use of a telemetry system and an incremental exercise test.\(^\text{15}\)

**Experimental design**—Airway sounds were recorded in each horse 3 times: without any alterations to the airway, after induction of LH, and after induction of DDSP. We used a randomized cross-over design, and recording sessions were separated by at least 1 week. On the day of each recording session, the upper airway of the horse was first examined, using a fiberoptic endoscope, to ensure that upper airway function was normal. If the horse was scheduled to undergo induction of LH or DDSP, the appropriate procedure was performed, and endoscopy was repeated to verify that the desired experimental condition had been created. After a 5-minute warm-up period on the treadmill at a speed of 4 m/s, horses were exercised at HR$_{max}$ for 2 minutes, and respiratory sounds were recorded. Endoscopy was repeated immediately after exercise to ensure that the desired experimental condition had persisted.

**Induction of LH and DDSP**—Laryngeal hemiplegia\(^{16}\) and DDSP\(^{17}\) were induced as described. Briefly, LH was induced by subcutaneous infusion of 3 ml of 2% mepivacaine into the region where the left recurrent laryngeal nerve passes over the caudal aspect of the left side of the cricoid cartilage. Dorsal displacement of the soft palate was induced by infusing 1 ml of mepivacaine beneath the pharyngeal branches of the vagus nerves as they course across the longus capitis muscles in the ventromedial compartments of the left and right auditory tube diverticula (guttural pouches). Laryngeal hemiplegia was successfully induced in all 5 Standardbred horses. Dorsal displacement of the soft palate was successfully induced in only 3 of the 5 Standardbreds. Therefore, an additional 2 horses (geldings, 4 and 7 years of age) were used for recording respiratory sounds after induction of DDSP. Changes in flow mechanics in horses with experimentally induced LH and DDSP are very similar to those in horses with naturally occurring disease.\(^{16}\)

**Sound recording equipment**—The tape recorder used in the study was designed for recording of speech in difficult environments, such as conference rooms. Therefore, it did not have a manual input gain control. Rather, the input section included a strong compression circuit that resulted in a constant recording level. When exposed to loud sounds, the compression circuit reduced the input gain, thereby providing automatic volume control.

Compression features of the recorder were evaluated in the laboratory. The environment was a sound-attenuating room with a volume of 14 m$^3$ and a negligible reverberation time (reverberation time is the time it takes a sound made in a room to diminish to 1 millionth of its original intensity). Test measurements were made with the microphone placed 27 cm from a loudspeaker that produced the sounds to be recorded. Static compression characteristics of the recorder were measured with a broadband noise that was flat (± 2 dB) from 200 to 5 kHz and limited on the low end by the capabilities of the loudspeaker and on the high end by a low-pass filter (–48 dB per octave). Sound pressure levels were measured at the position of the microphone, using a C-weighted sound level meter.

To determine the time-dependence of compression, compression was measured while generating signals with 2 loudspeakers. One speaker produced a continuous 1,000 Hz sine wave tone. The other speaker produced pulse noise. Noise pulses were 100 ms in duration and had a maximum sound pressure level at the recording microphone of 94 dB. Time-dependence of compression was measured by observing the recorded level of the sine tone, using a digital oscilloscope.

**Recording of respiratory sounds**—Respiratory sounds were recorded with a dynamic, unidirectional microphone taped to a 30-cm-long rod. The rod and microphone were taped to the horse’s forehead in such a way that the recording microphone was directed toward the nostrils and rested approximately 4 cm from the horse’s nose (Fig 1). The microphone was connected to the cassette recorder.

Respiratory sounds were analyzed by use of a computer-based spectrum analysis program. The program allowed us to simultaneously listen to the respiratory sounds and view the spectrogram, enhancing ease of interpretation. Because sound intensity varied between individual horses, the maximum sound intensity measured during exhalation was normalized by digital scaling to a nominal 0 dB. Normalization facilitated comparison of spectrograms between horses. From each spectrogram, we determined the duration of inspiratory time during which respiratory sounds were recorded (T$_{es}$), the duration of expiratory time during which respiratory sounds were recorded (T$_{es}$), the highest frequency at which there was a sound signal (~65 dB; F$_{max}$), and the highest frequency of at least ~25 dB sound intensity (F$_{25max}$).

**Measurement of pharyngeal pressure**—Pharyngeal pressure was measured by use of a pharyngeal catheter positioned at the level of the openings of the auditory tube diverticula, as described.\(^{15}\) Briefly, a side-hole pharyngeal catheter (2.15 mm inside diameter, 3.25 mm outside diameter) was introduced through the left nostril to the level of the openings of the auditory tube diverticula. Pharyngeal pressure...
was measured by use of a differential pressure transducer and recorded with a physiologic recorder. Before each recording session, the differential pressure transducer was calibrated between 10 and 50 cm of H2O, using a water manometer. Pharyngeal pressure measurements were used to determine inspiratory and expiratory times (Ti and Te, respectively) and to verify the timing of inspiration and expiration on the spectrogram.

Measurement of stride frequency—Stride frequency was measured using 2-meter-long polyethylene catheters with water balloons attached to the ends of the catheters. A catheter was taped to the distal portion of the right and left forelimbs of the horse and connected to a pressure transducer. The contact phase of the right or left forelimb produced positive pressure deflections, which were displayed on the physiologic recorder. Footfall and pharyngeal pressure recordings were aligned with the spectrogram, using a custom-made device that, when activated, produced simultaneous sound and voltage signal markings on the spectrogram and physiograph recording, respectively. This device was activated approximately every 10 seconds throughout each recording session.

Statistical analysis—Data were analyzed by use of 2-way ANOVA; the Tukey test was used for pairwise comparisons. A t-test was used to compare mean values within treatments. Significance was set at P < 0.05.

Results
Evaluation of sound recording equipment—Evaluation of static compression characteristics of the recorder indicated that a dynamic range of 50 dB at input was compressed into an output range of 20 dB (Fig 2). The output dynamic range was limited by internal noise, corresponding to an input sound pressure level of 43 dB, and by compression of sound pressure levels > 75 dB.

During evaluation of the time-dependence of compression, it was found that a burst of intense noise decreased the recorded level of the sine wave by a factor of 4.9. Compression was near maximum for approximately 1 second, then decreased to release from compression approximately 4 seconds after the noise burst (Fig 3).

Spectrograms of horses with normal airway function—When respiratory sounds were recorded from horses with normal airway function exercising at a speed corresponding to HRmax (Fig 4), Te, and Ti were not significantly different (Table 1). In all horses, expiratory sound predominated. Mean Fmax was 4.2 kHz, and mean F25max was 0.7 kHz.

Spectrograms of horses with LH—After induction of LH, expiratory sounds during exercise were similar to those recorded when horses had normal airway function (Fig 5). However, unlike horses with normal airway function, after induction of LH, inspiratory sounds were heard. In all horses with LH, these inspiratory sounds were characterized by 3 frequency bands (formants). For formant 1, mean ± SEM highest frequency was 0.6 ± 0.02 kHz. For formant 2, mean lowest and highest frequencies were 0.9 ± 0.04 kHz and 2.4 ± 0.06 kHz, respectively. For formant 3, mean lowest and highest frequencies were 2.8 ± 0.9 kHz and 4.8 ± 0.7 kHz, respectively.
After induction of LH, \( T_i \) was significantly longer than \( T_e \) (Table 1). The \( T_i \) and the \( T_{es} \) were not significantly different.

Spectrograms of horses with DDSP—After induction of DDSP, sounds associated expiration were altered, and expiratory sounds were characterized by rapid (32 ± 7 ms) periodicity (rattling) (Fig 6). When horses were exercising at a speed corresponding to \( HR_{max} \) after induction of DDSP, this expiratory sound was present with every breath in only 2 horses. In another 2 horses, abnormal-sounding breaths were interspersed with breath sounds that were indistinguishable from normal. In 1 horse with DDSP, abnormal sounds were not present during exercise at \( HR_{max} \) but instead occurred as the horse decelerated at the completion of the high-intensity exercise period. The \( T_e \) was significantly longer after induction of DDSP than when airway function was normal (Table 1), but \( T_i \) and \( T_{es} \) were not significantly different.

### Discussion

The method used in the present study appeared to be a practical method for recording respiratory sounds in exercising horses. Recording respiratory sounds in exercising horses has several challenges, including placement of the microphone and overcoming interference by extraneous noises associated with exercise. Placement of the microphone influences the sound recording obtained. Attenburrow et al., for instance, placed a microphone over the trachea to record upper airway sounds during exercise and reported that peak sound intensity increased with expiratory flow rate. In the present study, we wanted to record respiratory sounds that are audible to an observer. Therefore, the microphone was placed near the nostrils.

Several sources of extraneous noise can make recording respiratory sounds during exercise difficult, including footfalls and the sounds associated with treadmill operations. To minimize interference by these noises, we directed the microphone toward the nostrils and positioned it approximately 4 cm from the tip of the nose. Furthermore, we used a unidirectional microphone that because of its positioning, preferentially recorded respiratory sounds. Extraneous noises associated with exercise were further squelched by the compression circuit of the recorder. When activated by respiratory sounds associated with exhalation, the circuit reduced the gain, thereby decreasing the recording of extraneous noise. The time characteristics of the compression circuit were ideally suited for this kind of recording, as compression was maximal immediately following a burst of sound and faded over a 4-second period. Because the respiratory frequency of exercising horses is between 1 and 2 breaths/s, compression lasted throughout the respiratory cycle.

A disadvantage of using a compression circuit when recording sounds is the reduction in dynamic range. The dynamic range is the range of amplitudes over which there is a linear relationship between input and output. Because the dynamic range of the recorder used in the present study was 20 dB, respiratory sound amplitude outside this range could not be accurately recorded.

In the present study, pharyngeal pressure was used to determine the timing of inhalation and exhalation. With this information, we were able to correlate the phases of the respiratory cycle with the respiratory sounds. When horses with normal airway function

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>LH</th>
<th>DDSP</th>
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<tbody>
<tr>
<td>( T_i ) (ms)</td>
<td>269 ± 26</td>
<td>410 ± 60*</td>
<td>379 ± 85</td>
</tr>
<tr>
<td>( T_e ) (ms)</td>
<td>241 ± 24</td>
<td>252 ± 24</td>
<td>388 ± 621</td>
</tr>
<tr>
<td>( T_{es} ) (ms)</td>
<td>NA</td>
<td>355 ± 60</td>
<td>NA</td>
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<tr>
<td>( T_{es} ) (ms)</td>
<td>221 ± 16</td>
<td>251 ± 28</td>
<td>369 ± 76</td>
</tr>
<tr>
<td>( F_s ) (min⁻¹)</td>
<td>132 ± 9</td>
<td>134 ± 7</td>
<td>136 ± 9</td>
</tr>
<tr>
<td>( F_{\text{max}} ) (kHz)</td>
<td>0.7 ± 0.05</td>
<td>0.8 ± 0.1</td>
<td>0.6 ± 0.07</td>
</tr>
<tr>
<td>( F_{\text{max}} ) (kHz)</td>
<td>4.2 ± 0.7</td>
<td>3.7 ± 0.7</td>
<td>5.5 ± 0.4</td>
</tr>
</tbody>
</table>

Data are given as mean ± SEM. \( T_i \) = Inspiratory time, \( T_e \) = Expiratory time, \( T_{es} \) = Duration of inspiratory sounds, \( T_s \) = Duration of expiratory sounds, \( F_s \) = Stride frequency, \( F_{\text{max}} \) = Maximum frequency of at least –25 dB sound intensity, \( F_{\text{max}} \) = Maximum frequency at which there was a sound signal (–65dB). NA = Not applicable (inspiratory sounds were not recorded).

*Significantly (P < 0.05) different from \( T_e \) recorded after induction of LH.
†Significantly (P < 0.05) different from control value.
were galloping or trotting at a speed corresponding to HRmax, expiratory sounds predominated. In these horses, T1 and T2 were not significantly different; therefore, expiratory sound was present throughout exhalation. Mean expiratory sound frequency ranged up to 4.2 kHz. Because the audible range for humans ranges from 0.02 to 20 kHz,10 expiratory sounds of exercising horses are within the audible range. Most of the sound energy was contained in frequencies up to 0.8 kHz. This is similar to observations by Attenburrow et al.,11 who reported that peak sound intensity was in the region of 0.6 kHz. Spectrum analysis indicated that the timing, frequency, and amplitude of these sounds had an easily recognizable pattern, suggesting that it would be possible to determine whether respiratory sounds in exercising horses fall within this typical pattern.

Timing of the right and left footfalls was measured in this study to determine the effect of footfall on the spectrogram. Footfall noise could be easily isolated during periods when horses swallowed and, thus, did not breathe. Footfall produced a short-duration broad frequency band that did not interfere with interpretation of respiratory sounds.

Endoscopy before and after exercise indicated that all horses had grade-4 LH during recording sessions. With grade-4 LH, exercising horses experience dynamic collapse of the paralyzed arytenoid cartilage, so that the rima glottis is narrow during inhalation. During exhalation, positive pressure in the larynx, relative to atmospheric pressure, opens the rima glottis. Dynamic collapse of the affected arytenoid causes inspiratory upper airway obstruction and inspiratory noise.1,3

In the present study, expiratory sounds recorded when horses had LH did not differ from those recorded when horses had normal airflow function. Similarly, expiratory flows and pressures in horses with LH are also unaffected.3 In contrast, inspiratory sounds differed markedly. In every affected horse, inspiratory sounds occurred throughout inhalation. These sounds featured 3 distinct frequency bands centered at approximately 0.3, 1.6, and 3.8 kHz. In human speech analysis, these frequency bands are called formants and are characteristic of certain sounds, such as whispered vowels.11 These formants occur because the upper airway has its own resonant frequencies and preferentially transmits the formant frequencies. Thus, the sound associated with LH has a characteristic pattern that is likely to be unique. If this proves to be the case, spectrum analysis of respiratory sounds would be an easy, inexpensive, and noninvasive method of diagnosing LH. However, sounds associated with naturally occurring grade-4 ILH and with ILH of other grades were not determined in the present study, and characterization of these sounds awaits further study.

Unlike most upper airway obstructions in horses, which typically cause inspiratory noise, DDSP causes expiratory noise and does not affect inspiratory flow mechanics.5 Instead, DDSP results in an expiratory obstruction, and was associated with expiratory noise in the present study. The noise occurred throughout exhalation and was characterized by a rapidly periodic or rattling sound. Most likely, this sound was generated by vibrations of the dorsally displaced soft palate and was modified by the nasal chambers. Mean periodicity of the sound was 32 milliseconds; however, horses with naturally occurring DDSP need to be studied before it can be determined whether this periodicity is unique for DDSP.

Dorsal displacement of the soft palate was not associated with abnormal respiratory sounds in all horses in this study. In 1 horse, no abnormal sounds were recorded during exercise at HRmax but abnormal sounds were evident as the horse deaccelerated after the exercise period. In 2 other horses, some breaths taken during high-speed exercise were associated with the typical rattling noise, but others were not. In some horses with confirmed DDSP, there is no history of abnormal noise production.1,3 Factors that may influence whether a horse with DDSP has abnormal respiratory noise include airflow velocity, compliance of the dorsally displaced soft palate, and geometry of the individual horse's upper airway.

Dorsal displacement of the soft palate is usually an intermittent condition, occurring during high-speed exercise. Because of its intermittent nature, DDSP is difficult to study. Use of the local anesthetic technique described by Holcombe et al12 results in persistent DDSP that lasts for several hours, and persistent DDSP was confirmed endoscopically before and after exercise in all horses used in the present study. In a previous study, this procedure caused persistent DDSP in all experimental horses. In the present study persistent DDSP was achieved in only 3 of 7 horses.

In conclusion, this study described unique spectrogram patterns associated with LH in horses. Horses with DDSP that made respiratory noises also had a unique spectrogram pattern. If other upper airway conditions are also associated with unique sound patterns, then spectrum analysis of respiratory sounds may prove to be useful in the diagnosis of upper airway conditions of the horse. In addition, because spectrum analysis allows quantification of respiratory sounds it may be useful in evaluating the efficacy of surgical treatments intended to reduce respiratory noise. The technique used to record respiratory sounds in the present study was well tolerated by the horses, easy, and inexpensive. Therefore, respiratory sounds in exercising horses can easily be recorded in the field, and once sounds were recorded, the tape or digitized computer record could simply be sent to a referral center for help with interpretation of the spectrogram.

References


