

Lactate Removal Ability and $\dot{V}O_2$ Recovery Kinetics in Sickle Cell Trait Carriers Compared with Normal Haemoglobin Subjects: Preliminary Data

Philippe Connes^{*,1}, Stéphane Perrey², Fagnété Sara^{1,3}, Marie-Dominique Hardy-Dessources³, Mona Hedreville^{1,4} and Olivier Hue¹

¹Laboratory ACTES, UPRES-EA 3596, Department of Physiology, Faculty of Sports Sciences, University of the French West Indies, Campus of Fouillole, BP 592, 97159 Pointe a Pitre Cedex, Guadeloupe (FWI), France

²Laboratory Motor Efficiency and Deficiency EA 2991, Faculty of Sports Sciences, University of Montpellier 1, 34090 Montpellier, France

³UMR Inserm U 763-University of the French West Indies, Academic Hospital of Pointe a Pitre, Guadeloupe, France

⁴Department of Cardiology, Academic Hospital of Pointe a Pitre, Guadeloupe, France

Abstract: Because of the reduced affinity of haemoglobin S to oxygen and the altered blood rheological profile of sickle cell trait carriers (AS), it is often thought that exercise physiological responses should differ between AS and subjects with normal haemoglobin (AA). The present study aimed to compare the ability to remove blood lactate and the characteristics of oxygen uptake ($\dot{V}O_2$) recovery kinetics after supramaximal exercise in eight AS and eight matched AA. All subjects performed a supramaximal exercise test consisting of pedalling for 1 min at 110% maximal $\dot{V}O_2$. Following exercise, venous blood samples were obtained from AS and AA at different times to assess blood lactate concentrations. Mathematical modelling was applied during recovery to assess the blood lactate removal ability (time constant γ_2) and the kinetics for $\dot{V}O_2$ recovery (amplitude A_2 and time constant τ_2). Lactate removal ability and the $\dot{V}O_2$ recovery kinetics were not significantly different between the two groups ($P > 0.05$). No significant relationship was observed between γ_2 and A_2 ($r = 0.04$; $P > 0.05$) or between γ_2 and τ_2 ($r = -0.44$; $P > 0.05$) in all groups. It seems that the ability to recover or to remove lactate after a short supramaximal exercise does appear unaltered by sickle cell trait. It is possible that the elevated blood viscosity reported several times in AS could have promoted greater vasodilatation which in turn may favour exercise recovery to a similar level observed in subjects with normal haemoglobin. Our findings may suggest that AS and AA subjects need similar recovery after exhausting exercise. However, it is also known that AS may be prone to medical complications in response to exercise. So, the presence of clinical sign should justify to prolong recovery or to stop exercise in AS.

Keywords: Haemoglobin S, EPOC, Exercise, Anaerobic metabolism.

INTRODUCTION

Sickle cell trait (SCT) is the heterozygous form of sickle cell disease (SCD), which is the most prevalent genetic abnormality in the world. SCT is marked by the presence of both normal and abnormal haemoglobin (i.e. HbA and HbS, respectively) in red blood cells (RBCs).

The presence of both HbA and HbS led previous investigators to hypothesize that SCT carriers (AS) would have different physiological responses to exercise than subjects with normal Hb (AA) [1-5]. Because the presence of HbS into RBCs might change the oxygen-carrying properties of these cells [6] and because the increased blood viscosity found in AS could disturb blood flow and oxygen delivery to

tissues [7], one of the often discussed particularities of AS concerns lactate metabolism during exercise [5]. We tried to revisit the question of whether lactate metabolism regulation is different between AS and AA using bi-exponential modelling of lactate recovery curves [3, 8, 9] after a short strenuous exercise resulting in profound metabolic acidosis [10]. This mathematical model, instead of the isotope tracer method, has the advantage to be applied to non steady-state, supramaximal conditions.

Several studies have also focused on how lactate affects the recovery of oxygen consumption after exercise (i.e. on the excess postexercise oxygen consumption; EPOC). Using a radioactive tracer technique, Brooks *et al.* [11] demonstrated that a causal relationship between lactate and the slow component of EPOC is unlikely. On the other hand, several studies [12, 13] have shown results supporting the concept that lactate influences the slow component of EPOC time course. As lactate may be related to EPOC, we hypothesised that if lactate removal ability differs between

*Address correspondence to this author at the Laboratory ACTES UPRES-EA 3596, Faculty of Sports Sciences – Department of Physiology, University of the French West Indies, Campus of Fouillole, BP 592, 97159 Pointe a Pitre Cedex, Guadeloupe (FWI), France; Tel: + (590) 590 48 92 28; Fax: + (590) 590 48 92 79; E-mail: pconnes@yahoo.fr

AS and AA, EPOC (and particularly the slow component phase) will also differ between the two populations.

The dual purpose of the present study was to compare the ability to remove lactate and its temporal association to the EPOC slow component after supramaximal exercise in AS and AA subjects matched for ethnic origin and overall physical fitness level. To test these hypotheses, we used the same participants and exercise protocol as in a previous study [7].

METHODS

Subjects

Eight male SCT carriers (AS group; 24.1 ± 3.2 yrs, 181.3 ± 1.7 cm, 76.0 ± 3.4 kg) and eight male subjects with normal haemoglobin (AA group; 19.6 ± 0.5 yrs, 179.0 ± 1.7 cm, 68.9 ± 2.7 kg) participated in the present study. The haematological characteristics of the subjects are summarised in Table 1. All were students at the University of the French West Indies and Guyana and took part in the same training programme. They were moderately trained and practised athletic activities regularly (12 ± 2.1 h/week) but never at a high level. The subjects who did not have the required training status or who were unwilling to follow the study protocol were excluded.

Table 1. Haematological Parameters in the Two Groups

		Hb (g.dL ⁻¹)	Hct (%)	Ret (%)	HbS (%)
Group	AS (n = 8)	14.7 ± 0.2	45.8 ± 0.7	0.96 ± 0.07	38.0 ± 0.8
	AA (n = 8)	14.5 ± 0.3	46.2 ± 0.4	1.19 ± 0.15	-

Values are means \pm SEM. Hb (haemoglobin), Hct (haematocrit), HbS (haemoglobin S), Ret (reticulocytes), (n) number of subjects. No significant difference between the two groups.

Protocol

At the beginning of the university year, all new students of the Faculty of Sports underwent haemoglobin screening. Eight AS subjects were detected in this screening programme and included in the study. Eight AA subjects were then selected and matched for maximal oxygen uptake ($\dot{V}O_2$ max) and anthropometric and haematological data (Table 1). Subjects with anaemia and/or alpha-thalassaemia were excluded. The subjects were informed of the procedures and purposes of the study, which was approved by the local Ethics Committee, and gave written consent to participate. The protocol was in accordance with the guidelines set by Declaration of Helsinki.

On the first experimental day, all athletes performed a progressive and maximal exercise test to determine the maximal power output (MAP) and $\dot{V}O_2$ max (data not shown and already published in [7]). One week later, the same subjects performed a supramaximal exercise test consisting of pedalling for 1 min at 110% $\dot{V}O_2$ max, during which oxygen uptake ($\dot{V}O_2$) was measured breath-by-breath. This type of supramaximal test is well-known to induce increased blood lactate during the first moments of recovery before its clearance and consequently is appropriate for mathematical

modelling of blood lactate recovery curves (see below). Venous blood samples were obtained from AS and AA at different times to assess the haematological parameters and blood lactate concentrations. No additional drink was allowed 3 hours before and during exercise and the subsequent recovery.

SCT Diagnosis and Blood Analysis

Techniques used for SCT diagnosis were the same than those previously used [14, 15]. To test for the haemoglobin type, venous blood was drawn into tubes containing EDTA (i.e. ethylenediaminetetraacetate) and screened by isoelectric focusing. The results were confirmed by citrate agar electrophoresis. The various haemoglobins were isolated and quantified by high performance liquid chromatography (HPLC). A test of solubility confirmed the presence of HbS. Positive test results for SCT were confirmed by the presence of HbS (< 50%) and a normal percentage of HbA₂ [16]. Haemoglobin concentration ([Hb]), haematocrit (Hct) and percentage of reticulocytes (% Ret) were also studied for the indirect diagnosis of anaemia and alpha-thalassaemia, which results in haematological modifications [17].

Incremental Exercise Test

The progressive and maximal exercise test began with a 3-min warm-up at 60 W. Pedalling frequency remained constant (at 70 rpm) throughout testing, and the load was increased by 30 W every minute until $\dot{V}O_2$ max was reached. Oxygen uptake was considered maximal if at least three of the following criteria were met: 1) a respiratory exchange ratio greater than 1.10; 2) attainment of age-predicted maximal heart rate (HR max) [$210 - (0.65 \times \text{age}) \pm 10\%$]; 3) an increase in $\dot{V}O_2$ lower than 100 ml with the last increase in work rate; and 4) an inability to maintain the required pedalling frequency (70 rpm) despite maximum effort and verbal encouragement. A 5-min recovery period was then implemented with 2 min of pedalling and 3 min at rest. $\dot{V}O_2$ was continuously measured using a breath-by-breath automated metabolic system (Vmax 229 D series, SensorMedics Corp., Yorba Linda, CA, USA). A 10-lead electrocardiogram (Hellige, Marquette Medical Systems, Germany) was monitored continuously.

Supramaximal Exercise Test

During this session, a catheter was inserted into the antecubital vein for blood sampling. Each subject warmed up at moderate intensity (50% of $\dot{V}O_2$ max) for 5 min on a cycle ergometer and then rested for 5 min. The supramaximal exercise test consisted of pedalling at 110% of $\dot{V}O_2$ max for 1 min on the cycle ergometer [10]. Then, all subjects recovered passively for 1 hour on the cycle ergometer and in the same sitting position as during the exercise. During recovery, $\dot{V}O_2$ was measured breath-by-breath during the first 10 min.

Blood Lactate Sampling and Analysis

Blood was sampled at rest, immediately at the end of exercise and at minutes 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15,

of measurement. We noted a time effect ($P < 0.05$) demonstrating higher adjusted blood lactate concentration from the end of exercise ($4.68 \pm 0.88 \text{ mmol.L}^{-1}$ and $3.83 \pm 0.59 \text{ mmol.L}^{-1}$ of [La] in AS and AA, respectively) until the 50th min of recovery as compared with rest ($1.51 \pm 0.13 \text{ mmol.L}^{-1}$ and $1.58 \pm 0.13 \text{ mmol.L}^{-1}$ of [La] in AS and AA, respectively). No significant difference was observed between rest and the 60th min of recovery ($1.61 \pm 0.15 \text{ mmol.L}^{-1}$ and $1.89 \pm 0.15 \text{ mmol.L}^{-1}$ of [La] in AS and AA, respectively). The mean blood lactate recovery curves of the two groups are presented in Fig. (1). The Fig. (2) is a representative blood lactate recovery curve in a SCT carrier. The mean values of the parameters obtained with Eq.1 after the 1-min 110% $\dot{V}O_2$ max exercise are reported in Table 2. The mean velocity constants γ_1 and γ_2 , as well as the concentration parameters A_1 , A_2 and $La(0)$, were not different between the two groups.

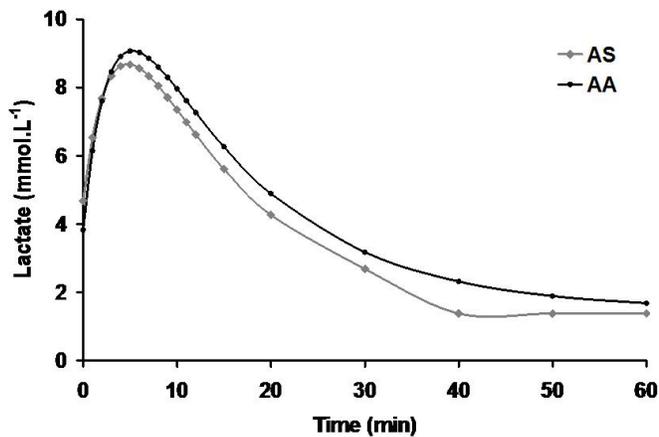


Fig. (1). Mean blood lactate recovery curves in the two groups. The two curves were not statistically different.

The parameters derived from the $\dot{V}O_2$ recovery kinetics are shown in Table 3. At this stage, because of a technical problem with the breath-by-breath automated metabolic system, modelling of four of the subjects (2 AS and 2 AA) was not completed. Therefore, the study of the $\dot{V}O_2$ recovery kinetics was conducted on six AS and six AA subjects. Neither the time constants nor amplitudes of the fast and slow components of $\dot{V}O_2$ recovery kinetics were significantly different between the two groups. The mean $\dot{V}O_2$ recovery kinetics curves of the two groups are presented in Fig. (3), and the Fig. (4) is showing a representative curve of a SCT carrier.

DISCUSSION

The dual purpose of the present study was to determine whether the ability to remove lactate (γ_2) and its temporal association to the slow component of $\dot{V}O_2$ recovery kinetics in response to a supramaximal exercise test were different between AS and AA. We found no significant difference in the ability to remove lactate between our two groups. Similarly, neither the EPOC slow component nor the fast component differed between the groups.

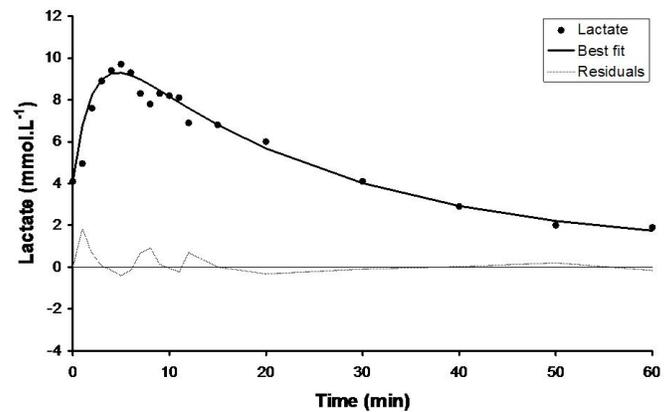


Fig. (2). Representative blood lactate recovery curve in a SCT carrier. Note the plot of residuals which demonstrates the good fitting procedure.

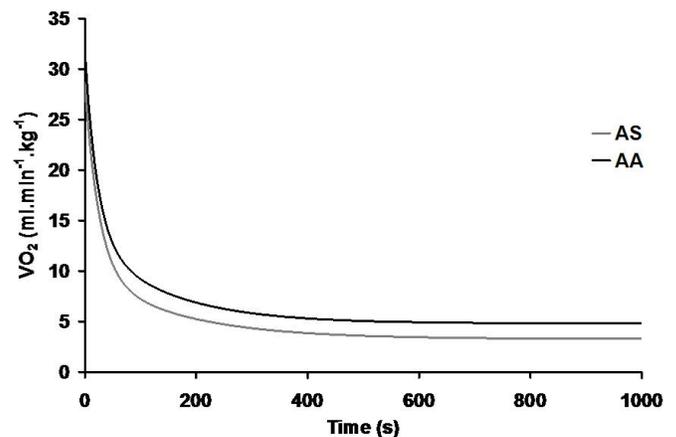


Fig. (3). Mean $\dot{V}O_2$ recovery kinetics curves in the two groups. The two curves were not statistically different.

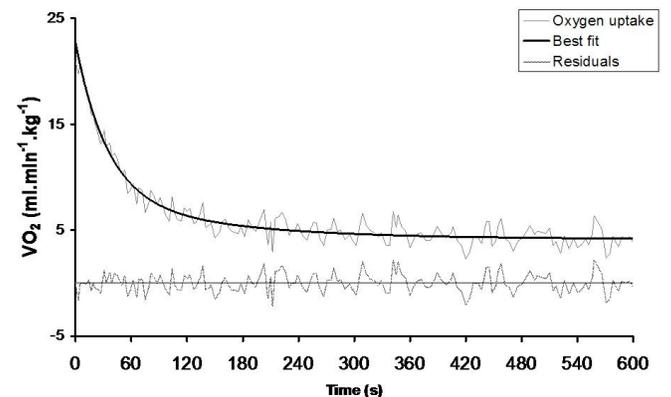


Fig. (4). Representative $\dot{V}O_2$ recovery kinetics curve in a SCT carrier. Note the plot of residuals which demonstrates the good fitting procedure.

Freund *et al.* [3] investigated the ability of AS to exchange and remove lactate from the blood circulation after a ramp exercise test and observed that AS were likely to produce more lactate than controls and/or to have an impaired ability to clear circulating lactate. However, it appears that AS and AA were not matched according to physical activity that may interfere with the interpretation of their results. The greater activity recently found for the RBC monocarboxylate transporter, MCT-1, in AS could

Table 2. Parameters of the Bi-Exponential Curves Fitted to Blood Lactate Recovery Curves Obtained from the 1-min Supramaximal Cycling Exercise

		La(0) (mmol.L ⁻¹)	A ₁ (mmol.L ⁻¹)	γ ₁ (min ⁻¹)	A ₂ (mmol.L ⁻¹)	γ ₂ (min ⁻¹)
Groups	AS (n = 8)	4.68 ± 0.88	11.11 ± 1.34	0.31 ± 0.04	-14.40 ± 1.26	0.08 ± 0.02
	AA (n = 8)	3.83 ± 0.59	11.57 ± 2.45	0.33 ± 0.07	-13.93 ± 2.36	0.07 ± 0.01

Values are means ± SEM. A₁ and A₂ (amplitude terms of the two exponential time functions), γ₁ and γ₂ (velocity constants which denote the abilities to exchange and remove lactate, respectively), La(0) (venous blood lactate concentration at the end of the exercise), (n) number of subjects. No significant difference between the two groups.

Table 3. Parameters of the $\dot{V}O_2$ Recovery Kinetics Obtained from the 1-min Supramaximal Cycling Exercise

		$\dot{V}O_{2B}$ (ml.kg ⁻¹ .min ⁻¹)	A ₁ (ml.kg ⁻¹ .min ⁻¹)	τ ₁ (sec)	A ₂ (ml.kg ⁻¹ .min ⁻¹)	τ ₂ (sec)
Groups	AS (n = 6)	28.7 ± 1.9	-18.7 ± 2.5	24.7 ± 2.7	-6.7 ± 1.2	163.3 ± 23.5
	AA (n = 6)	31.7 ± 1.9	-18.4 ± 2.1	22.4 ± 3.4	-8.5 ± 1.2	141.5 ± 14.6

Values are means ± SEM. $\dot{V}O_{2B}$ (baseline $\dot{V}O_2$, i.e. $\dot{V}O_2$ at the end of exercise), A₁ and τ₁ (amplitude and time constant of the primary component), A₂ and τ₂ (amplitude and time constant of the slow component), (n) number of subjects. Technical problem with the breath-by-breath automated metabolic system deprived us from mathematical modelling of 2 AS and 2 AA. No significant difference between the two groups.

contribute to the better regulation of lactate exchange between blood and other cellular compartments [26]. However, the present study demonstrated that the ability to remove lactate was quite similar in the two groups as already suggested in another recent study using a different methodological approach to assess mechanisms of lactate metabolism regulation during exercise [27]. Therefore, the mechanisms involved in blood lactate regulation during exercise, such as RBC MCT-1, might be saturated or depressed during recovery, which would lead in turn to quite similar lactate recovery curves in the two groups.

No significant relationship was observed between γ₂ and A₂ (r = 0.04; P > 0.05) or between γ₂ and τ₂ (r = -0.44; P > 0.05) in the two groups altogether.

Several studies have investigated the relationship between [La] and the slow component of $\dot{V}O_2$ recovery kinetics [11-13, 20, 28]. Some of them suggested that lactate removal might have an effect on the recovery rate of oxygen consumption after strenuous exercise [12, 13, 20]. These authors estimated that during the slow component of $\dot{V}O_2$ recovery kinetics, 50% of lactate is oxidised while the other 50% is reconverted to glycogen. Thus, a causal and temporal relationship between EPOC and lactate kinetics has been reported [12]. However, we found no significant relationship between lactate removal ability and the slow component of EPOC in the present study, thereby reinforcing the conclusion previously drawn by Brooks and Gaesser [11], who had used the radioactive tracer technique to demonstrate the absence of a causal relationship between lactate and EPOC. Rose *et al.* [29] found, in the horse, that despite the presence of a correlation between the slow component of EPOC and pulmonary artery plasma lactate level, the $\dot{V}O_2$ returned to baseline by 20 min whereas blood lactate remained elevated. It is suggested that the mechanisms which result in elevated blood lactate may also be associated to the prolonged post exercise elevation of $\dot{V}O_2$ [20]. In addition, the resultant lactic acidosis following exercise may stimulate ventilation by its action on the arterial chemoreceptors and this increased ventilation might participate (but not fully explain) to the increased $\dot{V}O_2$ during

recovery. Other mechanisms have been proposed to explain the slow component of EPOC such as catecholamines and temperature [20, 28] but we did not address any of these factors in the present study.

Connes *et al.* [4] recently reported that AS were prone to exercise intolerance and lower aerobic capacity during prolonged submaximal exercise due to higher $\dot{V}O_2$ -on slow component. This excess of $\dot{V}O_2$ during exercise should have an effect on the subsequent $\dot{V}O_2$ recovery kinetics. However, the parameters describing the first and second components of the $\dot{V}O_2$ recovery kinetics did not differ between the two groups in the present study. Exercise intensity and duration are known to influence EPOC magnitude [13]. The exercise performed by AS and AA in the present study and in the study of Connes *et al.* [4] were very different and could explain this discrepancy.

The lack of significant difference in lactate removal ability and EPOC between the two groups is quite surprising if we take into account the recent study performed by Connes *et al.* [7] on the same participants and exercise protocol. The authors investigated the changes in blood rheology in response to exercise in AS and AA and found higher blood viscosity and lower RBC deformability at rest, at the end of the 1-min supramaximal exercise test, and during the following recovery period in AS [7]. Altered haemorheology is known to disturb blood circulation and therefore adequate O₂ delivery to tissues [30, 31], which should influence EPOC and lactate metabolism. However, recent reports also indicate that high blood viscosity could have a beneficial effect because of the stimulation of endothelial nitric oxide synthase by increasing shear stress and the subsequent vasodilatation [32-34]. Therefore, the different blood rheology profile found in AS [7] could favour greater vasodilatation providing normal O₂ delivery to tissues, which would ensure normal lactic response and normal $\dot{V}O_2$ recovery kinetics. Besides, Connes *et al.* [35] recently reported a significant positive correlation between the increase of blood viscosity during exercise and the enlargement of the arterio-venous oxygen content in athletes suggesting that the increase

of blood viscosity may contribute to the increase of oxygen consumption. Further studies are needed to fully explain these mechanisms.

The main limitation of the present study was the limited number of participants and the present findings should be considered as preliminary. Our results suggest that lactate removal ability and $\dot{V}O_2$ recovery kinetics were not different between AS and AA in response to a short supramaximal exercise test. The ability to recover after a short supramaximal exercise seemed to be not altered by sickle cell trait. Nevertheless, the presence of clinical sign should justify to prolong recovery or to stop exercise in AS because it has been reported that AS might be at greater risk for medical complication in response to exercise than AA [36]. The mechanisms responsible for these results are not fully understood and require further studies in larger cohort. Also, different short-term supramaximal exercise (longer duration, all-out) need to be investigated to confirm these preliminary results.

ACKNOWLEDGEMENTS

We sincerely thank Dr. Maryse Etienne-Julan, Dr. Christian Saint-Martin and Laurent Marlin for their technical help. The authors also thank all the subjects who participated in the present study.

REFERENCES

- [1] Thiriet P, Le Hesran JY, Wouassi D, *et al.* Sickle cell trait performance in a prolonged race at high altitude. *Med Sci Sports Exerc* 1994; 26: 914-8.
- [2] Le Gallais D, Prefaut C, Mercier J, *et al.* Sickle cell trait as a limiting factor for high-level performance in a semi-marathon. *Int J Sports Med* 1994; 15: 399-402.
- [3] Freund H, Lonsdorfer J, Oyono-Enguelle S, *et al.* Lactate exchange and removal abilities in sickle cell trait carriers during and after incremental exercise. *Int J Sports Med* 1995; 16: 428-34.
- [4] Connes P, Monchanin G, Perrey S, *et al.* Oxygen uptake kinetics during heavy submaximal exercise: effect of sickle cell trait with or without alpha-thalassemia. *Int J Sports Med* 2006; 27: 517-25.
- [5] Connes P, Reid H, Hardy-Dessources MD, *et al.* Physiological responses of sickle cell trait carriers during exercise. *Sports Med* 2008; 38: 931-46.
- [6] Becklake MR, Griffiths SB, Mc GM, *et al.* Oxygen dissociation curves in sickle cell anemia and in subjects with the sickle cell trait. *J Clin Invest* 1955; 34: 751-5.
- [7] Connes P, Sara F, Hardy-Dessources MD, *et al.* Effects of short supramaximal exercise on hemorheology in sickle cell trait carriers. *Eur J Appl Physiol* 2006; 97: 143-50.
- [8] Freund H, Gendry P. Lactate kinetics after short strenuous exercise in man. *Eur J Appl Physiol Occup Physiol* 1978; 39: 123-35.
- [9] Freund H, Lonsdorfer J, Oyono-Enguelle S, *et al.* Lactate exchange and removal abilities in sickle cell patients and in untrained and trained healthy humans. *J Appl Physiol* 1992; 73: 2580-7.
- [10] Robergs R, Hutchinson K, Hendee S, *et al.* Influence of pre-exercise acidosis and alkalosis on the kinetics of acid-base recovery following intense exercise. *Int J Sport Nutr Exerc Metab* 2005; 15: 59-74.
- [11] Brooks GA, Gaesser GA. End points of lactate and glucose metabolism after exhausting exercise. *J Appl Physiol* 1980; 49: 1057-69.
- [12] Bahr R. Excess postexercise oxygen consumption—magnitude, mechanisms and practical implications. *Acta Physiol Scand Suppl* 1992; 605: 1-70.
- [13] Borsheim E, Bahr R. Effect of exercise intensity, duration and mode on post-exercise oxygen consumption. *Sports Med* 2003; 33: 1037-60.
- [14] Connes P, Sara F, Hardy-Dessources MD, *et al.* Does higher red blood cell (RBC) lactate transporter activity explain impaired RBC deformability in sickle cell trait? *Jpn J Physiol* 2005; 55: 385-7.
- [15] Tripette J, Hardy-Dessources MD, Sara F, *et al.* Does repeated and heavy exercise impair blood rheology in carriers of sickle cell trait? *Clin J Sport Med* 2007; 17: 465-70.
- [16] Serjeant G. Sickle cell disease. In: Publications OM, Ed. New York: Oxford university Press 1992.
- [17] Embury SH, Dozy AM. The alpha-globin genotype as a determinant of hematologic parameters in sickle cell trait. Sigler P, Ed. The molecular basis of mutant hemoglobin dysfunction. Amsterdam, The Netherlands: Elsevier 1981; pp. 63-7.
- [18] Bishop D. Evaluation of the Accusport lactate analyser. *Int J Sports Med* 2001; 22: 525-30.
- [19] Thomas C, Perrey S, Lambert K, *et al.* Monocarboxylate transporters, blood lactate removal after supramaximal exercise, and fatigue indexes in humans. *J Appl Physiol* 2005; 98: 804-9.
- [20] Langsetmo I, Poole DC. $\dot{V}O_2$ recovery kinetics in the horse following moderate, heavy, and severe exercise. *J Appl Physiol* 1999; 86: 1170-7.
- [21] Ozyener F, Rossiter HB, Ward SA, *et al.* Influence of exercise intensity on the on- and off-transient kinetics of pulmonary oxygen uptake in humans. *J Physiol* 2001; 533: 891-902.
- [22] Cleuziou C, Perrey S, Borrani F, *et al.* Dynamic responses of oxygen uptake at the onset and end of moderate and heavy exercise in trained subjects. *Can J Appl Physiol* 2004; 29: 32-44.
- [23] Lamarra N, Whipp BJ, Ward SA, *et al.* Effect of interbreath fluctuations on characterizing exercise gas exchange kinetics. *J Appl Physiol* 1987; 62: 2003-12.
- [24] Bearden SE, Moffatt RJ. $\dot{V}O_2$ and heart rate kinetics in cycling: transitions from an elevated baseline. *J Appl Physiol* 2001; 90: 2081-7.
- [25] Bearden SE, Moffatt RJ. $\dot{V}O_2$ kinetics and the O_2 deficit in heavy exercise. *J Appl Physiol* 2000; 88: 1407-12.
- [26] Sara F, Connes P, Hue O, *et al.* Faster lactate transport across red blood cell membrane in sickle cell trait carriers. *J Appl Physiol* 2006; 100: 437-42.
- [27] Sara F, Hardy-Dessources MD, Marlin L, *et al.* Lactate distribution in the blood compartments of sickle cell trait carriers during incremental exercise and recovery. *Int J Sports Med* 2006; 27: 436-43.
- [28] Gaesser GA, Brooks GA. Metabolic bases of excess post-exercise oxygen consumption: a review. *Med Sci Sports Exerc* 1984; 16: 29-43.
- [29] Rose RJ, Hodgson DR, Kelso TB, *et al.* Maximum O_2 uptake, O_2 EPOC, and deficit and muscle metabolites in Thoroughbred horses. *J Appl Physiol* 1988; 64: 781-8.
- [30] Connes P, Yalcin O, Baskurt O, *et al.* In health and in a normoxic environment, $\dot{V}O_2$ max is/is not limited primarily by cardiac output and locomotor muscle blood flow. *J Appl Physiol* 2006; 100: 2099.
- [31] Parthasarathi K, Lipowsky HH. Capillary recruitment in response to tissue hypoxia and its dependence on red blood cell deformability. *Am J Physiol* 1999; 277: 2145-57.
- [32] Martini J, Carpentier B, Negrete AC, *et al.* Paradoxical hypotension following increased hematocrit and blood viscosity. *Am J Physiol Heart Circ Physiol* 2005; 289: 2136-43.
- [33] Martini J, Carpentier B, Chavez NA, *et al.* Beneficial effects due to increasing blood and plasma viscosity. *Clin Hemorheol Microcirc* 2006; 35: 51-7.
- [34] Forconi S, Gori T. The evolution of the meaning of blood hyperviscosity in cardiovascular physiopathology: should we reinterpret Poiseuille? *Clin Hemorheol Microcirc* 2009; 42: 1-6.
- [35] Connes P, Tripette J, Mukisi-Mukaza M, *et al.* Relationships between hemodynamic, hemorheological and metabolic responses during exercise. *Biorheology* 2009; 46: 133-43.
- [36] Kark JA, Posey DM, Schumacher HR, *et al.* Sickle-cell trait as a risk factor for sudden death in physical training. *N Engl J Med* 1987; 317: 781-7.