

Function and dysfunction of respiratory and cardiovascular systems of the horse during exercise

Dr David Marlin, BSc, PhD. Visiting Professor in Respiratory and Cardiovascular Physiology, University of Bristol, UK.

The Response of The Respiratory System of the Horse to Exercise

At rest, tidal volume (V_T) in a 500kg horse is around 5 litres with a respiratory rate (f_R) of around 12 breaths/min, resulting in a minute ventilation (V_E) of around 60 litres/min. Average and peak flow rates on inspiration and expiration are low and of the order of only several litres/sec. At maximal exercise, tidal volume increases to around 15 litres and respiratory rate to around 120 breaths/min, giving a maximal minute ventilation (V_E) of close to 1,800 litres/min. If you have difficulty in visualising 1800 litres of air, this is equivalent to the volume of six normal sized baths. At this level of ventilation, mean inspiratory and expiratory flow rates are around 60 litres/sec, with peak expiratory flow rates close to 100 litres/sec. To put this in context, the typical flow rate of water from a Fireman's hose is of the order of 15 litres/sec.

Whilst oxygen uptake (also referred to as oxygen consumption or utilisation) increases linearly in relation to workload (in the case of a horse exercising in the field or on a treadmill, usually workload equates to running speed) and ventilation increases linearly in response to oxygen uptake, the strategy that the horse uses is not the same at all speeds or gaits. Initially, in achieving increases in ventilation from rest to slow-canter, respiratory frequency increases proportionally more than increases in tidal volume. However, in going from slow-canter through to gallop, the increases in ventilation comes primarily from increases in tidal volume. At rest, through walk and trot and up to and including slow-canter, there is no obligatory coupling between ventilation and locomotion. However, at speeds above a slow-canter ventilation becomes entrained and coupled to locomotion such that one breath cycle takes place over one stride, and with the same timing within each stride. As the horse increases speed above slow-canter primarily by lengthening, rather than by increasing stride frequency, this allows more time for inspiration and expiration so that tidal volume is increased, whilst respiratory frequency becomes limited by locomotory entrainment or coupling (See Figure 1).

Ventilatory Strategy of the Horse During Exercise

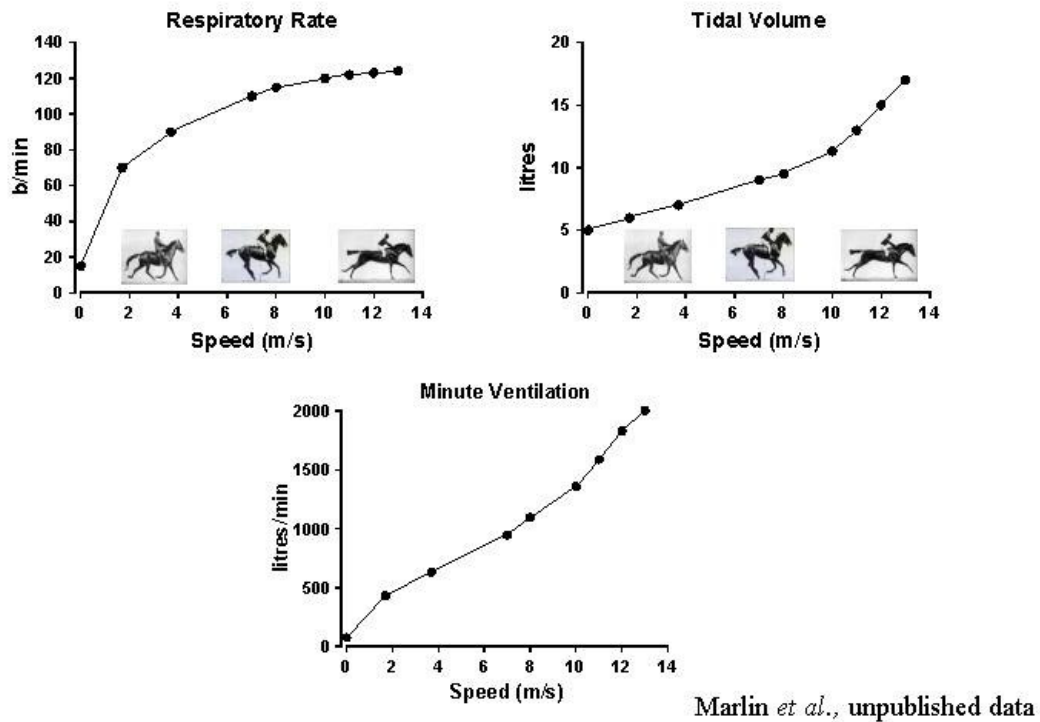
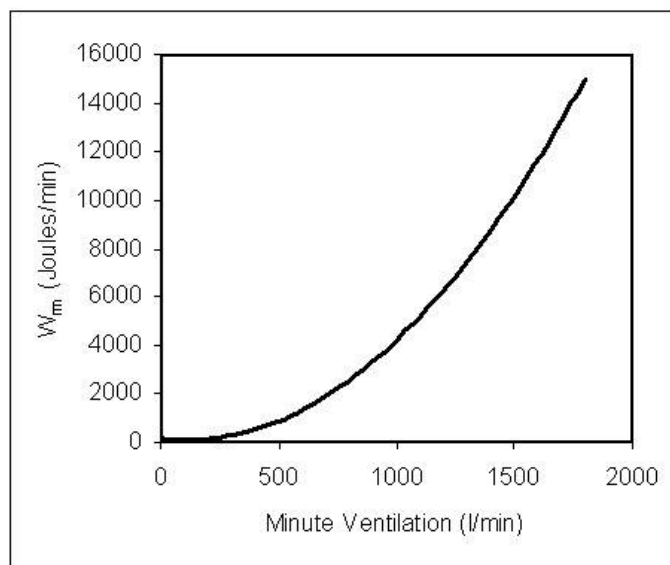


Figure 1. Ventilatory strategy of the horse during exercise.

Whilst minute ventilation increases linearly with workload or running speed, the work of breathing or energetic cost of ventilation increases exponentially (Figure 2). Thus at maximal exercise, even if a further increase in ventilation could be achieved, any increase in oxygen uptake as a result of increased ventilation would be unlikely to result in increased locomotory muscle utilisation and would almost certainly be consumed by the respiratory muscles (Art *et al.* 1990).



Based on data of Art *et al.* (1990)

Figure 2. The relationship between work of breathing (W_m) and minute ventilation (V_E) in the horse during exercise

In order to generate the volume and rate of airflow required during exercise, large gradients between pleural and nostril pressure are required. At rest in healthy horses, changes in oesophageal pressure (as a surrogate of pleural pressure) are of the order of 3-5 cmH₂O. During maximal exercise, the change in oesophageal pressure increases to around 100 cmH₂O. This is not distributed evenly between inspiration and expiration. During inspiration, the minimum oesophageal pressure falls as low as -60cmH₂O, with a maximum pressure during expiration of around +40cmH₂O.

The main obstruction to airflow in the horse resides in the upper airways (Figure 3). At rest, around two-thirds of the resistance to airflow resides in the upper airway, both on inspiration and expiration. However, during exercise, on inspiration the majority of the resistance to airflow is due to the upper airway (Art *et al.* 1988). Only on expiration during exercise does the lower airway resistance predominate over the upper airway (Art *et al.* 1988)(Figure 3). In addition, with increasing airflow rates, total pulmonary resistance increases, most likely due to partial collapse of extra-thoracic airways on inspiration and intra-thoracic airways on expiration. This would not be surprising given the large swings in intra-pleural oesophageal) pressure that occur during exercise in the horse.

Resistance to Air Movement in the Horse at Exercise

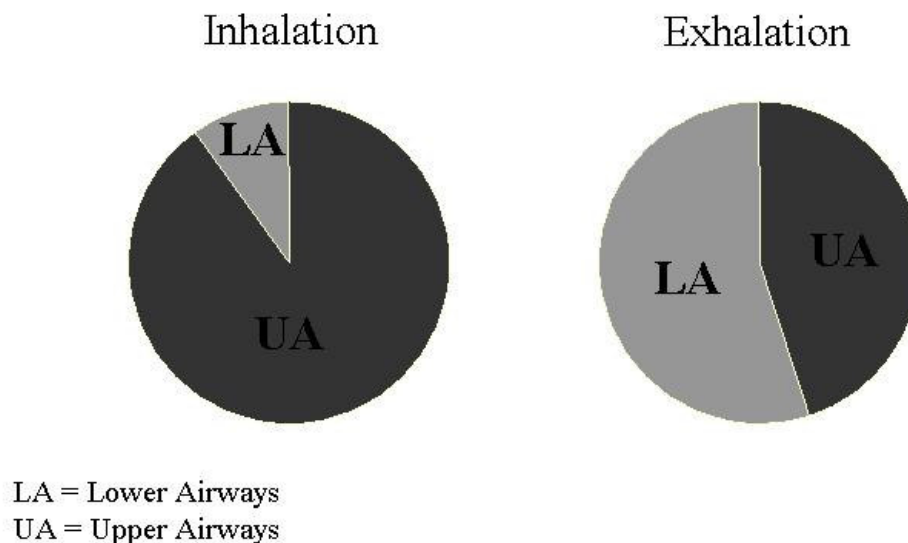


Figure 3. Upper and lower airway resistance on inhalation and exhalation during exercise – adapted from Art *et al.* 1988.

The conventional model for ventilation in most mammals that describes how the changes in intra-thoracic volume, and hence pressure gradients, are generated involves two components: diaphragmatic flattening and rib-cage expansion. In this model, rib-cage volume expansion is achieved by the inter-costal muscles which lift and tilt the sternum and pull the ribs upwards and outwards (Figure 4). In quadrupeds, such as the horse, the same mechanism is utilised at rest and during chemically stimulated ventilation or post-exercise hyperpnoea. However, the strategy utilised by the horse during exercise has only recently been described (Marlin *et al.* 2002).

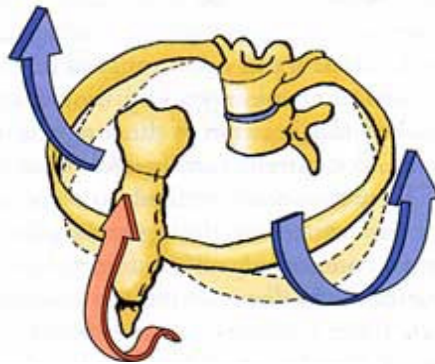


Figure 4. The mechanism for expansion of the thorax to generate pleural pressure gradients to drive airflow

Bramble and Carrier (Bramble and Carrier 1983) and Alexander (Alexander 1989) proposed three mechanisms for driving ventilation in the horse at exercise, which were subsequently investigated by Young *et al.* (Young *et al.* 1992). These were: (1) back flexion; (2) thoracic loading by the forelimbs; (3) a visceral piston. Young *et al.* rejected thoracic loading and the action of a visceral piston as being likely to contribute to driving ventilation, but concluded that back flexion could result in a large enough movement of the pelvis in a cranio-dorsal direction to account for expiratory tidal volume. This would also be aided by contraction of abdominal muscles (Attenburrow and Goss 1994).

However, recent studies in our laboratory demonstrated that whilst expansion of the thorax occurs at rest, walk, trot and slow-canter, at faster speeds there is limited changes in thoracic-circumference with ventilation (Marlin *et al.* 2002). In fact, at gallop changes in thoracic circumference are paradoxical to those of tidal volume such that minimum thoracic circumference occurs at the point of maximum abdominal circumference increase and mid-inspiration. Conversely, maximum thoracic circumference occurs close to end-expiration, when abdominal circumference is at its lowest. In addition, the absolute changes in thoracic circumference are around 1/5th of those seen in the abdominal circumference. This lead us to conclude that chest circumferential expansion plays a minimal role in ventilation in the horse during moderate to intense exercise.

At rest, the horse breathes around its functional residual capacity (FRC) rather than from its FRC, as we do (Koterba *et al.* 1994). FRC at rest in a 500 kg horse is around 20 litres or 40 ml/kg. This equates to around 50% of total lung capacity. However, during exercise it is unclear as to how horses breathe in relation to resting FRC. It is not clear whether excursions increase around the resting FRC or whether the horse increases FRC during exercise. During lobeline induced hyperpnoea at rest (i.e. in non-exercised standing horses), with an increase in ventilation to around 1000 litre/min, most of the increase in ventilation is achieved by breathing slightly below but predominantly above resting FRC (Marlin *et al.* 2002). That is, the horse ventilates farther up on its pressure-volume curve. However, it is not clear if this is the strategy that is utilised during running exercise.

The pulmonary circulation of the horse has greater compliance than the systemic circulation, primarily due to the fact that whilst the arteries and arterioles are generally shorter, they have less smooth muscle than those of the systemic circulation. Whilst at rest, the mean pressure of large pulmonary arteries may only be of the order of 20-30 mmHg in healthy animals, during intense exercise mean pressures may easily exceed 100 mmHg, thereby placing high stress on the vessel walls. Simultaneous measurements of pulmonary artery, aortic and oesophageal pressure in horses during moderately strenuous exercise indicated transmural pressures (an index of stress on the vessel wall) of 150 mmHg for the pulmonary artery and 175 mmHg for the aorta. Taking into account the considerably thinner wall of the pulmonary artery, rupture of the main pulmonary arteries is perhaps surprisingly rare. Although the absolute pressure within the pulmonary arterial circulation is considerably lower than in the systemic arterial circulation, the pressure waves, flow patterns and cardiac valve movements of both circulations are similar.

Within the lung, the pressure gradient between the pulmonary arteries and capillaries is similar to that between capillaries and pulmonary veins, which is in marked contrast to the gradients in the systemic circulation. As a result, approximately half of the total pulmonary vascular resistance is pre-capillary and flow is pulsatile rather than constant. At rest the pulmonary circulation contains around 1/5th of the total blood volume. The volume of blood within the pulmonary capillaries is relatively small compared to that within the larger vessels. During exercise the number of pulmonary capillaries that are recruited (perfused) increases dramatically.

At the transition from rest to intense exercise, cardiac output and therefore pulmonary blood flow, increase by around 10-12 fold. Pulmonary vascular pressures also increase both as result of the increased blood flow and also due to increases in blood viscosity caused by splenic contraction. However, pulmonary vascular pressures do not increase to the same extent as blood flow, with the overall effect that pulmonary vascular resistance initially falls from the transition from rest to light exercise and is then unchanged with increasing exercise intensity, despite further increases in cardiac output (Butler *et al.* 1993) (Manohar and Goetz 1999). The reductions in PVR despite the increased cardiac output are due to a combination of factors: recruitment of vessels previously un-perfused; further active vasodilation in vessels already perfused; distension of vessels already maximally relaxed.

In addition, inclined running has recently been shown to further increase cardiac output in the horse by around 20% (at the same heart rate) compared to running on the flat (McDonough *et al.* 2002). The same group, in a separate study, also demonstrated that inclined running reduced mean pulmonary artery pressure by around 10% (Kindig *et al.* 2003). This implies that inclined running reduces PVR further compared with running on the flat.

As a result of the significant pressure increase in both the pulmonary artery and left atrium during exercise, capillary pressure is also greatly increased (Sinha *et al.* 1996) (Figure 5).

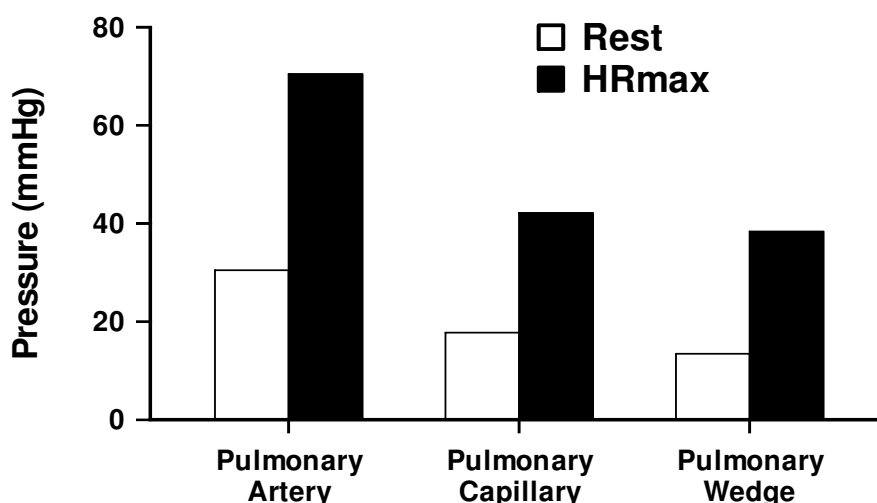


Figure 5. Pulmonary vascular pressures in the horse at rest and during intense exercise (at maximal heart rate) – adapted from Sinha *et al.* 1996.

Perfusion studies using microspheres (Bernard *et al.* 1996) and macroaggregates of human albumin (MAA) labelled with ^{99m}Tc (Harmegnies *et al.* 2002) have both shown an increase in pulmonary blood flow in the dorsal and dorso-caudal regions of the equine lung during intense exercise. The mechanism for preferential redistribution of blood flow to dorsal regions during exercise and the fact that, even at rest, blood flow is not dominated by gravity as in the conventional perfusion model may relate to regional variations in pulmonary arterial endothelial function. Thus, mediators that may produce vasoconstriction in pulmonary vessels from the ventral lung regions may paradoxically induce vasodilation in vessels of the dorsal lung (Pelletier *et al.* 1998). It appears that the regional differences in pulmonary perfusion, at least under resting conditions and in isolated vessels, may be largely determined by differences in NO release (Pelletier *et al.* 1998). Further evidence that NO may play a role in the control of pulmonary smooth muscle tone and pulmonary perfusion during exercise comes from studies using NO administration and antagonism. Thus, there is evidence that inhaled administration of NO reduces mean pulmonary artery pressure (Kindig *et al.* 2001; Mills *et al.* 1996a) whilst antagonism with L-NAME increases pressure (Mills *et al.* 1996b).

The redistribution of pulmonary blood flow to the dorsal regions of the lung during exercise almost certainly has implications when considering EIPH. However, increased flow does not necessarily imply increased pressure! A simple analogy is with a garden hose. If the tap is turned on and the outflow obstructed by the thumb, then the pressure is high but the flow is low. When the thumb is removed the flow increases but the pressure falls. The fact that NO can attenuate pulmonary vascular pressures during exercise, possibly by pulmonary endothelium-dependant vasodilation also goes against the conventional view of the pulmonary vascular bed being fully dilated during exercise. An explanation of why inhaled NO may increase EIPH is that it may transfer the site of pressure drop (resistance) into the capillary bed.

As a result of exercise, the pulmonary right-to-left shunt (due to the coronary and bronchial circulations and V/Q mismatch), which is only of the order of 1% of the total cardiac output at rest, is reduced to around a half (Wagner *et al.* 1989). Even in

Standardbreds with mild bronchiolitis, shunt was not increased during moderate exercise compared with healthy controls (Nyman *et al.* 1991). In addition, despite the increases in total blood flow and redistribution during exercise and evidence for heterogeneity of intrapleural pressures (which may influence regional ventilation), V/Q relationships during exercise appear to be similar to those at rest (Seaman *et al.* 1995; Wagner *et al.* 1989).

The very high pulmonary vascular pressures in the equine lung during exercise, and in particular, the pulmonary capillary pressures, might be reasonably considered to lead to an increase in extravasation of plasma into the interstitial space and airways. However, attempts to measure extra-vascular lung water with a dilution method failed to demonstrate a significant increase in horses during intense exercise (Wilkins *et al.* 2001). In addition, although diffusion limitation has been identified as the main component of exercise induced arterial hypoxaemia in the exercising horse (Wagner *et al.* 1989), this appears to primarily due to a function of short pulmonary capillary transit times. However, in EIPH there is clearly evidence of disruption to the integrity of the alveolar capillary membrane leading to red blood cells being found in the interstitium. It is not inconceivable that some extravasation would occur prior to haemorrhage. In fact the total protein concentration in broncho-alveolar lavage (BAL) fluid from horses collected soon after exercise is often increased, even without significant evidence of EIPH (Marlin, Schroter, Brown-Feltner and Deaton, unpublished observation).

In contrast to the musculo-skeletal and cardiovascular systems which undergo marked adaptive changes with training (i.e. repeated regular bouts of exercise), the respiratory system of the horse does not change following training. This raises the question of whether the respiratory system is a limiting factor in oxygen delivery. Evidence to suggest that the respiratory system is a limiting factor in the oxygen pathway comes from a number of studies. Firstly, if the inspired oxygen fraction is increased from 0.21 to 0.35, horses are able to use more oxygen and exercise for longer (Wagner *et al.* 1996). This indicates that there is additional capacity for the cardiovascular system to deliver oxygen to working muscles, and for the mitochondria within those muscles to utilise more oxygen. In addition, if the respiratory system is “unloaded” by allowing horses to breathe 21% oxygen in helium (i.e. 79% helium) compared with air (21% oxygen, 79% nitrogen), horses can run for longer and lactate production is lower (Erickson *et al.* 1994) (Marlin *et al.* unpublished data). This effect is due to a combination of reduced work of breathing and increased alveolar ventilation, both of which make more oxygen available at the level of mitochondria within locomotory muscles.

Dysfunction of the Respiratory System of the Horse During Exercise.

Lower Airways

Pre-existing lower airway disease (i.e. present prior to the onset of exercise) such as inflammatory airway disease (IAD) or recurrent airway obstruction (RAO or “heaves”, formerly known as equine COPD) has the capacity to adversely effect exercise performance through impairment of ventilation and hence gas exchange. The only common condition directly associated with the lower airway that occurs as a result of exercise is exercise-induced pulmonary haemorrhage (EIPH).

EIPH

Exercise-induced pulmonary haemorrhage (EIPH) refers to the condition in which blood is present in the airways following exercise. The most frequent classification of horses as EIPH positive or negative is currently based on post-exercise endoscopy. Until the introduction of endoscopy and surveys of horses following racing, it was generally considered that only few horses experienced “EIPH”, as the occurrence was essentially based only on the appearance of blood at the nostrils (epistaxis). Even today, the lay perception of a horse classified as a “bleeder” is frequently that which either has profuse amounts of blood in the trachea following training or racing or exhibits epistaxis. However, EIPH should now be considered ubiquitous in horses undertaking fast or intense exercise. The range of the condition varies from horses showing only a small increase in the number of red blood cells detectable in the airways using sensitive techniques such as bronchoalveolar lavage (BAL) to those showing marked epistaxis, with all grades in between.

There has been some debate as to the intensity of exercise required to induce EIPH. Whitwell and Greet (1984) reported that haemosiderophages were present in the tracheal wash of all horses in training when galloping. More recently, it was shown that lesions consistent with EIPH were present in the lungs at post mortem of 10 out of 13 Thoroughbred horses aged less than two years that had been trained at speeds of only 7-8.5 m/s (420-510 metres/min or 16-19 mph) Oikawa (1999). In addition, we have observed 100 fold increases in red blood cell numbers in BAL taken following treadmill exercise at only 600 m/min (22.5 mph) but without blood being present in the trachea.

Whilst for many years seen as a condition affecting the Thoroughbred racehorse, it is now clear that EIPH occurs in any horse undertaking fast or intense exercise, including Thoroughbred racing on turf or dirt, racing over jumps (hurdle and steeplechase), three-day eventing, polo, barrel racing, reining, roping and cutting, Quarter Horse racing, Appaloosa racing, Arab racing, Standardbred racing (pacing and trotting), show-jumping and even in draught and endurance horses. The greater the severity of EIPH the greater the implication for health and welfare. In addition, moderate to severe EIPH is commonly thought to be a contributing factor in poor performance. However, despite considerable anecdotal evidence, only Mason *et al* (1983) found that severe endoscopic EIPH was less common in placed than in unplaced horses. A recent report (Roberts and Marlin, 2001) showed that the incidence of endoscopic EIPH in a group of 166 horses examined immediately post-race in the UK (flat and jump racing) because of poor performance was no different to that of controls (horses performing to expectation). In addition, there was no relationship between EIPH incidence or severity and finishing position in either the control (223 horses) or poor performance group.

It is now generally accepted that in most cases EIPH affects the pulmonary circulation, although severe episodes of EIPH may involve disruption of the bronchial circulation. In young horses, 2-3 year old Thoroughbred racehorses, post mortem examination of the lungs reveals lesions consistent with EIPH almost exclusively in the tips of the dorso-caudal lung. These may be visible on gross examination or only on histological examination using microscopy. With increasing age there is a pattern for the lung to be stained a dark brown-blue (due to repeated and extensive haemosiderin deposition) and for the area of lung affected to be more extensive. The areas of staining are often approximately symmetrical in the left and right lung and may often be seen extend the most cranial along the medial spinal surface of both lungs.

A number of endoscopic surveys of EIPH in racehorses have described the incidence (the chance that an individual horse on a single occasion will have blood in the trachea post-exercise) as being between 30-80%. If multiple examinations are made on the same horse, the incidence rises to 82-95%. The endoscopic incidence of EIPH has been shown to increase from 40% in 2 year old Thoroughbreds racing on grass, to 65% in 3 year olds and 82% in horses aged 4 and over.

The incidence of epistaxis associated with Thoroughbred and Arab racing in Japan was recently reported to be 0.15% (Takahashi *et al*, 2001). Risk factors for epistaxis included jump racing, age greater than 2 years, race distances of less than 1600 m (1 mile), females. The recurrence rate in individual horses was relatively low (4.6%). In contrast to endoscopic EIPH and performance, epistaxis was shown to have a significant effect on the performance of Thoroughbred racehorses in Korea (Byungsun *et al*, 1998).

Aetiology

A number of different theories have been proposed to explain the occurrence of EIPH, however few, if any, have been able to explain the initial site of occurrence and pattern of progression of haemorrhage through the lung. The most widely accepted theory at present is that of pulmonary capillary stress failure due to high transmural pressures (pressures or stresses acting on the pulmonary capillaries). Pulmonary capillary transmural pressure is determined by pulmonary capillary pressure and airway pressure. The horse has high pulmonary vascular pressures during intense exercise. When the high pulmonary vascular pressures (exceeding 100 mmHg) distending the blood vessels are opposed by high positive airway pressures, such as occur during expiration, the transmural pressure (and by implication, wall stress) will be low. However, when the distending internal vascular pressure is associated with a large negative airway pressure (as occurs during inspiration), the transmural pressure and wall stress will be high. Studies *in vitro* have demonstrated that significant disruption of the pulmonary capillaries occurs at pressures of approximately 80 mmHg. *In vivo* it has also been shown in one study that there is probably a threshold mean pulmonary artery pressure of around 80-95 mmHg, above which significant haemorrhage is more likely to occur (Meyer *et al*, 1998; Langsetmo *et al* 2000). On the basis of this theory, any factor or disease that would increase pulmonary vascular pressures (e.g. hypervolaemia) or increase the magnitude of the negative pressures in the lung during inspiration (e.g. dynamic upper airway obstruction) would be expected to increase the severity of EIPH. Interestingly, it has been shown that neither experimentally induced laryngeal hemiplegia nor dorsal displacement of the soft palate increased pulmonary capillary transmural pressure (Jackson *et al* 1997; Hackett *et al* 1997). The limitation of the pulmonary capillary stress failure theory is that it does not in itself explain the site or pattern of progression of EIPH.

More recently a new theory for EIPH has been proposed based on locomotory forces. This theory claims to explain the site of initiation in the tips of the dorso-caudal lung, the nature of the damage and the pattern of progression. The theory is based on the fact that during galloping, the absence of any bone attachment of the forelegs to the spine causes the shoulder to compress the cranial rib cage. The compression occurs largely during the stance phase (when the limb is planted on the ground and the body swings over the limb). The shoulder is moved in a dorsal and cranial direction into the chest. The compression of the chest initiates a pressure wave of compression and expansion which spreads outwards. However, due to the shape of the lung and reflections off the chest wall, the wave of expansion and compression becomes focussed and amplified in the dorso-caudal lung. The alternate expansion and compression at the microscopic level in adjacent areas of lung tissue creates shear stress and capillary disruption. The notion that haemorrhage could occur in the lung in this way is consistent with that due to blunt trauma to the front of the chest or head which commonly results in lung or brain haemorrhage in car accidents victims and boxers. In both cases the haemorrhage occurs at the opposite side of the body to that which is initially struck. The theory predicts that haemorrhage would be more severe on hard track surfaces. At present this theory has not been investigated.

A number of other factors, such as concurrent airway inflammation, have been suggested to exacerbate EIPH. A recent epidemiological study in 7 training yards in the UK over three years has shown that risk for EIPH was 3 times higher in horses with mild inflammation and 10 times higher in horses with moderate to severe airway inflammation, as assessed by tracheal wash (R.Newton, personal communication).

A more pragmatic view of EIPH may be that it is a multi-factorial condition involving airway, vascular and locomotory components.

Effects of EIPH

Instillation of autologous blood into the airways causes inflammation (McKane *et al*, 1999; Couteil *et al*, 1999) and has been characterised by an early neutrophil influx and Whilst severe bleeding and epistaxis are probably now generally considered to affect performance, the effect of the “average” severity of bleeding is still unclear. It has been shown that instillation of 200 ml of autologous blood (but not saline) into each lung decreased maximal oxygen uptake and by implication, would be expected to affect performance.

Diagnosis of EIPH

A definitive diagnosis of EIPH is provided by post-exercise endoscopy and visualisation of blood in the trachea. The classification of a horse as EIPH positive or negative has for past 20-30 years been primarily based on the presence or absence of blood in the trachea following exercise. Simply recording EIPH as positive or negative is not particularly informative, especially if comparing a horse before and after treatment over time as the amount of blood may vary from as little as a single fleck to the trachea being completely covered with a film of blood. Various scoring systems have been described, for example *Grade 1*: flecks of blood; *Grade 2*: more than flecks, but less than a continuous stream; *Grade 3*: continuous stream less than half the tracheal width; *Grade 4*: continuous stream greater than half the tracheal width; *Grade 5*: airways awash with blood (Roberts *et al* ?). The timing of endoscopic examination may be critical in cases of milder EIPH. If endoscopy is performed immediately post-exercise, haemorrhage in the distal airways may not have progressed

to the trachea. Similarly, if endoscopy is undertaken too long after exercise, blood may have been removed by the muco-ciliary escalator and swallowed. On the basis of most reports in the literature, endoscopy 30-60 minutes post-exercise is recommended.

Relatively infrequently, blood in the trachea post-exercise may not originate from the lung but from the upper airway and can be inhaled. In this instance the pattern is usually different to that seen in typical EIPH, with more blood seen in the proximal trachea and decreasing amounts of blood observed moving towards the carina.

The presence of free red blood cells and haemosiderophages in tracheal wash fluid indicates a previous episode of haemorrhage. In horses undertaking canter and gallop exercise this most likely suggests a history of EIPH. Whilst the numbers of free red blood cells are likely to be highest immediately following exercise, peak numbers of haemosiderophages may not be seen until 7-21 days following an episode of EIPH. It is difficult to relate numbers of haemosiderophages to the severity of a previous episode of EIPH.

More recently the concentration of red blood cells (RBC) in bronchoalveolar lavage (BAL) has been used to quantify EIPH (Meyer *et al*, 1998) performed using an endoscope and has the advantage that a scoring of blood in the trachea and tracheal wash can be performed prior to BAL. The left and right lungs can also be selectively lavaged. BAL is performed around 30-60 min post-exercise with a volume of 300 ml per lung, in one or two aliquots (i.e. infuse 300 ml and aspirate or infuse 150 ml, aspirate and repeat). BAL may also be performed blind using a BAL tube (e.g. Bivona). This has the advantage of sometimes allowing a better wedge to be obtained due to the balloon cuff, but the disadvantage of not allowing tracheal scoring of blood or selective lung lavage.

Undoubtedly the use of BAL allows better quantification of EIPH and will detect EIPH at a level below that which results in visible blood in the trachea. It has been reported that blood is only seen in the trachea when the sum of BAL RBC counts for the left and right lung exceed approximately 13,000 RBC/ul (13×10^6 RBC/ml) of BAL fluid. At this concentration of RBC, BAL fluid appears clearly red rather than simply orange tinged or pink. To put this in context of volume of blood, a count of 13,000 RBC/ul represents a volume of blood of around 0.2ml. Thus, the physiological or patho-physiological consequence of bleeding at this level of haemorrhage *per se* is probably minimal.

In our laboratory sequential selective BAL in horses performed using an endoscope (as opposed to a blindly passed BAL tube) in both the left and right dorso-caudal lung has demonstrated that haemorrhage based on RBC counts is almost always greater in one lung than the other. There does not seem to be a consistent side which produces more haemorrhage between horses, but within a horse one side almost always shows more haemorrhage than the other.

The consequences of haemorrhage and its role in airway inflammation may be more important. To date the main use of RBC concentrations in BAL for detecting and quantifying EIPH has been in research (see below in treatment).

Chest radiography appears to be of limited value in diagnosing EIPH or even for detecting structural alterations in the lung as a result of many repeated episodes, even

over a number of years. Pulmonary scintigraphy may detect moderate to severe alterations in the perfusion and possibly ventilation of the dorso-caudal lung (O'Callaghan *et al*, 1987). The use of radio-labelled red blood cells and scintigraphy to localise and or quantify haemorrhage is not useful due to general sequestration of labeled RBC by the lung, even in the absence of haemorrhage (Votion *et al* 1998).

Post-mortem examination of the lungs of racehorses often shows gross darkened staining due to haemosiderin deposition indicative of a history of EIPH. Percutaneous lung biopsy or transbronchial lung biopsy of the dorso-caudal lung has been reported to be occasionally used in the diagnosis of EIPH (Savage *et al* 1998). However, EIPH is not always extensive within the right or left dorso-caudal lung and this technique would in most cases likely be of limited value, whether positive or negative histological evidence of EIPH was subsequently observed.

It has been suggested that ultrasound may be used to detect changes in the dorso-caudal lung fields associated with EIPH (Pascoe, Current Therapy in Equine Medicine 4).

Treatment of EIPH

The fact that the precise aetiology of EIPH is still far from clear and that it may well be multi-factorial or exacerbated by other co-existing disease processes or by inherited factors is reflected in the wide variety of approaches used to treat or manage EIPH. However, to date the number of treatments shown under close scientific scrutiny in properly conducted trials to have any efficacy in terms of reducing the severity of EIPH remains small. It should be considered that the goal of abolishing EIPH in an individual horse asked to exercise intensely is unrealistic. All horses will have EIPH to some extent, even if only detectable on the basis of BAL or identification of haemosiderophages in TW or BAL. However, treatment to reduce a horse consistently experiencing EIPH at grade 4 or 5 to grade 2-3 may well be achievable.

Furosemide: The mainstay of treatment for EIPH for over x years has been furosemide (Lasix). In North America and some other racing jurisdictions, racing after furosemide treatment is permitted. However, in many other countries, whilst training horses on furosemide is permitted, its use during racing is banned. There is now a wealth of evidence that furosemide reduces pulmonary vascular pressures both at rest and during exercise when administered in doses ranging from 250 to 500 mg 1-4 hours prior to exercise. Based on post-race surveys at racetracks it has been shown that furosemide does reduce the severity of bleeding (based on the amount of blood in trachea visualised endoscopically), but that in a significant proportion of horses there is no clear reduction in EIPH. The failure to record reductions in the severity of EIPH could point to a relative insensitivity of endoscopic grading in relation to the true severity of haemorrhage or to the fact that in some horses, the major underlying and precipitating cause of EIPH is not related to high pulmonary vascular pressures.

More recently a number of studies have been conducted using RBC counts in BAL to quantify the severity of EIPH in treadmill studies on horses treated with and without furosemide. Lester *et al* (1999) studied the effect of 250mg of furosemide given either i.v. or by nebulisation 30 or 240 min before track exercise and compared the RBC counts in BAL obtained from the right lung thirty minutes following exercise with that in a control run (no treatment). Furosemide given i.v. 30 min before exercise reduced mean pulmonary artery pressure during exercise by approximately 11% and BAL RBC count by 61%. The other three treatments (250mg i.v. 4 hours before exercise;

250 mg nebulised 30 min before exercise; 250mg nebulised 240 min before exercise) produced a much smaller decrease in both mean pulmonary artery pressure (<5%) and only around a 25% decrease in BAL RBC count with all three treatments. The reason why 250 mg furosemide i.v. in this study only produced a decrease in mean pulmonary artery pressure around half that seen by other workers is unclear.

Kindig *et al* (2001) demonstrated an average reduction in RBC count in BAL of 90% when horses were treated with 1 mg/kg furosemide i.v. 4h prior to exercise at 95% of maximal oxygen uptake. This intensity is perhaps slightly below that which many horses would experience in racing. A more recent study by Geor *et al* (2001) showed a reduction in RBC count in BAL of 66% at an intensity of 120% VO₂max following administration of furosemide at 0.5 mg/kg bwt (235-278 mg) i.v. 4h before treadmill exercise. In the latter study furosemide had the greatest effect on those horses that exhibited the most EIPH in the control run.

Other Vasodilators: Inhaled nitric oxide (NO; 80 ppm), a potent smooth muscle dilator, has been previously shown to decrease pulmonary vascular pressures during exercise in the horse from 98 to 84 mmHg (Mills *et al*, 1996). Infusion of nitroglycerin (an NO donor) at a dose of 20 ug/kg/min has been shown to decrease pulmonary vascular pressures at rest but to have no effect on pressures during maximal exercise (Manohar and Goetz, 1999) and both control and treated horses showed blood in the trachea after exercise. Oral nitroglycerin administered to horses at a dose of 22.5 mg however had no effect of pulmonary vascular pressures. The substrate for nitric oxide synthase (NOS), L-arginine at a dose of 200mg/kg i.v. has also been reported not to reduce pulmonary vascular pressures during moderate intensity exercise. However, L-arginine at this dose can reverse the increase in pulmonary vascular pressures caused by the administration of L-NAME, a NOS antagonist (Mills *et al*, 1996). A more recent study has shown that inhaled NO (80 ppm) produced a small but consistent reduction in pulmonary vascular pressures, but in fact the RBC count in BAL was doubled with NO inhalation compared with the control run (Kindig *et al*, 2002).

Whilst reduction in pulmonary vascular pressures by circulatory volume reduction with furosemide appears to be effective in reducing the severity of EIPH, reduction in pressure using vasoactive drugs may well increase the severity of EIPH. This points to the fact that the pre-capillary arterioles may be constricted in order to protect the pulmonary capillaries and thus be the cause of the high pulmonary vascular pressures seen in the horse. This would tend to suggest that treatment with vasodilators for EIPH is contra-indicated.

Recent studies with phosphodiesterase inhibitors in treadmill studies suggest that this class of drug may have efficacy in reducing the severity of bleeding in individual horses.

Nasal Strips: On the basis that a large proportion of the resistance to breathing occurs in the upper airways, and particularly in the nasal passages, nasal dilator strips have recently been developed for horses (FLAIR, CNS Inc, Minneapolis, Minnesota, USA). There is no doubt that the soft tissue overlying the nasal incisive notch is poorly supported and can be observed to be drawn inwards during inspiration, effectively narrowing the nasal passages. This would have the effect of increasing the airway component of transmural pressure during inspiration and place greater stress on the blood gas barrier. In fact, preliminary findings in one study have shown that the

FLAIR strip does decrease both upper airway resistance and tracheal pressure in horses during treadmill exercise (Holcombe *et al*, 2001). In addition, the FLAIR strip has also been shown to decrease oxygen consumption during exercise (Poole *et al*, 2000; Geor *et al* 2001), presumably due to decreased work of breathing.

In two recent treadmill studies, the FLAIR strip was shown to reduce the number of RBC in BAL by an average of 44% (Kindig *et al*, 2001) and by 74% (Geor *et al*, 2001). In the latter study, the greatest reduction in haemorrhage was seen in those horses exhibiting the higher volumes of bleeding in the control runs (no nasal strip). One recent study failed to demonstrate any change in the incidence of EIPH (that is scored as blood present or absent in the trachea following exercise)(Goetz *et al* 2001). However, given that the FLAIR strip in other studies has been shown to attenuate rather than abolish EIPH this “negative” finding is of limited consequence. It is also important to emphasise that correct placement of a nasal strip is essential. The tendency for many users appears to be to place the strip too high on the nose. For this reason a template is included with the FLAIR strip to facilitate correct placement and should be used.

In the UK and many other racing jurisdictions the use of nasal strips is currently prohibited during racing but allowed during training. This is in contrast to North America where its use in racing is widespread. The efficacy demonstrated in the recent study by Geor *et al* (2001) (74% reduction in BAL RBC count) approaches that of furosemide on the same horses (80%). The FLAIR strip and furosemide in combination reduced the average BAL RBC count by 87%. Thus, the use of nasal dilator strips based on these two treadmill studies, although on a limited number of horses, suggest that such devices merit strong consideration to use with or as an alternative to treatment with furosemide.

Others: Phlebotomy has been used as a treatment in hypervolaemic Standardbred trotters. A reduction of the total blood volume by 22% (36 ml/kg) did decrease the severity of EIPH but treadmill performance and other indices of function (e.g. heart rate and oxygen uptake) were adversely affected (Funkquist *et al* 2001).

Pentoxifylline (a phosphodiesterase inhibitor) is known to increase the deformability of RBC and decrease blood viscosity, and potentially might decrease pulmonary vascular pressures during exercise and attenuate EIPH. Administration of 8.5 mg/kg pentoxifylline i.v. had no effect on pulmonary vascular pressures or the incidence of EIPH and did not enhance the effect of furosemide when given in combination (Manohar *et al* 2001).

Clenbuterol (Ventipulmin) administered either alone or with furosemide appears to have no effect on pulmonary vascular pressures or pulmonary function in clinically healthy horses during exercise (Manohar *et al* 2000a; Manohar *et al* 2000b. Its effect on EIPH has not been investigated but it would be surprising if it did demonstrate any efficacy.

Water restriction is not an uncommon practice in many countries that have racing, in the belief that the dehydration may alter “blood pressure” and thus prevent or reduce the severity of EIPH. To the authors knowledge, there is no information in the scientific literature that demonstrates any efficacy of water deprivation against EIPH. Prolonged water deprivation and dehydration cannot be controlled in the same way as

with diuretics such as furosemide and any benefit from a reduction in severity of EIPH might well be offset by a reduction in performance due to prolonged dehydration.

Management

Goals in the management of horses with above average severity of EIPH should be to reduce them to the level of EIPH seen in the average racehorse. The goal for management of the horse which experiences the average degree of EIPH should be to avoid progression to a more severe degree of EIPH. At present, the only two treatments with proven efficacy are furosemide and the FLAIR strip.

However, the recent epidemiological finding that increased incidence of endoscopic EIPH is associated with bouts of airway inflammation point to a need to ensure that stable hygiene is optimal. Measures that can be taken include use of low-dust beddings such as paper and cardboard, provision of soaked hay or haylage (silage), ensuring and maintaining good ventilation, frequent steam or power cleaning of stables to prevent accumulation of dust and moulds on walls, floors and ceilings and ensuring that the horse is always removed from the stable when the bedding is changed or arranged. Many racing yards now undertake routine endoscopy in order to identify individuals with airway inflammation so that treatment can be instigated rapidly and the duration of disease reduced.

Atrial fibrillation appears to increase the severity of EIPH in many horses. On occasions when atrial fibrillation does not occur the severity of EIPH is often noticeably reduced. Atrial fibrillation should therefore be ruled out in cases where a sudden increase in the severity of EIPH occurs, possibly associated with loss of performance.

The role of dynamic upper airway obstruction in exacerbating EIPH is still unclear but the efficacy of the FLAIR strip would tend to support the notion that increased upper airway resistance may worsen EIPH.

Dysfunction of the Respiratory System of the Horse During Exercise.

Upper Airways

Obstructive conditions of the upper airways also occur relatively frequently in the horse and are a cause of abnormal respiratory noise and impairment to respiratory airflow. Whilst some conditions can be diagnosed at rest, there are numerous dynamic disorders which occur only during exercise and it has become accepted that these require exercising endoscopic examination on a high-speed treadmill to achieve an accurate diagnosis. The vast majority of horses acclimate well to treadmill exercise and after two or three training sessions most animals may be exercised at a level of work similar to that which they perform in the field.

However, there are now two recent and new possible alternatives to treadmill diagnosis. The first is the use of field-based systems for measuring airflow. The original field based systems for horses were the Spiroson system from Switzerland and the Cosmed system from Italy. In the early years both these systems had problems under field conditions. The Spiroson system was sensitive to moisture whilst the Cosmed system had too high a resistance. The resistance problems of the Cosmed system appear to have been corrected in the most recent version however the measurements of oxygen uptake and carbon dioxide production are still inaccurate. Whilst recording of flow patterns can be used to verify that the pattern and level of breathing (e.g. minute ventilation) are normal or abnormal, they do not give a specific diagnosis and this must still be undertaken by treadmill endoscopy. Therefore these systems are best suited to screening larger numbers of horses to identify those with unusual or abnormal respiratory function during exercise, which warrants further investigation.

Another method that has been studied and developed recently is the use of sound recordings. Both research and commercial systems have been developed and used to attempt to diagnose abnormal upper airway function under field conditions. The advantage of this approach is that the equipment is relatively simple, inexpensive and easy to use. The interpretation of “sonograms” recorded during exercise is however not straightforward. To date this technique still requires a significant amount of further development before it can be considered a reliable technique.

Thus, the gold-standard for diagnosing dynamic upper airway dysfunction during exercise remains treadmill based endoscopy during moderate to high intensity exercise.

The most frequently encountered dynamic upper airway obstructive condition is dorsal displacement of the soft palate (DDSP), but numerous conditions have now been identified that require exercise endoscopy for diagnosis. For example, whilst a horse with grade 4 laryngeal hemiplegia would not require treadmill endoscopy to confirm that this condition would obstruct airflow, a horse with grade 1 or 2 could improve or worsen during exercise. In addition, animals that make a noise during exercise cannot be assumed to have a major obstruction to airflow whilst conversely, horses that do not make a noise may still have some degree of impairment of airflow (ventilation). Thus, the best approach to investigation of the upper airway in relation to exercise is to measure function (ventilation) and to visually observe the upper airway (endoscopy) during intense exercise. However, it can often be difficult to conduct both procedures at the same time, depending on what equipment is being used.

The Response of The Cardiovascular System of the Horse to Exercise

At rest the heart rate of the horse is around 25 b.p.m. and during intense exercise can increase by approximately one order of magnitude. With stroke volumes of around 1 litre at rest and 1.7 litres during intense exercise, cardiac outputs in excess of 400 litres/min are attainable. Again, an order of magnitude increase over cardiac output at rest. The horse also has the capacity to double its packed cell volume during intense exercise compared to rest, greatly increasing the haemoglobin concentration per litre of blood. The cardiovascular system, even in the untrained horse, thus has an admirable capacity to deliver oxygen to the locomotory muscles. Indeed, the large heart size in elite horses such Secretariat, Mill Reef, Eclipse and Phar Lap has been part of horseracing legend for many years.

The high aerobic capacity of the horse is perhaps puzzling when the “feral” nature of the horse is considered. At birth horses are born with muscles that possess a high glycolytic (anaerobic or lactate producing) capacity. Feral horses spend the majority (probably in excess of 70%) of their time grazing; i.e. slowly moving. When startled by predators they undertake explosive sprint “exercise”, usually lasting seconds as opposed to minutes, to put distance between themselves and potential predators. In the wild, it would be unusual for a horse to run at racing speeds over the range of racing distances that are common in Thoroughbred or Standardbred racing. Thus, both the capacity for oxygen delivery and the adaptability of the equine cardiovascular are certainly remarkable.

During the transition from rest to intense exercise, the heart rate rises rapidly. Although pre-exercise anticipation and catecholamines release may already have increased heart rates to around 100 b.p.m., following the onset of near maximal exercise it may still take around 90-120 seconds for heart rate (and oxygen uptake) to reach a steady state. The kinetics of the increases in heart rate (and hence cardiac output) and oxygen uptake in the horse are incredibly fast when compared with those of other animals that have been studied, including the pony, man, dog and mouse (Langsetmo *et al.* 1997) (Kindig 2005).

Whilst it is common to talk of steady states, there is usually a slow upward drift and true plateaus are rarely reached. Whilst a true plateau beyond which no further increase in heart rate must theoretically exist, in almost all cases horses fatigue before this is reached. Indeed, the estimation of maximum heart rate or maximal oxygen uptake can be problematic in this respect.

Between heart rate at rest and around 200 b.p.m. during exercise, heart rate and workload are linearly related. This is provided that heart rate in this range is not elevated by extraneous factors, such as excitement or pain or thermal stress. This tends to be most problematic below heart rates of ~130-140 b.p.m. There is evidence that vagal inhibition of the sinus node is only present at heart rates below around 120 b.p.m. in horses based on administration of a vagolytic agent (P.W. Physick-Sheard, personal communication). At around heart rates of 130-140 b.p.m., circulating catecholamine concentrations begin to increase exponentially and the sympathetic system dominates (Snow *et al.* 1992).

The maximal capacity to use oxygen during exercise may well be primarily determined by cardiovascular capacity, and more specifically, by heart size. We have previously shown that around 60% of the variation in maximal oxygen uptake in

trained Thoroughbred racehorses can be explained by variation in left ventricular mass, estimated by echocardiography (Young *et al.* 2002). In addition, estimation of left ventricular mass and ejection fraction by echocardiography explains around a quarter of the variation in racetrack performance in Thoroughbred horse racing over the flat and over jumps (Young *et al.* 2005).

At rest, systemic arterial pressure is of the order of 130/80 mmHg and increases to around 230/110 mmHg during intense exercise. Concomitantly, there are marked increases in right and left atrial and ventricular pressures. Mean right atrial pressure at rest is of the order of 5 mmHg and may increase to around 40-50mmHg, whilst mean left atrial pressure may increase to 70 mmHg. The high mean left atrial pressure in the horse may be a consequence of high pulmonary vascular pressures, in turn due to an inability for the lung to accommodate the high level of cardiac output. Alternatively, a high pressure may be required to ensure rapid filling of the left ventricle at heart rates as high as 4 beats per second in order to maintain stroke volume. Systolic right and left ventricular pressures also increase to over 180 and 230 mmHg, respectively. Despite these marked increases in driving pressures and systemic circulatory pressures, due to vasodilation in both the vasculature in working muscles and in the systemic arterial system, there is a dramatic decrease in total pulmonary resistance during exercise.

One of the important features of intense exercise in the horse is the development of arterial hypoxemia and hypercapnia. Arterial PO₂ may fall as low as 60-70mmHg (temperature corrected to 37°C). This results in a small but physiologically significant fall in arterial oxygen saturation from ~95% at rest to ~85% (Wagner *et al.* 1996). Arterial hypoxaemia in the horse may develop during intense exercise as a result of reduced pulmonary capillary transit time, alveolar hypoventilation, increased pulmonary diffusion distance and V/Q mismatch. Of these factors, reduced pulmonary capillary transit time is believed to be the primary mechanism for exercise induced arterial hypoxaemia.

At rest, the average time that a red blood cell (RBC) spends in a pulmonary capillary is estimated to be of the order of 0.75 to 1.0 seconds. This duration is more than adequate to allow equilibration with the alveolar oxygen tension. However, during maximal exercise the mean capillary transit time for RBC's has been estimated to be reduced by around a ½ or even a ¼ of that at rest, allowing insufficient time for full equilibration.

During maximal exercise in the horse, PaCO₂ may increase from around 45 mmHg at rest to above 65 mmHg. This is considered to be a consequence of alveolar hypoventilation as horses breathing helium-oxygen during intense exercise show a decrease in PaCO₂ from 50 (air) to 44 mmHg (helium/oxygen). A secondary consequence of arterial hypercapnia and increased alveolar CO₂ will be a reduction in alveolar oxygen tension by around 5-10 mmHg, thus decreasing the alveolar driving pressure.

One potential factor in the development of arterial hypoxaemia and hypercapnia that has been essentially neglected is the development of interstitial oedema. In light of the high pulmonary vascular pressures that develop in horses during intense exercise, transudation of fluid from the pulmonary capillaries into the interstitial space should not be implausible. Indeed, electron micrographs of horse lungs post-exercise demonstrate the existence of partial disruption of pulmonary capillary walls and

accumulation of RBC and other material, which would have the effect of increasing diffusion distance (Birks *et al.* 1997). In addition, we have shown that protein concentration in broncho-alveolar lavage fluid is increased post-exercise in horses and that this can occur independent of haemorrhage (Marlin & Schroter, unpublished data).

Ventilation to perfusion (V/Q) mismatch does develop in horses during intense exercise but it is likely that this is only responsible for a small proportion of the arterial hypoxaemia (Wagner *et al.* 1989).

Despite the factors that serve to inhibit gas exchange, a number of factors serve to counteract these effects. The increase in PCV from around 0.35 litres/litre at rest to around 0.70 litres/litre at maximal exercise effectively doubles the oxygen carrying capacity of the blood by increasing the haemoglobin concentration from ~120g/100ml to 240g/100ml. Even accounting for decreases in saturation, the arterial oxygen content of the horse will be in excess of ~25 ml O₂/100ml of blood. With a cardiac output in the region of 300 litres/min, this allows delivery of oxygen at around 75 litres/min. For a 500 kg horse this equates to a delivery of ~150 mlO₂/kg/min, i.e. the VO_{2max} of an average Thoroughbred racehorse. In this case supply and demand (ability to utilise oxygen by the working muscles) are well matched.

Dysfunction of the Cardiovascular System of the Horse During Exercise.

The diseases and abnormalities of the cardiovascular system of the horse include abnormalities of rhythm, cardiac murmurs, diseases of the myocardium and pericardium and disease of the vessels.

Abnormalities of rhythm

Dysrhythmias occur commonly in athletic horses and the majority, with the notable exception of atrial fibrillation (AF), usually do not affect performance. Diagnosis of arrhythmias has been greatly enhanced by improvements in technology that allow ECG recordings to be taken readily in exercising horses either by telemetry or small on-board battery operated ECG equipment. Cardiac disease is a rare primary cause of poor performance in the equine athlete. When present, dysrhythmia is the commonest underlying cause. However, alterations in cardiac rhythm are common in athletic horses because of their normal high parasympathetic drive. Bradyarrhythmias (slow rhythms) are normal findings in athletic horses, as are sinus and atrioventricular block. Obvious arrhythmia such as atrial fibrillation is most likely to affect the performance of horses the more intense the sport they participate in. Cardiac rhythm disturbances often occur as a result of disease in other body systems or metabolic disturbances and in this instance the arrhythmia rarely indicates primary heart disease.

Cardiac Murmurs

A number of murmurs occur in normal horses that are not associated with underlying cardiac disease. These murmurs have been variously called, functional, physiological, innocent or flow murmurs. These murmurs are common in athletic horses of all breeds. Murmurs associated with mitral and tricuspid valve regurgitation are also commonly detected in performance horses, although it is still not clear to what extent they influence athletic performance. Severe regurgitation and resultant cardiac failure cause obvious performance decrements but the effect of mild and moderate regurgitant murmurs is less certain. Recent data have shown that atrioventricular (AV) valve regurgitation increases after six months race training in Thoroughbreds. It seems likely that the eccentric cardiac hypertrophy and increased blood volume that

accompany athletic training result in secondary stretch of the valve annulus and increased regurgitation. Endocarditis is a rare condition causing valvular regurgitation and cardiac murmurs. Blood-borne bacteria colonize the valves (usually mitral and aortic) and the resulting inflammation and deformation leads to chronic regurgitation. *Pasteurella*, *Actinobacillus* and *Streptococcus* species are most likely to be causative in horses, although other agents have also been reported. Prognosis is poor, even if the horse survives the early acute phase and bacterial cure is achieved; there may sufficient damage to the cardiac valves to preclude return to previous performance, or cause death from heart failure.

Diseases of the myocardium

Diseases of the myocardium are poorly understood in horses but are characterized by loss of performance and arrhythmias at rest and during exercise. Serum or plasma concentrations of cardiac troponin I and the isoenzymes of lactate dehydrogenase will be elevated in severe acute cases of myocardial inflammation and necrosis. Dilated cardiomyopathy occurs rarely in athletic horses and has been associated with nutritional deficiencies in young horses and cattle. Occasionally toxic damage to myocytes occurs when a cardiotoxin is accidentally introduced into equine feed. The ionophores salinomycin and monensin have caused a number of such outbreaks throughout the world. Horses that survive ingestion of cardiotoxins usually develop a dilated hypocontractile ventricle that mimics dilated cardiomyopathy. True inherited idiopathic cardiomyopathy as occurs in other species, has not yet been identified in horses.

Diseases of the Pericardium

Affected horses may present with general signs of malaise or evidence of heart failure including weakness and collapse. In horses affected with bacterial pericarditis, there will be associated signs of infection and sepsis. Cardiovascular signs depend upon the volume of pericardial fluid. In cardiac tamponade (large effusion compressing the right atrium), jugular distension, subcutaneous edema, ascites, pleural effusion and abdominal enlargement will be evident. Peripheral pulse quality is poor and heart rate is increased. There may be muffling of the heart sounds with the presence of pericardial friction rubs in some cases.

Disease of the vessels

Three general syndromes of large vessel disease are recognized in performance horses. These are: Sudden death due to large vessel rupture, acute or recurrent colic due to arteritis and thrombosis of the cranial mesenteric arteries, or renal arteries and a vague history of increasingly poor performance and hind limb lameness with aortoiliacofemoral thrombosis

Summary

During exercise the whole body metabolic rate is greatly increased, which is primarily due to increases in metabolic activity of locomotory muscles. This greatly increased metabolic demand is met by an integrated response involving a range of physiological mechanisms that permit the respiratory and cardiovascular system to support this increased demand in terms of oxygen delivery and carbon dioxide removal, but also in secondary roles including thermoregulation, acid-base balance and supply of energy sources. In exercise, the goal is to maintain oxygen delivery and avoid fatigue. The cardiovascular and respiratory systems work in a highly integrated way to service the requirements of the working muscles. Whilst exercise clearly disturbs homeostasis, it is a “stress” that the horse has evolved a range of mechanisms and a prestigious capacity to cope with.

Acknowledgements

Dr Marlin would like to acknowledge the help of specialist equine cardiologist Dr Lesley Young for her contribution to the area of cardiac dysfunction in the horse during exercise.