

Determination of the Site of Airway Obstruction Using Gases of Differing Density

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Summary

In unanaesthetized ponies, we measured dynamic and quasi-static lung compliance (C_{dyn} , C_{stat}), functional residual capacity (FRC), pulmonary resistance (R_L), and respiratory resistance (R_{tot}), using forced flow oscillations at a frequency of 3–5 Hz. R_{tot} was measured at a flow rate of 1 litre/s after breathing a dense gas mixture (20% O_2 , 80% SF_6), at 0.5 litre/s after breathing air, and at 0.25 litre/s after breathing a low density mixture (20% O_2 , 80% He). Obstructions were created in the trachea by partial occlusion of the tip of the endotracheal tube, and in the left mainstem bronchus by using a balloon. Tracheal obstruction failed to alter C_{dyn} and C_{stat} , but decreased FRC and increased R_L . R_{tot} increased 50% with He, two-fold with air and ten-fold with SF_6 . Bronchial obstruction failed to change C_{stat} and FRC but decreased C_{dyn} and increased R_L . R_{tot} increased 50% with He, 50% with air and three-fold with SF_6 .

Introduction

In order to investigate the pathophysiology of airway disease in horses, it is necessary to differentiate obstruction of central airways (trachea and bronchi) from obstruction of peripheral airways (bronchioles). Several approaches to this problem have been attempted in human medicine, including measurements of maximal expiratory flow volume curves before and after breathing helium (He). Recently, Drazen *et al.* (1976) described a technique for differentiation of increases in central and peripheral airways resistance in anaesthetized dogs. The technique is based on the principle that airflow in central airways is turbulent, whereas airflow in peripheral airways is laminar. Dense gases breathed at high flow rates accentuate turbulent airflow and therefore the resistive pressure drop in central airways. Gases of low density breathed at low flow rates accentuate laminar flow and minimize the central resistive pressure drop. Resistance of the respiratory system to gas flow is therefore measured using a dense gas, sulphur hexafluoride (SF_6) breathed at 1 litre/s, and helium (He), a light gas, breathed at 0.25 litres/s. Theoretically, central airway obstruction increases resistance measured with SF_6

(R_{totSF_6}) more than resistance measured with He (R_{totHe}), whereas peripheral airway obstruction increases R_{totHe} more than R_{totSF_6} .

In this paper we report an adaptation of this technique for use in sedated ponies, following the creation of a tracheal and bronchial obstruction. To date, we have been unable to successfully use the technique in ponies with peripheral airway obstruction. The results obtained using gases of differing density are compared with conventional measurements of compliance and pulmonary resistance.

Methods

Experiments were performed on mixed-breed male and female ponies sedated to effect with intravenous xylazine. Ponies were intubated via a permanent tracheostomy in the mid-cervical region and an oesophageal balloon was passed into the caudal thoracic oesophagus. The endotracheal tube was attached to a pneumotachograph transducer system for measurement of air flow rates. The flow signal was integrated for measurement of tidal volume. The pneumotachograph transducer system was calibrated daily using a rotameter. The oesophageal balloon was connected to a differential pressure transducer, the other side of which was connected to a similar balloon catheter system located just inside the distal end of the endotracheal tube. The measured pressure difference between the trachea and oesophagus was recorded as transpulmonary pressure (P_L). Air flow rate, tidal volume and transpulmonary pressure were recorded on a photorecording oscilloscope for subsequent calculation of dynamic compliance (C_{dyn}) and pulmonary resistance (R_L) (Amdur and Mead, 1958).

Quasi-static pressure volume curves were recorded between functional residual capacity (FRC) and total lung capacity (TLC). Using a Bird ventilator attached to the pneumotachograph and endotracheal tube, the lungs were slowly inflated from FRC to TLC ($P_L = 30 \text{ cm H}_2\text{O}$) and allowed to deflate slowly back to FRC. Lung volume and P_L were recorded on an X-Y recorder during the deflation manoeuvre. Quasi-static lung compliance (C_{stat}) was measured as the slope of the expiratory limb of the pressure-volume curve at FRC. Functional residual capacity was measured by a helium equilibration technique (Derksen *et al.*, 1982b).

Respiratory system resistance (R_{tot}) was measured by a forced oscillation technique. At end exhalation, the endotracheal tube was connected via the pneumotachograph to a speaker, amplifier and sine-wave generator which imposed sinusoidal flow oscillations on the respiratory system. During these oscillations, flow was plotted against tracheal pressure on an X-Y photorecording oscilloscope. Frequency of oscillation was adjusted until the pressure flow loop closed (between 3 and 5 Hz). The loop was photographed, and resistance was determined from the slope of the loop.

In order to measure resistance with gases of differing density, ponies were forcefully ventilated with either helium, sulphur hexafluoride or air, prior to resistance measurements. Fifty litres of a mixture of either 20% oxygen, 80% helium, air, or 20% oxygen, 80% sulphur hexafluoride were placed in a bag inside a sealed drum. The bag was connected via a non-rebreathing valve to the endotracheal tube. A Bird ventilator attached to the drum was used to provide inspiratory capacities of the test gas to the pony. Five to seven inspiratory capacities were provided, the pony was disconnected and resistance was measured by forced oscillation during the ensuing period of apnoea.

Helium resistance (R_{totHe}) was measured as the slope of the pressure flow loop at 0.25 l/s, R_{totair} at 0.5 l/s and R_{totSF_6} at 1.0 l/s.

Airway obstructions in the trachea and mainstream bronchus were created as follows: tracheal obstruction was caused by placing a rubber stopper in the distal end of the endotracheal tube. The stopper had a hole with a diameter of 13 mm. The inside diameter of the endotracheal tube was 20 mm. An obstruction was created in a mainstem bronchus by a partially inflated canine endotracheal tube cuff. The cuff was attached to a wire which was passed through the endotracheal tube and positioned with the aid of an endoscope. It was necessary to apply anaesthetic cream to the cuff to prevent excessive coughing. The cuff position was checked before and after measurements of C_{dyn} and resistance.

Each level of airway obstruction was created on a different day. The same ponies were used for tracheal and bronchial obstruction. In each case, baseline measurements were made prior to obstruction, and measurements were repeated during obstruction. Baseline and obstruction data were compared by the Student's *t*-test modified for paired replicates.

Results

Table 1 shows the effects of tracheal obstruction on compliance and resistance. Tracheal obstruction increased R_L 3.4-fold, R_{totair} 2.5-fold, R_{totHe} 1.38-fold and R_{totSF_6} 10.83-fold. Dynamic and static compliance were unaffected by tracheal obstruction, but functional residual capacity decreased slightly.

Bronchial obstruction doubled R_L , increased R_{totair} 1.47-fold, R_{totHe} 1.48-fold and R_{totSF_6} 3.13-fold. Dynamic compliance was significantly decreased, but C_{stat} and FRC were unaffected (Table 2).

TABLE 1. Effects of tracheal obstruction.

	Baseline 20 mm inside diameter	Obstructed 13 mm inside diameter
C_{dyn} (l/cm H ₂ O)	0.674 ± 0.126	0.605 ± 0.097
C_{stat} (l/cm H ₂ O)	1.16 ± 0.25	1.32 ± 0.21
FRC (l)	9.35 ± 0.78	8.97 ± 0.68*
R_L (cm H ₂ O/l/s)	0.28 ± 0.06	0.96 ± 0.08*
R_{totair} (cm H ₂ O/l/s)	0.38 ± 0.05	0.95 ± 0.17*
R_{totHe} (cm H ₂ O/l/s)	0.30 ± 0.05	0.42 ± 0.06*
R_{totSF_6} (cm H ₂ O/l/s)	0.75 ± 0.20	8.08 ± 1.91*

C_{dyn} = dynamic compliance, C_{stat} = static compliance, FRC = functional residual capacity, R_L = pulmonary resistance, R_{tot} = total respiratory resistance measured after breathing air, helium (He) or sulphur hexafluoride (SF₆).

Values are mean ± standard error, *n* = 5.

**p* < 0.05.

TABLE 2. Effects of unilateral bronchial obstruction

	Baseline	Obstructed
C _{dyn} (l/cm H ₂ O)	0.499 ± 0.078	0.296 ± 0.050*
C _{stat} (l/cm H ₂ O)	0.80 ± 0.153	0.752 ± 0.141
FRC (l)	7.02 ± 0.69	7.05 ± 0.64
R _L (cm H ₂ O/l/s)	0.30 ± 0.02	0.61 ± 0.05*
R _{totair} (cm H ₂ O/l/s)	0.42 ± 0.04	0.62 ± 0.04*
R _{totHe} (cm H ₂ O/l/s)	0.39 ± 0.02	0.58 ± 0.06*
R _{totSF₆} (cm H ₂ O/l/s)	0.89 ± 0.14	2.79 ± 0.96*

C_{dyn} = dynamic compliance, C_{stat} = atstatic compliance, FRC = functional residual capacity, R_L = pulmonary resistance, R_{tot} = total respiratory resistance measured after breathing air, helium (He) or sulphur hexafluoride (SF₆).

Values are mean ± standard error, n = 5

*p < 0.05.

Discussion

The results of this study clearly show that obstructions of central airways, i.e. trachea and mainstem bronchi, cause a much greater increase in the respiratory system resistance measured after breathing a dense gas (SF₆) than in resistance measured after breathing air or helium, less dense gases. The percentage change in R_{totSF₆} following partial tracheal obstruction was similar to that reported by Drazen *et al.* (1976), following tracheal banding in dogs.

As expected, tracheal obstruction was without effect on static and dynamic lung compliance. Static compliance is a measure of the elasticity of lung parenchyma and therefore should not be affected by obstruction of large airways. Dynamic compliance is lowered either by a decrease in static compliance or by inequalities of time constants in peripheral regions of the lung (Woolcock *et al.*, 1969), the latter generally resulting from non-uniform obstruction of bronchi or bronchioles. Dynamic compliance was unchanged because tracheal obstruction affects the time constants of all regions of the lung uniformly. The reason for the slight but significant decrease in FRC, following tracheal obstruction, is unknown but may be the result of an active exhalation against the airway obstruction.

The decrease in dynamic compliance observed after the partial obstruction of one mainstem bronchus was probably due to inequalities of time constants between the two lungs. Static compliance was unchanged but the unilateral obstruction prolonged the time constant of one lung.

The changes in pulmonary resistance and dynamic compliance observed in this study demonstrate the difficulties in interpreting changes in these measurements. Obstruction of airways at any level distal to the carina can decrease dynamic compliance, and narrowing of either central or peripheral airways or of both increases pulmonary resistance. These two measurements therefore do not allow differentiation of central and peripheral airway obstruction. However the results obtained with SF₆ offer some hope. The increase in R_{totSF₆} was greatest with tracheal obstruction and less with bronchial obstruction,

while changes in R_L , R_{totHe} and R_{totair} were similar with both levels of obstruction. If this trend continues, the R_{totSF_6} increase should be small in peripheral airway obstruction.

To date we have failed in our attempts to measure R_{totSF_6} and R_{totHe} during experimental peripheral airway obstruction. We have created peripheral obstruction by administration of 3-methyl-indole (Derksen *et al.*, 1982a) and by intravenous administration of histamine, following pretreatment with atropine (Drazen *et al.*, 1976). If we give these agents to cause only a slight decrease in dynamic compliance, the deep breaths prior to resistance measurements appear to reverse the airway constriction (Derksen *et al.*, 1982b). If we cause a large decrease in dynamic compliance, ponies are so distressed that we cannot make them apnoeic for the few seconds necessary for resistance measurement.

Acknowledgement

This work was supported by the American Quarter Horse Association.

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CARDIOVASCULAR SYSTEM

Cardiovascular Response to Exercise in the Horse: A Review

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Introduction

Valuable contributions to man's social and economic advancement, to physiology and to medicine have been achieved by using the equine species. Haemorrhagic shock was first studied and blood pressure first measured by the Reverend Stephen Hales (1733), using the horse. The timing and, in part, the origin of the second heart sound were determined in the donkey by Hope (1835) and later confirmed in the horse by Chauveau and Faivre (1855).

The first cardiac catheterization was performed on a horse by Bernard and Magendie in 1847 (Bernard 1876). From the demonstration that the temperature of the blood in the left ventricle was lower than that in the right ventricle it was deduced that oxidation in the lungs was not the process by which oxygen enters the blood. Intraventricular blood pressures were measured by Chauveau and Marey (1861), and the inverse relationship between blood pressure and heart rate (i.e. increased blood pressure, decreased heart rate), now known as 'Marey's Law', was first demonstrated in the horse by Chauveau and reported by Marey (1863) in the first of his important published works.

Muscle blood flow was first studied by Chauveau and Kaufmann (1887), using the horse, and the carotid artery pressure during exercise was measured with a mercury manometer by Zuntz and Kaufmann (1892). The Fick principle for determination of cardiac output and its increase with exercise was confirmed in equine treadmill studies by Zuntz and Hagemann (1898).

Although man has for centuries regarded *Equus caballus* as perhaps the finest of all natural athletes, the sheer size and speed of the horse have made it difficult to assess responses to strenuous exercise, at least by the more routine testing procedures used in man and the dog. Exercise studies have thus usually compared the horse at rest and at varying periods of time following work, in an attempt to better understand the cardiopulmonary and muscular adaptations to exercise and training. Post-exercise determinations of haematologic and metabolic changes and measurement of heart and respiratory rates during recovery from work have been used as a means of evaluating exercise tolerance. Although studies of this type yield important information, the general experimental approach has more recently been expanded to include determinations made