BLOOD VOLUME IN RELATION TO EXERCISE TOLERANCE IN TROTTERS

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SUMMARY

Blood volume can be regarded as an expression of the dimensional capacity of the cardiovascular system; as such it should be regarded as a limiting factor of the 'oxygen conduction system' conveying oxygen from the air to the metabolically active tissues of the body. An unimpeded flow of oxygen to the tissues is also dependent on the functional capacities of the cardio-respiratory system. Thus, blood volume should be correlated to parameters describing functional capacities of the cardio-vascular system; both dimensional and functional capacities should determine the exercise performance of the horse as well as in other animal species.

In the present communication the relationship is demonstrated between blood volume and working capacity assessed from several types of exercise-tolerance tests, based on heart rate and blood lactate response to exercise. The dependency of exercise performance on these parameters is discussed, as well as the clinical applicability of these relationships.

Exercise tolerance is related to the aerobic capacity of the cardio-respiratory system. Thus, both dimensional and functional capacities of this organ system are limiting factors for maximal oxygen uptake and, consequently, for exercise performance, as aerobic energy production predominates during work lasting more than about one minute. During heavy exercise, however, both aerobic and anaerobic energy production contributes to the work output. Obviously, an unimpeded flow of oxygen to the working muscles requires that the different dimensional and functional capacities of the cardiovascular system be related to each other, which, in fact, has been demonstrated to be true in man. Furthermore, an increasing demand on the energy production caused, for example, by continuous physical training, induces a corresponding dimensional and functional adaptation of the cardiovascular system. It should be possible to predict the degree of adaptation to physical work, that is exercise tolerance, from parameters indicative of cardiovascular efficiency. In the horse, the easiest of such parameters to determine are total blood volume (TBV), total red cell volume (CV) and total haemoglobin (THb). The splenic erythrocyte reservoir is mobilized by exercise or intravenous adrenal injection, the dye-dilution method allows these determinations to be done with a precision of ± 3 per cent. The variation of this parameter between individuals is about ± 10 per cent if variations owing to body mass (Bm), sex, age and breed is taken into account. It is further reduced if the state of training is taken into consideration. Several parameters are related to the functional capacity of the cardio-respiratory system. Many of those used in man, however, are not applicable to the horse. The obvious parameter describing the total work output in trotters is racing performance expressed, for instance, as kilometre time in seconds (kmt), i.e., the total time taken divided by the distance in kilometres in a standard race. This parameter is a relevant expression for the aerobic work capacity as it is significantly correlated with TBV. The racing performance, however, is affected by factors other than the aerobic capacity of the horse. Factors of general significance, such as anaerobic energy release, mechanical efficiency of the energy turnover, pace, body build and track conditions, tend to increase the variability of this parameter. Furthermore, racing performance in the trotter is greatly influenced by factors such as tactical driving and pulling up from the gallop.

For this reason, an exercise tolerance test based on the heart rate response to increasing, reproducible and measurable work loads on a treadmill was devised. Work load is defined as treadmill velocity which can be measured exactly. The treadmill velocity causing a heart rate (HR) of 150 beats/min is extra- or intrapolated from 3 to 4 submaximal work loads on the treadmill and this parameter (V_{150} metres/sec) is considered to be an expression of the circulatory capacity of the horse and, thus, correlated with the stroke volume of the heart and also with the arterio-venous oxygen difference of the blood.

On the average, the blood lactate level does not increase significantly above the resting level until the heart rate exceeds 158 beats/min (Fig. 1). This indicates that a work load causing a heart rate of 150 beats/min should be performed almost entirely aerobically in most horses and, thus, V_{150} should be an expression for the aerobic capacity of the animal. It should be noted (Fig. 1) that a very steep increase of the blood lactate level occurs at an exercise heart rate of about 200 beats/min, indicating that above this level the anaerobic energy release starts to play a significant role in work output.

![Blood lactate vs. heart rate](https://example.com/blood_lactate.png)

**Fig. 1:** Blood lactate (µmol/L) in relation to heart rate (HR, beats/min) at rest (mean value ± 2x S.D.) and during exercise in trotters.
If \( V_{150} \) reflects the aerobic capacity of the cardiovascular system, a relation to the dimensional capacity, or, for instance, TBV should prevail. This is the case in normal trotters provided body mass is taken into consideration. In adult mares and geldings this correlation is lacking, however. As the mean value for \( V_{150} \) is the same in trained adult mares and geldings as in adult stallions (7,0 m/s), in spite of lower TBV in mares and geldings, it seems that these have a hypokinetic circulation relative to the stallions, that is, they have a more efficient peripheral oxygen utilization and, thus, a wider arteriovenous oxygen difference during submaximal work. This might have a bearing on the lack of erythropoietic effect of testosterone on mares and geldings. Young horses, too, seem to be hypokinetic relative to adult stallions. This means that prediction of the aerobic working capacity from blood volume parameters in clinical work must take age and sex into consideration. The clinical application of this test has been described earlier.

A treadmill is an expensive piece of machinery. It is most useful for basic studies of cardio-respiratory function in the horse, but, for obvious reasons its use in clinical diagnostic work is restricted by economics. Therefore, the relevance of some exercise tolerance tests performed on the track was studied. These tests were based on the heart rate or the blood lactate response to work loads to which the horses were well accustomed.

The parameters were calculated from two types of experimental procedures. In one of these, the horse trotted at a constant speed of 10 m/s over 4 000 metres on a 1 000-metre track. The driver continuously checked the speed by timing the passing of poles 100m apart and the velocity was also checked by the investigator from the track tower. All the work tests were performed under standard track and weather conditions. Heart rates were calculated from electrocardiograms recorded by radiotelemetry towards the end of every 500-metre distance. As will be seen from figure 2, there was a gradual increase in heart rate throughout the work test. This is in accordance with earlier observations. Two parameters with reference to the heart rate response to this test were calculated: the mean heart rate denoted as \( HR_{10} \), that is, the mean HR at a speed of 10 m/s and the heart rate increase during the test denoted as \( HR_{incr} \) expressed as the regression coefficient for the pulse/distance relationship. Immediately after the end of work, and 2,5 and 5 minutes later, blood samples were taken for determination of blood lactate concentrations. Two parameters with reference to blood lactate response to this submaximal exercise test were used, namely: the blood lactate level immediately after work, denoted as \( LA_{90} \), that is, the lactic acid concentration at a work level of 10 m/s, and lactic acid clearance (LA \( CI \)) expressed as the regression coefficient for the blood lactate/time relationship during the 5-minute post-work period. Obviously, this parameter is negative for decreasing, and positive for increasing lactate levels.

The other exercise test was performed by trotting at four increasing submaximal speeds, each for 1 000 metres. The driver was instructed to maintain a constant speed at each level and the speed was calculated by the investigator. The work load at the highest submaximal level was chosen so that it would cause a heart rate slightly exceeding 200 beats/min. Immediately after the highest submaximal work level, the horse was made to trot one more round of 1 000 metres distance at its maximum speed. The heart rate at the end of each work level was assessed telemetrically as previously described and the blood lactate concentration was determined from samples taken in the same manner as after the constant-speed exercise test. The following variables with reference to heart rate and blood lactate response to this exercise test were used: \( V_{200} \), defined as the velocity attained at a heart rate of 200 beats/min, intrapolated from the linear pulse/speed relationship in metres/second; \( HR_{max} \), which is the heart rate at the end of the round at maximum speed and considered to represent the maximal heart rate of the horse; \( LA_{max} \) which is the blood lactate concentration immediately after the trot at maximum speed; \( LA_{max\ CI} \), which is the regression coefficient for the blood lactate/time relationship during the 5-minute period following maximal work. This is very often positive, that is, the blood lactate concentration increases (Fig. 3). The maximal velocity attained (\( V_{max} \) in metres/second) was considered to represent the maximal work output ability, or, the sum of the maximal capacities for aerobic and anaerobic energy release of the horse.

![Fig. 2: Mean heart rate (HR, m) ± SD at 500 metres interval during trotting at 10 m/s over 4 000 metres in 76 horses. r = correlation coefficient for the mean heart rate/distance relationship. Km = kilometre.](image1)

![Fig. 3: Lactic acid clearance (LA CI; see the text) in relation to the blood lactate concentration (LA) at the end of submaximal (filled symbols) and maximal (open symbols) exercise in trotters.](image2)
The reproducibility of the heart rate response to rack work is indicated by the relationship between HR<sub>10</sub><sub>obs.</sub> observed and predicted from the increasing work-load test in the same animal (Fig. 4). The reproducibility of the heart rate response to work (Fig. 5). The mean difference between observed and predicted heart rates: closed symbols = mares and geldings; open symbols = mares and geldings; closed symbols = stallions.

Some interrelationships found in the correlation matrix are shown in figure 6 and 7. As has been demonstrated earlier, there is a significant dependency of CV/Bm on age. This is true in mares and geldings up to four years of age and in stallions to five years of age. This difference due to sex explains the higher correlation coefficient in stallions. After the age of four and five years, respectively, age alone has no influence on the cardiovascular dimension.

The influence of age on the blood lactate response to this submaximal work load also seems to end at maturity (Fig. 8). This might indicate that the lower dimension and, consequently, the lower aerobic capacity is compensated for by a higher anaerobic energy release in young horses at this work level. The
higher correlation coefficient in mares and geldings could, in addition, have a bearing on their lower dimensional capacity. This will be further discussed later.

The positive dependency of $LA_{\text{max} Cl}$ on age is somewhat confusing (Fig. 9), but this might be due to the reasonable, positive correlation between $V_{\text{max}}$ and $LA_{\text{max} Cl}$ (Fig. 10) as $V_{\text{max}}$, too, is positively correlated with age.

The heart rate response to exercise, expressed either as $HR_{10}$ or as $V_{200}$, tends to be age-dependent as well only up to maturity (Fig. 11 and 12). The inverse correlation between $HR_{\text{max}}$ and age in stallions is of interest as it is concordant with observations in man. The lack of correlation in mares and geldings, on the other hand, is not in accord with the situation in man. It should be kept in mind, however, that most horses in this study were relatively young, from a biological point of view, and the age range was limited.

Both parameters based on the lactic acid and the heart rate response to submaximal exercise are significantly correlated to the dimensional capacity of the cardiovascular system. The inverse dependency of $LA_{10}$ on CV/Bm is significant for mares and geldings only (Fig. 13). This might be due to their sex-depen-
dent lower dimensional capacity with, therefore, a tendency to rely on anaerobic energy production even at this submaximal work load - a tendency significantly modified by increasing cardiovascular dimension. In almost half of the stallions this work load barely raised the lactate level.

Further, the equally high correlation between the maximal work output, expressed as \( \frac{CV}{IBm} \), and \( \frac{CV}{Bwt} \), means that the greater the \( CV/Bm \) the slower the \( LA_{10} \), is somewhat confusing. One would have expected the reverse relationship. Probably the explanation is the strong inverse relation between \( LA_{10} \) and \( LA_{10} \), which means that, up to a certain level, blood lactate is eliminated faster at increasing values for \( LA_{10} \). This is also seen in figure 3.

\[ \text{Fig. 17: Blood lactic acid at 10 m/s (LA}_{10} \text{) in relation to the total red cell volume divided by the body mass (CV/Bwt, ml). Symbols as in Fig. 5.} \]

The discrepancy in the dependency of the parameters based on heart rate response to exercise on \( CV/Bm \) is unexpected. The correlation between \( V_{200} \) and \( CV/Bm \) is fair and of the same degree as that between \( V_{150} \), measured on the treadmill, and \( CV/Bm \). The sex difference found in the latter relationship is not to be found in the \( V_{200}/CV \)-relation, at least not to the same extent. Obviously, \( V_{200} \) is as good an expression for the aerobic functional capacity as racing performance and \( V_{150} \), judging by its dependency on the blood volume parameters. Further, the equally high correlation between the maximal work output, expressed as \( V_{max} \), and \( CV/Bm \), suggests that the former, to a large extent, is limited by the oxygen transport capacity of the horse. The predictability of \( V_{max} \) from \( CV/Bm \) is equally reliable in both sex groups as the regressions are statistically identical (Fig. 14).

The correlation between \( LA_{10} \) and \( LA_{10} \) has been commented on previously. Obviously, the rate of elimination of lactate from the blood is dependent on the quantity of lactate to be removed. But, on the other hand, it is possible that the degree of accumulation of blood lactate is modified by the efficiency of removing lactate from the blood.

The dependency of \( LA_{10} \) on \( HR_{10} \) is probably an expression for an increasing demand on anaerobic energy production at increasing relative work loads (Fig. 15). As suggested by this relationship, there seems to be a gradually increasing blood lactate level with \( HR_{10} \) approaching \( HR_{max} \) that is, the correlation is curvilinear. At least in stallions, it seems that the anaerobic energy resource is not recruited until the heart rate exceeds 85 to 90 per cent of the maximal heart rate. Following this, it is not surprising to find a weak, but significant positive correlation between \( LA_{10} \) and \( HR_{10} \), or, in other words, the higher the heart rate and the faster it approaches the maximal heart rate, the higher the lactate accumulation in the blood, or from another point of view, a gradual accumulation of lactate tends to increase the heart rate.

\[ \text{Fig. 15: Blood lactic acid (LA}_{10} \text{) in relation to heart rate at 10 m/s as a percentage of the maximal heart rate (HR}_{10}/HR_{max} \times 100). Symbols as in Fig. 5. The broken line indicates the probable regression line.} \]

\( LA_{10} \) tends to be inversely dependent on the cardiovascular functional capacity, expressed as \( V_{200} \). Although not statistically significant, this relationship seems logical, but, judgment on its relevancy is restricted by too few observations. The inverse relation between \( LA_{10} \) and \( V_{max} \), on the other hand, is fair and of considerable interest. It means that horses which can trot 10 m/s with a low lactate accumulation in the blood, have a high maximal performance and vice versa. This should mean that a low \( LA_{10} \) reflects a high aerobic capacity. The difference between the sex groups, with a higher correlation coefficient in mares and geldings, also seen in the \( LA_{10}/CV \)-relationship, is probably due to the fact that about 2/3 of the stallions exhibit almost no increase of blood lactate at 10 m/s (Fig. 16). The higher correlation between \( V_{max} \) and \( LA_{10} \) than between \( CV/Bm \) and \( LA_{10} \) should be ascribed to the addi-

\[ \text{Fig. 14: Maximal trotting speed (V}_{max} \text{) in relation to the total red cell volume divided by the body mass (CV/Bwt). Symbols as in Fig. 5.} \]

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tional information of the functional capacity included in $V_{\text{max}}$ is as indicated by the dependency of this parameter on $HR_{10}$, which will be discussed later.

![Graph](image)

**Fig. 16:** Maximal trotting speed ($V_{\text{max}}$) in relation to blood lactic acid at 10 m/s ($LA_{10}$). Symbols as in Fig. 5.

The correlation between $LA_{10}$ and $V_{\text{max}}$ is probably due to the dependency of $LA_{10}$ on $LA_{10}$. On the other hand, a high capability of eliminating excess lactate might be beneficial for maximal exercise performance.

Apart from the relationships with $V_{200}$ and $HR_{10}$, which are obvious by definition, $HR_{10}$ is strongly correlated with $V_{\text{max}}$. Unexpectedly, this correlation is even better than that between $V_{200}$ and $V_{\text{max}}$. In both correlations the highest coefficient of correlations are found in mares and geldings. These correlations demonstrate the dependency of exercise tolerance on the cardiovascular functional capacity. This seems to indicate that mares and geldings, having a lower dimensional capacity, must rely on an increasing functional capacity in adaptation to continuous exercise stress. This is also indicated by the significantly higher regression coefficient in this sex group than in stallions in the $V_{\text{max}}/HR_{10}$ relationship (Fig. 17).

So far, it might be concluded that mares and geldings, lacking the anabolic effect of androgens, seem to depend, to a higher degree, on increasing cardiovascular functional capacity and anaerobic capacity to improve their exercise tolerance than is the case with stallions, which primarily increase their cardiovascular dimensional capacity.

**References**

4. PERSSON S.G.B. 1968 Blood volume state of training and working capa-

**Fig. 17:** Maximal trotting speed ($V_{\text{max}}$) in relation to heart rate at 10 m/s ($HR_{10}$). Broken regression line and open circles = mares and geldings; continuous regression line and closed circles = stallions; $b = \text{regression coefficient}$.

**Table:**

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<td>0.053**</td>
<td>0.38</td>
<td>0.29</td>
<td>2.4</td>
</tr>
</tbody>
</table>

**Fig. 18:** Stepwise multiple regression analysis of the dependency of maximal trotting velocity ($V_{\text{max}}$) on several variables. Abbreviations - see the text. $t = \text{test of hypothesis; } b_{10} = \text{regression coefficient. Degrees of significance as in Fig. 6.} \ t = \text{multiple correlation coefficient; } SD = \text{standard deviation; } n = \text{number of observations. (Bwt (body weight) = Bm (body mass) in text.}$

Finally, in a limited number of horses, the dependency of the maximal exercise performance, $V_{\text{max}}$ on several independent variables was tested, using a stepwise, multiple regression computer programme (Fig. 18). The results indicate that the main factors limiting maximal work performance in race horses are the dimensional and functional capacities, in that order, of the cardiovascular system, that is, an improved exercise tolerance is primarily achieved by an increased aerobic capacity.

**References**

4. PERSSON S.G.B. 1968 Blood volume state of training and working capa-

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DISCUSSION

M.C. Morison: You said that higher lactic acid clearance was evident in mares and geldings than in stallions. If this is the case, could you explain why mares are more liable to suffer from azoturia than stallions? Does this mean that there is less lactic acid build-up in stallions than in mares that suffer from this condition? Do these mares have an inability to excrete higher levels of lactic acid?

S.G.B. Persson: I did mention that the blood lactate response to submaximal exercise (10 m/s) is more evident in mares and geldings, whereas most stallions barely increase their blood lactate at all at this work level. Merely for purposes of discussion I have postulated the possibility of higher lactic acid clearance in mares. If it is an accepted fact that azoturia is more common in mares than in stallions, this might have a bearing on the tendency of mares to rely more on their anaerobic energy release, as this would mean higher lactic acid concentration in the working muscles. There is no evidence of a slower elimination of lactate from the blood in mares.

J.R. Gillespie: I am concerned about the temporal effects on lactic acid build-up in the blood. There must be a different rate of build-up with a different intensity of exercise. What do you mean by maximum work?

S.G.B. Persson: As was pointed out in the paper, the blood lactate accumulation during exercise is dependent on the intensity of exercise, or, rather on the relative work load, expressed as the rate response relative to the maximal heart rate of the horse. It was also mentioned that in many horses this lactic acid accumulation in the blood continues for at least five minutes after work. This is especially the case at high relative work loads. That was one reason for studying the so-called lactic acid clearance. The criteria for maximal work were that the horse was urged by the driver to trot as fast as it could; the heart rate then usually deviated significantly from the value extrapolated from the heart rate submaximal work regression line.