

Effect of Sub-Maximal Exercise and Training on Dead Space Ventilation in the Horse

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Summary

Whereas the effect of exercise on minute ventilation in the horse has been well described, the effect of exercise and training on dead space and alveolar ventilation is not well documented. We studied the effect of exercise and training on respiratory frequency (f), minute ventilation (\dot{V}_E), tidal volume (V_T), dead space to tidal volume ratio (V_D/V_T), dead space ventilation (\dot{V}_D) and alveolar ventilation (\dot{V}_A) in 8 normal mature horses. Measurements were made at rest and during standardized submaximal exercise on a treadmill (speed 100 m/min; 12% incline; heart rate 120) before and after training. Expired gases were collected through a face mask and a non-rebreathing valve into a meteorological balloon. Arterial blood gases, mixed expired oxygen and carbon dioxide tensions (PO_2 and PCO_2) and \dot{V}_E were measured at rest and at 5, 10 and 15 min after the onset of exercise. The training consisted of bouts of lunging and treadmill exercise of increasing duration for one month. At the onset of exercise minute ventilation increased from 75.2 L/min at rest to 434 L/min because tidal volume increased from 4.2 L to 7.4 L and respiratory frequency increased from 18.8 to 57.7 breaths/min. As exercise progressed there was a gradual increase in minute ventilation primarily because of an increase in respiratory rate. Mean V_D/V_T was 0.65 at rest, decreased to 0.56 at the onset of exercise and then increased slightly but significantly. These changes in V_D/V_T resulted in part from a 1.5-fold increase in dead space volume. With the onset of exercise, dead space ventilation increased from 48.8 to 242.1 L/min and alveolar ventilation increased from 26.4 to 191.9 L/min. As exercise progressed, the subsequent rise in \dot{V}_E was due to an increase in \dot{V}_D , \dot{V}_A remaining constant. After training V_D did not increase between 5 and 15 min of exercise whereas there was a significant increase in V_D over this time interval in the pre-training exercise test.

Index terms: Oxygen consumption; deadspace-tidal volume ratio; blood gases.

Introduction

The values of minute ventilation (\dot{V}_E) and tidal volume (V_T) are well described in the normal standing horse and pony (Gillespie *et al.*, 1966; Sasse, 1971; Orr *et al.*, 1975;

Willoughby and McDonell, 1979; Viel, 1980, Derksen *et al.*, 1982). Whereas the effect of some drugs and of environmental conditions on \dot{V}_E , V_T and respiratory rate (f) is well documented (Gillespie *et al.*, 1966; Muir and Hamlin, 1975; Derksen *et al.*, 1981; Derksen *et al.*, 1982), the effect of exercise and training on ventilation has not been widely reported. In man, exercise causes an increase in \dot{V}_E , V_T and f (Astrand and Rodahl, 1977; Gledhill *et al.*, 1977). In the horse and pony, racing, swimming and treadmill exercise also result in a significant increase in \dot{V}_E and f (Bisgard *et al.*, 1978; Thomas *et al.*, 1980; Thomas and Fregin, 1981; Hornicke *et al.*, 1983; Pan *et al.*, 1984). Few authors have described the variation of V_T during exercise. Bisgard *et al.* (1978) demonstrated an increase in V_T and dead space volume (V_D) in ponies during a graded treadmill exercise. Pan *et al.* (1983, 1984) compared the exercise-induced increase in \dot{V}_E , V_T and f in normal and carotid-body-denervated ponies in an attempt to explain the mechanisms controlling the exercise-induced hyperpnea. Thomas and Fregin (1981) reported an increase in \dot{V}_E in horses performing a graded treadmill exercise but did not report the exercise-induced changes in V_T and f . Hornicke *et al.* (1983) found an increase in V_T and f in horses subjected to an increasing speed of exercise. Forster *et al.* (1985) described an increase in dead space ventilation during moderate exercise in ponies. The dead space volume has been measured telemetrically during exercise by Pollman and Hornicke (1984). These authors recently described that the dead space did not increase during short term exercise in riding horses.

The effect of long term exercise on dead space ventilation (V_D) and alveolar ventilation (\dot{V}_A) and the changes in these parameters with training have not yet been described in the horse. This study evaluated the effect of moderate exercise and training on \dot{V}_E , V_T , V_D , \dot{V}_D , \dot{V}_A , f and dead space to tidal volume ratio (V_D/V_T).

Materials and Methods

Seven healthy Standardbred horses and one healthy Quarterhorse, aged 7 ± 2 years ($\bar{x} \pm \text{SEM}$) and weighing 418 ± 20 kg ($\bar{x} \pm \text{SEM}$) were included in this study. The experiments were performed on 4 mares and 3 geldings.

Animal preparation. A subcutaneous transposition of the right common carotid artery was performed under general anesthesia in order to facilitate arterial blood sampling during exercise. The surgery was followed by a 3 week period of stall rest and a 2 week period of adaptation to the experimental apparatus. During this period, the horses became accustomed to a motor-driven treadmill, to the face mask and the device collecting expired gas.

Experimental protocol. Each horse was studied 3 times on separate days both before and after a 1 month training period. The aerobic training used consisted of bouts of lunging and treadmill exercise of increasing duration, starting with 30 min of lunging at the trot and 15 min of exercise on the treadmill (speed 100 m/min; 12% incline) and increasing by 2 min every other day. The environmental temperature and relative humidity did not vary greatly between experiments. They were respectively $22 \pm 2^\circ\text{C}$ ($\bar{x} \pm \text{SEM}$) and $40 \pm 5\%$ ($\bar{x} \pm \text{SEM}$).

In each experiment, arterial blood samples and mixed expired gases were collected at rest and at various intervals during steady state submaximal exercise on a treadmill (Safe-T-Mill[®], Talbot-Carlson, Audubon, IA, USA) with a 12% angle at an average speed of 100 m/min. The speed was adjusted to obtain a heart rate (HR) of 120 beats/

min (BPM). To facilitate arterial blood sampling, a 16 gauge, 8.125 cm indwelling catheter (Deseret Medical Inc., Sandy, Utah, USA) was placed into the right common carotid artery. To collect expired gases, a fiberglass face mask, with low dead space, was applied over the mouth and nostrils. The mask was connected to a non-rebreathing valve as described by Gallivan (1981). Dead space of the expired gas collecting system was 1.242 L. The valve was connected to a 5 cm internal diameter (I.D.) polyvinylchloride (PVC) tubing system through a flexible 5 cm I.D. tubing (Shop-Vac[®], Montreal, Quebec, Canada). The PVC tubing system had four T-connections and valves allowing expired air to flow into four 500 l meteorological balloons.

Blood samples were obtained in heparinized plastic syringes (Becton-Dickinson & Co., Rutherford, NJ, USA) from the horse at rest and at 5, 10 and 15 min after the onset of exercise. Samples were stored on ice and analyzed within 2 hours for pH, PCO₂ and PO₂ using a blood gas analyzer (ABL-3, Radiometer, London, Ontario, Canada). Rectal temperature was recorded with a thermistor probe (Narco Biosystems Inc, Houston, TX, USA) during exercise and the blood gas values were corrected for body temperature. Mixed expired gas samples were collected for 8 min at rest and 2 min during exercise simultaneously with arterial blood sampling and were analyzed for the partial pressure of oxygen and CO₂ (P_EO₂, P_ECO₂) using the blood gas analyzer. The value of *f* was measured by counting of movements of the non-rebreathing valve. The volume of the collected gases was measured using a dry gas meter (American-Meter, Boston, MA, USA) and corrected to body temperature pressure saturated (BTPS) and standard temperature pressure dry (STPD). Temperature of the expired gases was assumed to be at body temperature. Minute ventilation, V_T, V_D, physiological dead space to tidal volume ratio (V_D/V_T), \dot{V}_D , \dot{V}_A , carbon dioxide production (\dot{V}_{CO_2}) and oxygen consumption (\dot{V}_{O_2}) were calculated using respiratory equations described by Otis (1964). Heart rate was measured at rest and during exercise using a digital cardiometer (Equistat Heart Rate Computer HR/6, Equine Biomechanics and Exercise Physiology Inc., Unionville, PA, USA).

Statistical analysis. The values obtained from each horse at the three measurement periods were averaged. A 3-way analysis of variance (ANOVA) with split plot design was performed to evaluate the effect of training and exercise. When an F value was significant at *P* < 0.05, a multiple range Tukey's test determined at which time of exercise the difference was significant.

Results

In the experiment performed before training, V_E increased significantly from a mean value of 75.2 L/min at rest to a mean of 434.1 L/min five min after the onset of exercise and subsequently continued to increase for the duration of the exercise (Fig. 1). A total V_E increase of 625% was observed. There was a significant difference in V_E at all times except between 10 and 15 min of exercise.

The increase in V_E was due to an increase in *f* and V_T (Fig. 1). The *f* increased 3.6-fold during the treadmill exercise. This increase was significant between rest and 5 min of exercise and between 5 and 15 min of exercise. V_T increased significantly between rest and exercise (Fig. 1). Tidal volume increased from a mean value of 4.21 L at rest to a mean of 7.38 L after 5 min of exercise but did not increase significantly between 5, 10 and 15 min of exercise.

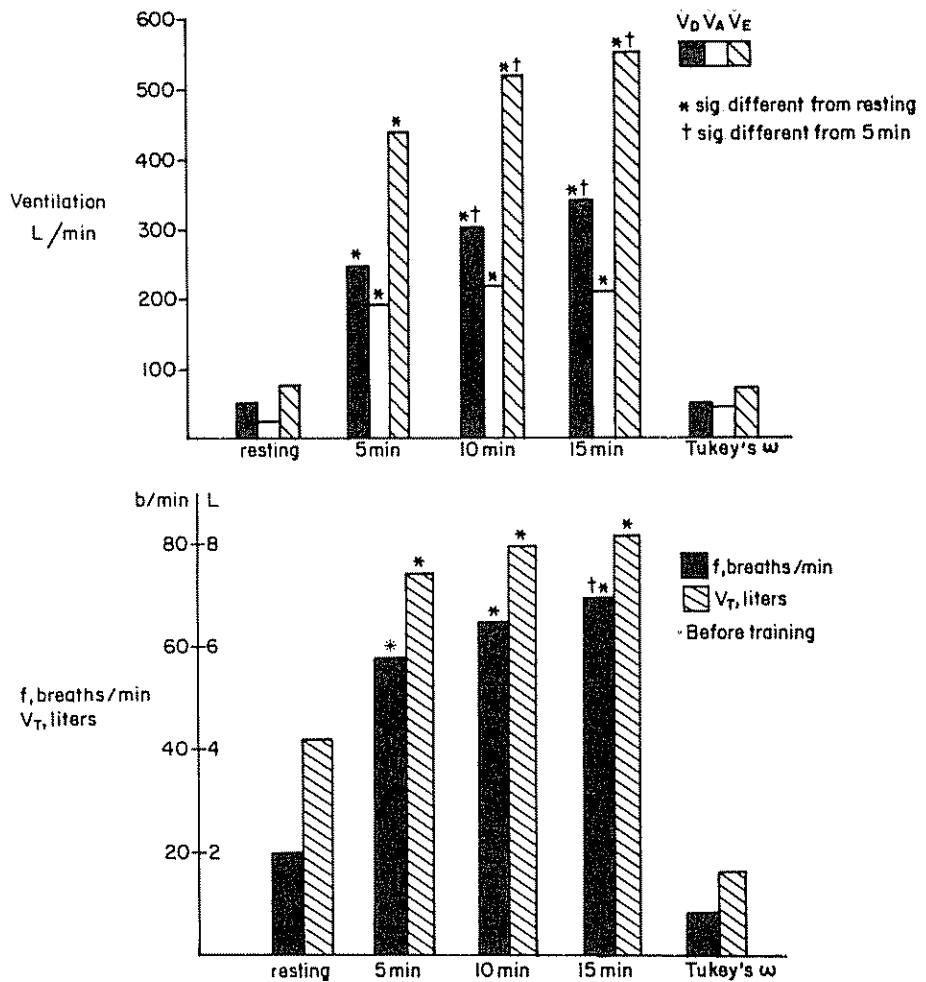


FIGURE 1. Effect of exercise on ventilation (L/min B T.P.S.), tidal volume (V_T , L B T.P.S.) and respiratory rate in untrained horses

The mean V_D/V_T decreased significantly from 0.651 at rest to 0.557 after 5 min of exercise (Fig. 2). It subsequently increased significantly to 0.622 at 15 min of exercise. There was no significant difference in V_D/V_T between 15 min of exercise and rest. The decrease in V_D/V_T at the onset of exercise coincided with a significant increase in V_D volume and in V_T from rest to 5 min of exercise. The V_D volume increased from a mean value of 2.7 L at rest to 3.98 L at 5 min of exercise. It continued to increase significantly to 5 L after 15 min of exercise.

The mean \dot{V}_D value increased significantly from rest to 5 min of exercise and continued to increase as exercise progressed. After 15 min of exercise \dot{V}_D was 588% higher than at rest (Fig. 1).

Whereas V_D increased significantly and progressively during exercise, V_A increased significantly during the first 5 min of exercise but remained constant during the rest of

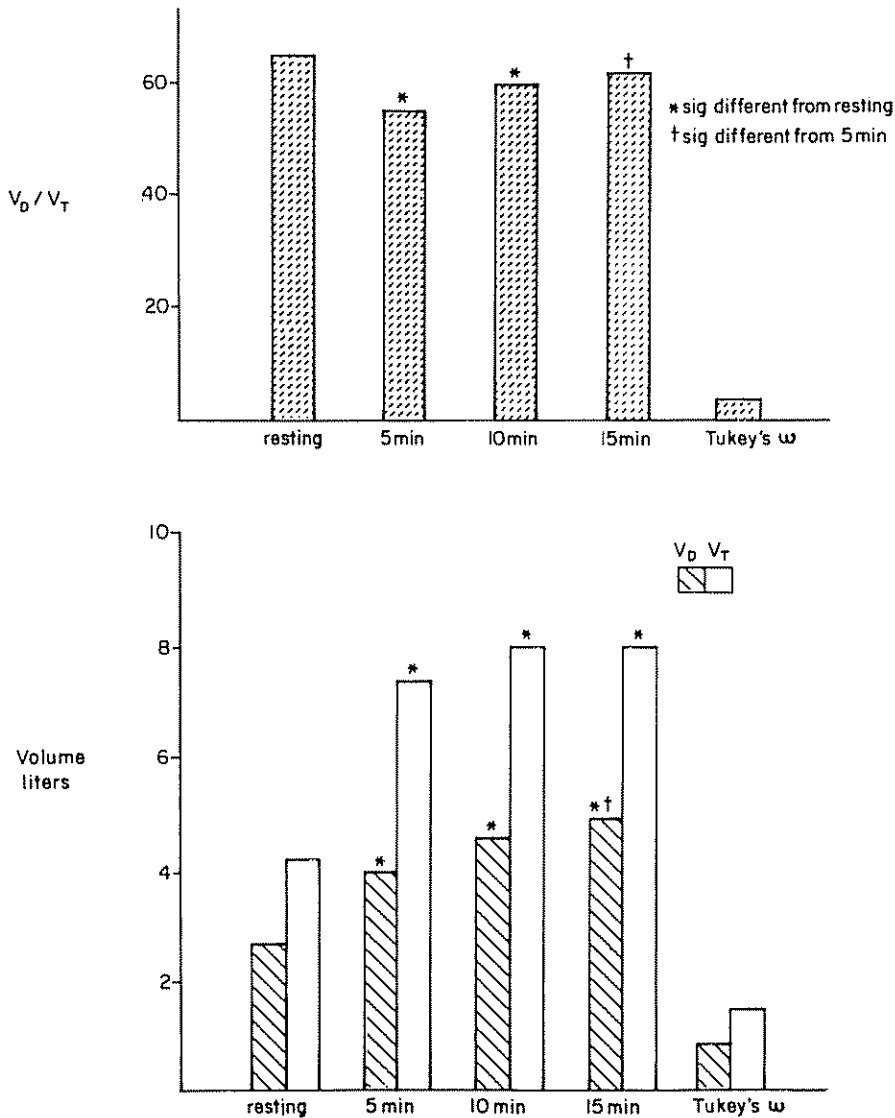


FIGURE 2. Effect of exercise on V_D/V_T ratio, tidal volume (V_T , L B T P S.) and dead space volume (V_D , L B T P S.) in untrained horses.

the exercise (Fig. 1). There was no significant difference in \dot{V}_A between 5, 10 and 15 min of exercise. At 15 min of exercise, \dot{V}_A had increased 8-fold compared to the resting value. \dot{V}_{O_2} increased significantly at the beginning of exercise, from a resting value of 1.36 L/min it increased (7.6-fold) to 10.35 L/min 5 min after the onset of exercise. The \dot{V}_{O_2} remained stable as exercise progressed and was 10.74 after 15 min of exercise. Similarly \dot{V}_{CO_2} increased rapidly and significantly at the onset of exercise. From rest to 5 min of exercise it increased from 1.22 L/min to 9.56 L/min. The \dot{V}_{CO_2} did not

increase significantly during the rest of exercise. Exercise did not cause any significant changes in arterial pH, PCO_2 and PO_2 (Table 2)

Training caused a significant decrease in the heart rate (HR) both at rest and during exercise. Training had little effect on \dot{V}_E , V_T , f , V_D/V_T , V_D , \dot{V}_D and \dot{V}_A . However, following training, V_D volume did not increase between 5 min and 15 min of exercise whereas it increased significantly over that period of time before training.

Discussion

At the onset of exercise, the horses had a six-fold increase in \dot{V}_E which was due to a 1.8-fold increase in V_T and a 3-fold increase in f . As the exercise progressed, we observed a gradual increase in \dot{V}_E mainly because of an increase in f , V_T remaining constant through the rest of exercise. Similar observations were made by Pan *et al.* (1983) and Forster *et al.* (1983) who demonstrated a rapid increase in \dot{V}_E in the first minute of exercise. They associated this increase in \dot{V}_E with an increase in V_T and f at the onset of exercise but during the rest of exercise only f increased, V_T remaining constant. These results agree with ours. Our study is the first to describe the increase in \dot{V}_E , V_T and f in the horse during a standardized exercise test. Hornicke *et al.* (1983) described a linear increase in \dot{V}_E as a function of speed and an increase of f and V_T during different gaits in horses. However they did not describe the changes in these parameters during a constant workload and their exercise was not well standardized since the stride length and speed were not the same in every horse. Similarly, Bisgard *et al.* (1978) described an increase in \dot{V}_E , f and V_T during graded exercise in ponies. They reported that the increase in \dot{V}_E , at mild to moderate workloads, was mainly due to an increase in f which plateaued at a \dot{V}_{O_2} of 5 times the resting value. V_T did not change significantly until \dot{V}_{O_2} exceeded 8 times the resting value. In our study \dot{V}_{O_2} increased 7.6 fold during steady state exercise (Fig. 3) and we also observed an increase in both f and V_T .

There are few reports on the variation in V_D/V_T during steady state exercise. In our

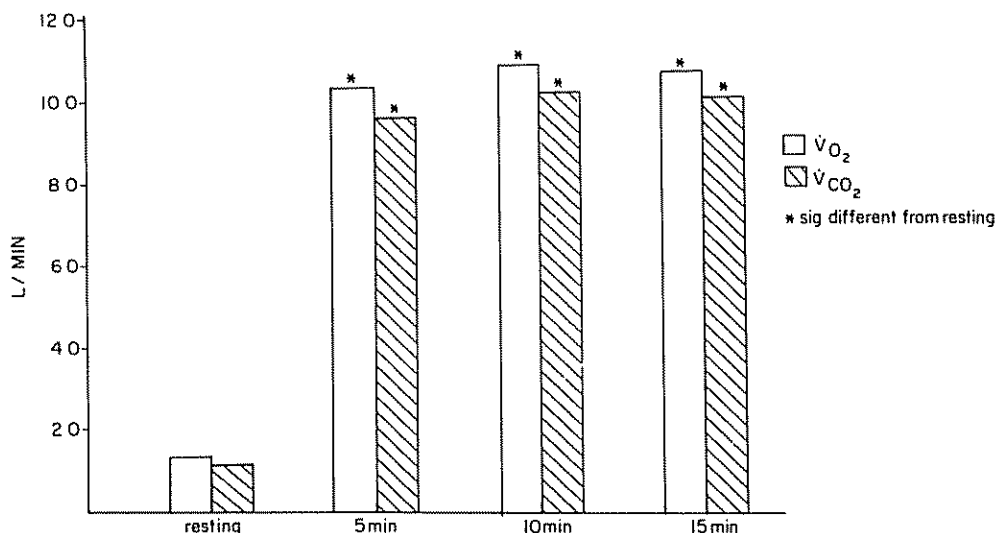


FIGURE 3 Oxygen uptake and CO_2 production during exercise in untrained horses

study, V_D/V_T decreased significantly at the onset of exercise and subsequently increased significantly as exercise progressed. This decrease in V_D/V_T occurred despite an increase of 1.5-fold in V_D volume, tidal volume increasing 1.9-fold. As exercise progressed V_D increased gradually which resulted in a V_D/V_T returning to the resting value. Similar results have been observed in humans (Gledhill *et al.*, 1977). Bisgard *et al.* (1978) have also noted that at low to moderate workloads, V_D/V_T stays near resting values. The proportion of the increase of V_D compared to V_T during exercise (460 ml V_D for each 1000 ml V_T) in our study agrees with the values observed by Bisgard *et al.* (1978).

With the onset of exercise, V_D increased 5-fold at 5 min of exercise and V_A was 7.25 times greater than at rest. The further increase in \dot{V}_E between 5 and 15 min of exercise was due to the progressive increase in V_D during exercise while V_A remained constant. The constant \dot{V}_{O_2} and \dot{V}_{CO_2} during the exercise (Fig. 3) made an increase in V_A unnecessary and agrees with findings that \dot{V}_E and \dot{V}_A increase to match the increase in \dot{V}_{O_2} and \dot{V}_{CO_2} during exercise (Bisgard *et al.*, 1978; Sutton and Jones, 1979).

The increase in V_D may be caused by an increase of upper and/or lower airway diameter or it could have been caused by larger transmural pressure variations exerted on a more compliant airway during exercise as suggested by Forster *et al.* (1985). Forster *et al.* (1985) showed that V_D increases less in tracheotomized ponies than in normal ponies suggesting that V_D increases in both upper and lower airways. The increase in lower airway V_D may reflect changes in \dot{V}/\dot{Q} matching during exercise. The increase in \dot{V}_D and \dot{V}_E during exercise at fixed workload may be necessary for thermoregulation. We observed an increase in rectal temperature of 1.5°C during exercise. Sexton (1985) has observed that rectal temperature increases less and more slowly than blood temperature. Thus the increase in blood temperature due to muscular activity could be an important factor in explaining the increase in both \dot{V}_D and \dot{V}_E during exercise.

It has been suggested that it is difficult to get a true resting value for \dot{V}_E (Thomas *et al.*, 1981) because of the influence of excitement on \dot{V}_E . Also, Pan *et al.* (1983) have postulated a "startle effect" of treadmill initiation that could exaggerate the increase in \dot{V}_E associated with exercise. To minimize the influence of external stimuli on \dot{V}_E , our study was conducted in a quiet environment. To avoid treadmill noise influence the horses were accustomed to the treadmill during the adaptation period. In addition, Pan *et al.* (1983) showed that $PaCO_2$ decreased when treadmill speed was increased in exercising ponies. The opposite change was observed if they decreased the running speed suggesting that the hyperventilation is due to running speed. Thus, treadmill initiation has little or no effect on the ventilatory response to treadmill exercise.

Our values of V_D/V_T in the resting horse are higher than those reported previously by Bisgard *et al.* (1978), Gallivan (1981) and Derksen *et al.* (1981, 1982). This can be explained by the volume of the face mask and the non-rebreathing valve. Most of the authors reporting values of \dot{V}_E , V_T , \dot{V}_D and \dot{V}_A have not corrected their measurements for the dead space of the gas collection apparatus (Willoughby and McDonnell, 1979; Thomas *et al.*, 1980; Derksen *et al.*, 1982; Hornicke *et al.*, 1983). This can give false values in resting and exercising \dot{V}_E , V_T and f . In the standing horse, Gallivan (1981) has corrected both V_T and V_D because the dead space of the collecting apparatus is additive for both variables. For the resting and exercising pony, Bisgard *et al.* (1978) have corrected V_D volume but not V_T . We corrected our data for the dead space volume of the apparatus (Table 1). We observed the same ventilatory adjustments to exercise

TABLE 1. Effect of exercise prior to training on ventilation variables after correction of the data for dead space of collection apparatus.

	Resting	Exercise		
		5 min	10 min	15 min
Minute ventilation (L/min) B.T.P.S.	51.8	362.25	396.65	459.1
Tidal volume (L) B.T.P.S.	3.21	6.76	7.27	7.17
V_D/V_T	0.506	0.460	0.516	0.548
V_D volume (L) B.T.P.S.	1.59	3.14	3.72	3.86
Dead space ventilation (L/min) B.T.P.S.	26.4	170.23	204.67	250.1
Alveolar ventilation (L/min) B.T.P.S.	26.43	191.95	191.98	209.6

Values expressed as mean \pm standard error ($\bar{X} \pm$ SEM)

V_D = dead space; V_T = tidal volume

before and after the correction of the data ($P < 0.05$). This suggests that the dead space of our expired gases collection device did not significantly affect the ventilatory response of the horses to exercise. However, it is difficult to evaluate precisely the effective dead space volume of the collecting apparatus during exercise. During exercise the airflow is more turbulent causing a better mixing of the gases contained in the mask and valve. Thus, increasing flow rates during exercise could cause an increase in total V_D volume. Similarly improved gas mixing in the upper airways may have contributed to the increased V_D observed during exercise.

Training had little effect on ventilation variables. However since the increase in V_D observed during the pre-training exercise test was not apparent after training, the training regime may have had an effect on the ventilatory response of the horses to prolonged exercise. However conclusions are hard to make as to the true training effect since the changes in V_D after training are not significant. This may reflect the true training effect or the training regime may not have been severe enough to affect \dot{V}_E , V_T , V_D , V_D and \dot{V}_A . However the significant increase in oxygen pulse (V_{O_2}/HR) following training suggests that there was a significant training effect (Table 2). The low intensity of exercise

TABLE 2. Effect of exercise on arterial pH, $PaCO_2$ and PaO_2 in untrained horses

	Resting	Exercise			
		2 min	5 min	10 min	15 min
pH	7.365 \pm 0.012	7.383 \pm 0.019	7.396 \pm 0.013	7.398 \pm 0.013	7.412 \pm 0.014
$PaCO_2$	44.15 \pm 0.86	43.41 \pm 0.6	40.75 \pm 0.78	44.3 \pm 0.57	43.8 \pm 0.34
PaO_2	95.8 \pm 1.72	90.8 \pm 2.06	96.5 \pm 2.4	97.1 \pm 2.81	98.5 \pm 2.21

Values expressed as mean \pm standard error ($\bar{X} \pm$ SEM).

in our study could also be the cause of the lack of changes related to training. Most authors (Thomas *et al.*, 1980; Bayly *et al.*, 1983; Thornton *et al.*, 1983) have used a more intense and longer training regime.

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