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Evaluation of the upper respiratory tract in the horse during treadmill exercise – A review
Part II: Measurement of upper airway flow mechanics

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Summary

Literature pertaining to the evaluation of the upper respiratory tract of the horse during exercise was reviewed. Articles were found by searching two databases. Videoendoscopy of the upper airways during exercise is presented in part I of this review. Part II describes upper airway pressure and airflow measurements for objective assessement of the prescence of a respiratory limitation. Different measurement techniques and definitions of upper airway pressure as well as airflow measurement techniques are described.
Upper airway pressures and flow indices increase linearly with increasing exercise. Airflow resistance as caused by laryngeal hemiplegia grade IV increases negative upper airway pressure and limits inspiratory flow. Dorsal displacement of the soft palate alters both inspiratory and expiratory pressures.

keywords: horse, airflow, upper airway pressure, flow resistance, flow-volume loop

Beurteilung der oberen Luftwege des Pferdes während der Belastung auf dem Laufband – Eine Literaturstudie

Teil II: Messung der Atemmechanik der oberen Luftwege

Die vorliegende Literaturstudie beschäftigt sich mit der Untersuchung der oberen Atemwege des Pferdes unter Belastung auf einem Laufband. Im ersten Teil wurde die Belastungsendoskopie beschrieben. Im vorliegenden zweiten Teil werden Druck- und Atemstromstärkemessungen in den oberen Atemwegen dargestellt. Die Literaturdatenbanken Index Medicus (Medline) und Commonwealth Agricultural Bureaux (CAB) wurden nach den Begriffen „horse" or „equine" und „treadmill" abgefragt. Die Artikel, welche die oberen Atemwege betrafen wurden manuell ausgesucht. Die Abfrage erfolgte für den Zeitraum von „1966 bis heute".
Die einfachste objektive Methode zur Überprüfung der Funktion der oberen Atemwege ist die Messung der Druckgradienten entlang der oberen Atemwege. Dazu wird ein Katheter perkutan oder nasotracheal im proximalen Teil der Trachea und/oder im Pharynx platziert und die Druckdifferenzen zwischen Trachea und Pharynx beziehungsweise Trachea und atmosphärischem Druck gemessen. In Tabelle 1 sind die Druckgradienten für gesunde Pferde bei steigender Belastung zusammengefasst. Die Dorsalverlagerung des weichen Gaumens führt zu einem geringeren Inspirationsdruck in Trachea und Pharynx, einem geringeren Exspirationsdruck im Pharynx und einem verstärkten Exspirationsdruck in der Trachea. Die Hemiplegia laryngis Grad IV verursacht hauptsächlich einen stark erhöhten Unterdruck bei der Inspiration.
Die Druckfluktuationen zwischen Ein- und Ausatmung in den oberen Luftwegen sind sowohl von der Atemstromstärke als auch vom Atemwegswiderstand abhängig. Deshalb sind zur genaueren Beurteilung Messungen der Atemstromstärke notwendig. Zur Messung der Atemstromstärke wird am häufigsten ein Fleisch Pneumotachograph verwendet, daneben existieren verschiedene Ultraschall Messgräte. Normalwerte für Pferde ohne Beeinträchtigung der Funktion der oberen Luftwege sind in Tabelle 2 dargestellt. Die Hemiplegia laryngis Grad IV führt in Ruhe zu nicht messbaren Veränderungen des Atemstromes. Hingegen können im submaximalen Belastungsbereich bereits erste signifikante Veränderungen verschiedener inspiratorischer Atmungsparameter gemessen werden. Die maximale inspiratorische Atemstromstärke ist signifikant niedriger als bei gesunden Pferden.
Eine Methode die sich nur auf die Messung der Atemstromstärke stützt und dadurch wenig invasiv ist, ist die Darstellung und Auswertung von sogenannten „Tidal Breathing Flow Volume Loops" (TBVFL). Eine korrekte Auswertung dieser Schleifen ist jedoch nur möglich bei angestrebter Maximalatmung. Dies wird beim Pferd durch die Belastungsuntersuchung errreicht. Eine Hemiplegia laryngis Grad IV führt dazu, dass die höchste maximale Atemstromstärke sehr früh erreicht wird in Kombination mit einer Limitierung des Luftflusses (Plateaubildung). Hauptsächlich die inspiratorischen Indices der TBVFLs sind verändert.
Die Kombination einer Belastungsendoskopie mit einer der hier beschriebenen Methoden gilt als das derzeitige Optimum zur Beurteilung der Funktion der oberen Atemwege des Pferdes unter Belastung.

Schlüsselwörter Pferd, Atemstromstärke, Trachealdruck, Atemwegswiderstand, Atemstrom-Volumen Schleife

Introduction

The importance of the evaluation of the upper respiratory tract function during exercise lies in the fact that many functional disorders are not apparent at rest. On the other hand abnormal findings at rest do not necessarily mean a respiratory limitation during exercise *(Williams et al., 1990a, 1990b, Morris and Seeherman, 1991)*. In additon, some methods are not sensitive enough to diagnose mild disease stages at rest.

There are different methods of assessing upper respiratory function in exercising horses. These include endoscopy, upper airway pressure measurement and airflow measurement (pneumotachography). Recently there have been many advances in the techniques and the knowledge about the diagnostic value of these tests. The purpose of this review is to list the different techniques of upper respiratory tract evaluation in the horse during exercise, and describe their indications, usefulness and diagnostic value.
Part I described exercise endoscopy. In Part II the measurement of airflow and upper airway pressures are presented.

Material and Methods

The methods used for localization of the literature pertaining to the evaluation of the upper airways during exercise are given in part I of this review *(Kästner et al., 1998)*.

Results

Upper airway pressure measurements

Techniques
The simplest test of upper airway function is the measurement of the pressure gradient along the upper airway. Several measurement techniques and definitions for upper airway pressure have been used. A catheter (polyethylene, polytetrafluoroethylene, teflon tubing) is placed percutaneously through the wall of the trachea into the cranial part of the trachea *(Derksen et al., 1986; Shappell et al., 1988; Funkquist et al., 1988; Williams et al., 1990a; Lumsden et al., 1993; Roethlisberger-Holm, 1993)* or nasotracheally *(Williams et al., 1990a; Williams et al., 1990b; Ducharme et al., 1994; Rehder et al., 1995)* into the pharynx and the cranial part of the trachea. *Williams and assistants (1990a)* have shown that the pressure recordings via a transnasal catheter are not different from recordings made by a transtracheal catheter but less invasive and therefore more suitable for clinical use. The static pressure is measured by differential pressure transducers and the pressure changes are recorded continously during the respiratory cycle. Several different definitions for upper airway pressure are reported: Intratracheal pressure *(Funkquist et al., 1988; Roethlisberger-Holm, 1993)*, the pressure difference between the pressure recordings in the trachea and pressure recordings at the horse's mouth *(Derksen et al., 1986, Shapell et al., 1988; Lumsden et al., 1993)*, the difference between tracheal pressure and atmospheric pressure *(Williams et al., 1990a)*, the difference between tracheal and pharyngeal pressure *(Ducharme et al., 1994; Rehder et al., 1995)* and the difference between pharyngeal and mask pressure *(Bayly et al., 1994)*. Most studies use the measurement of peak static tracheal and pharyngeal pressures to evaluate the function of the upper respiratory tract based on the assumption that peak pressures cause collapse or vibration of the proximal part of the airways. A study on repeatability and normal values for measurements of pharyngeal and tracheal pressures *(Ducharme et al., 1994)* has shown that mean pressure measurements have better repeatability than peak pressure measurements. At least 96% of all mean pressure measurements were within 5 cm H_2O of the mean value for any horse. At least 96% of all peak pressure measurements were within 10 cm H_2O of the mean peak pressure measurements for any horse.

Pressure Measurement during Exercise

Normal Function of the Upper Airways

Several experimental studies have shown that pressure along the upper respiratory tract increases with increasing exercise (Table 1). Because of the different definitions for upper airway pressure it is difficult to directly compare the results from the different research groups. Similar pressures in the upper respiratory tract as during exercise can be achieved during nasal occlusion *(Holcombe et al., 1996)*.

Abnormal Function of the Upper Airways

Laryngeal Hemiplegia (LH)

Studies on experimentally induced laryngeal hemiplegia grade IV (neurectomy or anesthesia of the recurrent nerve) agree on significantly increased (negative) inspiratory upper airway pressures *(Derksen et al., 1986; Funkquist et al., 1988; Shappell et al., 1988; Williams et al., 1990a; Lumsden et al., 1994; Ducharme et al., 1994)* compared to healthy horses. *Williams and assistants (1990a)* also observed a significant increase in expiratory pressure. Horses with complete laryngeal hemiplegia were readily identified by measurement of tracheal and pharyngeal pressures *(Ducharme et al., 1994)*, but it still needs to be determined how sensitive and useful these measurements are in less severe grades of LH.

Dorsal Displacement of the soft Palate (DDSP)

To correctly identify the occurence of DDSP in the exercising horse it is necessary to perform endoscopy during exercise. It has been shown that the prescence of a 9 mm endoscope in the upper respiratory tract does not interfere with pressure measurements in the trachea and the pharynx *(Ducharme et al., 1994)*. Compared with clinically normal horses, horses with intermittent DDSP did not have excessive negative inspiratory pressures before displacement during exercise *(Rehder et al., 1995)*. Displacement of the soft palate occured during inspiration, expiration or after swallowing. Some horses displaced the soft palate at the initiation of exercise, some at peak speed and some while slowing down *(Rehder, et al., 1995)*. But the same horse seems to displace consistently at the same time in the breathing cycle when subjected to the exercise test repeatedly. After displacement the airway pressures were significantly altered. Pharyngeal and tracheal inspiratory pressures were decreased, pharyngeal expiratory pressure decreased and tracheal expiratory pressure increased *(Rehder et al., 1995)*, indicating mainly an impairment of expiration.

ways. Therefore airflow needs to be measured to correctly assess a respiratory limitation. Upper airway resistance is defined as the ratio of peak upper airway pressure and peak airflow rates for a given inspiration or expiration. Airflow is measured by a pneumotachograph or an ultrasonic flow meter in addition *(Robinson, 1992)*.

Mostly Fleisch pneumotachographs are used to measure airflow in humans and animals. A pneumotachograph measures the pressure difference over a tube with known diameter and resistance and along a laminar flow profile. This pressure difference is directly proportional to the flow. Integration over time equals the ventilated volume. The measurement accuracy of this system depends on the absolute pressure, temperature and humidity of the gas. *Derksen and assistants (1986)* used in their early experiments two No. 4 Fleisch pneumotachographs (Dynasciences, Blue Bell, Pa, USA) mounted on a facemask. Later a pneumotachograph with a diameter of 15.2 cm was developed for the use in exercising horses *(Shappell et al., 1988; Belknap, et al., 1990; Lumsden et al., 1994)*. A tight fitting fiberglass mask mounted with the pneumotachograph is placed over the horse's nose. The mask allows free movement of the nostrils. A rubber shroud is used to seal the mask against the face. Pressure differences

Tab. 1: Normal values for peak pressures in the upper airways in exercising horses.
Normalwerte für Maximaldrücke in den oberen Atemwegen von Pferden in der Bewegung.

Inspiratory Tracheal Pressure	Expiratory Tracheal Pressure	Inspiratory Pharyngeal Pressure	Expiratory Pharyngeal Pressure	Speed	Author
−12 to −24 mm Hg	6 to 8 mm Hg			7 m/s	*Funkquist et al., 1988*
−40 to −50 cm H_2O	15 to 28 cm H_2O	−20 to−26 cm H_2O	10 to 24 cm H_2O	14m/s	*Ducharme et al., 1994*

Inspiratory Tracheal –Atmospheric Pressure	Expiratory Tracheal– –Atmospheric Pressure	Speed	Author
−29 to −30.6 cm H_2O	11.7 to 12.6 cm H_2O	gallop	*Williams et al., 1990*
−29.7 ± 4 cm H_2O	11.9 ± 1.5 cm H_2O	7.2 m/s	*Shappell et al., 1988*

Inspiratory Tracheal –Mask (mouth)Pressure	Expiratory Tracheal –Mask (mouth) Pressure	Speed	Author
(−) 1.94 ± 0.22 cm H_2O		standing	*Lumsden et al., 1994*
(−) 22.29 ± 1.15 cm H_2O		75% HR max	
(−) 38.57 ± 3.93 cm H_2O		HR max.	
(−) 27.49 ± 3.36 cm H_2O	7.85 ± 1.51 cm H_2O	75% HR max.	*Petsche et al., 1995*
(−) 40.82 ± 3.92 cm H_2O	8.07 ± 1.90 cm H_2O	HR max.	

Abbreviations: 75% HR max.: 75% of the maximal heart rate; HR max.: Maximal heart rate

Other Abnormalities

Complicated epiglottic entrapment (thick membrane, ulcers) produced modest increases, uncomplicted entrapment and pharyngeal lymphoid hyperplasia grade IV produced slight increases in inspiratory (negative) pressure. Arytenoid chondropathy produced pressure changes similar to LH grade IV *(Williams et al., 1990b)*.

Airflow Measurement

Techniques

Pressure can be affected by changes in flow rate as well as changes in resistance (impedance) of the upper airacross the pneumotachograph are measured with a differential pressure transducer (Model DP 45-22, Validyne Sales, Northridge, Ca, USA) and recorded on a physiograph (Model 8188, Gould Inc., Madison Hts, Mich., USA) *(Shappell et al., 1988; Belknap, et al., 1990; Lumsden et al., 1994).*

Ultrasonic flowmeters measure the transmission time of ultrasound signals through a given flow channel. The speed of the gas flow is calculated from the difference of absolute transmission time of ultrasound beams with and against the airstream. With the known diameter of the flow channel the respiratory flow can be calculated. Integration of the flow over time gives the ventilated volume. Several different systems are in use for equine respiratory research like the Spiroson® (Figure 1) [Spiroson Scientific, Isler Bioengineering AG, Zurich, Switzerland *(Buess et al., 1986; Weishaupt et al., 1995)*], an ultrasonic phase-shift flowmeter [British patent application 8608906 *(Woakes et al., 1987)*] and a density corrected pneumotachometer [UF202, Novex Instruments Inc. Redmond, WA, USA *(Beadle et al., 1995)*].

Fig. 1: Horse equipped with a facemask and an ultrasonic flowmeter (Spiroson®) during exercise on a treadmill.

Pferd mit Atemmaske und Ultraschallgerät zur Messung der Atemstromstärke (Spiroson®) während der Bewegung auf dem Laufband.

Upper Airway Flow Mechanics during Exercise

Normal Function of the Upper Airways

Different experimental studies *(Derksen et al., 1986; Shappell et al., 1988; Belknap et al., 1990; Lumsden et al., 1993; Lumsden et al., 1994; Connally and Derksen, 1994, Petsche et al., 1994; Guthrie et al., 1995)* give normal values for horses without dysfunctions of the upper airway (Table 2). These studies have shown that increasing speed progressively increased respiratory frequency (f), tidal volume (VT), minute ventilation (VE), peak inspiratory flow (PIF), peak expiratory flow (PEF), mean inspiratory flow (MIF), mean expiratory flow (MEF), peak inspiratory pressure (Pui), and peak expiratory pressure (Pue). Inspiratory resistance (Zi) and expiratory resistance (Ze) remained unchanged during exercise *(Derksen et al., 1986; Shappell et al, 1988; Belknap et al., 1990).*

Abnormal Function of the Upper Airways

After surgically induced laryngeal hemiplegia grade 4 (neurectomy) no significant changes were observed at rest. Peak inspiratory pressure (Pui) and inspiratory resistance (Zi) were significantly increased at speeds 4.2 m/s and greater. Peak inspiratory flow was significantly decreased at speed 4.3 m/s *(Derksen et al., 1986)* or 7.2 m/s and greater *(Shappell et al., 1988; Belknap et al., 1990; Weishaupt et al., 1995)*. This inspiratory limitation leads to an increased inspiratory time reflected in a significantly decreased expiratory: inspiratory time ratio (Te/Ti) at speeds of 4.2 m/s and greater. *Weishaupt and assistants (1995)* observed additionally a significant decrease in tidal volume, minute ventilation and peak expiratory flow at submaximal exercise levels in a reversible laryngeal hemiplegia model (anesthesia of the left recurrent nerve), reflecting an inspiratory as well as an expiratory limitation.

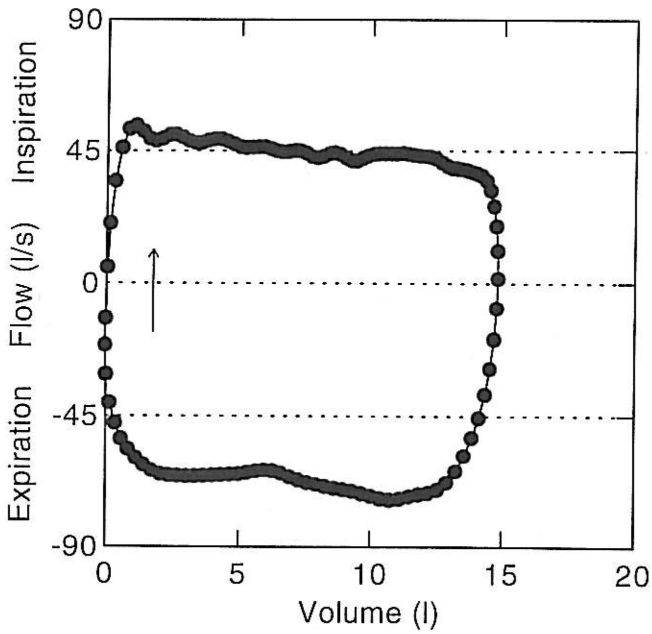

Fig. 2: Tidal Breathing Flow Volume Loop from a horse with laryngeal hemiplegia grade IV at a heart rate of 200 (V200). Note the early peak flow and the plateau formation during inspiration.

Tidal Breathing Flow Volume Loop von einem Pferd mit Hemiplegia laryngis Grad IV bei einer Herzfrequenz von 200 (V200). Während der Inspiration sind die frühzeitige Spitzenatemstromstärke und die Plateaubildung zu beachten.

Different surgical procedures for the treatment of LH and DDSP have been evaluated with this method. It could be shown that laryngoplasty alleviated the flow limitations of induced LH *(Derksen et al., 1986; Shappell et al., 1988)*. Ventriculocordectomy additionally did not further improve upper airway function *(Tetens et al., 1996)*. No improvement could be observed after ventriculectomy *(Shappell et al., 1988)* and subtotal arytenoidectomy *(Belknap et al., 1990)*. Partial arytenoidectomy improved respiratory flow limitations at submaximal exercise but at near maximal exercise some inspiratory flow limitations remained *(Lumsden et al., 1994)*.

ty, specificity and repeatability of the test depends on patients cooperation for maximal inhalation and exhalation *(Lumsden et al., 1993)*. In human neonates and infants tidal breathing flow volume loops (TBFVL) have been evaluated. This variation of the test lacks sensitivity and has great flow variability compared to maximal breathing *(Abramson et al., 1982)*. Qualitative and quantitaive analysis of flow-volume-loops and airflow rates at rest in Standardbreds has shown large intra- and interhorse variations for the TBFVL indices *(Lumsden et al., 1993)* reflecting different breathing strategies in the individual horse. This limits the clinical usefulness of TBFVLs obtained in resting horses. During high-speed treadmill exercise airflow of horses are near maximal breathing *(Belknap et al., 1990)*. The coefficients of variation for TBFVL indices progressively decreased with increasing exercise level indicating that respiratory patterns became less variable *(Lumsden et al., 1993)*.

Evaluation of upper airway function by TBFVLs requires the same equipment and near maximal exercise protocols as airflow measurements described above. Specific computer software allows the analysis of loop shape and quantitative TBFVL indices *(Petsche et al., 1994)*. Loops are usually calculated by the means of 10 breaths, loop closure is accepted as adequate if there is less than 5 % difference in expiratory and inspiratory volume.

Tab. 2: Upper airway flow mechanics in normal horses, effect of exercise.
Atemmechanik der oberen Atemwege, Einfluss der Belastung.

	At rest	Speed	
		4.2 m/s ~HR 75 max	11 m/s ~HR max
HR (1/min)	30.8± 1.1 to 50 ± 9	143.6 ± 18.5 to 185. ± 3	217. 17 ± 2.37 to 225.5 ± 4.92
f (1/min)	15.6 ± 3.1 to 33 ± 3	67.2 ± 3.5 to 97.3 ± 9.7	92.6 ± 15.16 to 117.4 ±9.25
VT (L)	5.39 ± 0.39 to 6.02 ± 0.92	11.69 ± 0.94 to 13.11 ± 0.8	12.87 ± 1.72 to 15.73 ±1.27
VE (L/min)	147 ± 0.08 to 151.41 ± 15.01	950.23 ± 59.02 to 1256 ± 63	1295.97 ± 127.52 to 1858 ± 109
PIF (L/sec)	4.3 ± 0.5 to 7.2 ± 0.8	38 ± 4.7 to 56.3 ± 1.0	74.77 ± 3.86to 75.52 ± 9.35
PEF (L/sec)	4.9 ± 1 to 7.9 ± 1.1	40.1 ± 4.2 to 47. 5 ± 4.5	65.43 ± 5.3 to 66.05 ± 5.58
Pui (cm of H_2O)	1.94 ± 0.22 to 2.4 ± 0.4	20.9 ± 3.8 to 22.29 ± 1.15	38.57 ± 3.93
Pue (cm of H_2O)	1.5 ±0.2 to 1.8 ± 0.4	7.3 ± 0.5 to 9.5 ± 2	11.86 ±3.41
Zi (cm of H_2O/L/s)	0.38 ± 0.04 to 0.63 ± 0.08	0.37 ± 0.06 to 0.53 ± 0.06	0.53 ± 0.04
Ze (cm of H_2O/L/s)	0.14 ± 0.03 to 0.43 ± 0.11	0.16 ± 0.02to 0.25 ± 0.06	0.19 ± 0.06
Ti (sec)	0.74 ± 0.08 to 1.99 ± 0.65	0.32 ± 0.04 to 0.38 ±0.02	0.25 ± 0.028
Te (sec)	0.92 ± 0.11 to 2.23 ± 0.77	0.33 ± 0.04 to 0.39 ± 0.03	0.28 ± 0.024
Te/Ti	0.99 ± 0.05	0.94 ± 0.03	0.98 ±0.05

Abbreviations: HR = heart rate, f = respiratory frequency, VT = tidal volume, VE = minute ventilation, PIF = peak inspiratory flow, PEF = peak expiratory flow, MIF = mean inspiratory flow, MEF = mean expiratory flow, Pui = inspiratory pressure (tracheal pressure - mask pressure), Pue = expiratory pressure (tracheal pressure – mask pressure), Zi = inspiratory impedance, Ze = expiratory impedance Ti = inspiratory time, Te = expiratory time, Te/Ti = ratio expiratory time : inspiratory time.

Myectomy of the sternothyrohyoid muscle is often used as a treatment for DDSP. But in healthy horses myectomy increased the negative inspiratory pressures and inspiratory resistance in the upper respiratory tract *(Holcombe et al., 1994)*.

Tidal Breathing Flow Volume Loops (TBFVL)

The clinical use of upper airway pressure and impedance measurement is limited *(Stick and Derksen, 1989, Williams et al., 1990b)* because of its invasive nature. Flow-volume analysis is a common test for respiratory function in humans because it is noninvasive and sensitive. But sensitivi-

Normal Function of the Upper Airways

At rest four basic shapes occured. The inspiratory curve was mono-, bi- or triphasic with PIF early or late in inspiration, the expiratory flow was biphasic with peak flow early in expiration. During exercise inspiratory flow was monophasic, biphasic or a combination of both, predomaninantly a biphasic inspiratory shape occured. The expiratory curve was mono- or biphasic. *(Lumsden et al., 1993).*
Representative values for TBFVL indices in healthy horses are given by *Lumsden and assistants (1993)* and *Petsche and assistants, (1994).*

Abnormal Function of the Upper Airways

After surgically induced LH grade 4 (LRLN) no changes in loop shape were seen at rest *(Lumsden et al., 1993).* During submaximal and near maximal exercise loop shapes were markedly altered. The inspiratory limb shows a peak flow early in inspiration followed by a marked reduction in airflow [plateau formation] (Figure 2). The expiratory curve is approximately the same as in normal horses.
After induced LH grade IV mainly the inspiratory indices were altered. PEF/PIF, the expiratory flow at 50% of the volume : inspiratory flow at 50% of the volume ratio (EF 50/IF 50) and Ti/Ttot increased and PIF decreased significantly at submaximal and near maximal exercise. IF 50, IF 25 and Te/Ti decreased significantly at near maximal exercise compared to normal horses *(Lumsden et al., 1993, Lumsden et al., 1994).*
Flow measurements in horses with DDSP are presently difficult to perform because it is almost impossible to determine when the horse displaces the palate without a concurrent videoendoscopy *(Rehder et al., 1995).* In addition, horses with DDSP tend to start mouth breathing. Mouth breathing produces a high amount of saliva which can interfere with the flow measurement technique.
In conclusion, examination of the upper respiratory tract during exercise on high-speed treadmills can be a useful tool in evaluation of upper respiratory tract disorders. It has been shown that many functional disorders only occur during high intensity exercise. On the other hand some abnormalities observed at rest do not produce a functional disorder during exercise. An evaluation on the treadmill should not be used as a routine diagnostic tool. A good history, careful physical examination and endoscopic examination at rest are necessary before dynamic evaluation is indicated. Many horses with a functional upper airway obstruction during exercise have a history of an abnormal respiratory noise during exercise or suggestive diagnostic findings at examination at rest. Videoendoscopy during treadmill exercise as a subjective technique already can accomplish a good assessment of the upper airway function. But a final diagnosis of the presence of a respiratory limitation can only be made by the quantitative measurement of respiratory mechanics (airway pressure and flow-volume measurement). Videoendoscopy coupled with these objective methods is currently considered the optimum method to evaluate upper airway function

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