HYPEROXIA SPEEDS PULMONARY OXYGEN UPTAKE KINETICS AND INCREASES CRITICAL POWER DURING SUPINE CYCLING

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NEW FINDINGS:

What is the central question of this study?

Critical power (CP) is a fundamental parameter defining high-intensity exercise tolerance, and is related to the phase II time constant of pulmonary oxygen uptake kinetics ($\tau_{\dot{V}O2}$). To test whether this relationship is causal, we assessed the impact of hyperoxia on $\tau_{\dot{V}O2}$ and CP during supine cycle exercise.

What is the main finding and its importance?

The results demonstrate that hyperoxia increased muscle oxygenation, reduced $\tau_{\dot{V}O2}$ (i.e. sped the $\dot{V}O_2$ kinetics), and subsequently, increased critical power when compared to normoxia. These results therefore suggest that $\tau_{\dot{V}O2}$ is a determinant of the upper limit for steady-state exercise, i.e. critical power.

ABSTRACT

The present study determined the impact of hyperoxia on the phase II time constant of pulmonary oxygen uptake kinetics ($\tau_{\dot{V}O2}$) and critical power (CP) during supine cycle exercise. 8 healthy males completed an incremental test to determine maximal oxygen uptake and the gas exchange threshold (GET). Eight separate visits followed, whereby CP, $\tau_{\dot{V}O2}$ and absolute concentrations of oxyhaemoglobin ([HbO_2]; via near-infrared spectroscopy) were determined via four constant-power tests to exhaustion, each repeated once in normoxia and once in hyperoxia (FiO_2 = 0.5). A 6-minute bout of moderate intensity exercise (70% GET) was also undertaken prior to each severe intensity bout, in both conditions. CP was greater (hyperoxia = 148 ± 29 W vs. normoxia = 134 ± 27 W, P = 0.006) and the $\tau_{\dot{V}O2}$ was reduced (hyperoxia = 33 ± 12 s vs. normoxia = 52 ± 22 s, P = 0.007) during severe exercise in hyperoxia when compared to normoxia. Furthermore, [HbO_2] was enhanced in hyperoxia compared to normoxia (hyperoxia: 67 ± 10 *versus* normoxia: 63 ± 11 μM; P = 0.020). $\tau_{\dot{V}O2}$ was significantly related to CP in hyperoxia (R^2 = 0.89, P < 0.001), however no relationship was observed in normoxia (R^2 = 0.03, P = 0.68). Muscle oxygenation was increased, $\tau_{\dot{V}O2}$ was reduced and CP was increased in hyperoxia compared to normoxia, suggesting that $\tau_{\dot{V}O2}$ is an independent determinant of CP. That $\tau_{\dot{V}O2}$ was related to CP in hyperoxia but not normoxia further supports this notion.

Keywords critical power, exercise tolerance, oxidative metabolism, oxygen uptake kinetics, power-duration relationship, hyperoxia.

INTRODUCTION

The tolerable duration of high-intensity exercise is well described by a two-parameter hyperbolic relationship between power and duration (Moritani et al., 1981; Poole et al., 1988). The asymptote of this relationship is termed "critical power", with *W'* representing the rectangular constant of the hyperbola, equivalent to a fixed quantity of work performable above critical power. The functional significance of critical power is demonstrated by the observation that pulmonary oxygen uptake ($\dot{V}O_2$) and muscle metabolic variables (e.g. muscle lactate concentration, [L^-]; [H^+]; phosphocreatine concentration, [PCr]; [P_i]) do not reach a steady-state during exercise above critical power. Instead these parameters achieve consistently high (e.g. $\dot{V}O_2$, [L^-], [H^+], [P_i]) or low ([PCr]) values at the limit of tolerance (Black et al., 2017; Jones et al., 2008; Vanhatalo et al., 2016). Critical power therefore represents a metabolic rate (i.e. a "critical $\dot{V}O_2$") that demarcates the boundary between steady-state (heavy-intensity) and non-steady-state (severe-intensity) exercise (Poole et al., 2016). Exercise performed at a metabolic rate exceeding critical power will therefore become predictably limited in accordance with the parameters of the power-duration relationship and their physiological corollaries. These physiological corollaries therefore define the tolerable duration of severe-intensity exercise, yet remain incompletely understood.

At the onset of muscular work, pulmonary $\dot{V}O_2$ kinetics increase in a near-exponential fashion with a time constant ($\tau_{\dot{V}O2}$) that closely approximates that of muscle $\dot{V}O_2$ (Grassi et al., 1996). A strong inverse relationship has been observed between $\tau_{\dot{V}O2}$ and critical power during upright cycle exercise (Murgatroyd *et al.*, 2011; Goulding *et al.*, 2017, 2018*a*), suggesting that these parameters may be causally related. In support of this we recently showed that a prior bout of heavy-intensity "priming" exercise reduced $\tau_{\dot{V}O2}$ and increased critical power (Goulding et al., 2017). However the concomitant improvements in critical

power and $\tau_{\dot{V}O2}$ may have been due to the enhanced O_2 availability that attended priming exercise, rather than a dependence of critical power on $\tau_{\dot{V}O2}$ *per se*. Subsequent to this study, we demonstrated a concomitant increase in $\tau_{\dot{V}O2}$ and reduction in critical power, independent of O_2 availability, when exercise was initiated from an elevated moderate-intensity baseline work rate compared to a baseline of unloaded cycling (i.e. "work-to-work" cycle exercise) in both the upright and supine position (Goulding *et al.*, 2018*a*, 2018*b*). Taken together, these findings strongly suggest a prevailing dependence of critical power on $\tau_{\dot{V}O2}$.

Despite our recent data (Goulding *et al.*, 2017, 2018*a*, 2018*b*), stronger evidence for a determining effect of $\tau_{\dot{V}O2}$ on critical power would arguably come from the establishment of a relationship between the changes in critical power (ΔCP) and $\tau_{\dot{V}O2}$ ($\Delta\tau_{\dot{V}O2}$) between two conditions where $\tau_{\dot{V}O2}$ would be expected to differ. However, a valid assessment of this relationship requires the precise characterisation of the value of $\tau_{\dot{V}O2}$ via repeated, identical exercise transitions in each condition (Lamarra et al., 1987; Whipp et al., 1982). In contrast, our previously employed interventions (i.e. priming exercise and work-to-work exercise; Goulding *et al.*, 2017, 2018*a*, 2018*b*) precluded the precise characterisation of the value of $\tau_{\dot{V}O2}$ in each condition since this would have placed undue time commitments on the participants. Conversely, inspired hyperoxic air has the potential to reduce $\tau_{\dot{V}O2}$, at least during supine exercise where O_2 delivery is rate-limiting (Macdonald et al., 1997). However, unlike our previously imposed interventions (Goulding *et al.*, 2017, 2018*a*, 2018*b*), hyperoxia does not require a prolonged wash-out period before the physiological responses to further exercise can be considered as being normal. Hence during supine exercise, hyperoxia represents a convenient means by which to manipulate $\tau_{\dot{V}O2}$, observe any effect on critical power, and precisely characterise $\tau_{\dot{V}O2}$ via bouts of moderate intensity exercise undertaken shortly prior to the criterion bouts that determine critical power. This enables a valid assessment of $\Delta\tau_{\dot{V}O2}$ versus ΔCP to be undertaken, with the establishment of a $\Delta\tau_{\dot{V}O2}$ – ΔCP

relationship providing definitive support for a mechanistic role of $\tau_{\dot{V}O2}$ in determining critical power.

The aim of the present study was therefore to determine the impact of hyperoxia on $\tau_{\dot{V}O2}$ and critical power during supine exercise, with $\tau_{\dot{V}O2}$ precisely characterised via multiple bouts of identical exercise in each condition. We hypothesised that (1) hyperoxia would reduce $\tau_{\dot{V}O2}$ compared to normoxia, (2) hyperoxia would increase critical power compared to normoxia, (3) ΔCP would correlate with $\Delta\tau_{\dot{V}O2}$.

METHODS

Ethical approval. The experiment was approved by Liverpool Hope University Research Ethics Committee (approval reference number: S-15-06-2017 PA 015). The experiment conformed to the standards set by the Declaration of Helsinki, except for registration in a database. All participants provided written informed consent.

Participants. Eight healthy male subjects (mean ± SD, age = 22 ± 3 years; height = 180 ± 9 cm; mass = 80 ± 9 kg) participated. Participants were instructed to avoid alcohol and strenuous exercise 24 h prior to each visit, not to consume caffeine 3 h prior to each visit, and to arrive 3 h postprandial. Tests were separated by at least 24 h, with each test performed at the same time of day (± 2 h).

Procedures. All tests took place in a temperature-controlled laboratory (maintained between 18-21 ^{o}C). The experiment involved nine visits over a 3-5 week period, including one preliminary trial and eight experimental trials. All tests were performed on a supine cycle ergometer, which consisted of an electronically-braked ergometric unit (Lode Angio, Groningen, The Netherlands) positioned on an Echo Cardiac Stress Table (Lode, Groningen, The Netherlands). The ergometric unit was positioned such that the quadriceps were above the level of the heart during exercise. Participants lay supine on the table whilst exercising,

and hand rails were available for participants to grip throughout the tests to prevent backwards movements from occurring when forces were applied to the pedals. An adjustable shoulder pad was positioned above the participant's shoulder to further impede any rear movements. Participant's feet were securely strapped to the pedals throughout all tests. The position of the shoulder pad and the distance between the hip and the crank, as well as each participant's chosen hand grip position, was recorded at the first visit and replicated during each subsequent visit. Throughout all exercise tests, participants were instructed to cycle at a self-selected cadence between 70-90 rev/min (which was recorded and replicated in subsequent visits), with task failure being defined as the point at which the cadence dropped below 50 rev/min. The limit of tolerance was recorded to the nearest second in all tests.

Preliminary trial. Following measurement of height and weight, participants performed an incremental ramp test to the limit of tolerance to determine $\dot{V}O_2$ max and the gas exchange threshold (GET), such that the power outputs for subsequent visits could be calculated. The ramp test consisted of 3 min baseline pedalling at 30 W, followed by a ramped increase in power of 25 $W.min^{-1}$ until task failure occurred. Ventilatory and gas exchange variables were measured continuously breath-by-breath throughout each test. $\dot{V}O_2$ max was defined as the highest 30 s value recorded throughout the test. The GET was estimated via visual determination of the time point at which the following occurred: 1) increased CO_2 production ($\dot{V}CO_2$) compared to $\dot{V}O_2$, 2) increased minute ventilation ($\dot{V}E$) relative to $\dot{V}O_2$ ($\dot{V}E/\dot{V}O_2$) without an increase in $\dot{V}E/\dot{V}CO_2$, and 3) an increase in end tidal O_2 tension without decreasing end tidal CO_2 tension. The mean response time (MRT) was defined as the time between the beginning of the ramp test and intersection between baseline $\dot{V}O_2$ (average $\dot{V}O_2$ measured during last 30 s of baseline; $\dot{V}O_{2b}$) and backwards extrapolation of the $\dot{V}O_2$-time relationship (Boone *et al.*, 2008). This technique was also used to calculate power outputs for subsequent visits.

164 *Experimental trials*. The eight experimental trials that followed required exercise at four
165 fixed severe-intensity power outputs performed until the limit of tolerance. Each power
166 output was repeated twice, i.e. once in normoxia (breathing room air) and once in hyperoxia
167 (fraction of inspired O_2 0.5; British Oxygen Company). The power outputs were estimated to
168 be in the range of 50%Δ (i.e. 50% of the difference between the GET and $\dot{V}O_2$ max) – 110%
169 $\dot{V}O_2$ max, such that the range of exercise tolerance times was 2-15 minutes for each subject
170 (Hill, 1993). If tolerance time for a particular test fell outside of this range, the power output
171 was modified and the test repeated on a subsequent day. The four power outputs utilised for
172 each participant will hereafter be referred to as WR1, WR 2, WR 3, and WR 4, with WR 1
173 being the lowest and WR 4 being the highest power outputs, respectively. Power outputs
174 were presented in random order, with participants alternating between normoxic and
175 hyperoxic conditions. In both normoxia and hyperoxia, tests began with 3 minutes of 20 W
176 baseline cycling, before a step change in power output to 70% GET for 6 minutes. The
177 purpose of the 6 minute bout of moderate exercise was to precisely characterise $\dot{V}O_2$ kinetics
178 in each condition via averaging of multiple identical trials (*see data analysis*) to facilitate
179 comparisons of the magnitude of change of related parameters between conditions. After
180 these 6 minutes of moderate cycling, the power output was reduced to 20 W for a further 10
181 minutes. Subsequent to these 10 minutes of 20 W cycling, a step increase in power output
182 was abruptly applied to the desired severe-intensity (i.e. WR's 1-4), and participants
183 exercised until the limit of tolerance was reached.

184 Participants wore a silicone face mask (Hans Rudolph, Kansas, United States) with a flow
185 sensor (Geratherm Respiratory, GmbH, Germany) attached, which was attached in turn via a
186 capillary line to a metabolic cart (Blue Cherry, Geratherm Respiratory, GmbH, Germany)
187 that was used to measure pulmonary gas exchange and ventilation breath-by-breath
188 throughout all tests. Gases of known concentration were used to calibrate gas analysers, and a

3-liter syringe (Hans Rudolph, Kansas City, MO) was used to calibrate flow sensors. A two-way non-rebreathing valve (Hans Rudolph T-Shape Two-Way Non-Rebreathing Valve Series 2600; Hans Rudolph, Kansas, United States) was attached to the flow sensor via a piece of rubber tubing. A 200 L Douglas bag was connected to the inlet port of this valve. In the hyperoxic condition, Douglas bags were continuously filled with the 50% O_2 gas mixture via a pressurised cylinder, and in the normoxic condition the Douglas bag was bypassed so that participants breathed room air. In the hyperoxic condition, participants rested quietly on the ergometer for 10 minutes before exercise to allow body O_2 stores to become equilibrated, a procedure that was also replicated in the normoxic condition with participants inhaling room air. Heart rate was determined every 1 s throughout all tests using short-range radiotelemetry (Garmin FR70, Garmin Ltd., Switzerland). In both conditions, blood was drawn from the thumb of the right hand at rest, during the final minute of baseline pedalling prior to the onset of severe exercise, and immediately upon reaching the limit of tolerance. Whole blood [L^-] was determined using a Biosen C-Line lactate analyser (EKF, Germany).

Absolute concentrations of muscle and microvascular deoxyhaemoglobin + deoxymyoglobin ([HHb + Mb]), oxyhaemoglobin + oxymyoglobin ([HbO_2 + MbO_2]), and total haemoglobin + total myoglobin ([THb + Mb]) were determined using a frequency-domain multidistance NIRS system (OxiplexTS, ISS, Chapaign, IL, USA). This technique has been described in detail previously (Broxterman *et al.*, 2014; Goulding *et al.*, 2017). Briefly, this device consists of one detector fibre bundle and eight light-emitting diodes (LED) operating at wavelengths of 690 and 830 nm (four LEDs per wavelength), with LED-detector fibre bundle separation distances of 2.25, 2.75, 3.25 and 3.75. The device measures and incorporates dynamic reduced scattering coefficients to provide absolute concentrations of [HHb + Mb] and [HbO_2 + MbO_2]. The NIRS probe was calibrated prior to each test according to the manufacturer's instructions. Two flexible NIRS probes were placed on the participant; one

longitudinally along the belly of the right vastus lateralis (VL), the other longitudinally along the belly of the rectus femoris (RF) muscle. The probes were held firmly in place via Velcro strapping, and the area underneath the probe was cleaned, shaved and marked with pen such that probe position could be accurately replicated for each trial. Measurements began with participants in a resting position on the ergometer, with feet strapped into the pedals and the right leg extended. To account for the influence of adipose tissue thickness (ATT) on the NIRS signal, we employed the correction factor employed by Craig *et al.* (2017), i.e. with separate correction factors for the RF and VL (Figure 1).

Data analysis. Breath-by-breath $\dot{V}O_2$ data were edited to remove data points lying more than 4 standard deviations (SD) outside the local 5-breath mean (Lamarra *et al.*, 1987). These data were then linearly interpolated to provide second-by-second values. For $\dot{V}O_2$, [HHb + Mb], [HbO_2 + MbO_2] and heart rate data in response to moderate exercise transitions, second-by-second data for the four identical transitions were averaged together to produce a single dataset. The severe-intensity exercise bouts for each condition were not repeated and were therefore modelled separately. The following mono-exponential function was then used to fit the $\dot{V}O_2$, [HHb + Mb] and heart rate responses to exercise:

$$Y_{(t)} = Y_{(b)} + A_Y * (1 - e^{-(t - TD/\tau)}) \quad (1)$$

Where $Y_{(t)}$ is the value of the independent variable at time t, $Y_{(b)}$ is the baseline value measured over the final 30 seconds of baseline pedalling, A_Y is the amplitude of increase in Y above baseline, TD is the time delay and τ is the time constant of the response. For $\dot{V}O_2$, the end of the "cardiodynamic" phase was determined to be the time at which a drop in respiratory exchange ratio and end-tidal O_2 pressure was observed, and data preceding this point were excluded from the modelling process. For moderate exercise, $\dot{V}O_2$ responses were

fit to 360 s. During severe transitions, the onset of the $\dot{V}O_2$ slow component was determined by progressively increasing the fitting window, beginning from the end of phase I to 60 seconds and then successively extending the window to the limit of tolerance. The onset of the slow component was taken as the time point at which a departure from "flatness" in the plot of $\tau_{\dot{V}O2}$ and/or χ^2 versus time was observed, as described previously (Rossiter *et al.*, 2001; Goulding *et al.*, 2017). This method allows fitting of the isolated fundamental component without arbitrary parameterization of the slow component. The magnitude of the $\dot{V}O_2$ slow component was calculated as the difference between end exercise $\dot{V}O_2$ (i.e. mean $\dot{V}O_2$ over final 30 s of exercise) and $A_Y + Y_{(b)}$. For [HHb + Mb], data preceding the time point at which the [HHb + Mb] signal increased above 1 SD of the pretransition baseline value were removed. On occasions where [HHb + Mb] decreased after the exercise onset, data preceding the first point showing a sustained increase in [HHb + Mb] were removed from the modelling process. Although [HHb + Mb] data were modelled with the TD allowed to vary freely such that the fit could be optimised, the time point at which [HHb +Mb] began to increase is presented in the results (see Table 3) as this is the more physiologically relevant parameter (Spencer *et al.*, 2011). Heart rate increased with no TD, therefore the response was constrained to the start of exercise. For moderate exercise, [HHb + Mb] data were fit to Eq. 1 using the iterative procedures described for the determination of the $\dot{V}O_2$ kinetics but with the fitting window commencing at 20 s. This modelling strategy thus allows for the determination of the optimum "phase II" fitting window even in the presence of a [HHb + Mb] overshoot. By plotting the resultant $\tau_{[HHb+Mb]}$ values against time, and identifying the point at which a sustained decrease (overshoot) or increase in $\tau_{[HHb+Mb]}$ was observed alongside a sharp increase in the χ^2 value. For severe-intensity exercise for both [HHb + Mb] and heart rate, the model window was constrained to the time of onset of the $\dot{V}O_2$ slow component. The amplitude of the [HHb + Mb] and heart rate "slow component" during

severe exercise was calculated by subtracting $Y_{(b)} + A_Y$ from the mean value of Y during the final 30 s of exercise. Intersite coefficient of variation (CV% = 100 * SD/ mean of the two sites) was calculated to quantify the spatial heterogeneity for $TD_{[HHb+Mb]}$ and $\tau_{[HHb+Mb]}$. Confidence intervals for all τ parameters were obtained in Origin 6.0 (OriginLab Corporation, MA, USA). For [HbO_2 + MbO_2] and [THb + Mb] during moderate exercise, 30 second averages were determined at baseline, and every 30 seconds thereafter until the end of the transition. For severe exercise, mean [HbO_2 + MbO_2] and [THb + Mb] was determined at baseline, at 30 and 120 seconds into the transition (15 second bins centred on each time point), and at end-exercise (final 30 seconds) to allow comparisons between conditions.

Critical power and *W'* were determined by inputting power output (P), time to task failure (T) and work done (W) into three models: the hyperbolic power-time model (Eq. 2), the linear work-time model (Eq. 3), and the linear power versus the inverse-of-time models (4):

(2) $$P = W' / T + CP$$

(3) $$W = CP * T + W'$$

(4) $$P = W' * (1/T) + CP$$

The standard errors of the estimates (SEE) associated with critical power and *W'* were expressed as a coefficient of variation (CV) relative to the parameter estimate. Best individual fit parameter estimates were obtained for each participant by selecting the model producing the lowest summed CV for both parameters across conditions. The same model was used in both conditions for each individual participant.

Statistical analyses. All kinetic parameters (i.e. $\dot{V}O_2$, [HHb + Mb], and heart rate), blood [L^-], [HbO_2 + MbO_2], [THb + Mb] and spatial heterogeneity of [HHb + Mb] during severe exercise were analysed using two- (condition * work rate or condition * muscle), three- (condition * work rate * time or condition * muscle * time), or four-way (condition * muscle

* work rate * time) repeated measures ANOVAs, as appropriate. Where significant differences were found, planned repeated and simple contrasts were used to identify the location of these differences. $\dot{V}O_2$, heart rate and spatial heterogeneity of [HHb + Mb] for moderate exercise as well as differences in critical power and *W'* between conditions were compared using student's paired t-tests. Pearson's correlation coefficient was used to determine relationships between variables of interest. All data are presented as mean ± SD unless otherwise stated. For clarity, and to highlight values for parameters measured across all four severe-intensity work rates, the overall mean across work rates ± SD are presented in text, with work rate-specific mean ± SD presented in tables. Statistical significance was accepted at $P < 0.05$.

RESULTS

Mode-specific $\dot{V}O_2$ max determined from the ramp test was 3.26 ± 0.75 L.min^{-1} (40.8 ± 9.0 mL.kg.min^{-1}), and this was associated with a peak work-rate of 238 ± 39 W. The GET was 1.61 ± 0.21 L.min^{-1} (87 ± 12 W), and as such the exercise bouts at 70% GET were conducted at 61 ± 8 W. There was no main effect of condition [hyperoxia vs. normoxia] ($P = 0.51$) or condition * time interaction effect ($P = 0.79$) on blood [L^-], indicating that blood [L^-] accumulation did not differ between conditions. Blood [L^-] did not differ between rest and baseline (rest: 1.63 ± 0.29 mmol.L^{-1} *versus* baseline: 1.63 ± 0.37 mmol.L^{-1}), however it rose significantly at end-exercise (8.83 ± 1.90 mmol.L^{-1}, main effect of time, $P < 0.001$).

There was a main effect of condition on time to task failure ($P < 0.001$), with time to task failure being greater at WR 1 (hyperoxia: 655 ± 158, normoxia: 482 ± 176 s) and WR 2 (hyperoxia: 403 ± 95, normoxia: 278 ± 60 s) in hyperoxia compared to normoxia. Individual fit optimisation resulted in the W-T model being used for 3 participants and the hyperbolic P-T model for 5 participants. CP was greater in hyperoxia than in normoxia (hyperoxia: 148 ±

311 29, normoxia: 134 ± 27 W; P = 0.006; Table 1), whereas W' was not different between
312 conditions (hyperoxia: 12.8 ± 4.7 kJ, normoxia: 13.9 ± 4.7 kJ; P = 0.50; Table 1). Figure 2
313 illustrates the effect of hyperoxia on the power-duration relationship in a representative
314 participant.

315 Group mean $\dot{V}O_2$ responses to moderate exercise in each condition are displayed in Figure 3,
316 whereas $\dot{V}O_2$ responses to severe exercise at a representative work rate from a representative
317 participant are displayed in Figure 4. $\dot{V}O_2$ peak did not differ between the constant work rate
318 prediction trials in normoxia and the ramp incremental test (P = 0.94), nor between any of the
319 constant work rate trials in hyperoxia (P = 0.73). $\tau_{\dot{V}O2}$ was reduced in hyperoxia compared to
320 normoxia during both moderate exercise (hyperoxia: 33 ± 14 *versus* normoxia: 49 ± 14 s, P =
321 0.019) and severe exercise (hyperoxia: 33 ± 12 *versus* normoxia: 52 ± 22 s, P = 0.007). There
322 were no other differences in any of the $\dot{V}O_2$ kinetics parameters for moderate exercise (Figure
323 3). During severe exercise, there was an increased $\dot{V}O_2$ peak (P = 0.007) in hyperoxia, with a
324 concomitant increase in the $\dot{V}O_2$ slow component amplitude (P = 0.004) (Table 2). There
325 were no other differences in any of the $\dot{V}O_2$ kinetics parameters for severe exercise (Table 2).

326 $\tau_{\dot{V}O2}$ during moderate exercise in hyperoxia was inversely correlated to critical power in
327 hyperoxia (r = -0.89, P < 0.001, Figure 5*B*), however no relationship was observed between
328 $\tau_{\dot{V}O2}$ during moderate exercise in normoxia and normoxic critical power (r = -0.07, P = 0.68,
329 Figure 5*A*). There was no significant linear relationship between ΔCP and $\Delta\tau_{\dot{V}O2}$ derived from
330 the moderate intensity bouts (r = -0.45, P = 0.27, Figure 5C).

331 [HbO_2 + MbO_2] was increased in hyperoxia during both moderate (hyperoxia: 67 ± 17
332 *versus* normoxia: 63 ± 14 μM; P = 0.004, Figure 6*A*, 6*B*) and severe (hyperoxia: 67 ± 10
333 *versus* normoxia: 63 ± 11 μM; P = 0.020) exercise. [THb + Mb] was unchanged between
334 conditions during both moderate (hyperoxia: 92 ± 19 *versus* normoxia: 90 ± 19 μM, P = 0.23;

Figure 6*C*, *D*) and severe exercise (hyperoxia: 153 ± 82 *versus* normoxia: 152 ± 82 μM, P = 0.78). Baseline [HHb + Mb] was lower in hyperoxia compared to normoxia during moderate exercise (hyperoxia: 19 ± 7 *versus* normoxia: 22 ± 8 μM, P = 0.049; Figure 7), however there were no other differences in [HHb + Mb] kinetic parameters for either moderate (Figure 7*A*, 7*B*) or severe (Table 3) exercise. Furthermore, the CV for the $TD_{[HHb + Mb]}$ (moderate, hyperoxia: 27 ± 14 *versus* normoxia: 31 ± 17%, P = 0.19; severe, hyperoxia: 62 ± 38 *versus* normoxia: 43 ± 21%, P = 0.65) and the $\tau_{[HHb + Mb]}$ (moderate, hyperoxia: 41 ± 26 *versus* normoxia: 21 ± 15%, P = 0.11; severe, hyperoxia: 49 ± 14 *versus* normoxia: 57 ± 13%, P = 0.21) did not differ between conditions. There were no differences in any parameters of the heart rate kinetics, apart from a reduction in the absolute amplitude of the heart rate response in hyperoxia (hyperoxia: 98 ± 2 beats.min^{-1} *versus* normoxia: 105 ± 6 beats.min^{-1}, P = 0.005).

DISCUSSION

We have previously demonstrated a causal relationship between $\dot{V}O_2$ kinetics (specifically $\tau_{\dot{V}O2}$) and critical power (Goulding *et al.*, 2017, 2018*a*, 2018*b*). However, stronger evidence in favour of a determining effect of $\tau_{\dot{V}O2}$ on critical power would come from the scaling of any change in critical power (ΔCP) to that of the change in $\tau_{\dot{V}O2}$ ($\Delta\tau_{\dot{V}O2}$). We therefore examined the effect of hyperoxia on $\tau_{\dot{V}O2}$ and critical power compared to normoxia during supine exercise, with $\tau_{\dot{V}O2}$ being precisely determined via multiple repeated bouts of identical exercise in each condition. Our data were consistent with our first two hypotheses; hyperoxia induced a reduction in $\tau_{\dot{V}O2}$ when compared to normoxia during supine exercise, with this speeding of pulmonary $\dot{V}O_2$ kinetics being coincident with an increased critical power. However, the relationship between ΔCP and $\Delta\tau_{\dot{V}O2}$ was not sufficiently consistent across participants to be able to confidently assert that ΔCP scales with $\Delta\tau_{\dot{V}O2}$.

Pulmonary $\dot{V}O_2$ kinetics are typically slower during supine compared to upright cycle exercise (Koga *et al.*, 1999; Jones *et al.*, 2006; Goulding *et al.*, 2017), typically attributed to a loss of the effect of gravity, which impairs perfusion pressure due to the withdrawal of the hydrostatic gradient. Furthermore, femoral artery leg blood flow kinetics are also slower at the onset of exercise in this position (MacDonald *et al.*, 1998), possibly due to the exercising muscles being positioned above the level of the heart, as in the present study, which has been shown to impair heart rate kinetics (Schneider *et al.* 2002) and thus slow the adjustment of convective O_2 delivery relative to exercise performed below the level of the heart (Hughson et al. 1996). In the present study, therefore, it was reasoned that improvements in O_2 delivery afforded by hyperoxia in this body position would be expected to mitigate the extant O_2 delivery limitation and result in a reduction in $\tau_{\dot{V}O2}$ during both moderate and severe exercise. Consequently we observed a ~32 and 40% reduction in $\tau_{\dot{V}O2}$ in response to hyperoxia-induced increases in O_2 delivery during moderate and severe exercise, respectively. The present study therefore provides the first demonstration of a hyperoxia-induced speeding of the fundamental phase of pulmonary $\dot{V}O_2$ kinetics in healthy humans performing whole-body exercise. These findings are significant for the understanding of metabolic control since they provide direct empirical support for the "tipping point" hypothesis proposed by Jones & Poole (2005).

That hyperoxia alleviated an O_2 delivery limitation induced by the supine body position is supported by our NIRS data. The [HHb + Mb] signal derived from NIRS represents the relative balance between O_2 supply and O_2 utilization within the field of interrogation (De Blasi *et al.*, 1993; Ferrari *et al.*, 1997; Grassi *et al.*, 2003). In hyperoxia, baseline [HHb + Mb] was reduced prior to moderate exercise, and $\tau_{[HHb + Mb]}$ was unchanged in the face of faster $\dot{V}O_2$ kinetics, data which are suggestive of an increased O_2 availability. Furthermore, [HbO_2 + MbO_2] was enhanced during both moderate and severe exercise in hyperoxia despite

383 no changes in [THb + Mb]. This observation is consistent with previous studies
384 demonstrating that hyperoxia affords meaningful increases in arterial O_2 content (CaO_2) with
385 unchanged muscle blood flow ($\dot{Q}_m$), such that muscle O_2 delivery (the product of CaO_2 and
386 $\dot{Q}_m$) and thus intracellular PO_2 is increased (Knight *et al.*, 1993; Richardson *et al.*, 1999).
387 Collectively therefore, the present results suggest that the increased CaO_2 afforded by
388 hyperoxia raised intracellular PO_2 and enabled faster $\dot{V}O_2$ kinetics at exercise onset in
389 hyperoxia compared to normoxia.

390 Importantly, we observed a concomitant ~14 W increase in critical power in hyperoxia
391 compared with normoxia. This finding coheres with our previous investigations
392 demonstrating that critical power is increased when $\dot{V}O_2$ kinetics are faster (Goulding *et al.*,
393 2017), and reduced when $\dot{V}O_2$ kinetics are slower (Goulding *et al.*, 2018*a*, 2018*b*). It has
394 previously been suggested that the inability to attain a steady-state above critical power arises
395 because critical power represents the highest power output for which the O_2 deficit can be
396 stabilized (Rossiter, 2010; Murgatroyd *et al.*, 2011). Since a smaller $\tau_{\dot{V}O2}$ results in a smaller
397 O_2 deficit for a given step increase in power output, this would therefore also increase the
398 maximum power output for which the O_2 deficit can be stabilised (i.e. increased critical
399 power).

400 The metabolic basis for this effect is likely to reside, at least in part, with the products of ATP
401 hydrolysis within the exercising skeletal muscles. During high-intensity exercise (i.e. above
402 the GET), there is an additional increase in ATP hydrolysis with time, such that the ATP cost
403 of the work increases above that predicted from the linear relationship between ATP usage
404 and power output below the GET (Grassi *et al.*, 2015; Korzeniewski & Rossiter, 2015;
405 Korzeniewski, 2018). Given the sigmoidal relationship between [ADP] and $\dot{V}O_2$ *in vivo*
406 (Wüst *et al.*, 2011), this additional ATP breakdown during high-intensity exercise would

push [ADP] further towards the flatter portion of the curve, leading to a progressively smaller $\dot{V}O_2$ response for a given elevation in [ADP]. If the exercise intensity is high enough, eventually the $\dot{V}O_2$ response to further elevations in [ADP] would become too small to meet the rising demand for ATP turnover, setting $\dot{V}O_2$ on an irrevocable trajectory towards $\dot{V}O_2$ max. Critical power may therefore represent the power output at which a "critical [ADP]" is achieved during the rest-exercise transition; a low $\tau_{\dot{V}O2}$ would attenuate [ADP] accumulation during the rest-work transition, thus enabling a higher power to be achieved before a critical [ADP] is attained and accounting for a causal relationship with critical power.

Given this proposed mechanism for a causal relationship between $\tau_{\dot{V}O2}$ and critical power, the examination of the ΔCP-$\Delta\tau_{\dot{V}O2}$ relationship between conditions was central to the present study. Though our previous data suggests a determining effect of $\tau_{\dot{V}O2}$ on critical power (Goulding *et al.*, 2017, 2018*a*, 2018*b*); such causality would be more strongly inferred if ΔCP scaled with $\Delta\tau_{\dot{V}O2}$. Hence critical power and precise measures of $\tau_{\dot{V}O2}$ were derived in each condition, the latter via multiple bouts of identical exercise that were otherwise unobtainable in previous investigations (Goulding *et al.*, 2017, 2018*a*, 2018*b*). Despite the observation of a concomitant reduction in $\tau_{\dot{V}O2}$ and increase in critical power in hyperoxia in the present study, the ΔCP-$\Delta\tau_{\dot{V}O2}$ relationship was not consistent across all participants (Fig. 5C). Such a finding thus questions the ubiquity of a causal relationship between $\tau_{\dot{V}O2}$ and critical power and may indicate that, as previously suggested (Goulding *et al.*, 2017), the relative importance of $\tau_{\dot{V}O2}$ in determining critical power may be dependent upon the presence or absence of an O_2 availability limitation to $\tau_{\dot{V}O2}$. Indeed a consistent feature of exercise in the supine position is the lack of an association between critical power and $\tau_{\dot{V}O2}$ (Goulding *et al.*, 2017, 2018*b*), which was restored in hyperoxia (r = -0.89, Figure 5B). Moreover, the concentration of a given respiratory regulator (e.g. ADP, Pi, NADH + H^+, etc.) required to elicit a given $\dot{V}O_2$ is dependent upon the intracellular PO_2 (Wilson *et al.*, 1979; Wilson &

Erecińska, 1985; Rumsey *et al.*, 1990; Hogan *et al.*, 1992*a*, 1992*b*). Hence the increased intracellular PO_2 afforded by hyperoxia could have reduced the intracellular perturbations in [ADP] required to elicit a given $\dot{V}O_2$ and independently increased the work-rate at which a "critical [ADP]", and thus critical power, was attained.

However, this interpretation of the data in Figure 5 is not consistent with our previous study in the supine position demonstrating that a slowing of $\dot{V}O_2$ kinetics via work-to-work exercise, independent of the extant O_2 delivery limitation, reduced critical power (Goulding *et al.*, 2018*b*). The lack of association between $\tau_{\dot{V}O2}$ and critical power in the supine position can thus be alternatively explained by this body position introducing a kinetic dissociation between pulmonary and muscle $\dot{V}O_2$ ($\dot{V}O_{2m}$; the former being a proxy of the latter) due to the inherent low baseline O_2 availability and slow O_2 delivery kinetics (Barstow *et al.*, 1990; Benson *et al.*, 2013). Computer modelling shows that this would cause pulmonary $\dot{V}O_2$ kinetics to become faster than $\dot{V}O_{2m}$ kinetics (Benson *et al.*, 2013), dissociating $\tau_{\dot{V}O2}$ from $\tau_{\dot{V}O2m}$ and obscuring the critical power - $\tau_{\dot{V}O2}$ relationship. Improvements in O_2 availability due to hyperoxia would thus reverse the otherwise impaired O_2 availability and restore the kinetic coupling between pulmonary and muscle $\dot{V}O_2$ kinetics (see Figure 5B). Such an explanation retains consistency with our previous data both in the upright and supine positions (Goulding *et al.*, 2018*a*, 2018*b*) and thus supports the notion of a prevailing dependency of critical power on $\tau_{\dot{V}O2}$. The inconsistent ΔCP-$\Delta\tau_{\dot{V}O2}$ relationship is therefore likely due to moving between conditions where the absolute values of $\tau_{\dot{V}O2m}$ and $\tau_{\dot{V}O2}$ are and are not dissociated.

In contrast to other reports of the effect of hyperoxia on critical power & *W'* (Vanhatalo *et al.*, 2010), whilst critical power increased, *W'* remained unchanged. We also observed an increased $\dot{V}O_2$ slow component amplitude in the present study in hyperoxia, a finding that

456 contrasts with previous reports of a decreased slow component amplitude in hyperoxia
457 (Haseler *et al.*, 2004; Wilkerson *et al.*, 2006). However, in these studies the slow component
458 was measured over a 6 minute period, whereas in the present study exercise was continued
459 until the limit of tolerance. In contrast, in the present study, the fundamental $\dot{V}O_2$ amplitude
460 was unchanged with an increased $\dot{V}O_2$ peak, necessitating an increased $\dot{V}O_2$ slow component.
461 However, since there was a concomitant increase in critical power and $\dot{V}O_2$ peak, this likely
462 determined the unchanged *W'*. Additionally, the $\dot{V}O_2$ slow component amplitude is greatest at
463 work rates nearest to critical power (Poole *et al.*, 1994); since critical power was increased in
464 hyperoxia, this would have caused the criterion trials to be conducted in closer proximity to
465 critical power and thus raise the $\dot{V}O_2$ slow component relative to normoxia.

466 In summary, the present finding of a reduction in $\tau_{\dot{V}O2}$ and increase in critical power during
467 supine exercise in hyperoxia provides further support for the notion that $\tau_{\dot{V}O2}$ is an
468 independent determinant of critical power. However, the inconsistent relationship between
469 ΔCP and $\Delta\tau_{\dot{V}O2}$ does not permit the exclusion of a role for O_2 availability *per se*, at least in
470 the supine position where O_2 availability is limiting. Hence, despite our previous findings
471 (Goulding *et al.*, 2018*b*) the absence of a relationship between $\tau_{\dot{V}O2}$ and critical power in
472 normoxia, and its subsequent restoration in hyperoxia may be considered as supportive for a
473 predominant role of O_2 availability in determining critical power during supine exercise.
474 Equally however, in line with our previous study this finding may reflect a kinetic distortion
475 between pulmonary and muscle $\dot{V}O_2$ in the supine position between $\tau_{\dot{V}O2}$ and critical power
476 that is restored in hyperoxic conditions. Hence, despite our previous findings (Goulding *et*
477 *al.*, 2018*b*), further research is required to precisely elucidate the relative contributions of
478 $\tau_{\dot{V}O2}$ and O_2 as determining factors for critical power.

479

ADDITIONAL INFORMATION

The authors declare no competing interests or external sources of funding. SM conceived the idea for this project. SM, DMR and RPG design the experiments, RPG collected and analysed the data and drafted the manuscript. SM, DMR and RPG revised it critically for intellectual content and all authors approved the final version of the manuscript. All authors agree to be accountable for all aspects of the work.

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646 **TABLES**

647

Table 1. The critical power and *W'* estimates for each participant in normoxia and hyperoxia

	Critical power (W)			*W'* (kJ)		
Participant	Normoxia	Hyperoxia	Δ (%)	Normoxia	Hyperoxia	Δ (%)
1	98	115	17.0	8.9	6.2	-30.9
2	130	133	2.1	13.3	13.9	4.1
3	181	196	8.8	19.0	21.3	12.3
4	154	159	3.0	7.9	7.9	-1.3
5	139	151	8.7	14.6	14.0	-4.5
6	111	124	12.0	10.9	14.6	33.9
7	146	183	25.2	21.7	10.6	-51.3
8	114	127	10.8	15.1	14.1	-6.3
Mean	134	149 *	10.9	13.9	12.8	-5.5
S.D	27	29	7.5	4.7	4.7	26.0

Δ is the percentage difference between conditions. * indicates significantly difference from normoxia ($P < 0.05$).

Table 2. Pulmonary oxygen uptake responses to severe-intensity constant work rate exercise in each condition.

Parameter	Normoxia	Hyperoxia
$\dot{V}O_2$ baseline, L.min^{-1}		
WR 1	1.02 ± 0.07	1.03 ± 0.13
WR 2	1.12 ± 0.13	1.00 ± 0.12
WR 3	0.99 ± 0.10	1.00 ± 0.22
WR 4	1.04 ± 0.12	0.97 ± 0.12
$TD_{\dot{V}_{O2}}$, s		
WR 1	9 ± 7	13 ± 6
WR 2	13 ± 12	14 ± 10
WR 3	6 ± 9	14 ± 11
WR 4	16 ± 9	18 ± 4
$\tau_{\dot{V}O2}$, s *		
WR 1	51 ± 12	34 ± 15
WR 2	57 ± 21	39 ± 7
WR 3	54 ± 8	28 ± 13
WR 4	47 ± 17	32 ± 13
$A_{\dot{V}_{O2}}$, L.min^{-1} ‡		
WR 1	1.72 ± 0.36	1.71 ± 0.62
WR 2	1.94 ± 0.42	2.16 ± 0.48
WR 3	2.26 ± 0.52	2.15 ± 0.65
WR 4	2.28 ± 0.53	2.39 ± 0.43
Absolute $A_{\dot{V}_{O2}}$, L.min^{-1} ‡		
WR 1	2.72 ± 0.39	2.74 ± 0.62
WR 2	2.93 ± 0.41	3.07 ± 0.51
WR 3	3.26 ± 0.69	3.15 ± 0.73
WR 4	3.32 ± 0.49	3.36 ± 0.38
$SC_{\dot{V}_{O2}}$, L.min^{-1} *‡		
WR 1	0.45 ± 0.34	0.81 ± 0.34
WR 2	0.27 ± 0.38	0.51 ± 0.34
WR 3	0.05 ± 0.09	0.45 ± 0.25
WR 4	0.00 ± 0.00	0.17 ± 0.51
End-exercise $\dot{V}O_2$ (L.min^{-1}) *		
WR 1	3.16 ± 0.44	3.55 ± 0.63

WR 2	3.31 ± 0.63	3.66 ± 0.73
WR 3	3.14 ± 0.58	3.62 ± 0.68
WR 4	3.11 ± 0.51	3.54 ± 0.72

$TD_{\dot{V}O2}$, fundamental time delay; $\tau_{\dot{V}O2}$, fundamental time constant; $\tau_{\dot{V}O2}$ 95% CI, 95% confidence interval associated with the fundamental time constant; $A_{\dot{V}O2}$, fundamental amplitude; Absolute $A_{\dot{V}O2}$, baseline $\dot{V}O_2$ + fundamental $\dot{V}O_2$ amplitude; Gain, increase in fundamental phase $\dot{V}O_2$ per unit increase in power output; $SC_{\dot{V}O2}$, magnitude of the $\dot{V}O_2$ slow component. * indicates significant main effect of condition, † indicates significant main effect of work rate ($P < 0.05$).

Table 3. Muscle deoxygenation kinetic responses at each power output for both muscle sites in normoxia and hyperoxia.

	Rectus Femoris		Vastus Lateralis	
Parameter	Normoxia	Hyperoxia	Normoxia	Hyperoxia
$[HHb+Mb]_{(b)}$, μM				
WR 1	19.3 ± 8.3	19.1 ± 10.6	20.8 ± 6.4	20.1 ± 7.3
WR 2	21.7 ± 9.5	19.2 ± 8.6	18.9 ± 7.7	22.5 ± 8.2
WR 3	19.7 ± 11.3	18.8 ± 8.7	23.2 ± 7.5	17.6 ± 9.6
WR 4	16.7 ± 8.3	18.7 ± 8.1	20.5 ± 9.4	18.9 ± 4.3
$TD_{[HHb+Mb]}$, s				
WR 1	10 ± 5	7 ± 3	7 ± 7	4 ± 3
WR 2	4 ± 2	7 ± 7	6 ± 6	5 ± 3
WR 3	5 ± 8	5 ± 3	3 ± 2	5 ± 8
WR 4	4 ± 3	10 ± 5	5 ± 3	11 ± 6
$\tau_{[HHb+Mb]}$, s # *				
WR 1	19 ± 10	16 ± 11	10 ± 3	13 ± 11
WR 2	24 ± 15	21 ± 21	9 ± 4	9 ± 3
WR 3	21 ± 7	19 ± 14	10 ± 4	13 ± 8
WR 4	21 ± 10	19 ± 10	9 ± 3	6 ± 3
$A_{[HHb+Mb]}$, μM				
WR 1	8.2 ± 3.7	5.4 ± 3.6	19.0 ± 18.4	19.0 ± 19.1
WR 2	9.3 ± 5.5	7.2 ± 5.6	20.5 ± 16.2	19.8 ± 16.6
WR 3	8.4 ± 5.5	9.7 ± 7.1	24.1 ± 19.7	20.2 ± 16.6
WR 4	10.9 ± 6.5	11.3 ± 5.2	18.7 ± 16.5	18.0 ± 17.5
Absolute $A_{[HHb+Mb]}$, μM				
WR 1	27.5 ± 11.7	24.6 ± 11.0	39.7 ± 21.6	39.1 ± 23.5
WR 2	29.9 ± 11.9	26.4 ± 11.5	36.9 ± 22.2	42.4 ± 21.7
WR 3	27.0 ± 13.7	28.6 ± 12.2	41.4 ± 26.2	37.8 ± 25.1
WR 4	27.5 ± 14.2	30.0 ± 12.0	39.1 ± 24.3	36.9 ± 20.3
$SC_{[HHb+Mb]}$, μM				
WR 1	2.6 ± 3.7	6.2 ± 17.0	2.3 ± 2.9	0.0 ± 9.8
WR 2	3.9 ± 7.3	8.1 ± 15.2	2.0 ± 2.9	0.0 ± 3.9
WR 3	1.1 ± 1.7	0.0 ± 2.6	0.0 ± 4.9	1.6 ± 3.7
WR 4	0.1 ± 2.2	0.0 ± 1.2	0.0 ± 15.7	0.1 ± 1.5
End-exercise [HHb + Mb] (μM)				
WR 1	30.1 ± 12.6	30.8 ± 22.0	42.0 ± 22.5	36.1 ± 17.4
WR 2	33.7 ± 14.1	34.5 ± 18.4	39.4 ± 23.5	42.3 ± 21.2

WR 3	28.1 ± 14.4	28.5 ± 13.1	40.1 ± 23.8	39.4 ± 24.2
WR 4	27.6 ± 13.0	30.0 ± 11.7	34.2 ± 17.2	37.1 ± 19.6

$[HHb+Mb]_{(b)}$, mean [HHb+Mb] over last 30 s of baseline; $TD_{[HHb+Mb]}$, time delay before exponential rise in [HHb+Mb]; $\tau_{[HHb+Mb]}$, time constant of [HHb+Mb] response; $A_{[HHb+Mb]}$, amplitude of [HHb+Mb] response; Absolute $A_{[HHb+Mb]}$, baseline [HHb + Mb] + amplitude [HHb + Mb]; $SC_{[HHb+Mb]}$, magnitude of the [HHb+Mb] slow component; End-exercise [HHb + Mb], mean [HHb + Mb] during finals 30 s of exercise. # indicates significant main effect of muscle ($P < 0.05$).

685 **FIGURE LEGENDS**

686 Figure 1. Group relationship between subcutaneous adipose tissue thickness (ATT) and
687 resting total haemoglobin ([THb + Mb]) measured by NIRS in the rectus femoris (*A*; RF) and
688 vastus lateralis (*B*; VL). Normalization procedure is detailed in the *methods* section.

689 Figure 2. The hyperbolic power-duration relationship (*A*; equation 4) and the linear work-
690 time relationship (*B*; equation 5) in normoxia (clear circles) and hyperoxia (black circles) in
691 participant 5. In *A*, the critical power is the power asymptote and *W'* is the curvature constant.
692 In *B*, the critical power is the gradient and the *W'* is the *y*-intercept of the linear regression.

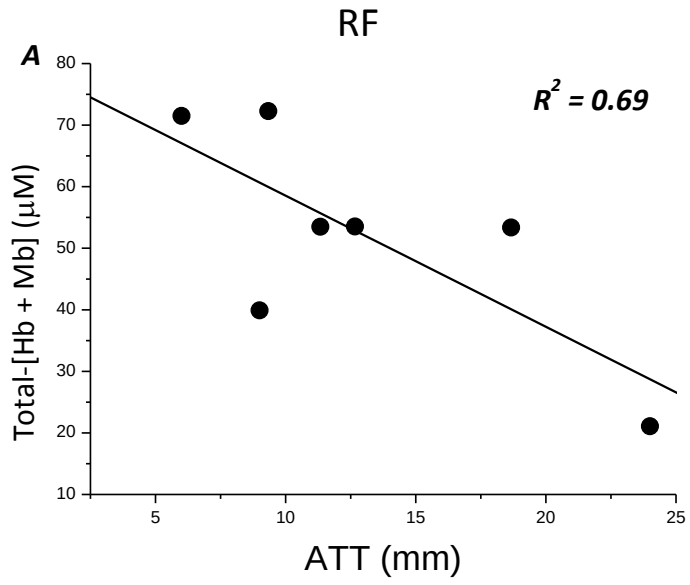
693 Figure 3. Group mean pulmonary oxygen uptake ($\dot{V}O_2$) responses to moderate exercise in
694 normoxia (dashed grey line) and hyperoxia (solid black line). Group mean exponential fits
695 are overlaid onto the $\dot{V}O_2$ responses as solid curved lines to highlight differences between
696 conditions. Error bars omitted for clarity. FiO_2; fraction of inspired O_2.

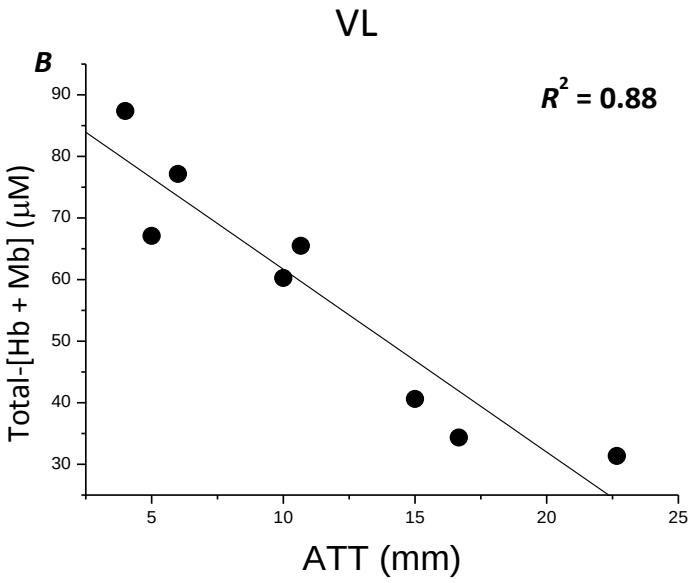
697 Figure 4. Pulmonary oxygen uptake ($\dot{V}O_2$) responses and best-fit modelled responses of a
698 representative participant at a single work rate during severe exercise in the normoxic (grey
699 line) and hyperoxic (black line) conditions. The time constant values for the fundamental
700 phase of pulmonary oxygen uptake kinetics ($\tau_{\dot{V}O2}$) are displayed for each transition, with the
701 solid curved lines representing the modelled fits. Lines of residuals for each condition are
702 displayed at the bottom.

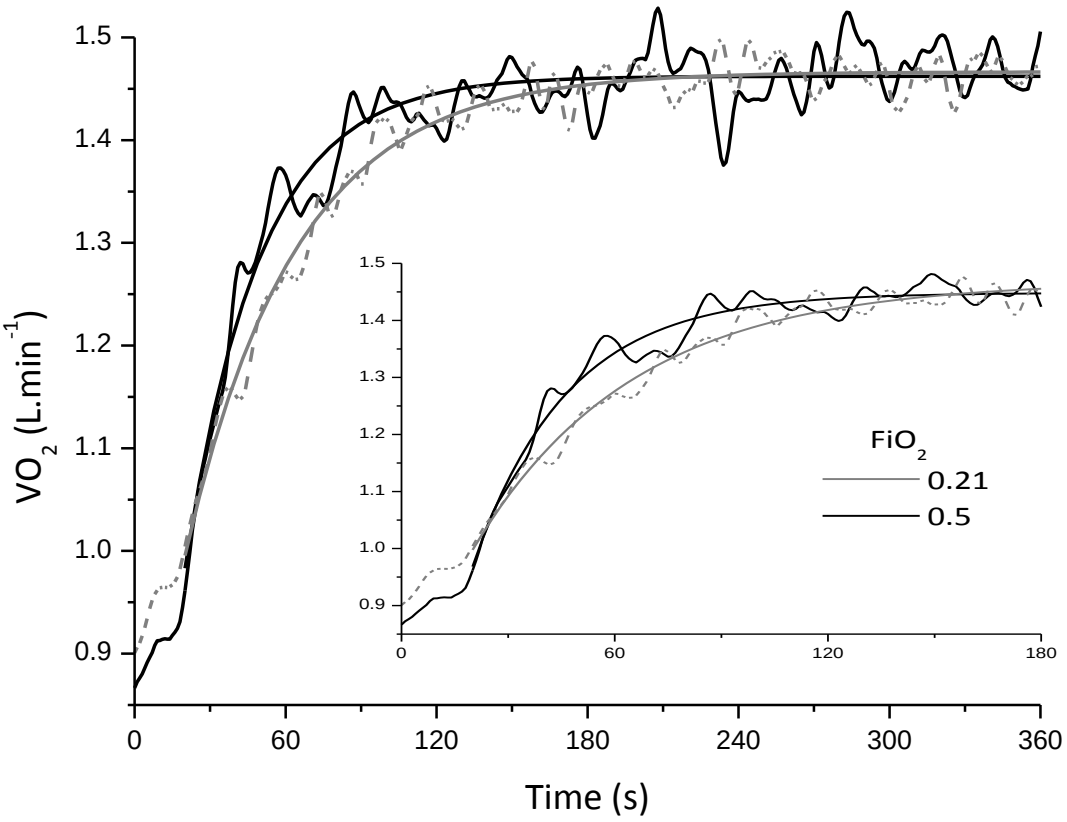
703 Figure 5. Correlations between critical power normalized to body mass and the time constant
704 for the fundamental phase of pulmonary oxygen uptake kinetics ($\tau_{\dot{V}O2}$) for the normoxic (*A*)
705 and hyperoxic (*B*) conditions during moderate exercise. The relationship between the change
706 in critical power (ΔCP) and the change in $\tau_{\dot{V}O2}$ ($\Delta\tau_{\dot{V}O2}$) is also displayed. The correlation
707 shown in *B* was significant ($P < 0.001$).

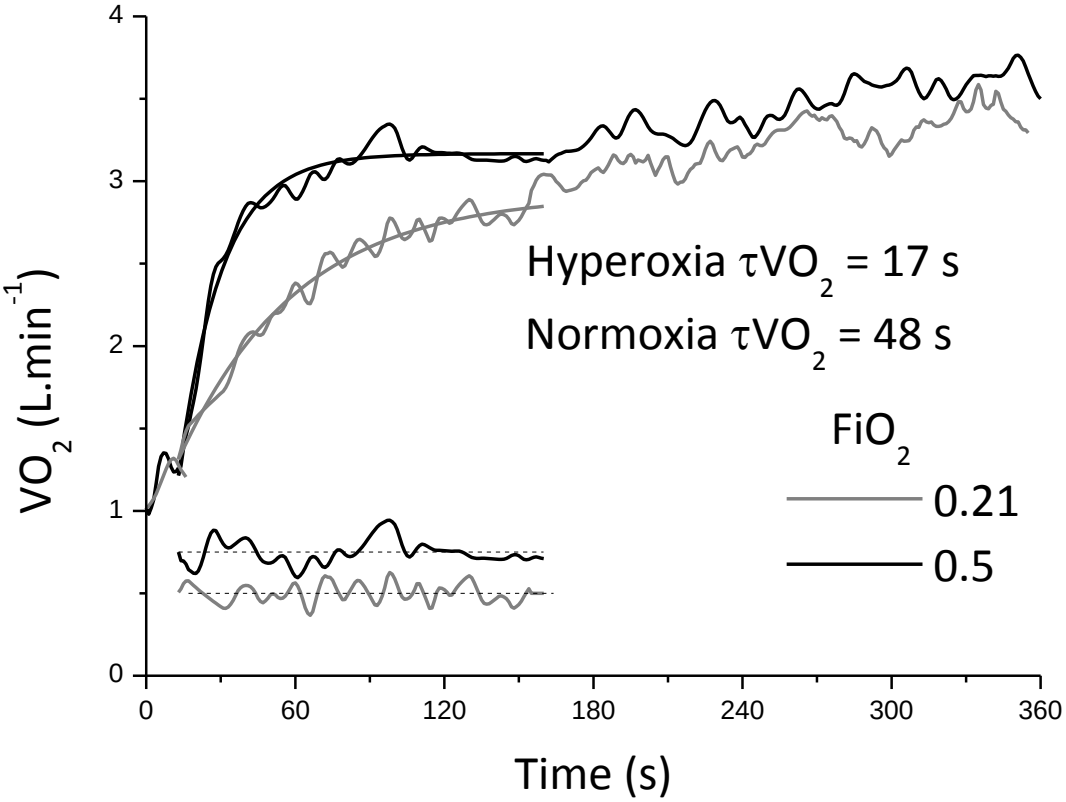
Figure 6. Comparisons of group means ± SD during moderate exercise across both muscles for oxyhaemoglobin (*A & B*; [HbO_2 + MbO_2]) and total haemoglobin (*C & D*; [THb + Mb]) between conditions. Responses for the rectus femoris (RF) are displayed in *A* and *C*, whereas vastus lateralis (VL) is displayed in *B* and *D*. Open circles, normoxia; closed circles, hyperoxia. * indicates significant difference between conditions ($P > 0.05$).

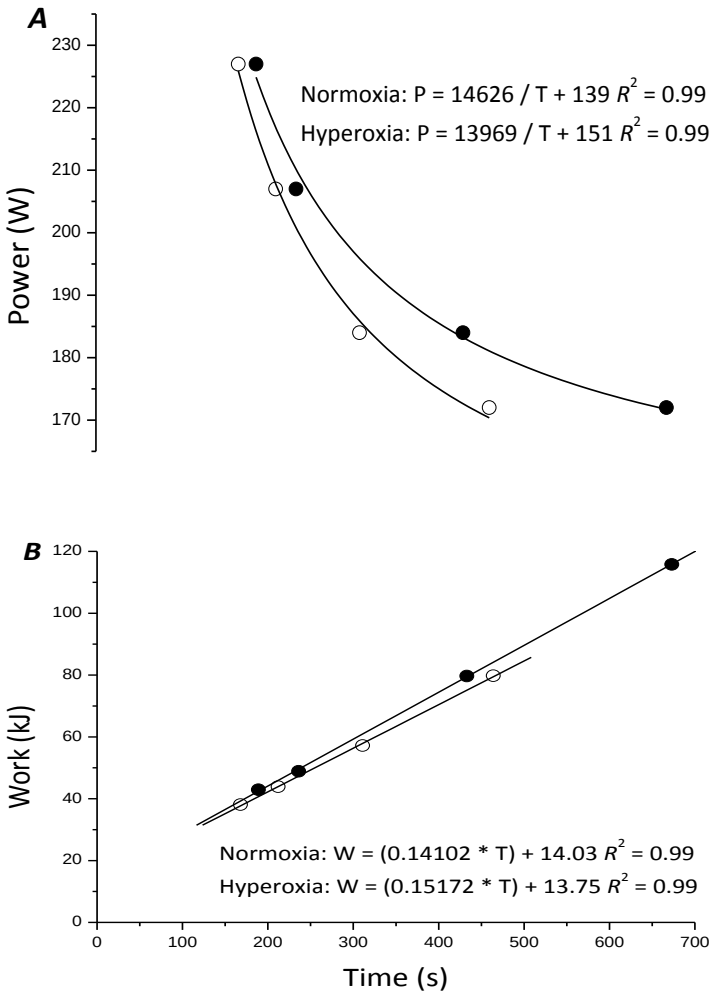
Figure 7. Group mean muscle deoxyhaemoglobin (HHb + Mb) responses to moderate exercise in the rectus femoris (*A*; RF) and the vastus lateralis (*B*; VL). Error bars omitted for clarity. Dashed vertical line indicates exercise onset. FiO_2; fraction of inspired O_2.

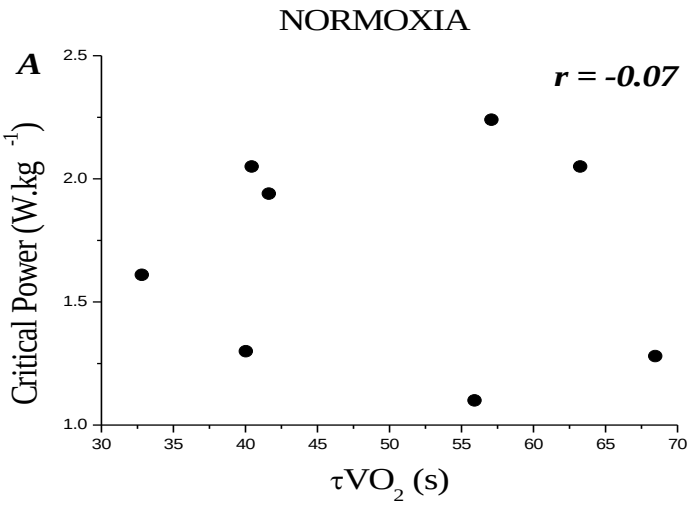

RF
A
R^2 = 0.69
Total-[Hb + Mb] (μM)
ATT (mm)
80
70
60
50
40
30
20
10
5
10
15
20
25

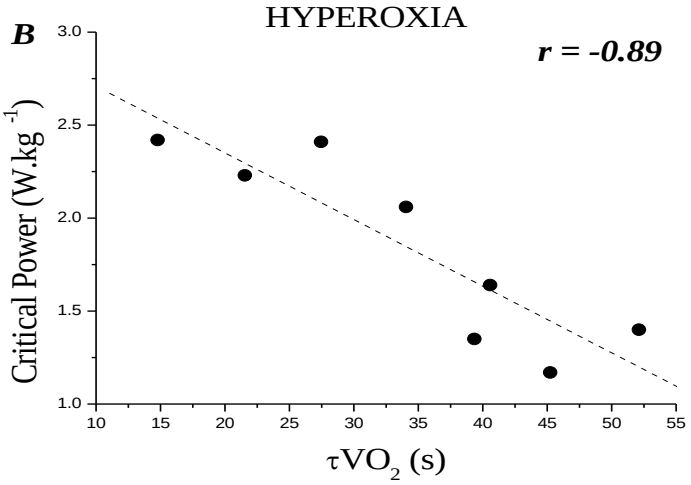

VL
B
R^2 = 0.88
Total-[Hb + Mb] (μM)
ATT (mm)
90
80
70
60
50
40
30
5
10
15
20
25

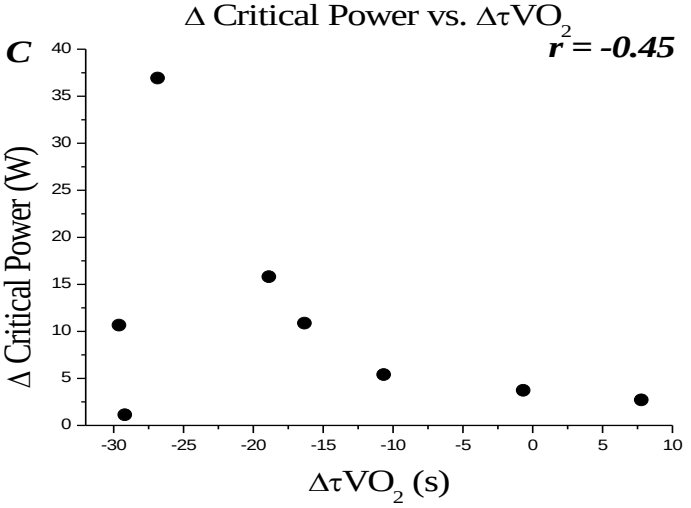

1.5
1.4
1.3
1.2
1.1
1.0
0.9
VO2 (L.min-1)
0
60
120
180
240
300
360
Time (s)
FiO2
0.21
0.5

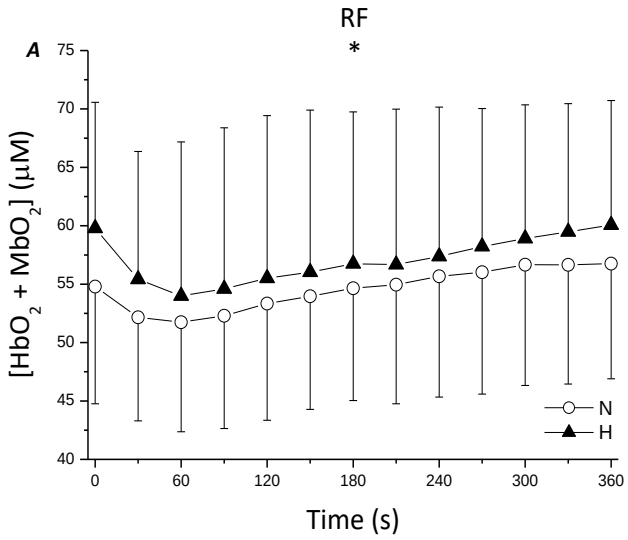

4
3
2
1
0
0
60
120
180
240
300
360
VO2 (L.min-1)
Time (s)
Hyperoxia τVO2 = 17 s
Normoxia τVO2 = 48 s
FiO2
0.21
0.5

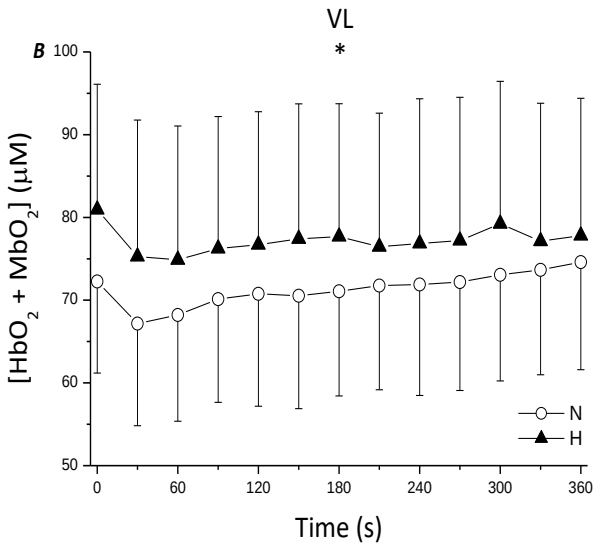

A
Power (W)
230
220
210
200
190
180
170
Normoxia: P = 14626 / T + 139 R^2 = 0.99
Hyperoxia: P = 13969 / T + 151 R^2 = 0.99
B
Work (kJ)
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Time (s)
Normoxia: W = (0.14102 * T) + 14.03 R^2 = 0.99
Hyperoxia: W = (0.15172 * T) + 13.75 R^2 = 0.99

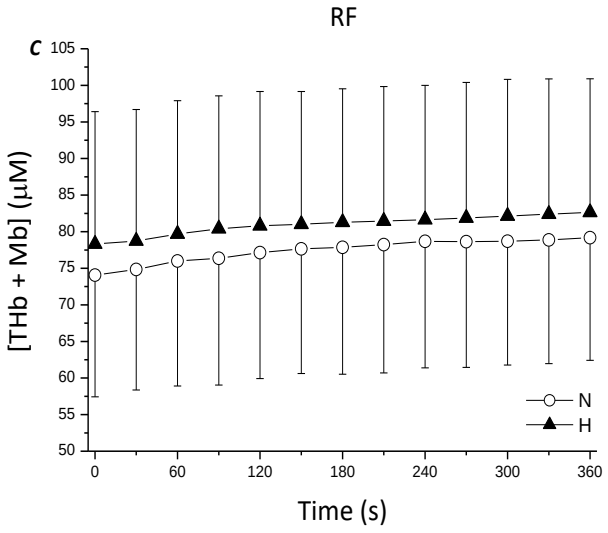

NORMOXIA
A
r = -0.07
Critical Power (W.kg -1)
2.5
2.0
1.5
1.0
30
35
40
45
50
55
60
65
70
τVO2 (s)

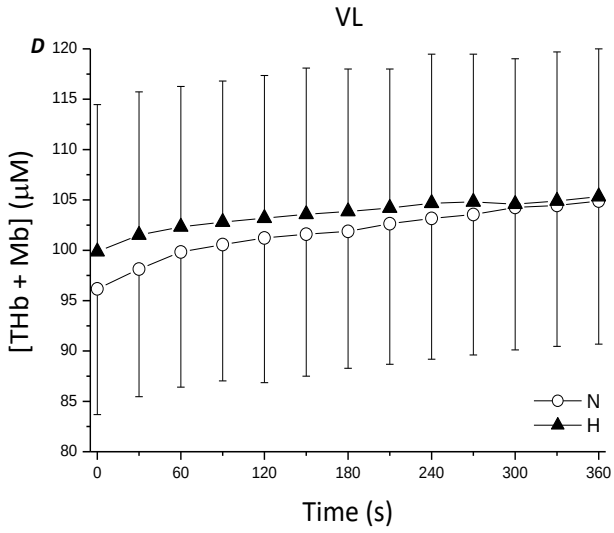

HYPEROXIA
B
r = -0.89
Critical Power (W.kg -1)
3.0
2.5
2.0
1.5
1.0
10
15
20
25
30
35
40
45
50
55
τVO2 (s)

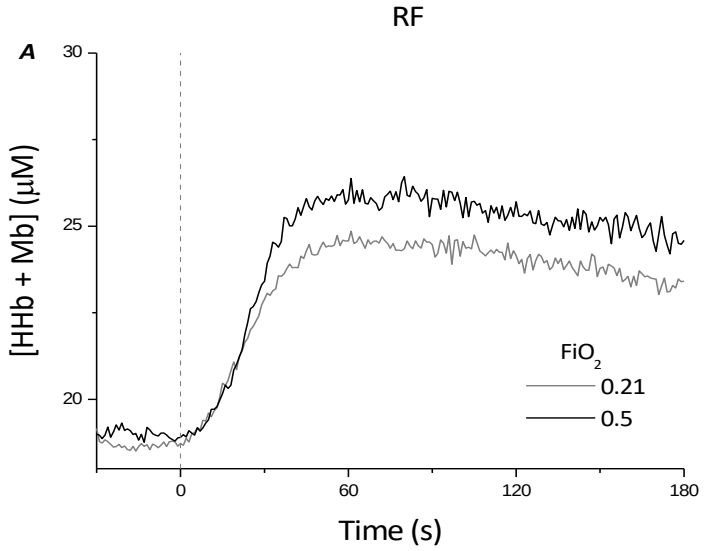

Δ Critical Power vs. ΔτVO2
C
r = -0.45
Δ Critical Power (W)
40
35
30
25
20
15
10
5
0
-30
-25
-20
-15
-10
-5
0
5
10
ΔτVO2 (s)

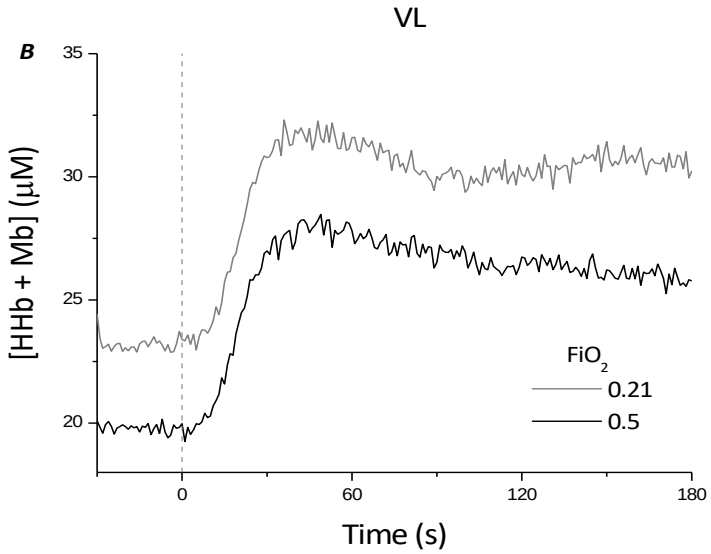

RF
*
A
[HbO2 + MbO2] (μM)
Time (s)
N
H


VL
*
B
[HbO2 + MbO2] (μM)
Time (s)
N
H


RF
C
[THb + Mb] (μM)
Time (s)
N
H


VL
D
[THb + Mb] (μM)
Time (s)
N
H


RF
A
30
25
20
[HHb + Mb] (μM)
FiO2
0.21
0.5
0
60
120
180
Time (s)


VL
B
35
30
25
20
[HHb + Mb] (μM)
FiO2
0.21
0.5
0
60
120
180
Time (s)