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STUDIES ON THE PHYSIOPATHOLOGY OF CHRONIC OBSTRUCTIVE PULMONARY DISEASE IN THE HORSE. V. BLOOD GAS AND ACID-BASE VALUES DURING EXERCISE

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Abstract

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The haemoglobin concentration, the partial pressures of oxygen and carbon dioxide, the oxygen content and the pH were determined in the arterial and mixed venous blood of 5 normal and 3 horses with chronic obstructive pulmonary disease (COPD) at 3 stages of an exercise distance of 1200 m. Arterial and mixed venous samples were collected simultaneously by means of an automatic technique during the walk, trot and gallop at 0–100 m, at 500–600 m and at 1100–1200 m.

The standard bicarbonate and the lactic and pyruvic acid concentrations were also determined in arterial and mixed venous blood.

Highly significant changes in the mean values of $P\bar{v}O_2$, O_2 content and $\triangle$ a–$\bar{v}$ O_2 content occurred during exercise in COPD subjects, and significant changes in $P\bar{v}O_2$ and $\triangle$ a–$\bar{v}$ O_2 content occurred during exercise in normal subjects.

We concluded that COPD subjects compensated for respiratory dysfunction during exercise by extracting more oxygen from the blood than did normal horses.

There was a highly significant correlation between the changes in standard bicarbonate and the changes in lactic acid concentration during exercise in both normal and COPD subjects. This led to the conclusion that lactic acid production was primarily, but not completely, responsible for the metabolic acidosis of exercise in horses.

Résumé

ÉTUDES SUR LA PHYSIOPATHOLOGIE DE LA MALADIE D'OBSTRUCTION PULMONAIRE CHRONIQUE DU CHEVAL. V. GAZ DU SANG ET VALEURS ACIDE-BASE PENDANT L'EXERCICE

La concentration d'haemoglobine, les pressions partielles d'oxygène et de dioxyde de carbone, la teneur en oxygène et le pH ont été déterminés dans le sang artériel et le sang veineux mélangé de cinq chevaux normaux et de trois chevaux atteints de la maladie d'obstruction pulmonaire chronique (COPD) à trois stades d'un exercice couvrant une distance de 1 200 m. Les échantillons artériels et le sang veineux mélangé furent pris simultanément au moyen d'une technique automatique pendant la marche, le trot et le gallop à 0–100 m, à 500–600 m et à 1 100–1 200 m.

Les concentrations standards de bicarbonate et d'acide lactique et pyruvique furent également déterminées dans le sang artériel et le sang veineux mélangé.

Des changements significativement élevés dans les valeurs moyennes de teneur $P\bar{v}O_2$, O_2 et $\triangle a\text{–}\bar{v}\ O_2$ survinrent durant l'exercice des sujets COPD et des changements significatifs dans la teneur $P\bar{v}O_2$ et $\triangle a\text{–}\bar{v}O_2$ survinrent pendant l'exercice des sujets normaux.

Nous en avons déduit que les sujets COPD compensaient le manque respiratoire pendant l'exercice en prélevant plus d'oxygène du sang que ne le faisaient les chevaux normaux.

Il y eut une corrélation hautement significative entre les changements dans la concentration standard du bicarbonate et d'acide lactique pendant l'exercice tant chez les sujets normaux que chez les sujets COPD. Ceci conduisit à la conclusion que la production d'acide lactique était principalement, mais non complètement, responsable de l'acidose métabolique de l'exercice chez les chevaux.

Introduction

Bergsten (1974) determined the blood gas and acid-base values of 17 normal horses and 7 horses with chronic obstructive pulmonary disease (COPD) while working on a treadmill at a velocity of 4 m/sec. Samples of arterial and mixed venous blood were collected after 10 minutes exercise on the treadmill.

In the normal subjects he noted significant decreases in the partial pressure of carbon dioxide in arterial blood ($PaCO_2$) and in the partial pressure of oxygen in mixed venous blood ($P\bar{v}O_2$). In the COPD subjects there was a significant increase in the partial pressure of oxygen in arterial blood (PaO_2).

When the blood gas values of the COPD subjects were compared with those of normal subjects, Bergsten (1974) found that the mean PaO_2 of COPD subjects remained significantly lower than those of normal subjects and that the mean $P\bar{v}CO_2$ (partial pressure of carbon dioxide in mixed venous blood) increased significantly in the COPD subjects with exercise, to a greater extent than in normal subjects.

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Arterial blood gases and pH were recorded in normal horses by Milne, Muir, Skarda, & Nicholl (1977) during tethered swimming. They found that the PaO_2 decreased, the $PaCO_2$ increased and the arterial pH decreased during the tethered swimming exercise.

Since there was no information regarding the effect of faster velocities or the effect of mass carried in the form of a rider, the following studies were designed to investigate the effect of exercise at the walk, trot and gallop under the saddle on the blood gas and acid-base values of normal horses and horses with COPD. It was considered that an analysis of such effects would help to elucidate how horses with COPD compensate for lung dysfunction.

Materials and Methods

Subjects

Five clinically normal horses comprising 2 Thoroughbreds, 1 Thoroughbred cross and 2 ponies were used as a control group. Subjects with COPD were 1 Thoroughbred cross and 2 ponies. The left carotid artery of each subject was translocated

surgically to the subcutaneous position by the technique of Tavernor (1969).

Collection of blood samples during exercise

Simultaneous arterial and mixed venous blood samples were collected during exercise by means of the technique described by Littlejohn & Kruger (1976).

Analysis of blood samples

Blood gas partial pressures were determined by means of the techniques described in the preceding paper of this series (Littlejohn & Bowles, 1981). The oxygen content of blood samples collected during exercise was determined by the method of Van Slyke & Neill (1924) using a Van Slyke manometric gas apparatus* and following the technique published by the authors.

The oxygen content of blood samples collected at rest was determined by calculation from the haemoglobin PO_2 and acid-base values, using the Severinghaus (1966) blood gas calculator to determine the percentage O_2 saturations of the blood samples.

The haemoglobin concentration of the blood samples was determined by the alkaline haematin method of Clegg & King (1942). Solution of the following equation provided oxygen content values in vols %:

$$O_2 \text{ vols } \% = \frac{Hb \text{ (gm/100 m}\ell) \times 1,33 \times SO_2\%}{100} + \frac{a \times 100 \times PO_2}{760}$$

where 1,33 = oxygen content of 1 g of fully saturated haemoglobin

SO_2 = percentage saturation of haemoglobin with oxygen

a = solubility coefficient of oxygen at 38 °C and 760 mm Hg BP

= 0,021

The value in vols % was then converted to ℓ/ℓ.

The haematocrit values were determined by microcentrifugation.

Excess lactate

Lactic acid and pyruvic acid concentrations in blood samples were determined enzymatically using Sigma† reagents. The techniques followed were those described in Sigma Technical Bulletin No. 726-UV and No. 826-UV. A Bausch and Lomb Spectronic 70 spectrophotometer was used throughout. Values were determined by interpolation from calibration curves constructed for lactic and pyruvic acid with standard solutions.

The excess lactate was calculated from the equation XL=(Ln—Lo)—(Pn—Po) (Lo/Po) in which L and P denote lactate and pyruvate concentration in blood, and the postscripts n and o denote observed and control values respectively (Huckabee, 1958).

Design of experiment

Since the majority of horses involved in the racing industry in South Africa are trained and raced over distances of 800–1 600 m, we considered that the most informative and relevant results would be gained by collecting samples at several stages of a work distance of 1 200 m.

The track chosen was 600 m in length and oval in shape. Blood was collected from subjects at 3 stages during a 1 200 m work distance, namely:

1. During the first 100 m
2. Between 500 m and 600 m
3. Between 1 100 m and 1 200 m

The oval shape of the track ensured that the subject could return to the saddling enclosure immediately after the samples had been collected. There was therefore a time lag of only 2 min. at most between the collection of the samples and their analysis, or the preparation of aliquots for analysis as in the case of lactic and pyruvic acid.

Subjects were ridden daily for 3 weeks prior to the experiment so that each subject was in a similar state of physical ability.

The blood collections were done as follows: Each day subjects were ridden at walk, trot and canter for 1 200 m at each pace. Cannulae were placed *in situ* in the carotid artery and right ventricle the day before the first collection. On the first sampling day, samples were collected during the first 100 m of the walk, the trot and the canter, by instructing the rider to release the spring-loaded plungers at the moment horse and rider set off.

On the second day samples were collected during the 500 m–600 m period by instructing the rider to release the mechanism at the moment of passing the 500 m mark.

On the third day, samples were collected during the 1 100–1 200 m period by instructing the rider to release the mechanism at the moment of passing the 1 100 m mark.

The horse and rider returned immediately to the saddling enclosure as soon as the 100 m, 600 m or 1 200 m marks had been passed.

On days when 100 m or 600 m samples were collected, the 1 200 m circuit at each pace was completed so that subjects received the same work period every day.

The speed of horse and rider was measured over a distance of 50 m during each occasion when blood was collected to ensure that work loads for both normal and COPD horses, although not identical, were comparable.

Statistical analyses of results

The standard error of the difference ($S\bar{d}$) formula for determining the "t" values of paired observations was as follows:

$$S\bar{d} = \frac{(\Sigma \text{ individual differences})^2}{n(n-1)} - \frac{\Sigma \text{ (individual differences)}^2}{n(n-1)}$$

For unpaired observations

$$S\bar{d} = \frac{n_1 SD_1^2 + n_2 SD_2^2}{n_1 + n_2 - 2}$$

The level of probability accepted as significant was $P < 0,01$.

Results

The mean values and standard deviations of each determination obtained from the 2 groups of subjects at the 0–100 m, 500–600 m and 1 100–1 200 m stages of the work periods at walk, trot and gallop are plotted in Fig. 1–8.

* Baird & Tatlock, London

† Sigma Chemical Co., Missouri

TABLE 1 Significant changes from control values of blood determinations in normal and COPD subjects at the 0–100 m, 500–600 m and 1100–1200 m stages of work distances at walk, trot and gallop

Exercise		Normal			COPD		
		0–100 m	500–600 m	1100–1200 m	0–100 m	500–600 m	1100–1200 m
Ht	Walk $\bar{v}$					↑	
	Trot $\bar{v}$						
	Gallop $\bar{v}$		↑ ↑	↑ ↑ ↑		↑	↑
Hb	Walk $\bar{v}$					↑ ↑	
	Trot $\bar{v}$					↑	
	Gallop $\bar{v}$		↑	↑ ↑		↑	↑
PO_2	Walk $\frac{a}{\bar{v}}$		↑			**	*
	Trot $\frac{a}{\bar{v}}$	↓ ↓				** ↓ ↓	** ↓ ↓
	Gallop $\frac{a}{\bar{v}}$	↓ ↓		↓ ↓	* ↓ ↓	↓ ↓ ↓	** ↓ ↓ ↓
O_2 content	Walk $\frac{a}{\bar{v}}$				↓ ↓ *	↑ ↑ ↑	
	Trot $\frac{a}{\bar{v}}$			↑		↑ ↑ ↓ ↓ ↓	↓
	Gallop $\frac{a}{\bar{v}}$		↑	↑		↓ ↓	↑ ↓ ↓
(a–$\bar{v}$) O_2 content	Walk	↑					
	Trot			↑ ↑	↑ ↑ ↑	↑ ↑ ↑ **	↑
	Gallop		↑	↑ ↑			↑ ↑ ↑
PCO_2	Walk $\frac{a}{\bar{v}}$			↓	↓		↑ ↑
	Trot $\frac{a}{\bar{v}}$						
	Gallop $\frac{a}{\bar{v}}$	↓ ↓ ↓	↓ ↓ ↑	↓ ↓ ↑	*	↑	↑
pH	Walk $\frac{a}{\bar{v}}$						
	Trot $\frac{a}{\bar{v}}$						
	Gallop $\frac{a}{\bar{v}}$			↓			↓
Standard bicorbonate	Walk a						
	Trot a						
	Gallop a		↓	↓ ↓			
Excess lactate	Walk a						
	Trot a						
	Gallop a	↑ ↑	↑ ↑	↑ ↑ ↑	↑ ↑ ↑	↑ ↑	↑ ↑

Legend:

a = arterial
$\bar{v}$ = mixed venous
↑ or ↓ = Mean value different from control value at $P<0,05$
↑ ↑ or ↓ ↓ = Mean value significantly different from control value at $P<0,01$
↑ ↑ ↑ or ↓ ↓ ↓ = Mean value significantly different from control value at $P<0,001$
* = Mean value different from corresponding mean value of normal subjects ($P<0,05$)
** = Mean value significantly different from corresponding mean value of normal subjects ($P<0,01$)

Significant changes from control resting values of each group are given in Table 1 in addition to significant differences between corresponding mean values of each group. Changes in individual parameters are discussed below.

The mean speeds at walk, trot and gallop and standard deviations in m/sec. for 5 normal and 3 COPD subjects were as follows:

Walk; normal = 1,58 ± 0,32, COPD = 1,51 ± 0,10
Trot; normal = 3,73 ± 0,69, COPD = 4,19 ± 0,64
Gallop; normal = 7,74 ± 1,12, COPD = 7,59 ± 1,86

The above figures were calculated from the speed measured at the time of blood collection. There were no significant differences between the mean values of normal and COPD subjects at corresponding paces.

Discussion

Haematocrit and haemoglobin

The large increases in haematocrit and haemoglobin which occur in horses subjected to stressful stimuli have been well documented; thus they increase during excercise (Persson, 1967; Bergsten, 1974; Von Engelhardt, 1977), excitement (Torten & Schalm, 1964; Stewart & Steel, 1974), casting (Littlejohn, 1969), swimming (Fregin & Nicholl, 1977) and after injection of adrenalin (Irvine, 1958; Persson, 1967).

Persson (1967) showed that the venous haematocrit of horses trotting on a treadmill increased from 36–44% to 46–52% during trotting exercise on a treadmill at 5 m/sec. In the present study, the mean mixed venous haemoglobin concentration of normal

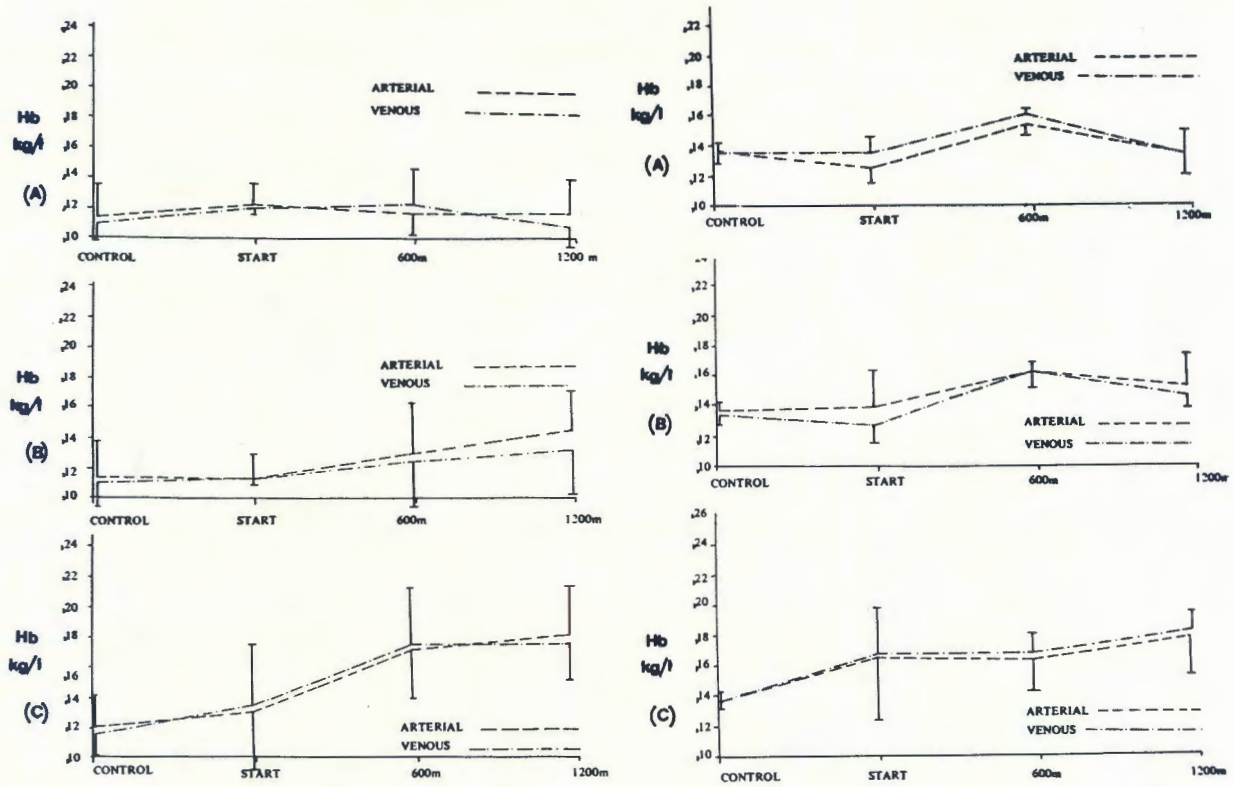

FIG. 1 Haemoglobin concentrations during 1200 m walk (A), trot (B) and gallop (C) in normal (left column) and COPD subjects (right column)

subjects increased to 0,175 kg/ℓ during the final 100 m of the 1 200 m gallop. COPD subjects attained a mean Hb concentration of 0,181 kg/ℓ. At corresponding stages of the exercise periods, there was a significant correlation between the Hb concentrations of normal and COPD subjects (arterial; $r=0,66$, $t=3,73$, $P<0,01$; venous, $r=0,80$, $t=5,65$, $P<0,001$). There was no statistically demonstratable difference between the Hb concentrations of normal and COPD subjects at any stage of the exercise tests.

The increases in haematocrit and Hb concentration observed in horses during exercise are considerably greater than those recorded in man. According to Ekblom & Hermansen (1968), an increase in Hb concentration of 10–15% is regarded as normal in man, from rest to maximal exercise; in athletes the increase was considerably less, being only of the order of 5,9% (13,5–14,3 g/100 mℓ). The present studies in horses showed increases of up to 50,9% (from 0,116–0,175 kg/ℓ) in mixed venous blood. It has been demonstrated by Torten & Schalm (1964) and Persson, Ekman, Lydin & Tufvesson (1973a) and (1973b) that the spleen is the major reservoir for red cells in the horse. It is possible that each horse has its own threshold value for haemoconcentration beyond which the viscosity becomes too great for the cardiovascular system to maintain maximum cardiac output. There is, however, no evidence for or against such a threshold concept.

PO_2

The results recorded in Table 1 and Fig. 2 were similar to those of Bergsten (1974), who reported significantly lower PaO_2 values in event horses with COPD than in normal event horses after 6 minutes trotting on a treadmill. Results during walk and gallop have not been previously reported.

The venous PO_2 of normal subjects decreased significantly during the first 100 m of the gallop, whereas in COPD subjects the venous PO_2 was significantly lower than the control value at all 3 stages of the gallop. Similarly, the venous PO_2 of COPD subjects decreased significantly during the middle and final stages of the trotting period, whereas this did not occur in normal subjects. These results suggested that, in order to compensate for their lower PaO_2 during exercise, the extraction of more oxygen from the blood by COPD subjects resulted in a significantly lower $P\bar{v}O_2$.

It was of interest that the PaO_2 of normal subjects rose slightly during the walk and decreased significantly at the end of the gallop. This trend was also evident in COPD subjects, although not significantly so. It thus appeared that in the normal subjects cardiac and pulmonary functions were most beneficially interrelated at the walk, whereas sustained galloping resulted in hypoxia.

Tethered swimming, which may be classified as heavy exercise, also causes a significant decrease in the PaO_2 of arterial blood (Milne *et al.*, 1977).

In man even very heavy exercise is not associated with a decrease in PaO_2. Both Holmgren & McIlroy (1964) and Wasserman, Van Kessel & Burton (1967) showed that no significant drop in PaO_2 occurred even after 40 min of very heavy exercise in man. Heavy exercise in the horse thus has a different effect from heavy exercise in man.

Two possible reasons for this present themselves: firstly, the mass of rider and saddle plus the constricting effect of the girth probably inhibit respiration during a gallop and, secondly, the respiratory frequency of a galloping horse is known to "lock on" precisely with the stride frequency (Attenburrow,

1976). Thus, since a galloping horse is unable to increase respiratory frequency during a gallop at a constant velocity, this method of compensating for temperature rise and pH decrease cannot be used by a horse. For these reasons alveolar ventilation in saddle horses during exercise may not be as efficient as in man during exercise.

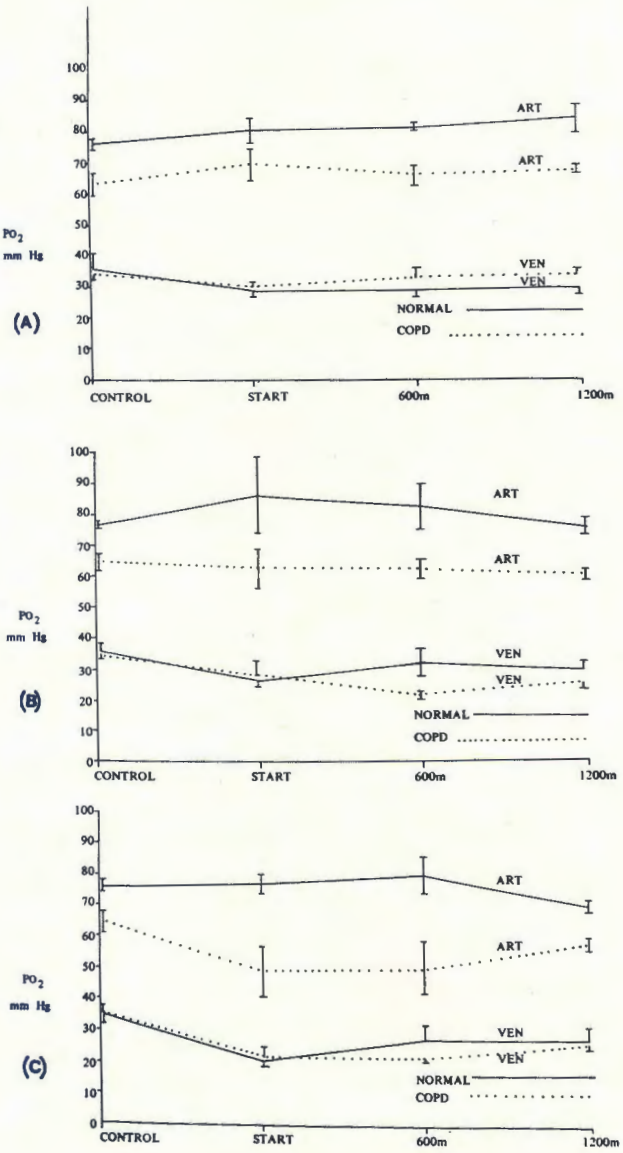

FIG. 2 Arterial and venous PO_2 values during 1200 m walk (A), trot (B) and gallop (C) in normal and COPD subjects

O_2 content

At no stage during exercise did the venous or arterial O_2 content of normal subjects change significantly. In contrast, significant changes in O_2 content were recorded during several stages of exercise in COPD subjects. It was thus apparent that COPD subjects compensated for their low PaO_2 during exercise by extracting more oxygen from the blood, and the result was a lower O_2 content in venous blood. However, their initial response, which was evident after 600 m walking, was an increase in the O_2 content of arterial blood.

In athletes the oxygen content of arterial blood was calculated to be $0,181 \pm 0,092$ ℓ/ℓ during maximal exercise (Ekblom & Hermansen, 1968). In the normal horses in this study the oxygen content of arterial blood was more than 0,210 ℓ/ℓ during the gallop.

The greater O_2 capacity of horse blood compared to that of human blood during exercise is undoubtedly due to the ability of the horse to increase the haemoglobin concentration of the blood to a much greater extent than man.

$(a-\bar{v})O_2$ content difference

In 8 human athletes of international standard, working at maximal work load, a mean $(a-\bar{v})O_2$ difference of 0,156 ℓ/ℓ was recorded by Ekblom & Hermansen (1968). The 5 normal horses of the present study, working at a submaximal speed of 7,7 m/sec, attained a mean $(a-\bar{v})O_2$ difference of 0,145 ℓ/ℓ. In trained horses of top standard, working at maximal speed, a much greater $(a-\bar{v})O_2$ difference can be expected, since training has the effect of increasing the haemoglobin concentration of the blood.

At the 500–600 m stage of the exercise period while trotting, there was a significant difference between the mean $(a-\bar{v})O_2$ difference of normal and COPD subjects. All other stages of walk, trot and gallop showed a good correlation between the $(a-\bar{v})O_2$ differences of normal and COPD subjects ($r=0,90$, $t=5,54$, $P<0,001$). We were unable to explain the anomaly at the 600 m stage of the trot, an anomaly for which a significantly lower $P\bar{v}O_2$ in the COPD subjects was responsible (Table 1, Fig. 4). However, the results showed in general that the adaptive mechanisms of the COPD subjects appeared to be efficient in this respect.

PCO_2

Significant decreases in $PaCO_2$ and significant increases in $P\bar{v}CO_2$ were reported by Bergsten (1974) in 16 normal horses trotting on a treadmill at a speed of 4 m/sec. He recorded decreases of 4 mm Hg below resting value in $PaCO_2$ and increases of 3 mm Hg above resting value in $P\bar{v}CO_2$. In the present study, changes comparable to those reported by Bergsten (1974) were recorded at the trot. During the gallop, however, changes in $PaCO_2$ and $P\bar{v}CO_2$ were greater than those that occurred during the trot. $PaCO_2$ decreased by a mean of 8,5 mm Hg and $P\bar{v}CO_2$ increased by a mean of 26,6 mm Hg (Fig. 5).

Milne (1974) was unable to detect any increase in $P\bar{v}CO_2$ in 4 horses after a 3 500 m gallop at 11,66 m/min. However, Milne's (1974) samples were collected after exercise. During recovery from exercise, muscle metabolism diminishes greatly but ventilation proceeds at a rate which favours rapid recovery of oxygen debt and elimination of CO_2 from venous blood. Thus post-exercise blood gas values do not reflect the metabolic status of a horse during exercise.

Bergsten (1974) found that the $P\bar{v}CO_2$ of horses with emphysema was significantly greater ($P<0,05$) than the $P\bar{v}CO_2$ of normal horses, after 10 minutes of exercise at 4 m/sec. In the present study, no significant differences were noted between $P\bar{v}CO_2$ values of normal and COPD subjects at any stage of exercise.

Of interest, however, was the general trend shown by both normal and COPD subjects: as the velocity of horse and rider increased, the $PaCO_2$ fell and the

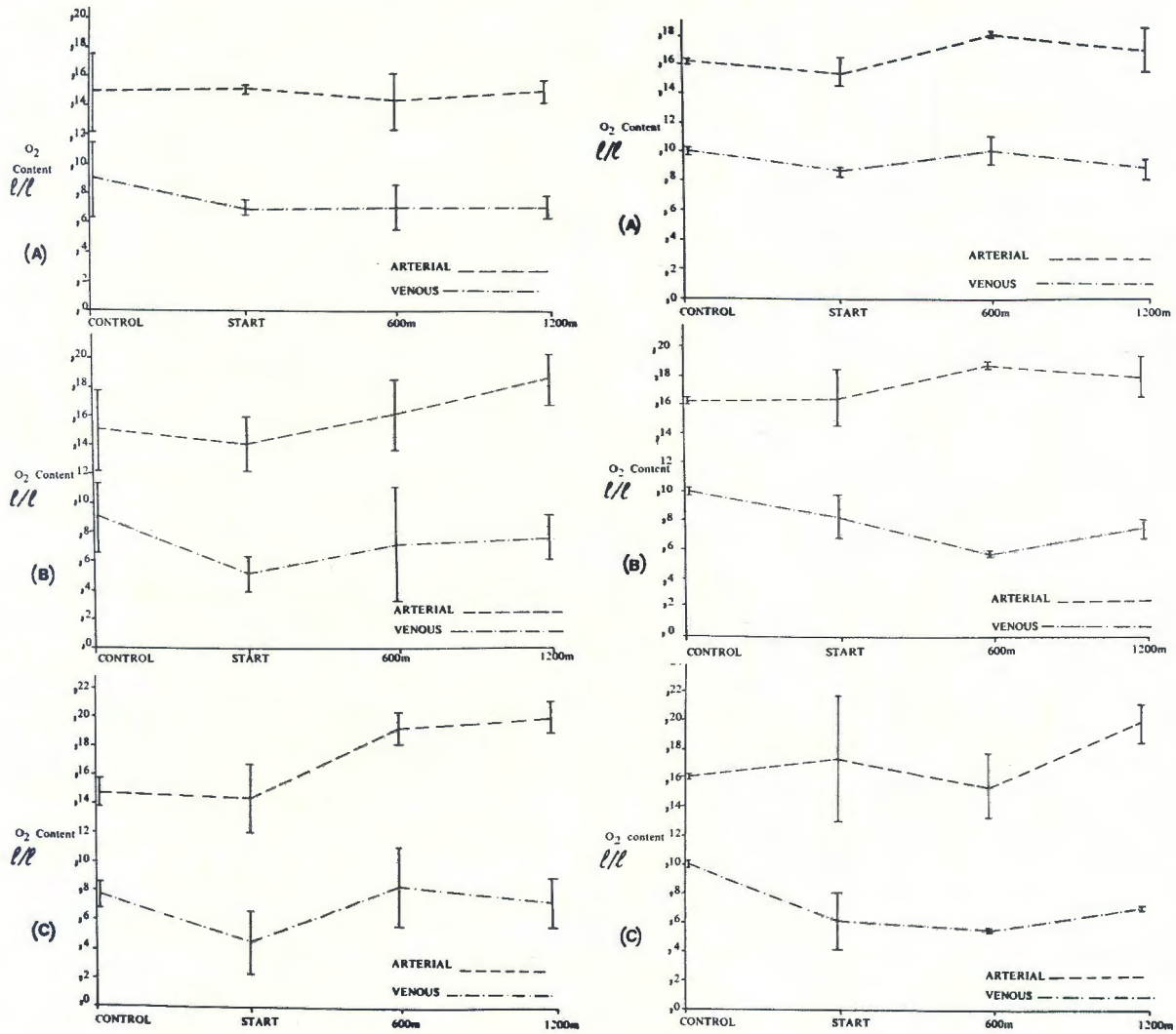

FIG. 3 Arterial and venous O_2 content values during 1200 m walk (A), trot (B) and gallop (C) in normal (left column) and COPD subjects (right column)

$P\bar{v}CO_2$ rose. These changes have important implications regarding the uptake of oxygen in the lungs and the release of oxygen to the tissues. In 1933, Margaria & Green showed that the O_2 dissociation curve of horse haemoglobin was shifted significantly to the right (by approximately 30%) in CO_2-bicarbonate solutions compared with NaCl solutions of the same ionic strength and pH. This result has been confirmed by the majority of subsequent investigators (Kreuzer, Roughton, Rossi-Bernardi & Kernohan, 1972). In subsequent experiments with bovine haemoglobin solution, Kreuzer *et al.* (1972) concluded that there was a specific effect of bicarbonate on the O_2 haemoglobin equilibrium and they pointed out that the favourable adaptive effect of a right shift of the O_2 dissociation curve in situations of stress has repeatedly been demonstrated. Such a shift is particularly advantageous if the venous point is displaced to the right more than the arterial point. In the present studies no attempt could be made to assign specific amounts of O_2 made available to the tissues by the mechanisms of the Bohr effect (pH difference), and the CO_2-bicarbonate effect described by Kreuzer *et al.* (1972). It is likely, however, that both mechanisms contributed to the release of O_2 to the tissues during trot and gallop in the subjects of this study. It has been calculated that in man the Bohr effect unloads up to 26% more oxygen to working muscle (Bartels, 1972).

In human athletes, changes in $PaCO_2$ during moderate, heavy and severe exercise were reported by Wasserman *et al.* (1967). The values reached were 37, 34 and 30 mm Hg respectively, a result which was very similar to that recorded in the present study.

There was one important difference between the normal and COPD subjects: COPD subjects did not show any significant decrease in $PaCO_2$ at any stage of the gallop. All the $PaCO_2$ values of COPD subjects were higher than those of normal subjects during the gallop. The $PaCO_2$ is a sensitive measure of alveolar ventilation (Dripps & Severinghaus, 1955). There is therefore strong evidence that COPD subjects have less efficient alveolar ventilation than normal subjects during heavy work, and this would partly explain the decreased arterial PO_2 of the COPD subjects' blood compared with that of the normal subjects.

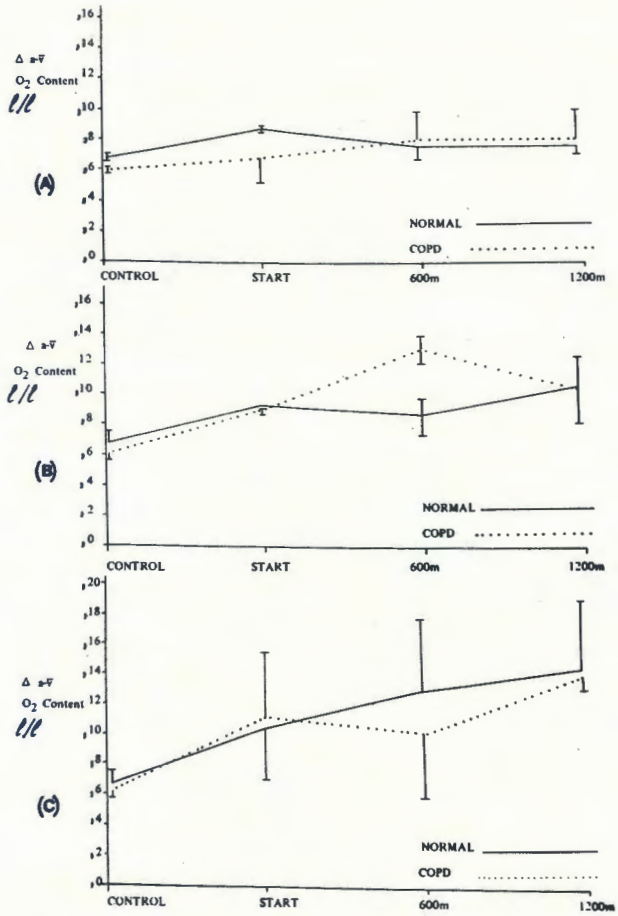

FIG. 4 a–$\bar{v}O_2$ content difference during 1200 m walk (A), trot (B) and gallop (C) in normal and COPD subjects

pH and Standard bicarbonate

Despite significant changes in blood gas partial pressures, the hydrogen ion concentration showed only one change (and then only at $P<0,05$) at the end of the 1200 m gallop in both normal and COPD subjects. This suggests that buffering mechanisms in the blood of both normal and COPD subjects were equally efficient.

Bergsten (1974) did not measure pH in his experimental horses. Milne (1974) reported a decrease of approximately 0,15 pH unit in venous and arterial blood samples collected after the end of a 3500 m ride at 11,66 m/sec.

In 10 medical students, Wasserman *et al.* (1967) recorded a mean fall in arterial pH of approximately 0,05 pH unit during heavy exercise.

The normal subjects of the present study showed a decrease of 0,038 pHa unit at 1200 m at the gallop, whereas the COPD subjects showed an increase of 0,024 pHa at 1200 m at the gallop. Neither of these changes was significant.

In 10 healthy human males, the arterial pH fell significantly during heavy exercise on a cycle ergometer (Wasserman *et al.*, 1967), denoting incompletely compensated metabolic acidosis. The results of the present study show a similar trend for normal subjects.

Despite the fact that standard bicarbonate did not decreasc significantly in COPD subjects, decreases did occur during the trot and the gallop. These were smaller than those in normal subjects. One explanation for the significant decrease in standard bicarbo-

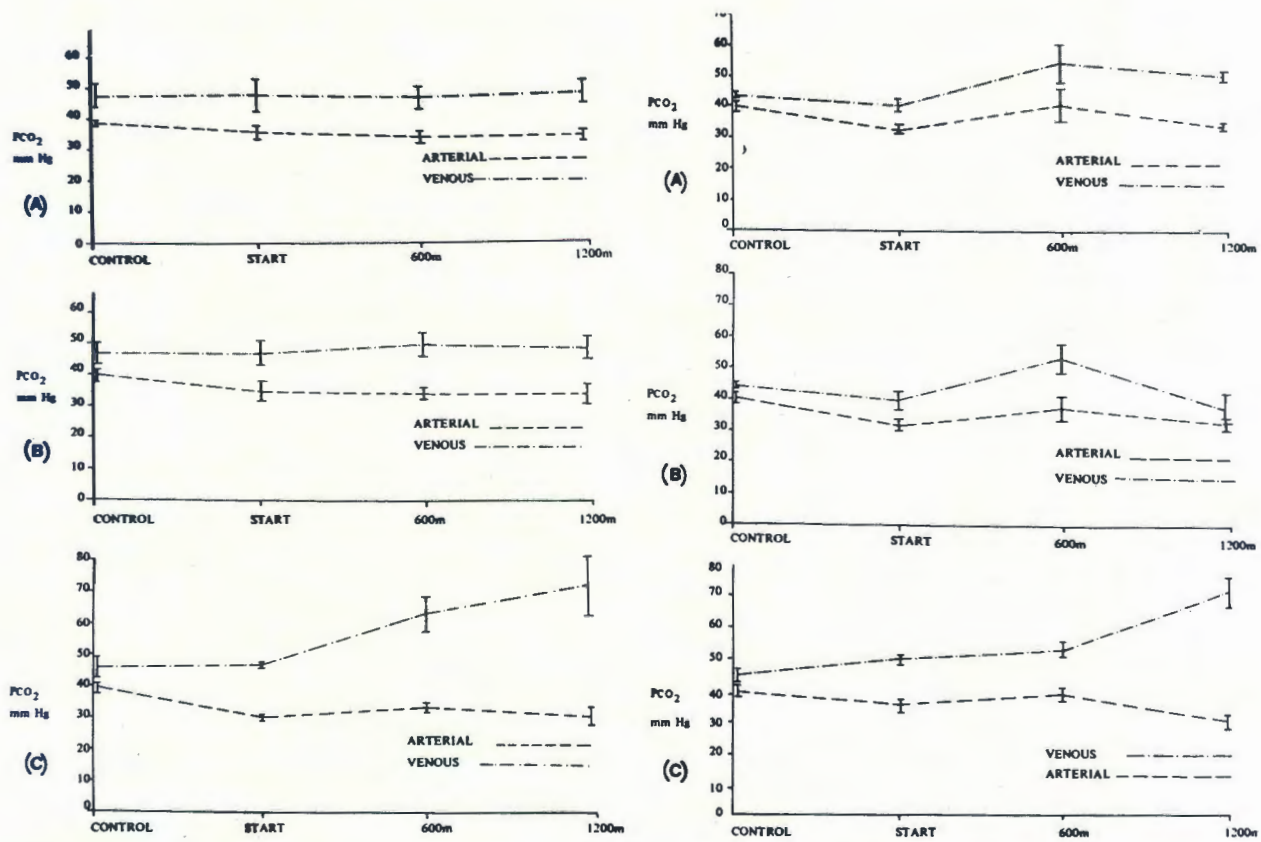

FIG. 5 Arterial and venous PCO_2 values during 1200 m walk (A), trot (B) and gallop (C) in normal (left column) and COPD subjects (right column)

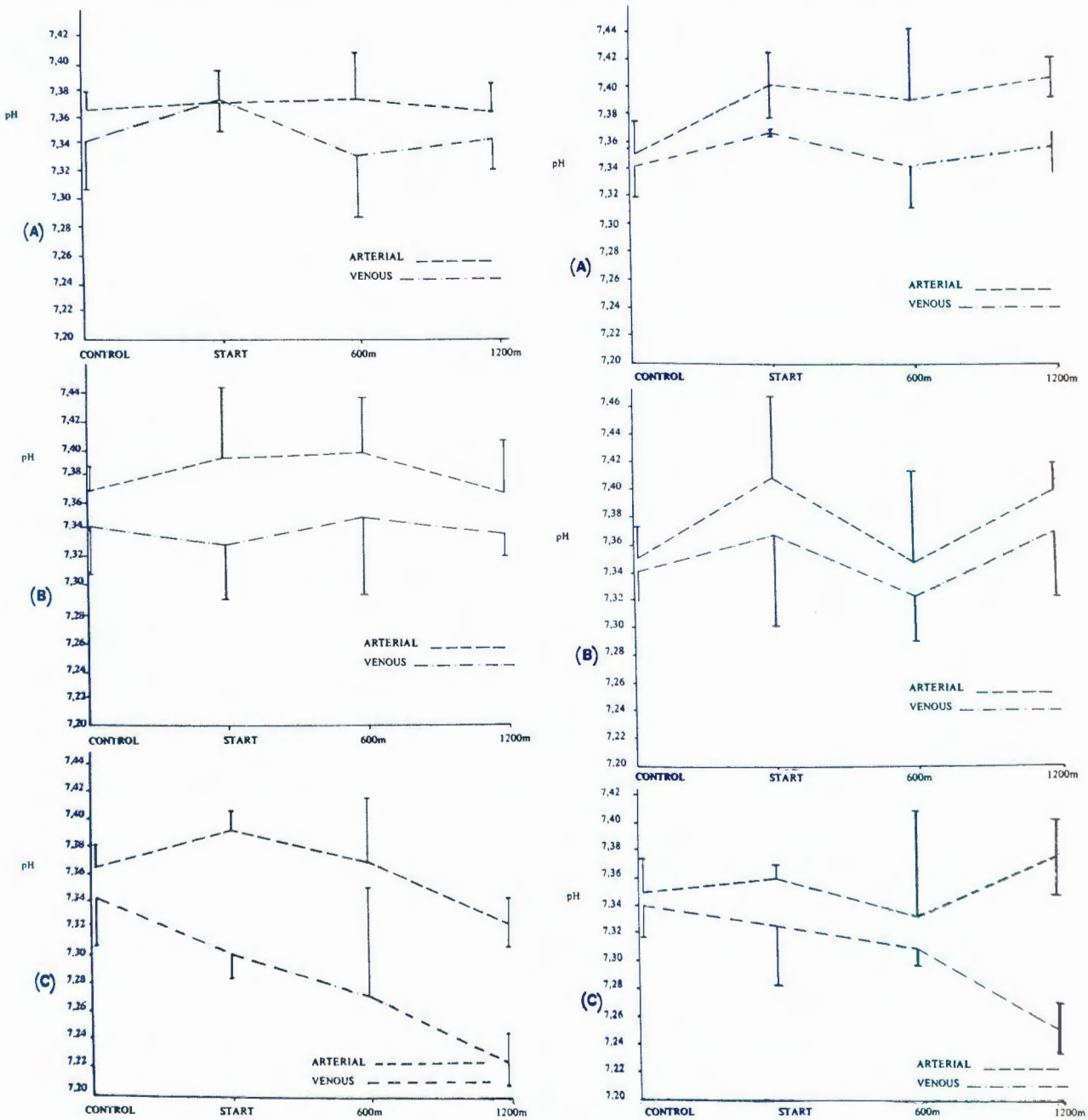

FIG. 6 Arterial and venous pH values during 1200 m walk (A), trot (B) and gallop (C) in normal (left column) and COPD subjects (right column)

nate of normal subjects compared with that of COPD subjects may be that the *in vivo* buffer line of the blood of COPD subjects may be different from the *in vitro* buffer line (Davenport, 1969). If this were so in COPD subjects, then it suggests that total body buffering in COPD subjects is more efficient than in normal subjects. The *in vivo* slope of the blood buffer line depends upon:

(a) the ratio of interstitial fluid to blood volume,

(b) the intracellular buffers, and

(c) the lean body mass (Davenport, 1969).

None of the above factors was measured in these studies and there is therefore no information on possible effects of COPD upon *in vivo* buffering systems.

Excess lactate

Excess lactate (XL) was defined by Huckabee (1958) as lactate produced by an inadequate O_2 supply relative to metabolic needs. By this criterion anaerobic metabolism began to become evident, though not significantly so, at the trot, and was present to a significant degree at all 3 stages of the gallop in both normal and COPD subjects.

There was no significant difference between the XL of normal subjects and that of COPD subjects—a finding which was perhaps not unexpected in view of the results which showed that the amount of O_2 delivered to the tissues per unit volume of blood in the COPD subjects was not significantly different from that in normal subjects.

TABLE 2 Linear regression of change in lactate concentration with change in standard bicarbonate during exercise

Correlation	Group	n	r	m (slope)	b (intercept)	t	Significance
△ Standard bicarbonate (mM/ℓ)	Normal	44	0,52	0,56	0,15	3,97	$P<0,001$
△ Lactate concentration (mM/ℓ)	COPD	27	0,68	0,48	0,61	4,65	$P<0,001$

Both Persson & Ullberg (1974) and Asheim, Knudsen, Lindholm, Rulcker & Saltin (1970) found that blood lactate values began to increase at approximately 4 m/sec and increased very rapidly after work at speeds in excess of 10 m/sec. Marked increases in blood lactate post exercise were also reported by Lindholm & Saltin (1974), Lindholm (1974), Milne (1974), Krzywanek (1974) and Aitken, Anderson, Mackenzie & Sanford (1974). However, none of the above authors calculated XL, although Aitken *et al.* (1974) reported lactate/pyruvate ratios which they considered more closely reflected the degree of anaerobic metabolism than lactate alone, an opinion with which the authors concur.

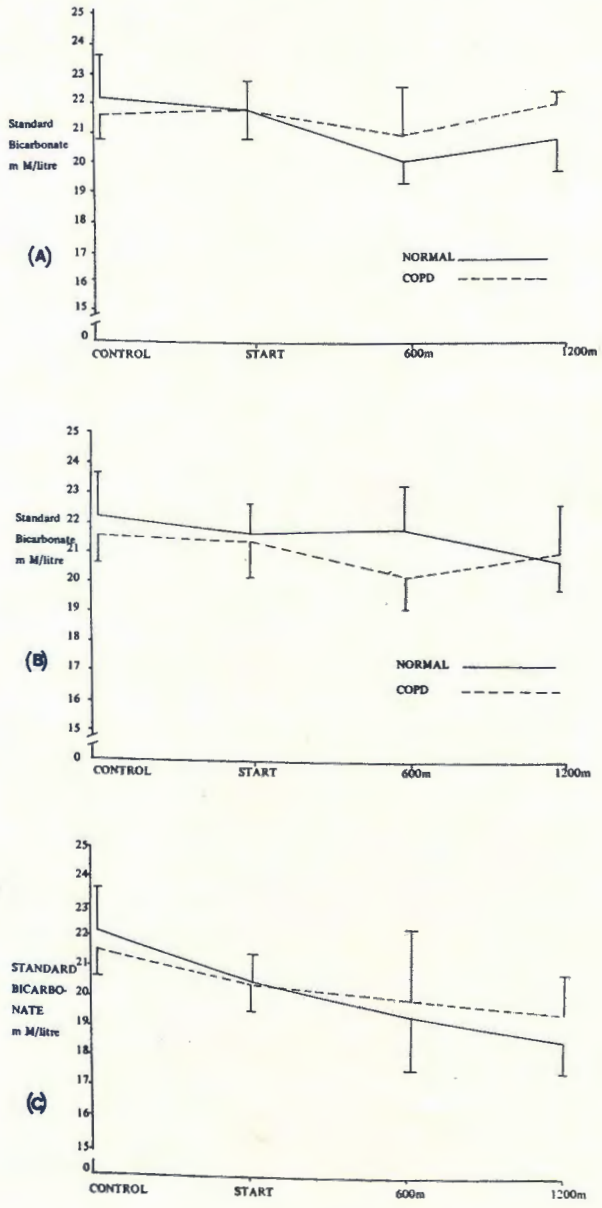

FIG. 7 Standard bicarbonate values during 1200 m walk (A), trot (B) and gallop (C) in normal and COPD subjects

The correlations between the change in lactate concentration and the change in standard bicarbonate were highly significant in both normal and COPD subjects. Increases in lactate and decreases in standard bicarbonate during exercise were calculated as the difference between concentrations during exercise at different stages and speeds, and concentrations at rest. The results indicate that the metabolic acidosis of exercise in both normal and COPD horses is due primarily to lactic acid production. The slope of the regression line, however, suggests that other acids, of which pyruvic is one, also play a role. Pyruvic acid *per se* was not produced in sufficient molar concentration to account for the deviation of the slope of the regression line from 1–0,56 (Table 2).

In human non-athletes, the concentrations of free fatty acids and ketone bodies increase significantly during running and to a greater extent than in athletes (Johnson, Walton, Krebs & Williamson, 1969). It is possible that these metabolites were present in the blood of the untrained subjects of the present study during exercise in concentrations sufficient to account for the decreases in standard bicarbonate not attributable to lactic and pyruvic acid.

Conclusion

From the results of Maier (1976), Littlejohn, Kruger & Bowles (1977) and these studies, it is apparent that 2 separate mechanisms are brought into play during exercise to compensate for pulmonary dysfunction.

The first mechanism is a simple one and involves no extra expenditure of energy by the horse: as the O_2 requirements of working tissues increase, more O_2 is released from the capillary blood. This is supported by the significant decrease in O_2 content of venous blood of COPD subjects and by the lower mean $P\bar{v}O_2$ of the COPD subjects during exercise. Thus the decrease in O_2 saturation occasioned by a PaO_2 of around 50 mm Hg (as was the case during the gallop) is compensated by an increase in unloading of O_2 from the capillary blood, and the amount of O_2 released to tissues remains adequate.

The second mechanism is an increase in heart rate (Maier, 1976; Littlejohn *et al.*, 1977). As Von Engelhardt (1977) pointed out, this implies an increase in cardiac output, and this would further increase the amount of oxygen supplied to the tissues per unit time.

Other methods of compensation such as increased efficiency of tissue enzyme of buffer systems remain conjectural.

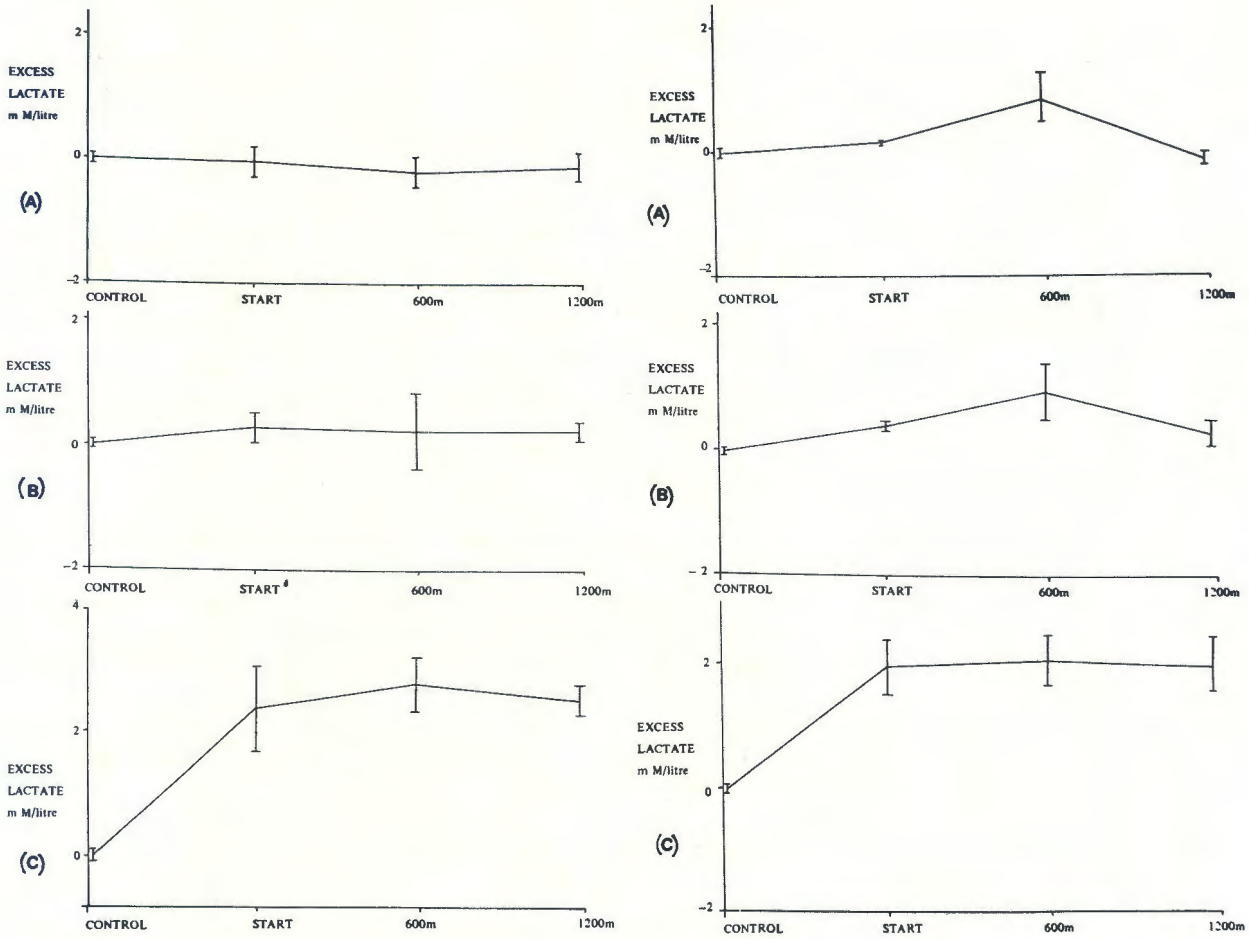

FIG. 8 Excess lactate values during 1200 m walk (A), trot (B) and gallop (C) in normal (left column) and COPD subjects (right column)

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