Dietary nitrate supplementation attenuates the reduction in exercise tolerance following blood donation

Original Article

Sinead T. J. McDonagh[1], Anni Vanhatalo[1], Jonathan Fulford[2], Lee J. Wylie[1], Stephen J. Bailey[1], and Andrew M. Jones[1]

[1]Sport and Health Sciences, College of Life and Environmental Sciences, St. Luke's Campus, University of Exeter, Heavitree Road, Exeter, EX1 2LU, UK. [2]University of Exeter Medical School, St. Luke's Campus, University of Exeter, Heavitree Road, Exeter, EX1 2LU, UK.

Running head: Nitrate, blood donation and exercise performance

Address for correspondence:
Andrew M. Jones, Ph.D.
College of Life and Environmental Sciences
University of Exeter, St. Luke's Campus
Exeter, Devon, EX1 2LU, UK.
E-mail: a.m.jones@exeter.ac.uk
Tel: 01392 722886
Fax: 01392 264726

ABSTRACT

We tested the hypothesis that dietary nitrate-rich beetroot juice (BR) supplementation could partially offset deteriorations in O_2 transport and utilization, and exercise tolerance, after blood donation. Twenty-two healthy volunteers performed moderate-intensity and ramp incremental cycle exercise tests prior to and following the withdrawal of ~450 mL of whole blood. Before donation, all subjects consumed 7 x 70 mL of nitrate-depleted beetroot juice shots (PL) in the 48 h preceding the exercise tests. During the 48 h after blood donation, subjects consumed 7 shots of either BR (each containing 6.2 mmol nitrate; n=11) or PL (n=11) before repeating the exercise tests. [Hemoglobin] and hematocrit were reduced by ~8-9% following blood donation (P<0.05), with no difference between the BR and PL groups. When compared with pre-donation, steady-state $\dot{V}O_2$ during moderate-intensity exercise was ~4% lower post-donation in BR (P<0.05) but was unchanged in PL. The ramp test peak power decreased from pre-donation (PL: 341 ± 70 *vs.* BR: 331 ± 68 W) to post-donation (PL: 324 ± 69 *vs.* BR: 322 ± 66 W) in both groups (P<0.05). However, the decrement in performance was significantly less in BR (2.7%) compared with PL (5.0%; P<0.05). Nitrate supplementation reduced the O_2 cost of moderate-intensity exercise and attenuated the decline in ramp incremental exercise performance following blood donation. These results have implications for improving functional capacity following blood loss.

New and Noteworthy: Dietary nitrate supplementation with beetroot juice lowered the O_2 cost of moderate-intensity exercise, better preserved muscle oxygenation and attenuated the decline in incremental exercise test performance following donation of 450 mL whole blood. These results have implications for improving functional capacity following blood loss.

Key words: blood withdrawal; beetroot juice; O_2 transport; O_2 uptake; exercise performance; nitric oxide

INTRODUCTION

The peak rate of pulmonary oxygen uptake ($\dot{V}O_{2peak}$) is an important determinant of exercise capacity and is influenced by the interaction of several central and peripheral factors (6, 53, 64). $\dot{V}O_{2peak}$ and exercise performance can be altered by manipulating the capability of the cardiovascular system to transport O_2 to contracting skeletal muscles during exercise (5, 11, 18, 51, 57, 67). For example, interventions involving the infusion of erythrocytes (18, 19) or the stimulation of erythropoiesis (57, 67) to enhance hemoglobin concentration ([Hb]), increase $\dot{V}O_{2peak}$ during maximal exercise. Conversely, limiting O_2 transport to working muscle by reducing [Hb] via whole blood withdrawal consistently results in a lowered $\dot{V}O_{2peak}$ (11, 18, 47, 54). During sub-maximal exercise, however, Panebianco et al. (47) reported no change in $\dot{V}O_2$ at two and seven days post 450 mL blood donation, despite significant reductions in [Hb]. Compensatory adjustments in cardiovascular control, such as increases in heart rate (HR) and cardiac output ($\dot{Q}$), offset the lower [Hb] and enable muscle O_2 delivery to be maintained during low-intensity exercise after blood donation (19, 27, 51).

The gaseous physiological signaling molecule, nitric oxide (NO), plays a key role in the regulation of vascular tone. NO can be synthesised via the oxidation of L-arginine in a reaction catalysed by the NO synthases (NOS; 32) or it can be produced via the reduction of nitrate (NO_3^-) to nitrite (NO_2^-) and subsequently NO (8). Recently, dietary NO_3^- supplementation has been employed to augment plasma [NO_2^-] and the potential for O_2-independent NO synthesis (4, 38, 65). This NO_3^--NO_2^--NO pathway may be particularly important when NOS activity is compromised (20, 42), O_2 availability is limited (14, 25, 34,

35) and pH is low (44). Limitations in systemic O_2 transport can result in tissue hypoxia and greater metabolic perturbation (41, 60), which can contribute to reduced exercise tolerance (1), as is commonly observed at altitude (2) and in a number of disease states (35, 68). There is evidence to suggest that NO and NO_2^- can combat an insufficient muscle O_2 supply by increasing muscle blood flow via hypoxia-induced vasodilatation (13, 61). Therefore, it is possible that dietary NO_3^- supplementation could ameliorate deteriorations in exercise performance when 'normal' O_2 availability is reduced, during for example, high-intensity exercise, in hypobaric hypoxia or after blood donation.

We and others have reported that, in healthy subjects, dietary NO_3^- supplementation can significantly impact the physiological responses to exercise (4, 15, 38, 59). Specifically, a reduction in the O_2 cost of moderate-intensity exercise has been reported after supplementation with both sodium NO_3^- (38, 39, 40) and NO_3^--rich beetroot juice (BR; 3, 4, 15, 59, 69). In addition, a significantly increased time to task failure (TTF), indicating improved exercise tolerance, has been reported following BR ingestion when recreationally-active, but not highly trained, subjects completed severe-intensity (3, 4, 37) and ramp incremental exercise (59). These alterations may be due to a NO_2^- or NO-related reduction in the ATP cost of muscle contraction (3), greater mitochondrial efficiency (40), changes in muscle redox status (66), and/or enhanced muscle blood flow, particularly to type II fibres (21, 22). Such changes could be particularly advantageous after whole blood withdrawal when [Hb] is reduced and O_2 transport is challenged (11, 18, 54). Indeed, BR supplementation has been shown to reduce muscle metabolic perturbation during exercise in normobaric hypoxia and to restore exercise tolerance and oxidative function to the values observed in normoxia (60, 61). In addition, it has been reported that, when the fraction of inspired O_2 is lowered to 11-13%, BR supplementation can improve muscle oxygenation

status (43), reduce $\dot{V}O_2$ during sub-maximal exercise (34, 46), and enhance TTF during incremental exercise (43). BR supplementation has also been reported to increase arterial O_2 saturation following dynamic apnea (i.e., breath-hold diving), which supports an O_2 sparing effect of NO_3^- ingestion (48). Collectively, these studies suggest that NO_3^- ingestion may enhance the physiological response to exercise when O_2 availability is limited, by sparing muscle O_2 demand and/or better preserving muscle O_2 supply. However, it is not known whether the reductions in O_2 carrying capacity and exercise performance subsequent to the withdrawal of whole blood can be offset by BR supplementation. If so, this may have important implications for clinical conditions in which [Hb] is lowered, for example in anemia, following surgery or involuntary blood loss, or in athletes wishing to donate blood without compromising training.

The purpose of the present study was to determine whether 48 h of BR supplementation following 450 mL of whole blood withdrawal alters the physiological responses to sub-maximal and maximal intensity cycle exercise. It was hypothesized that BR supplementation would lower the O_2 cost of moderate-intensity exercise, improve muscle oxygenation status, and attenuate the expected reduction in TTF during ramp incremental exercise following blood donation.

METHODS

Subjects

Twenty-two recreationally active and pre-registered National Health Service (NHS) blood donors (males, n = 14; females, n = 8) volunteered to participate in this study, which was approved by the Institutional Research Ethics Committee and conformed to the ethical principles of the Declaration of Helsinki. None of the subjects were tobacco smokers or

habitual users of dietary supplements. All subjects provided written informed consent prior to the commencement of the study, after the experimental procedures, associated risks and potential benefits of participation had been explained.

Subjects were instructed to arrive at the laboratory in a rested and fully hydrated state, at least 3 h postprandial, and to avoid strenuous exercise in the 24 h preceding each visit. In addition, subjects were asked to avoid alcohol consumption, chewing gum and antibacterial mouthwash throughout each supplementation period and to avoid caffeine intake in the 3 h preceding each laboratory visit. Each subject recorded habitual diet and exercise undertaken during the first supplementation period and were asked to replicate these habits during the second supplementation period. Prior to data collection, subjects were fully familiarized with the exercise testing procedures. This minimized any possible learning effects during the study. Exclusion criteria were the presence of known cardiovascular disease, hypertension and anemia, the use of antihypertensive medication and antibiotics, and having major surgery or giving blood within 6 months of the study commencing.

Experimental Overview

Subjects were asked to report to the laboratory on three separate occasions over a ten day period. The first visit included a 5 min bout of moderate-intensity cycle exercise at 80 W, followed by a ramp incremental test to task failure with no dietary supplementation. This served as the pre-intervention familiarization test. Hematocrit (Hct), [Hb], plasma [NO_3^-] and [NO_2^-], pulmonary $\dot{V}O_2$ dynamics, muscle oxygenation status, HR, blood lactate concentration ([lactate]), blood glucose concentration ([glucose]) and TTF during ramp incremental exercise were measured during the first visit and repeated during each visit to the laboratory. Prior to visit 2, subjects consumed 7 shots of NO_3^--depleted beetroot juice (PL)

over ~48 h. On the final day of supplementation, subjects completed the same moderate-intensity exercise bout and ramp incremental test on a cycle ergometer as was performed at pre-intervention. Two days before the final visit to the lab, subjects attended a National Health Service (NHS) blood donation clinic. Each subject lay supine on a bed before ~450 mL of whole blood was drawn from an antecubital vein over a 15 min period. The blood withdrawal was performed by the NHS as part of the national blood donation service. Following blood donation, each subject was randomly assigned, in a double-blind, placebo controlled fashion to consume 7 shots of either NO_3^--rich beetroot juice (BR; *n* = 11; mean ± SD; females, *n* = 4: age 23 ± 3 years, body mass 67 ± 4 kg, height 1.76 ± 0.05 m; males, *n* = 7: age 26 ± 5 years, body mass 81 ± 12 kg, height 1.80 ± 0.10 m) or NO_3^--depleted beetroot juice as a placebo (PL; *n* = 11; mean ± SD; females, *n* = 4: age 22 ± 3 years, body mass 77 ± 11 kg, height 1.75 ± 0.10 m; males, *n* = 7: age 28 ± 7 years, body mass 77 ± 8 kg, height 1.79 ± 0.10 m) over the next ~48 h. Visit 3 occurred on the final day of supplementation with the exercise tests conducted 2 h following final supplement ingestion. All tests were performed at the same time of day (± 2 h) to minimise diurnal variation on the physiological variables under investigation.

Exercise tests

During the first visit to the laboratory subjects performed a short bout of low-intensity exercise at 80 W, followed by a ramp incremental exercise test to task failure on an electrically-braked cycle ergometer (Lode Excalibur Sport, Gronigen, The Netherlands) for determination of $\dot{V}O_{2peak}$ and gas exchange threshold (GET). The protocol began with 3 min of 'unloaded' baseline cycling at 20 W, followed by 5 min at 80 W and 10 min of passive rest. Subsequently, 3 min of baseline cycling at 20 W was performed and then the power output was increased linearly by 30 $W \cdot min^{-1}$ until the subject was unable to continue. The

subjects cycled at a self selected cadence (~80 rpm), and this cadence, along with saddle and handle bar configuration, was recorded and replicated for subsequent tests. Pulmonary gas exchange was measured breath-by-breath and averaged into 10-s bins. $\dot{V}O_{2peak}$ was taken as the highest 30-s mean value attained during the test. The GET was determined as described previously (59). The work rate that would require 80% of the GET (moderate-intensity exercise) was calculated, taking into account the mean response time for $\dot{V}O_2$ during ramp exercise (59).

Subjects returned to the laboratory on two further occasions. The second visit was preceded by PL supplementation (n = 22) and the third visit, ~48 h post blood donation, was preceded by 2 days of either BR (n = 11) or PL (n = 11) supplementation. The final visit was conducted 48 h post donation to allow restoration of total blood volume (23) and to minimize the risk of a syncopal episode occurring during maximal exercise. On each of these two laboratory visits, subjects completed a single 5-min bout of moderate-intensity exercise (at 80 % of the GET) and a ramp incremental test to task failure, separated by 10 min of passive rest. The incremental test was terminated when cadence fell more than 10 rpm below the chosen cadence, despite strong verbal encouragement. TTF was recorded to the nearest second and the power output achieved at the point of test termination was recorded as the peak power output (PPO). Feedback on performance was only provided once all experimentation for the entire study had been completed.

Measurements

During each visit to the laboratory, a venous blood sample (~4 mL) was drawn from an antecubital vein into lithium-heparin tubes (Vacutainer, Becton-Dickinson, NJ, USA) and centrifuged for 10 min at 3000 *g* and 4˚C, within 2 min of collection. Subsequently, the

plasma was extracted and frozen at -80˚C for later determination of [NO_3^-] and [NO_2^-] using a modified chemiluminescence technique (7) as previously described (69). Blood samples from a pre-warmed fingertip were collected into four 30 μl heparinized microhematocrit tubes (Hawksley and Sons Ltd, Lancing, Sussex, England) which underwent microcentrifugation for 1 min for the determination of Hct (1560 Micro-haematocrit reader, Hawksley and Sons Ltd, Lancing, Sussex, England). In addition, blood from the same fingertip was collected into four microcuvettes for determination of [Hb] (HemoCue AB, Ängelholm, Sweden).

Pulmonary gas exchange and ventilation were measured breath-by-breath throughout all exercise tests. Subjects wore a nose clip and breathed through a mouthpiece and impeller turbine assembly (Jaeger Triple V). The inspired and expired gas volume and gas concentration signals were sampled continuously at 100 Hz, with the latter using paramagnetic (O_2) and infrared (carbon dioxide; CO_2) analyzers (Oxycon Pro, Jaeger, Hoechberg, Germany) via a capillary line connected to the mouthpiece. These analyzers were calibrated before each test with gases of known concentration, and the turbine volume transducer was calibrated using a 3-litre syringe (Hans Rudolph, Kansas City, MO, USA). The volume and concentration signals were time-aligned by accounting for the delay in capillary gas transit and analyzer rise time relative to the volume signal. Pulmonary O_2 uptake ($\dot{V}O_2$), CO_2 output ($\dot{V}CO_2$), minute ventilation ($\dot{V}E$) and respiratory exchange ratio (RER) were calculated and displayed breath-by-breath. HR was measured at rest and during all cycle tests using short-range radiotelemetry (Polar S610, Polar Electro Oy, Kempele, Finland). A fingertip blood sample was collected into a capillary tube over the 20 s preceding the step transition in work rate to moderate-intensity exercise and the incremental test. Capillary samples were also collected during the final 20 s of the moderate-intensity exercise bout and following exhaustion in the ramp test. These samples were analyzed within 60 s of

collection to determine blood [lactate] (YSI *2300*, Yellow Springs Instruments, Yellow Springs, OH, USA).

The oxygenation status of the *m. vastus lateralis* of the right leg was monitored using near-infrared spectroscopy (NIRS; model NIRO 300, Hamamatsu Photonics KK, Hiugashi-ku, Japan). Four different wavelength laser diodes provided the light source (776, 826, 845 and 905 nm) and a photomultiplier tube in the spectrometer was used to detect the light returning from the tissue. The intensity of incident and transmitted light was recorded continuously throughout exercise at 2 Hz and used to estimate the change in concentration from baseline for oxygenated, deoxygenated, and total tissue Hb and myoglobin. The NIRS data therefore represent a relative change based on the optical density measured in the first data point collected. The deoxyhemoglobin concentration ([HHb]) was assumed to represent the balance between local O_2 supply and utilization and therefore to provide an estimate of changes in O_2 extraction within the field of interrogation (28, 36). Prior to the cycling exercise, the right leg was cleaned and shaved around the belly of the muscle, the probes were placed in the holder and attached to the skin with an adhesive 20 cm above the fibular head. An elastic bandage was wrapped around the subject's leg to secure the holder and wires in place and to minimize the possibility of extraneous light influencing the signal. Pen marks were made around the probe holder to allow for precise reproduction of the position of the probe in subsequent tests. The probe gain was set at rest with the subject in a seated position and the leg extended at down stroke on the cycle ergometer. NIRS data were collected continuously throughout the moderate-intensity and incremental exercise tests.

Supplementation

After completion of the familiarization test, subjects consumed 7 shots of NO_3^--depleted beetroot juice (PL; beetroot juice containing ~0.04 mmol NO_3^- per 70 mL; Beet It Sport Stamina Shot, James White Drinks, Ltd., Ipswich, UK) over ~48 h before completing the pre-donation control trial (PL-Pre and BR-Pre for the PL and BR groups, respectively). This was done in order to control for the antioxidants and polyphenols that exist in both the NO_3^--rich and NO_3^--depleted beverages. The PL was created by passing NO_3^--rich BR through a Purolite A520E ion-exchange resin which selectively removes NO_3^- (37). After blood donation, subjects were randomly assigned, in a double-blind, placebo-controlled fashion, to consume 7 shots of either NO_3^--rich (BR; beetroot juice containing ~6.2 mmol NO_3^- per 70 mL; Beet It Sport Stamina Shot, James White Drinks, Ltd., Ipswich, UK; *n* =11) or NO_3^--depleted beetroot juice (PL; beetroot juice containing ~0.04 mmol NO_3^- per 70 mL; Beet It, James White Drinks, Ltd., Ipswich, UK;*n* =11) over ~48 h (PL-Post and BR-Post for the PL and BR groups, respectively). During both supplementation periods subjects were instructed to consume 2 x 70 mL of the beverage in the evening (~7 p.m.) two days prior to testing, and 1 x 70 mL in the morning (~10 a.m.) and 1 x 70 mL in the evening (~7 p.m.) one day prior to testing. On each experimental day, subjects consumed a further 2 x 70 mL, 2 h prior to testing and 1 x 70 mL on arrival at the laboratory. The supplementation periods were separated by a mean of 8 days (BR: 7 ± 5 days, PL: 9 ± 5 days).

Data Analyses

The breath-by-breath $\dot{V}O_2$ data collected during the exercise tests were initially examined to exclude errant breaths caused by, for example, coughing, swallowing and sighing, and those values lying more than four standard deviations (SDs) from the local mean were removed. $\dot{V}O_{2baseline}$ was defined as the mean $\dot{V}O_2$ measured over the last 60 s of baseline cycling and end-exercise $\dot{V}O_2$ was defined as the mean $\dot{V}O_2$ measured over the last 30 s of exercise. The

baseline and end-exercise $\dot{V}CO_2$, RER, $\dot{V}E$ and HR values were calculated in the same manner.

To provide information on muscle oxygenation, the changes in [HHb] and the tissue oxygenation index (TOI; calculated as the fraction of oxygenated [Hb] compared to total [Hb]) during moderate-intensity exercise were assessed at baseline (60 s preceding the transition to moderate-intensity exercise), in 10 s time bins surrounding 60 s, 120 s, 240 s, and at end-exercise (mean response over the final 30 s of exercise). During ramp incremental exercise, the changes in [HHb] and TOI were assessed at baseline, in 10 s time bins surrounding 120 s, 240 s, 360 s and at task failure.

Blood lactate accumulation (Δ blood [lactate]) was calculated as the difference between blood [lactate] at end-exercise and blood [lactate] at baseline. Similarly, the change in blood glucose concentration (Δ blood [glucose]) was calculated as the difference between blood [glucose] at end-exercise and blood [glucose] at baseline.

Statistical Analyses

Differences in Hct, [Hb], plasma [NO_3^-] and [NO_2^-], pulmonary $\dot{V}O_2$ dynamics, HR, blood [lactate], NIRS-derived variables and TTF were assessed using a mixed model ANOVA. Significant main and interaction effects were further explored using Fisher's LSD. Independent t-tests were used to assess the relative change between the BR and PL treatment groups. Pearson's product moment correlation coefficient was used to explore relationships between changes in [Hb] and Hct and changes in TTF. Statistical analyses were performed using SPSS version 19.0 (Chicago, IL, USA). Data are presented as mean ± SD, unless otherwise stated. Statistical significance was accepted at $P<0.05$.

RESULTS

Subjects' self-reported adherence to the supplementation regimen prior to and post blood donation was 100%. All subjects reported that their physical activity and dietary patterns were similar throughout each of the supplementation periods. The ingestion of BR and PL supplements were well tolerated and no negative side effects were reported. Subjects did, however, report beeturia (red-stained urine).

[Hb] and Hct

The group mean [Hb] and Hct data prior to and following blood donation and BR or PL ingestion are displayed in Table 1. There was a significant main effect by time for both [Hb] and Hct ($P<0.01$) but no main effect by group and no interaction effect ($P>0.05$). Prior to donation, [Hb] and Hct were not different between the BR and PL treatment groups. [Hb] and Hct were both significantly reduced from pre to post donation ($P<0.05$), with no differences between PL and BR groups ($P>0.05$).

Plasma [NO_3^-] and [NO_2^-]

The group mean plasma [NO_3^-] and [NO_2^-] pre and post blood donation in the BR and PL groups are shown in Table 1. There was a significant main effect by time and group and an interaction effect on plasma [NO_3^-] and [NO_2^-] *(*$P<0.01$). Prior to blood donation, neither plasma [NO_3^-] nor [NO_2^-] were different between groups ($P>0.05$). Following blood donation, there was a substantial increase in plasma [NO_3^-] and [NO_2^-] in the BR group ($P<0.05$). A small (~11%) rise in plasma [NO_3^-] ($P<0.05$) was also observed in the PL group but there was no change in plasma [NO_2^-] ($P>0.05$).

$\dot{V}O_2$ response to moderate-intensity and incremental exercise

Moderate-intensity exercise

The pulmonary gas exchange and ventilatory responses to moderate-intensity exercise pre and post blood donation in PL and BR groups are reported in Table 2 and the group mean $\dot{V}O_2$ response profiles in BR and PL groups pre and post blood donation are shown in Figure 1. There was a significant main effect by time (P<0.01) but no main effect by condition and no interaction effect (P>0.05) for the $\dot{V}O_2$ measured during the baseline cycling period and at end-exercise. Prior to donation, there were no differences in baseline or end-exercise $\dot{V}O_2$ between BR and PL groups (P>0.05). Follow-up tests revealed that both baseline $\dot{V}O_2$ (P<0.01) and end-exercise $\dot{V}O_2$ (P<0.05) were reduced in the BR group post-donation compared with pre-donation.

The $\dot{V}CO_2$, $\dot{V}E$, RER, blood [lactate] and blood [glucose] data during moderate-intensity exercise are reported in Table 2. Prior to donation, there were no differences in these variables at baseline or at end-exercise between the BR and PL groups (P>0.05) and there were no significant main effects by condition or time and no interaction effects (P>0.05).

Ramp incremental exercise

The effects of blood donation and BR and PL supplementation on the ramp incremental test parameters are reported in Table 3 and illustrated in Figures 2 and 3.

There was a significant main effect by time on $\dot{V}O_{2peak}$ (P<0.05), but no main effect by condition or an interaction effect (P>0.05). There were no differences between the groups at baseline (P>0.05). Follow-up tests indicated that, from pre to post donation, there was a significant reduction (0.19 $L \cdot min^{-1}$; ~5%) in $\dot{V}O_{2peak}$ in the PL group (P<0.05) but not in the

BR group (0.12 $L \cdot min^{-1}$; ~3%; $P>0.05$). There was a significant main effect by time and an interaction effect ($P<0.05$) but no main effect by condition ($P>0.05$) for PPO and TTF. Post hoc tests revealed a significant reduction in PPO and TTF in both PL and BR groups from pre to post donation ($P<0.01$). There were no differences in PPO or TTF between the groups prior to blood donation ($P>0.05$). However, the reduction in PPO and TTF following blood donation was more pronounced in PL compared with BR (5% vs. 3%; $P<0.05$). The change in [Hb] and Hct from pre to post donation was correlated with the change in TTF during ramp incremental exercise in PL (r = 0.58; $P=0.06$, and r = 0.70; $P<0.05$, respectively) but not BR (r = -0.10; $P>0.05$ and r = -0.41; $P>0.05$, respectively).

There was a significant interaction effect, but no main effects by time or group, for peak $\dot{V}CO_2$. Specifically, peak $\dot{V}CO_2$ was reduced in the PL group ($P<0.05$), but was unaffected in the BR group ($P>0.05$). There was no main effect by time or condition nor an interaction effect for peak $\dot{V}E$ ($P>0.05$). There was a significant main effect by time and an interaction effect for peak RER ($P<0.05$). Despite no difference at baseline, post hoc tests revealed an increase in peak RER in the BR group from pre to post donation ($P<0.01$).

NIRS measurements

Moderate-intensity exercise

There were no differences for total Hb (THb) between or within conditions during the moderate-intensity exercise bout. The [HHb] and TOI values measured during moderate-intensity exercise are reported in Table 4. There were no main effects by condition or time and no interaction effect for baseline [HHb] ($P>0.05$). There was a significant main effect by time for [HHb] from pre to post donation at 60 s, 120 s, 240 s and end-exercise ($P<0.05$), but no main effect by condition or an interaction effect at any time point ($P>0.05$). Post hoc tests

revealed a trend toward an increase in [HHb] in the PL group, but not the BR group, from pre to post donation at 120 s and 240 s of moderate exercise ($P<0.10$). There were no main effects by time or interaction effects for TOI at 60 s, 120 s, 240 s and end-exercise ($P>0.05$). However, there was a trend toward a main effect by condition for all time points ($P<0.10$). Follow-up tests revealed that blood donation resulted in reductions in TOI in the PL group at 60 s, 120 s and 240 s during moderate exercise, respectively ($P<0.05$; Table 4).

Ramp incremental exercise

There were no differences for THb between or within conditions during ramp incremental exercise. The [HHb] and TOI values measured during ramp incremental exercise are reported in Table 4 and the [HHb] profile is shown in Figure 4. There was a significant main effect by time ($P<0.05$) but no main effect by condition or an interaction effect ($P>0.05$) for [HHb] at 120 s and 240 s during ramp incremental exercise. Post hoc tests showed that [HHb] increased from pre to post donation at 240 s in PL ($P<0.05$) but not BR ($P>0.05$; Table 4). There was a significant main effect by time ($P<0.05$) and a trend for an interaction effect for [HHb] at 360 s ($P<0.10$) and at end-exercise ($P<0.05$) during the incremental exercise test. Post hoc tests revealed that [HHb] increased significantly from pre to post donation in the PL group at both 360 s and end-exercise ($P<0.05$; Table 4). The change in [HHb] from pre to post donation was higher in PL versus BR at end-exercise ($P<0.05$) and tended to be higher at 360 s ($P<0.10$).

DISCUSSION

The principal original findings in this study, consistent with our hypotheses, were that NO_3^--rich beetroot juice ingestion lowered the O_2 cost of moderate-intensity exercise, better preserved muscle oxygenation during moderate and ramp incremental exercise and attenuated

401 the reduction in ramp incremental exercise test performance and $\dot{V}O_{2peak}$ following blood
402 donation. These results indicate that dietary NO_3^- supplementation can ameliorate decrements
403 in exercise performance in a situation (i.e. reduction in blood O_2-carrying capacity) which
404 would be expected to compromise physiological function during exercise.
405
406 *Effects of blood donation on [Hb] and Hct*
407 The standard NHS blood bank donation (~450mL) reduced [Hb] and Hct by a similar
408 magnitude in the PL and BR groups. These results concur with previous studies that have
409 investigated the influence of whole blood withdrawal on [Hb]. For example, Gordon et al.
410 (27) and Mora-Rodriguez et al. (45) reported ~8% and ~7% reductions in [Hb], 24 and 48 h
411 post blood donation, respectively. The ~8% reduction in Hct in the present study is also
412 similar to the values reported by Burnley et al. (11) and Gordon et al. (27) who reported a ~7-
413 8% decrease in Hct one day after 450 mL blood donation. The reduction in blood O_2 carrying
414 capacity, secondary to the lower [Hb] and Hct, can result in a reduction in muscle O_2 delivery
415 and muscle O_2 diffusing capacity during maximal exercise, with significant implications for
416 exercise performance (5, 11, 18, 47, 54).
417
418 *Effects of nitrate supplementation on plasma [NO_3^-] and [NO_2^-]*
419 The ingestion of NO_3^--rich BR significantly elevated plasma [NO_3^-] and [NO_2^-] when
420 compared with baseline values. These findings are in agreement with earlier studies which
421 also examined the influence of BR supplementation in young, healthy subjects (4, 34, 69).
422 A small but significant rise in plasma [NO_3^-] was also noted in the PL group post
423 donation. This may be explained by a slight hemoconcentration or an upregulation in NOS
424 activity consequent to the reduction in whole body iron concentration after donating blood
425 (62). Plasma [NO_2^-] rose by ~800% in the BR group from pre to post donation, suggesting

appreciably enhanced NO bioavailability. Numerous other studies have also reported increases in plasma [NO_2^-] after BR supplementation, but the percentage increases attained were approximately half of those reported in this study (56, 69). This finding is likely a result of the higher dose of NO_3^- ingested (~43 mmol over 48 h) when compared with previous short-term BR supplementation studies. Interestingly, unlike in some earlier studies (4, 38, 59, 69), BR supplementation did not reduce resting blood pressure (BP) despite the elevated plasma [NO_2^-] (mean arterial pressure, pre- vs. post-donation: 81 ± 7 vs. 80 ± 7 mmHg). Similar BP values pre- vs. post-donation in the PL group indicates that total blood volume was restored 48 h following blood donation. The lack of effect of BR on BP in the present study may be related to the relatively low baseline BP values of the study participants (115/64 mmHg) and the relatively large number of female participants. It has been reported that females are less sensitive than males to the influence of NO_3^- supplementation on BP and that the extent of BP reduction with NO_3^- supplementation is correlated with the baseline BP (33).

Effects of blood donation and nitrate supplementation on the physiological responses to moderate-intensity exercise

The $\dot{V}O_2$ during both the unloaded baseline period and in the steady state of moderate-intensity exercise was significantly reduced (by ~4%) in the BR group, but not the PL group, after blood donation. A similar reduction in the O_2 cost of moderate-intensity exercise has been reported by Bailey et al. (4) after six days of non-concentrated NO_3^--rich BR ingestion and by Larsen et al. (38) after three days of $NaNO_3$ supplementation. The present findings are consistent with those of Kelly et al. (34) who observed that, in hypoxia, BR supplementation resulted in a decrease in both baseline and steady-state $\dot{V}O_2$ when compared with placebo. It has also been reported that acute (46) and 6 days (43) BR ingestion resulted in significant

reductions in $\dot{V}O_2$ during submaximal cycling exercise in hypoxia (15% and 11% O_2, respectively). Acute BR supplementation has also been reported to better preserve arterial O_2 saturation following dynamic apnea (48).

The lowering of the O_2 cost of submaximal exercise after NO_3^- supplementation may be due to a number of mechanisms, including a reduction in the ATP cost of muscle force production (4) and/or an improvement in mitochondrial efficiency (40) and/or changes in redox signalling (66). In addition to changes in muscle contractile or metabolic efficiency, muscle O_2 delivery or its intramuscular distribution may be altered following NO_3^- supplementation (21, 22). Exercise, particularly in hypoxia or under conditions that may limit O_2 carrying capacity, such as blood donation, acts as a potent stimulus for vasodilatation and delivery of O_2 to working muscle (12, 13). Both NO and O_2 compete for the binding site at cytochrome-*c* oxidase (COX) in the mitochondrial electron transport chain (9). An elevation in NO availability via NO_3^- supplementation, perhaps especially in conditions limiting O_2 delivery, increases the likelihood of NO binding to COX and therefore inhibiting O_2 consumption at the mitochondrion (10). As a result, NO may modify the intramuscular distribution of O_2 and improve the oxygenation status of muscle fibres that are situated further away from the capillaries (29, 55, 63). Compared to placebo, BR supplementation has been reported to enable a greater maximal rate of mitochondrial ATP resynthesis (Q_{max}) and result in faster muscle phosphocreatine recovery kinetics following exercise in hypoxia (60, 61), indicating improved muscle O_2 availability at least in the immediate post-exercise period (61).

In the present study, TOI was significantly reduced and [HHb] tended to be higher during moderate-intensity exercise post- compared to pre-donation in the PL group, suggesting that muscle O_2 availability was lower and a greater muscle fractional O_2 extraction was necessary to achieve the required $\dot{V}O_2$ (24, 36). These changes were attenuated in the BR group,

consistent with our hypothesis that BR supplementation would better preserve muscle oxygenation during moderate-intensity exercise when compared with PL. These results are consistent with Masschelein et al. (43) who reported that BR resulted in a greater muscle TOI and lower [HHb] during submaximal exercise in normobaric hypoxia. Collectively, these studies indicate that under conditions which may impair blood O_2 carrying capacity, such as following blood donation (present study) or in normobaric hypoxia (43), BR ingestion promotes a better matching between muscle O_2 delivery and O_2 demand, i.e. less O_2 extraction is required for the same moderate-intensity work rate, perhaps due to the lower exercise $\dot{V}O_2$ (34) or to preferential alterations in muscle perfusion (21, 22, 61). An increased ratio of O_2 delivery to O_2 consumption at a given work rate would be expected to retard the rate of fatigue development and to improve exercise performance.

Effects of blood donation and nitrate supplementation on the physiological responses to incremental exercise

As expected, blood donation and the associated reduction in O_2 carrying capacity resulted in a significant reduction in PPO and TTF during ramp incremental exercise. Panebianco et al. (47) also reported a significant reduction in PPO during incremental exercise, 2 days post blood donation. An important original finding in the present study was that ingestion of BR in the 48 hours post blood donation partly negated the decrement in performance when compared with PL. Specifically, the reduction in PPO and TTF following blood donation was significantly more pronounced in the PL group compared with BR. Interestingly, the reduction in TTF in the PL group was quite well correlated with the reduction in [Hb] ($r = 0.58$, $P=0.06$) and Hct ($r = 0.70$, $P<0.05$) following blood donation, whereas in the BR group, the correlations were weaker and non-significant ([Hb]: $r = -0.10$; Hct: $r = -0.41$; both $P>0.05$), implying that BR supplementation compensated for the lower [Hb] and Hct. These

findings are consistent with those of Masschelein et al. (43) who reported that, compared to PL, BR ingestion significantly attenuated the reduction in TTF when incremental exercise was performed in hypoxia.

$\dot{V}O_{2peak}$ was reduced by 5% from pre to 48 h post donation in the PL group. Similarly, Burnley et al. (11) reported a 4% decrease in $\dot{V}O_{2peak}$ during severe-intensity exercise 24 h following blood donation. This reduction was proportional to the reduced [Hb] and thus the ability to deliver O_2 to the working skeletal muscle during maximal exercise. In the present study, the reduced $\dot{V}O_{2peak}$ in the PL group following blood donation occurred in conjunction with an increased muscle [HHb], which may be interpreted as an increase in muscle fractional O_2 extraction in an (ultimately unsuccessful) attempt to offset the effects of a reduced [Hb] and lower muscle O_2 delivery (51, 54). In contrast, $\dot{V}O_{2peak}$ and [HHb] during the incremental test were not significantly altered by blood donation in the BR group. These results may indicate that the O_2 sparing effect of BR ingestion (Figure 2B), coupled perhaps with altered perfusion distribution (21, 22, 61), enabled muscle oxygenation to be better preserved during incremental exercise, such that an increased muscle fractional O_2 extraction was not mandated to achieve a given $\dot{V}O_{2peak}$. Ferguson et al. (21, 22) have reported that, in rats, BR supplementation can enhance vascular conductance and blood flow to working muscle and elevate the microvascular partial pressure of O_2 (PO_{2mv}), particularly in type II fibres. If similar effects occur in humans, this may enhance the blood-myocyte O_2 exchange gradient during higher intensity exercise, better preserving muscle oxygenation status, homeostasis and performance. It is also possible that a portion of the preserved ramp incremental test performance following blood donation with BR compared to PL may be attributable to effects of NO_3^- on muscle contractile function (50), perhaps particularly in type II fibers (31).

The mechanistic bases for the positive effects of BR ingestion on vascular and metabolic function in this and other situations warrants further investigation. In particular, while it is widely believed that the effects may be attributed to greater NO bioavailability or bioactivity, it is presently unclear precisely how this NO pool is stored and transported. NO is a highly reactive molecule with a short-half life *in vivo* and its rapid reaction with, for example, O_2 or heme proteins (30) suggests that the free transport of NO may be limited in plasma and within cells. It has been proposed that NO_2^- itself represents a principal means of 'NO' storage and transport, with the one electron reduction of NO_2^- to NO in blood and other tissues being facilitated, amongst many other factors including xanthine oxidoreductase, by deoxyhemoglobin and deoxymyoglobin, which will naturally be present in greater abundance in contracting skeletal muscle (16, 42). However, BR ingestion likely also increases the production and storage of other reactive nitrogen species. In particular, low molecular weight thiol groups may react with nitrogen oxides to yield s-nitrosothiol species (SNOs) which can be transported in the blood as s-nitrosohemoglobin (HbSNO) (17). It has recently been reported that the reduction in blood pressure following NO_3^- or NO_2^- ingestion in a rat model of hypertension was more closely related to plasma [s-nitrosothiol] than to plasma [NO_2^-] (49) and that s-nitrosothiol bioactivity derived through βCys93 may be essential for hypoxic vasodilation by erythrocytes (70). In contrast, in humans, Gladwin et al. (26) reported a significant arterial-venous NO_2^- gradient during forearm exercise and concluded that SNOs and HbSNO do not play a significant role in the regulation of vascular tone. The role of SNOs and HbSNO in the physiological effects of nitrate ingestion in humans remains to be clarified. Equally, the precise mechanisms by which an elevation of tissue [NO_2^-] following NO_3^- ingestion influences metabolic and vascular control at rest and during exercise remains unclear. While it is possible that NO_2^- itself is bioactive (58), unresolved questions include

the triggers and time course for the possible reduction of NO_2^- to NO, and the nature of both NO transport to, and storage within, biological targets. Resolution of these issues will likely require synthesis of experimental data deriving from 'competing' hypotheses.

Perspectives

This study has shown for the first time that despite a significant reduction in [Hb] post blood withdrawal, BR supplementation lowered the O_2 cost of moderate-intensity exercise, better preserved muscle oxygenation during moderate-intensity and ramp incremental exercise, and attenuated the reduction in $\dot{V}O_{2peak}$ and incremental exercise test performance. These results may have significant implications for athletes who wish to give blood without significant detriment to training, individuals with clinical conditions which reduce blood O_2 carrying capacity, such as anemia, and in conditions resulting in acute blood loss such as surgery or military combat. In this context, it is of interest that transfusion of stored blood may impair vasodilatory capacity, an effect that might be linked to the loss of NO bioavailability that occurs during blood storage (17, 52). Treating banked blood to better maintain NO stores might lead to improved functional outcomes following transfusion. In conclusion, BR supplementation attenuates the decline in functional capacity arising from blood donation.

Acknowledgements

We thank James White Drinks Ltd., Ipswich, UK, for the supply of juices used in the study *gratis*. We also thank Matthew Black, James Kelly and Daryl Wilkerson for assistance with data processing.

REFERENCES

1. Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev* 88: 287-332, 2008.

2. Amann M, Calbet JA. Convective oxygen transport and fatigue. *J Appl Physiol* 104: 861-870, 2008.

3. Bailey SJ, Fulford J, Vanhatalo A, Winyard P, Blackwell JR, DiMenna FJ, Wilkerson DP, Benjamin N, Jones AM. Dietary nitrate supplementation enhances muscle contractile efficiency during knee-extensor exercise in humans. *J Appl Physiol,* 109: 135-148, 2010.

4. Bailey SJ, Winyard P, Vanhatalo A, Blackwell JR, DiMenna FJ, Wilkerson DP, Tarr J, Benjamin N, Jones AM. Dietary nitrate supplementation reduces the O_2 cost of low-intensity exercise and enhances tolerance to high-intensity exercise in humans. *J Appl Physiol*, 106: 1144-1155, 2009.

5. Balke B, Grillo GP, Konecci EB, Luft UC. Work capacity after blood donation. *J Appl Physiol* 7: 231-238, 1954.

6. Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc* 32: 70-84, 2000.

598 7. Bateman RM, Ellis CG, Freeman DJ. Optimization of nitric oxide chemiluminescence
599 operating conditions for measurement of plasma nitrite and nitrate. *Clin Chem* 48: 2020-
600 2027, 2002.
601
602 8. Benjamin N, O'Driscoll F, Dougall H, Duncan C, Smith S, Golden M, McKenzie H.
603 Stomach NO synthesis. *Nature* 368: 502, 1994.
604
605 9. Brown GC. Regulation of mitochondrial respiration by nitric oxide inhibition of
606 cytochrome *c* oxidase. *Biochem Biophys Acta* 1504: 46-57, 2001.
607
608 10. Brown GC, Cooper C. Nanomolar concentrations of nitric oxide reversibly inhibit
609 synaptosomal respiration by competing with oxygen at cytochrome oxidase. *FEBS Letter*
610 356*:* 295-298, 1994.
611
612 11. Burnley M, Roberts CL, Thatcher R, Doust JH, Jones AM. Influence of blood donation
613 on O_2 uptake on-kinetics, peak O_2 uptake and time to exhaustion during severe-intensity
614 cycle exercise in humans. *Exp Physiol* 91: 499-509.
615
616 12. Calbet JA, Rådegran G, Boushel R, Saltin B. On the mechanism that limit oxygen uptake
617 during exercise in acute and chronic hypoxia: role of muscle mass. *J Physiol* 587: 477-490,
618 2009.
619
620 13. Casey DP, Madery BD, Curry TB, Eisenach JH, Wilkins BW, Joyner MJ. Nitric oxide
621 contributes to the augmented vasodilation during hypoxic exercise. *J Physiol* 588: 373-385,
622 2010.

14. Castello PR, David PS, McClure T, Crook Z, Poyton RO. Mitochondrial cytochrome oxidase produces nitric oxide under hypoxic conditions: implications for oxygen sensing and hypoxic signalling in eukaryotes. *Cell Metab* 3: 277-287, 2006.

15. Cermak NM, Gibala MJ, van Loon LJC. Nitrate supplementation's improvement of 10-km time trial performance in trained cyclists. *Int J Sport Nutr Exerc Metab* 22: 64-71, 2012.

16. Cosby K, Partovi KS, Crawford JH, Patel RP, Reiter CD, Martyr S, Yang BK, Waclawiw MA, Zalos G, Xu X, Huang KT, Shields H, Kim-Shapiro DB, Schechter AN, Cannon RO 3rd, Gladwin MT. Nitrite reduction to nitric oxide by deoxyhemoglobin vasodilates the human circulation. *Nat Med* 9: 1498-1505, 2003.

17. Doctor A, Stamler JS. Nitric oxide transport in blood: a third gas in the respiratory cycle. *Compr Physiol* 1: 541-568, 2011.

18. Ekblom B, Goldbarg AN, Gullbring B. Response to exercise after blood loss and reinfusion. *J Appl Physiol* 33: 175-180, 1972.

19. Ekblom B, Wilson G, Astrand PO. Central circulation during exercise after venesection and reinfusion of red blood cells. *J Appl Physiol* 81: 379-383, 1976.

20. Ferguson SK, Glean AA, Holdsworth CT, Wright JL, Fees AJ, Colburn TD, Stabler T, Allen JD, Jones AM, Musch TI, Poole DC. Skeletal muscle vascular control during exercise:

impact of nitrite infusion during nitric oxide synthase inhibition in healthy rats. *J Cardiovasc Pharmacol Ther* 21: 201-208, 2016.

21. Ferguson SK, Hirai DM, Copp SW, Holdsworth CT, Allen JD, Jones AM, Musch TI, Poole DC. Effects of nitrate supplementation via beetroot juice on contracting rat skeletal muscle microvascular oxygen pressure dynamics. *Respir Physiol Neurobiol* 187: 250-255, 2013.

22. Ferguson SK, Hirai DM, Copp SW, Holdsworth CT, Allen JD, Jones AM, Musch TI, Poole DC. Impact of dietary nitrate supplementation via beetroot juice on exercising muscle vascular control in rats. *J Physiol* 59: 547-557, 2013.

23. Fernández-Real JM, Peñarroja G, Castro A, García-Braado F, López-Bermejo A, Ricart W. Blood letting in high-ferritin type 2 diabetes: effects on vascular reactivity. *Diabetes Care* 25: 2249-2255, 2002.

24. Ferreira LF, Koga S, Barstow TJ. Dynamics of noninvasively estimated microvascular O_2 extraction during ramp exercise. *J Appl Physiol* 103: 1999-2004, 2007.

25. Giraldez RR, Panda A, Xia Y, Sanders SP, Zweier JL. Decreased nitric-oxide synthase activity causes impaired endothelium-dependent relaxation in the postischemic heart. *J Biol Chem* 272: 21420-21426, 1997.

26. Gladwin MT, Shelhamer JH, Schechter AN, Pease-Fye ME, Waclawiw MA, Panza JA, Ognibene FP, Cannon RO 3rd. Role of circulating nitrite and S-nitrosohemoglobin in the

672 regulation of regional blood flow in humans. *Proc Natl Acad Sci U S A* 97: 11482-11487,
673 2000.
674
675 27. Gordon D, Marshall K, Connell A, Barnes RJ. Influence of blood donation on oxygen
676 uptake kinetics during moderate and heavy intensity cycle exercise. *Int J Sports Med* 31: 298-
677 303, 2010.
678
679 28. Grassi B, Pogliaghi S, Rampichini S, Quaresima V, Ferrari M, Marconi C, Cerretelli P.
680 Muscle oxygenation and pulmonary gas exchange kinetics during cycling exercise on-
681 transitions in humans. *J Appl Physiol* 95: 149-158, 2003.
682
683 29. Hagen T, Taylor CT, Lam F, Moncada S. Redistribution of intracellular oxygen in
684 hypoxia by nitric oxide: effect of HIF1α. *Science* 302: 1975-1978, 2003.
685
686 30. Hakim TS, Sugimori K, Camporesi EM, Anderson G. Half-life of nitric oxide in aqueous
687 solutions with and without haemoglobin. *Physiol Meas* 17: 267-77, 1996.
688
689 31. Hernández A, Schiffer TA, Ivarsson N, Cheng AJ, Bruton JD, Lundberg JO, Weitzberg E,
690 Westerblad H. Dietary nitrate increases tetanic $[Ca^{2+}]_i$ and contractile force in mouse fast-
691 twitch muscle. *J Physiol* 590: 3575-3583, 2012.
692
693 32. Ignarro LJ. Endothelium-derived nitric oxide: actions and properties. *FASEB J* 3: 31-36,
694 1989.
695

696 33. Kapil V, Milsom AB, Okorie M, Maleki-Toyserkani S, Akram F, Rehman F, Arghandawi
697 S, Pearl V, Benjamin N, Loukogeorgakis S, Macallister R, Hobbs AJ, Webb AJ, Ahluwalia
698 A. Inorganic nitrate supplementation lowers blood pressure in humans: role for nitrite-derived
699 NO. *Hypertension* 56: 274-281, 2010.
700
701 34. Kelly J, Vanhatalo A, Bailey SJ, Wylie LJ. Tucker C, List S, Jones AM. Dietary nitrate
702 supplementation: effects on plasma nitrite and pulmonary O_2 uptake dynamics during
703 exercise in hypoxia and normoxia. *Am J Physiol Regul Integr Compar Physiol* 307: R920-
704 R930, 2014.
705
706 35. Kenjale AA, Ham KL, Stabler T, Robbins JL, Johnson JL, VanBruggen M, Privette G,
707 Yim E, Kraus WE, Allen JD. Dietary nitrate supplementation enhances exercise performance
708 in peripheral arterial disease. *J Appl Physiol* 110: 1582-1591, 2011.
709
710 36. Koga S, Kano Y, Barstow TJ, Ferreira LF, Ohmae E, Sudo M, Poole DC. Kinetics of
711 muscle deoxygenation and microvascular PO(2) during contractions in rat: comparison of
712 optical spectroscopy and phosphorescence-quenching techniques. *J Appl Physiol* 112: 26-32,
713 2012.
714
715 37. Lansley KE, Winyard PG, Fulford J, Vanhatalo A, Bailey SJ, Blackwell JR, DiMenna FJ,
716 Gilchrist M, Benjamin N, Jones AM. Dietary nitrate supplementation reduces the O_2 cost of
717 walking and running: a placebo-controlled study. *J Appl Physiol* 110: 591-600, 2011.
718
719 38. Larsen FJ, Weitzberg E, Lundberg JO, Ekblom B. Effects of dietary nitrate on oxygen
720 cost during exercise. *Acta Physiol* 191: 59-66, 2007.

721

722 39. Larsen FJ, Weitzberg E, Lundberg JO, Ekblom B. Dietary nitrate reduces maximal
723 oxygen consumption while maintaining work performance in maximal exercise. *Free Rad*
724 *Biol Med* 48: 342-347, 2010.

725

726 40. Larsen FJ, Schiffer TA, Borniquel S, Sahlin K, Ekblom B, Lundberg JO, Weitzberg E.
727 Dietary inorganic nitrate improves mitochondrial efficiency in humans. *Cell Metab* 13: 149-
728 159, 2011.

729

730 41. Linnarsson D, Karlsson J, Fagraeus L,Saltin B. Muscle metabolites and oxygen deficit
731 with exercise in hypoxia and hyperoxia. *J Appl Physiol* 36: 399-402, 1974.

732

733 42. Lundberg JO, Weitzberg E, Gladwin MT. The nitrate-nitrite-nitric oxide pathway in
734 physiology and therapeutics. *Nat Rev Drug Disc* 7: 156-167, 2008.

735

736 43. Masschelein E, Van Thienen R, Wang X, Van Schepdael A, Thomis M, Hespel P. Dietary
737 nitrate improves muscle but not cerebral oxygenation status during exercise in hypoxia. *J*
738 *Appl Physiol* 113: 736-745, 2012.

739

740 44. Modin A, Björne H, Herulf M, Alving K, Weitzberg E, Lundberg JO. Nitrite-derived
741 nitric oxide: a possible mediator of 'acidic-metabolic' vasodilation. *Acta Physiol Scand* 171:
742 9-16, 2001.

743

744 45. Mora-Rodriguez R, Aguado-Jimenez R, Del Coso J, Estevez E. A standard blood bank
745 donation alters the thermal and cardiovascular responses during subsequent exercise.
746 *Transfusion* 52: 2339-2347, 2012.
747
748 46. Muggeridge DJ, Howe CCF, Spendiff O, Pedlar C, James PE, Easton C. A single dose of
749 beetroot juice enhances performance in simulated altitude. *Med Sci Sports Exerc* 46: 143-150,
750 2014.
751
752 47. Panebianco RA, Stachenfeld N, Copan NL, Gleim GM. Effects of blood donation on
753 exercise performance in competitive cyclists. *Am Heart J* 130: 838-840, 1995.
754
755 48. Patrician A, Schagatay E. Dietary nitrate enhances arterial oxygen saturation after
756 dynamic apnea. *Scand J Med Sci Sports* doi: 10.1111/sms.12684. [Epub ahead of print].
757
758 49. Pinheiro LC, Amaral JH, Ferreira GC, Portella RL, Ceron CS, Montenegro MF, Toledo
759 JC Jr, Tanus-Santos JE. Gastric S-nitrosothiol formation drives the antihypertensive effects of
760 oral sodium nitrite and nitrate in a rat model of renovascular hypertension. *Free Radic Biol*
761 *Med* 87: 252-262, 2015.
762
763 50. Rimer EG, Peterson LR, Coggan AR, Martin JC. Acute dietary nitrate supplementation
764 increases maximal cycling power in athletes. *Int J Sports Physiol Perform* 2015 [Epub ahead
765 of print].
766

767 51. Roach RC, Koskolou MD, Calbet JA, Saltin B. Arterial O_2 content and tension in
768 regulation of cardiac output and leg blood flow during exercise in humans. *Am J Physiol* 276:
769 H438-445, 1999.
770
771 52. Roback JD, Neuman RB, Quyyumi A, Sutliff R. Insufficient nitric oxide bioavailability: a
772 hypothesis to explain adverse effects of red blood cell transfusion. *Transfusion* 51: 859-866,
773 2011.
774
775 53. Saltin B, Calbet JA. Point: in health and in a normoxic environment, VO_2 max is limited
776 primarily by cardiac output and locomotor muscle blood flow. *J Appl Physiol* 100: 744-5,
777 2006.
778
779 54. Schaffartzik W, Barton ED, Poole DC, Tsukimoto K, Hogan MC, Bebout DE, Wagner
780 PD. Effect of reduced haemoglobin concentration on leg oxygen uptake during maximal
781 exercise in humans. *J Appl Physiol* 75: 491-498, 1993.
782
783 55. Thomas DD, Liu X, Kantrow SP, Lancaster JR. The biological lifetime of nitric oxide:
784 implications for the perivascular dynamics of NO and O_2. *Proc Nat Acad Sci* 98: 355-360,
785 2001.
786
787 56. Thompson C, Wylie LJ, Fulford J, Kelly J, Black MI, McDonagh STJ, Jeukendrup AE,
788 Vanhatalo A, Jones AM. Dietary nitrate improves sprint performance and cognitive function
789 during prolonged intermittent exercise. *Eur J Appl Physiol*, 115: 1825-1834, 2015.
790

791 57. Thomsen JJ, Rentsch RL, Robach P, Calbet JA, Boushel R, Rasmussen P, Juel C, Lundby
792 C. Prolonged administration of recombinant human erythropoietin increases submaximal
793 performance more than maximal aerobic capacity. *Eur J Appl Physiol* 101: 481-486, 2007.
794
795 58. van Faassen EE1, Bahrami S, Feelisch M, Hogg N, Kelm M, Kim-Shapiro DB, Kozlov
796 AV, Li H, Lundberg JO, Mason R, Nohl H, Rassaf T, Samouilov A, Slama-Schwok A, Shiva
797 S, Vanin AF, Weitzberg E, Zweier J, Gladwin MT. Nitrite as regulator of hypoxic signaling
798 in mammalian physiology. *Med Res Rev* 29: 683-741, 2009.
799 59. Vanhatalo A, Bailey SJ, Blackwell JR, DiMenna FJ, Pavey TG, Wilkerson DP, Benjamin
800 N, Winyard P, Jones AM. Acute and chronic effects of dietary nitrate supplementation on
801 blood pressure and the physiological responses to moderate-intensity and incremental
802 exercise. *Am J Physiol* 299: R1121-R1131, 2010.
803
804 60. Vanhatalo A, Fulford J, Bailey SJ, Blackwell JR, Winyard PG, Jones AM. Dietary nitrate
805 reduces muscle metabolic perturbation and improves exercise tolerance in hypoxia. *J Physiol*
806 589: 5517-5528, 2011.
807
808 61. Vanhatalo A, Jones AM, Blackwell JR, Winyard PG, Fulford J. Dietary nitrate
809 accelerates postexercise muscle metabolic recovery and O_2 delivery in hypoxia. *J Appl*
810 *Physiol* 117: 1460-1470, 2014.
811
812 62. Van Jaarsveld H, Pool GF. Beneficial effects of blood donation on high density
813 lipoprotein concentration and the oxidative potential of low density lipoprotein.
814 *Atherosclerosis* 161: 395-402, 2002.

63. Victor VM, Nuñez C, D'Ocón P, Taylor CT, Esplugues JV, Moncada S. Regulation of oxygen distribution in tissues by endothelial nitric oxide. *Circ Res* 104: 1178-1183, 2009.

64. Wagner PD. Determinants of maximal oxygen transport and utilization. *Ann Rev Physiol* 58: 21-50, 1996.

65. Webb AJ, Patel N, Loukogeorgakis S, Okorie M, Aboud Z, Misra S, Rashid R, Miall P, Deanfield J, Benjamin N, MacAllister R, Hobbs AJ, Ahluwalia A. Acute blood pressure lowering, vasoprotective, and antiplatelet properties of dietary nitrate via bioconversion to nitrite. *Hypertension* 51: 784-790, 2008.

66. Whitfield J, Ludzki A, Heigenhauser GJ F, Senden JMG, Verdijk LB, van Loon LJC, Spriet LL, Holloway GP. Beetroot juice supplementation reduces whole body oxygen consumption but does not improve indices of mitochondrial efficiency in human skeletal muscle. *J Physiol* 594: 421-435, 2016.

67. Wilkerson DP, Rittweger J, Berger NJA, Naish PF, Jones AM. Influence of recombinant human erythropoietin treatment on pulmonary O_2 uptake kinetics during exercise in humans. *J Physiol* 568: 639-652, 2005.

68. Wilson JR, Martin JL, Schwartz D, Ferraro N. Exercise intolerance in patients with chronic heart failure: role of impaired nutritive flow to skeletal muscle. *Circulation* 69:1079-87, 1984.

840 69. Wylie LJ, Kelly J, Bailey SJ, Blackwell JR, Skiba PF, Winyard PG, Jeukendrup AE,
841 Vanhatalo A, Jones AM. Beetroot juice and exercise: pharmacodynamics and dose-response
842 relationships. *J Appl Physiol* 115: 325-336, 2013.
843
844 70. Zhang R, Hess DT, Qian Z, Hausladen A, Fonseca F, Chaube R, Reynolds JD, Stamler
845 JS. Hemoglobin βCys93 is essential for cardiovascular function and integrated response to
846 hypoxia.. 112: 6425-6430, 2015.
847
848

FIGURE LEGENDS

Figure 1: Pulmonary oxygen uptake ($\dot{V}O_2$) response following BR and PL supplementation prior to and following blood donation during a step increment to a moderate-intensity work rate. Responses prior to blood donation are shown as solid, filled circles, while responses post blood donation are shown as open, unfilled circles. The dotted vertical line represents the abrupt imposition of the moderate work rate from a baseline of 'unloaded' cycling. *A:* Group mean $\dot{V}O_2$ response to moderate-intensity exercise following PL ingestion. *B:* Group mean $\dot{V}O_2$ response to moderate-intensity exercise following BR ingestion. *C:* Steady state $\dot{V}O_2$ following PL and BR supplementation relative to pre blood donation baseline. The O_2 cost of moderate-intensity exercise was reduced following BR supplementation and blood donation compared with pre donation values, $*P<0.05$.

Figure 2: Group mean pulmonary $\dot{V}O_2$ response to incremental exercise prior to blood donation and following BR and PL supplementation after blood donation. Responses prior to blood donation are shown as solid, filled circles, while responses post blood donation are shown as open, unfilled circles. The dotted vertical line represents the onset of the ramp incremental test from a baseline of 'unloaded' cycling. The $\dot{V}O_{2peak}$ was reduced in the PL group ($*= P<0.05$), but not the BR group, after blood donation. TTF was reduced in both groups post donation ($^{\#} = P<0.05$), however, the reduction in TTF was greater in the PL group when compared with the BR group ($^{\$} = P<0.05$).

Figure 3. Group mean time to task failure (TTF) in the ramp incremental test prior to and post blood donation, following BR and PL supplementation. Responses prior to blood donation are shown as solid, filled bars, while responses post donation are shown as open,

873 unfilled bars. The TTF was reduced in both groups post donation (*= $P<0.05$); however, the
874 reduction in TTF was greater in the PL group when compared with the BR group ($^{\#}=P<0.05$).

875

876 **Figure 4.** Group mean changes in deoxyhaemoglobin ([HHb]) prior to and post blood
877 donation, following BR and PL ingestion. Responses prior to blood donation are shown as
878 solid, filled circles, while responses post blood donation are shown as open, unfilled circles.
879 The dotted vertical line represents the onset of the ramp incremental test from a baseline of
880 'unloaded' cycling. [HHb] increased significantly from pre to post donation in the PL group
881 at 360 s and end-exercise (*=$P<0.05$). [HHb] was not altered from pre to post donation in the
882 BR group. TTF was reduced in both groups post donation ($^{\#}$ = $P<0.05$), however, the
883 reduction in TTF was greater in the PL group when compared with the BR group ($^{\$}$ =
884 $P<0.05$).

885

886

Table 1: Blood pressure, resting heart rate, plasma nitrate and nitrite concentrations, hemoglobin concentration and hematocrit prior to and following blood donation in the PL and BR groups.

	PL		BR	
	Pre	**Post**	**Pre**	**Post**
Blood pressure (mmHg)				
Systolic	119 ± 7	118 ± 9	115 ± 11	113 ± 11*
Diastolic	69 ± 7	67 ± 7	64 ± 7	63 ± 7
Mean Arterial	86 ± 6	84 ± 8	81 ± 7	80 ± 7
Resting HR ($b \cdot min^{-1}$)	62 ± 9	66 ± 9	66 ± 11	71 ± 10*
Plasma [NO_3^-] (µM)	45 ± 11	50 ± 14*	47 ± 17	845 ± 350$^{*\$}$
Plasma [NO_2^-] (nM)	73 ± 18	72 ± 21	81 ± 29	619 ± 363$^{*\$}$
[Hb] ($g \cdot L^{-1}$)	149 ± 12	132 ± 18*	148 ± 15	137 ± 19*
Hct (%)	45 ± 2	41 ± 4*	45 ± 3	42 ± 5*

Values are mean ± SD. PL, Placebo group; BR, Nitrate group; Pre, pre-donation; Post, post-donation ; HR, heart rate; [NO_2^-], nitrite concentration; [NO_3^-], nitrate concentration; [Hb], hemoglobin concentration; Hct, hematocrit. *Significantly different from pre in the same condition (P<0.05). $^{\$}$Significantly different from post supplementation value in the PL group (P<0.05).

Table 2: Ventilatory and gas exchange dynamics, and blood lactate and glucose concentrations during moderate-intensity exercise prior to and following blood donation in the PL and BR groups

	PL		BR	
	Pre	**Post**	**Pre**	**Post**
$\dot{V}O_2$ **(L·min^{-1})**				
Baseline	1.01 ± 0.17	0.97 ± 0.20	0.96 ± 0.20	0.87 ± 0.21$^{\#}$
End exercise	1.72 ± 0.50	1.69 ± 0.53	1.65 ± 0.32	1.59 ± 0.34$^{\#}$
$\dot{V}CO_2$ **(L·min^{-1})**				
Baseline	0.88 ± 0.19	0.86 ± 0.19	0.89 ± 0.19	0.81 ± 0.19$^{\#}$
End exercise	1.60 ± 0.52	1.56 ± 0.50	1.53 ± 0.29	1.54 ± 0.29
RER				
Baseline	0.88 ± 0.08	0.90 ± 0.06	0.89 ± 0.05	0.92 ± 0.09
End exercise	0.94 ± 0.06	0.93 ± 0.06	0.93 ± 0.04	0.96 ± 0.06$^{\#}$
$\dot{V}E$ **(L·min^{-1})**				
Baseline	25 ± 5	24 ± 5	24 ± 5	22 ± 5$^{\#}$
End exercise	42 ± 11	40 ± 11	38 ± 6	38 ± 6
Δ **Blood [lactate]** (mM)	0.0 ± 0.3	0.1 ± 0.4	0.1 ± 0.3	0.1 ± 0.4
Δ**Blood [glucose]** (mM)	0.1 ± 0.7	- 0.2 ± 0.7	0.00 ± 0.3	0.1 ± 0.5

Values are mean ± SD. PL, Placebo group; BR, Nitrate group; Pre, pre-donation; Post, post-donation; [Bla], blood lactate concentration; [glu], blood glucose concentration; HR, heart rate. $^{\#}$Significantly different from pre in the same condition (P<0.05).

Table 3: Physiological responses to ramp incremental exercise prior to and following blood donation in the PL and BR groups.

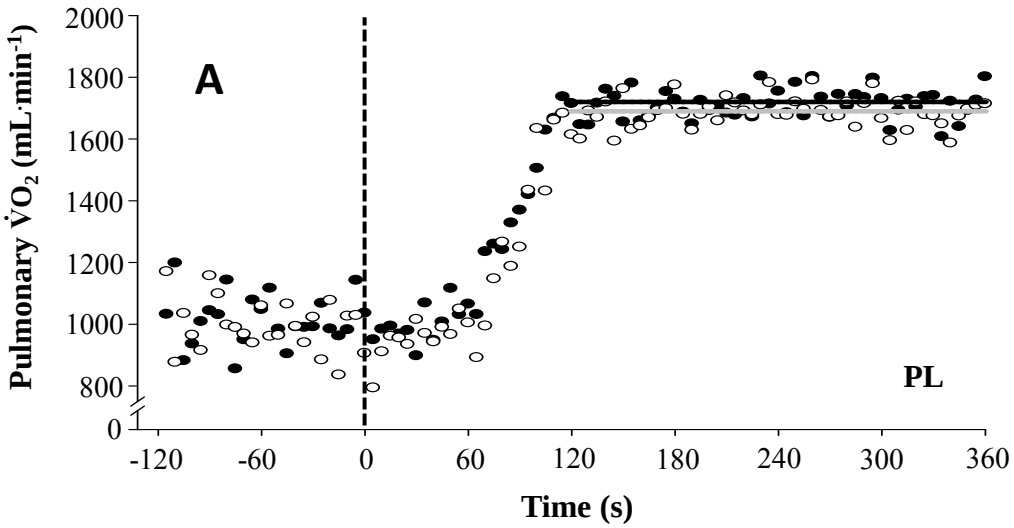
	PL		BR	
	Pre	**Post**	**Pre**	**Post**
$\dot{V}O_2$peak ($L \cdot min^{-1}$)	3.84 ± 0.91	3.65 ± 0.85*	3.52 ± 0.65	3.40 ± 0.73
$\dot{V}O_2$peak ($mL \cdot kg^{-1} \cdot min^{-1}$)	49.9 ± 11.0	47.4 ± 10.0*	46.6 ± 6.0	44.9 ± 6.0
Peak power (W)	341 ± 70	324 ± 69*	331 ± 68	322 ± 66*
GET ($L \cdot min^{-1}$)	1.76 ± 0.40	1.68 ± 0.43	1.64 ± 0.44	1.63 ± 0.44
GET (W)	117 ± 29	109 ± 27	116 ± 35	112 ± 24
$\dot{V}CO_2$peak ($L \cdot min^{-1}$)	4.69 ± 1.12	4.44 ± 0.97*	4.26 ± 0.68	4.36 ± 0.77
RER peak	1.22 ± 0.06	1.22 ± 0.05	1.22 ± 0.06	1.29 ± 0.06*
$\dot{V}E$peak ($L \cdot min^{-1}$)	156 ± 44	150 ± 43*	134 ± 28	137 ± 32
HRpeak ($b \cdot min^{-1}$)	177 ± 16	181 ± 9	178 ± 12	179 ± 10
Δ Blood [lactate] (mM)	6.1 ± 1.4	5.5 ± 1.2	6.1 ± 1.9	6.8 ± 2.5
Δ Blood [glucose] (mM)	-0.2 ± 0.7	0.0 ± 1.1	-0.2 ± 0.4	0.0 ± 1.1

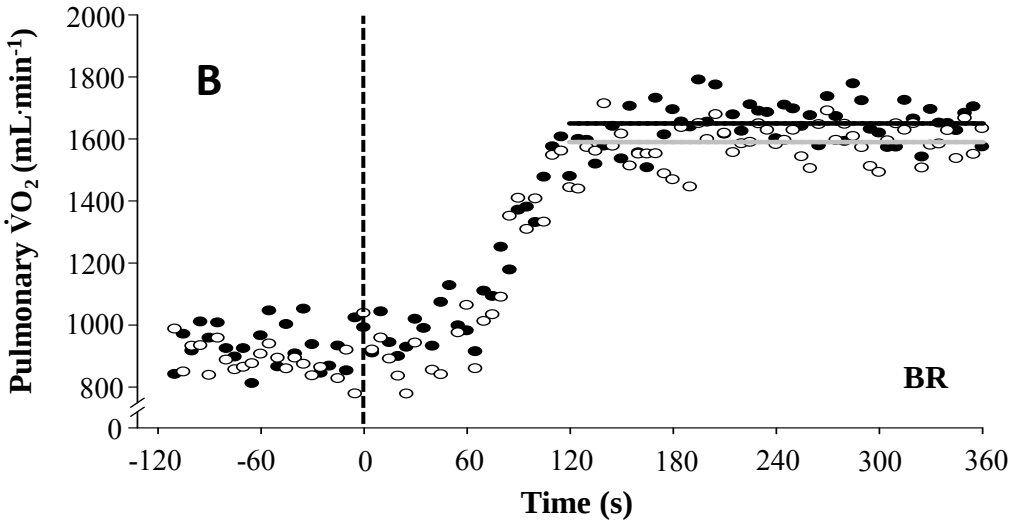
Values are mean ± SD. PL, Placebo group; BR, Nitrate group; Pre, pre-donation; Post, post-donation; GET, Gas exchange threshold; [Bla], blood lactate concentration; [glu], blood glucose concentration; HR, heart rate. *Significantly different from pre in the same condition (P<0.05).

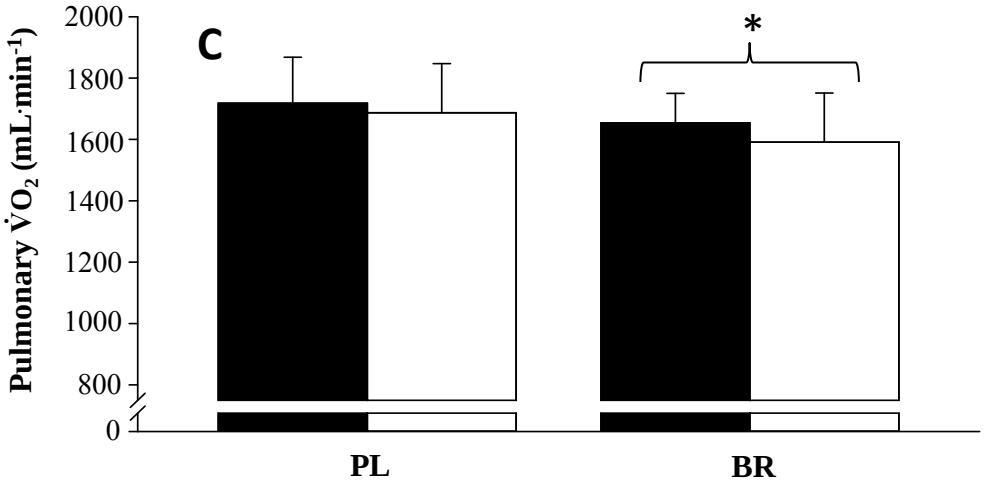
Table 4: Near-infrared spectroscopy-derived [HHb] and TOI dynamics during moderate-intensity and ramp incremental exercise prior to and following blood donation in the PL and BR groups.

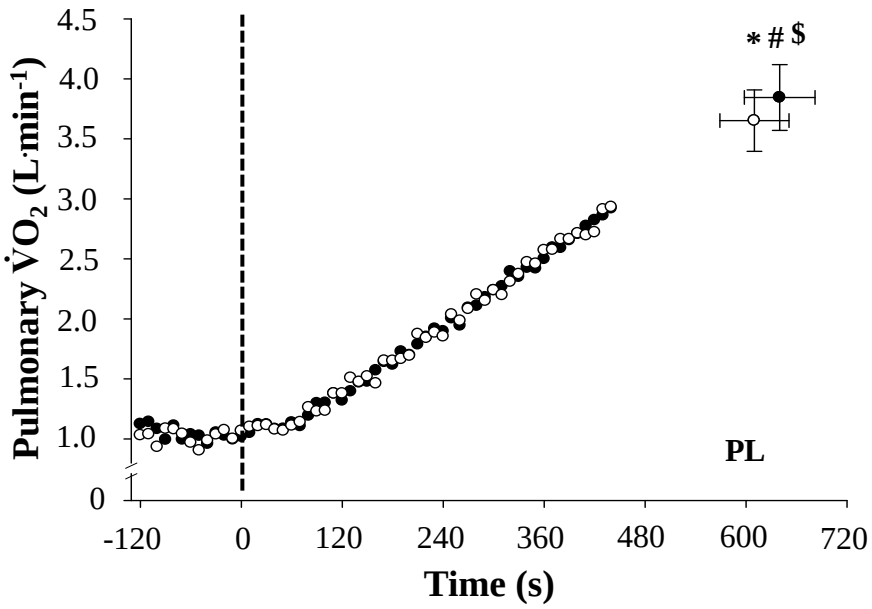
	PL		BR	
	Pre	**Post**	**Pre**	**Post**
	Moderate-intensity exercise			
[HHb]				
Baseline (AU)	-4.4 ± 3.0	-2.3 ± 3.1	-3.1 ± 3.7	-1.9 ± 2.5
60 s (AU)	-1.2 ± 2.3	2.3 ± 5.0	-0.1 ± 5.0	0.6 ± 3.9
120 s (AU)	-0.9 ± 3.0	3.5 ± 6.2	-0.1 ± 4.9	1.0 ± 3.7
240 s (AU)	-0.7 ± 3.9	2.3 ± 5.2	0.1 ± 4.9	1.1 ± 3.6
End (AU)	0.0 ± 4.4	2.5 ± 4.9	0.0 ± 4.9	1.0 ± 3.4
TOI				
Baseline (%)	65.3 ± 3.4	63.4 ± 3.3*	68.2 ± 4.3	70.1 ± 5.8
60 s (%)	61.9 ± 4.9	57.7 ± 5.0*	64.6 ± 6.5	65.6 ± 8.5
120 s (%)	61.9 ± 4.8	57.1 ± 5.7*	64.8 ± 6.1	65.6 ± 8.8
240 s (%)	60.7 ± 6.6	58.1 ± 4.8*	64.8 ± 6.5	65.8 ± 8.9
End (%)	61.4 ± 6.4	57.8 ± 5.0	65.3 ± 6.3	65.8 ± 8.9
	Ramp incremental exercise			
[HHb]				
Baseline (AU)	-6.2 ± 4.1	-3.4 ± 3.6	-5.1 ± 4.1	-2.6 ± 2.5
120 s (AU)	-3.3 ± 5.4	-0.1 ± 5.0	-2.7 ± 5.0	-0.7 ± 3.3
240 s (AU)	-0.8 ± 6.2	3.3 ± 5.8*	-0.6 ± 5.8	1.4 ± 4.4
360 s (AU)	2.0 ± 9.4	7.3 ± 9.1*	1.5 ± 6.6	3.4 ± 5.8
End (AU)	6.2 ± 11.3	12.8 ± 10.1*	3.8 ± 7.6	5.3 ± 7.2
TOI				
Baseline (%)	66.5 ± 3.9	67.3 ± 7.1	71.5 ± 3.9	72.5 ± 4.7
120 s (%)	63.3 ± 5.1	64.6 ± 8.6	68.6 ± 5.5	69.5 ± 6.9
240 s (%)	60.8 ± 6.5	60.7 ± 9.2	65.8 ± 7.5	65.9 ± 9.7
360 s (%)	57.3 ± 11.5	55.4 ± 12.3	61.9 ± 8.6	61.7 ± 11.4
End (%)	49.5 ± 12.6	47.6 ± 14.9	57.1 ± 7.0	57.2 ± 10.9

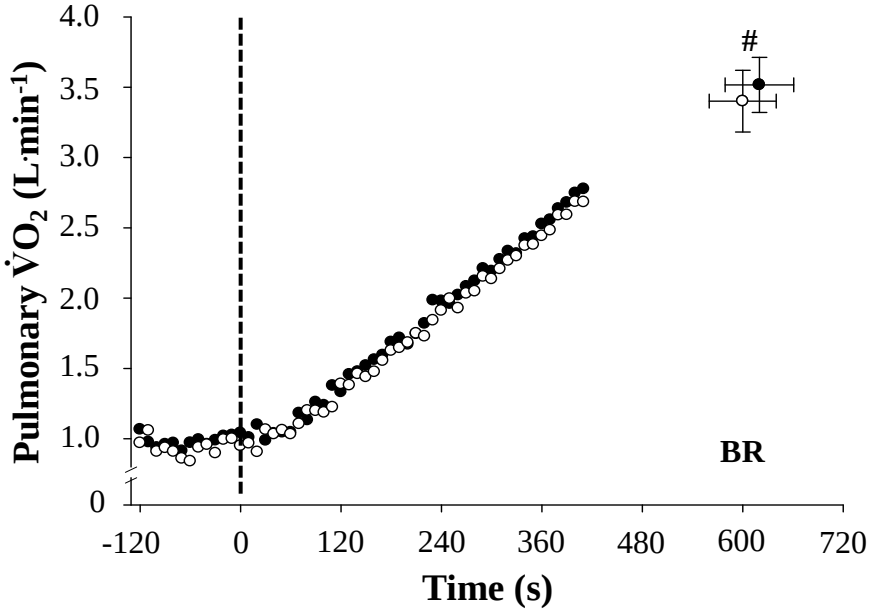
Values are mean ± SD. PL, Placebo group; BR, Nitrate group; Pre, pre-donation; Post, post-donation; [HHb], deoxygenated haemoglobin concentration; TOI, tissue oxygenation index; AU, arbitrary units. *Significantly different from pre in the same condition (P<0.05).

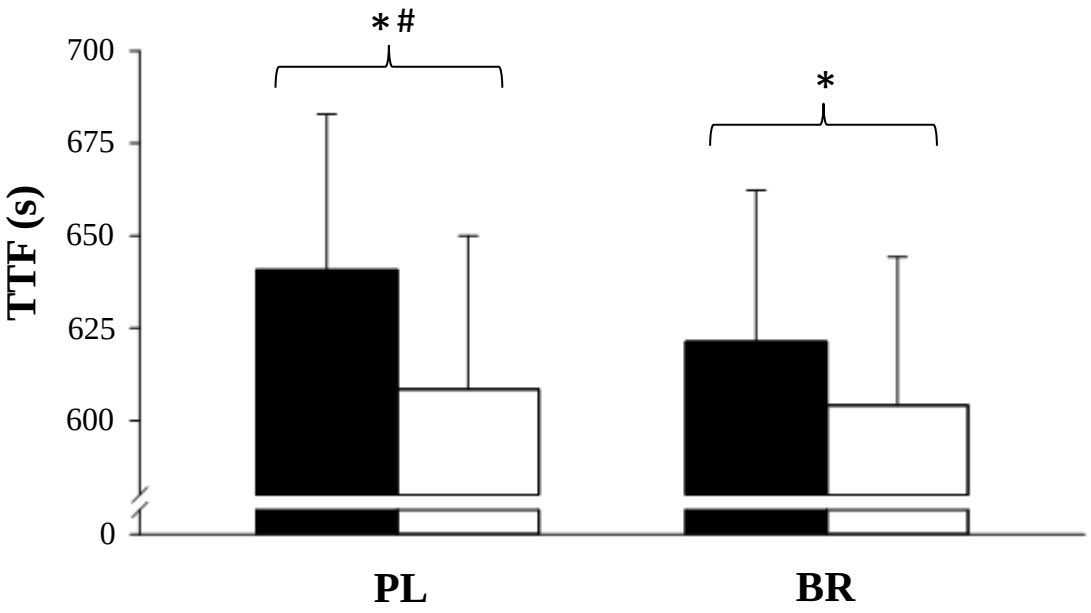

A
PL
Pulmonary $\dot{V}O_2$ (mL·min^{-1})
2000
1800
1600
1400
1200
1000
800
0
-120
-60
0
60
120
180
240
300
360
Time (s)

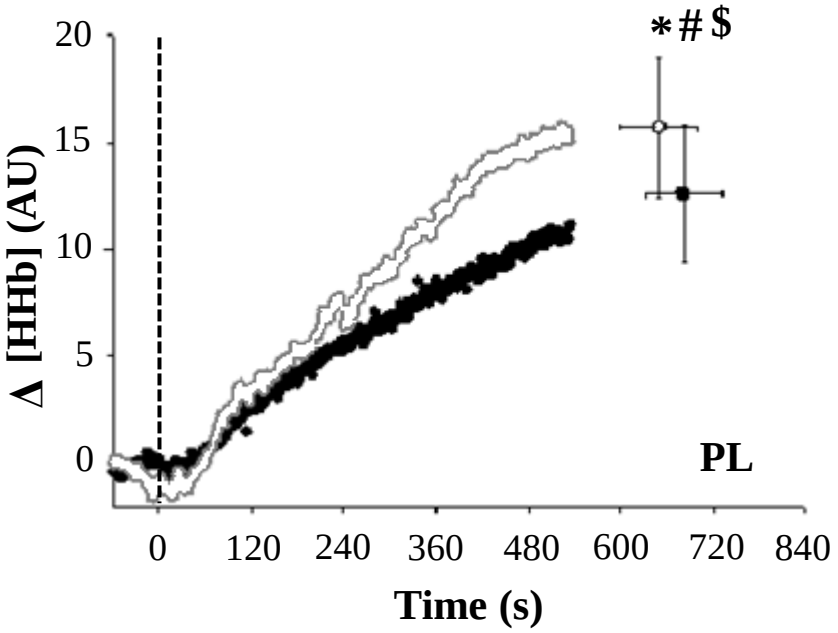

B
BR
Pulmonary $\dot{V}O_2$ (mL·min^{-1})
2000
1800
1600
1400
1200
1000
800
0
-120
-60
0
60
120
180
240
300
360
Time (s)

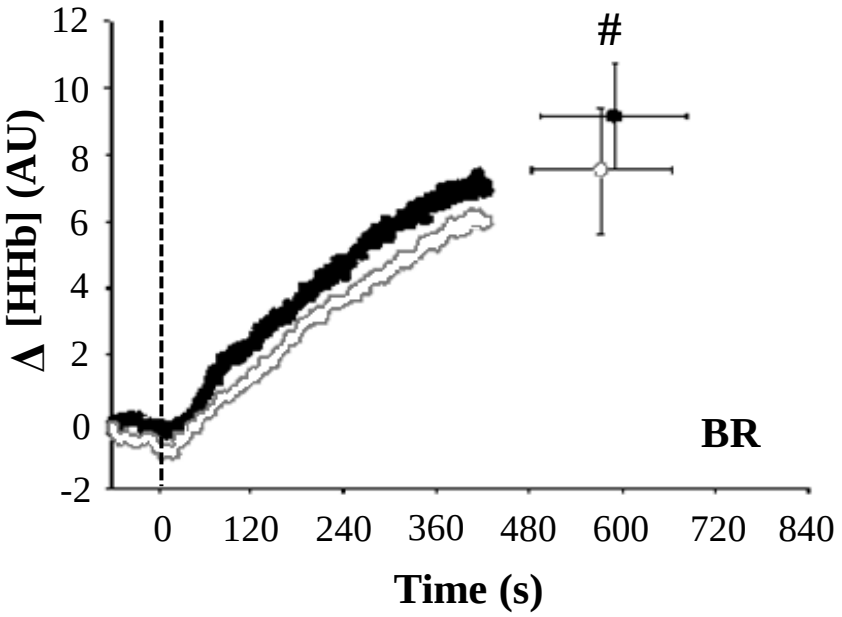

C
*
Pulmonary $\dot{V}O_2$ (mL·min^{-1})
2000
1800
1600
1400
1200
1000
800
0
PL
BR


Pulmonary $\dot{V}O_2$ (L·min^{-1})
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
-120
0
120
240
360
480
600
720
Time (s)
* # $
PL


Pulmonary $\dot{V}O_2$ (L·min^{-1})
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
-120
0
120
240
360
480
600
720
Time (s)
#
BR


*#
*
700
675
650
625
600
0
TTF (s)
PL
BR


*#$
20
15
10
5
0
Δ [HHb] (AU)
PL
0
120
240
360
480
600
720
840
Time (s)


#
12
10
8
6
4
2
0
-2
Δ [HHb] (AU)
BR
0
120
240
360
480
600
720
840
Time (s)