Intensity-dependence of exercise and active recovery in high-intensity interval training

Ole J. Kemi[1]*, Ewan Fowler[1], Karen McGlynn[1], Deborah Primrose[1], Rachel Smirthwaite[1], John Wilson[1]

[1]School of Life Sciences and Institute of Cardiovascular and Medical Sciences; College of Medical, Veterinary and Life Sciences; University of Glasgow, Glasgow, UK.

*Corresponding author: Dr Ole J Kemi, Sir James Black Building, University of Glasgow, Glasgow, G12 8QQ, UK. E-mail: ole.kemi@glasgow.ac.uk; Phone: +44 (0)141 330 5962

ABSTRACT

BACKGROUND: High-intensity interval training (HIIT) with interspersing active recovery is an effective mode of exercise training in cohorts ranging from athletes to patients. Here, we assessed the intensity-dependence of the intervals and active recovery bouts for permitting a sustainable HIIT protocol.

METHODS: 14 males completed 4x4-minute HIIT protocols where intensities of intervals ranged 80-100% of maximal oxygen uptake (VO_{2max}) and active recovery ranged 60-100% of lactate (La^-) threshold (LT). Blood La^- measurements indicated fatigue, while tolerable duration of intervals indicated sustainability.

RESULTS: HIIT at 100% of VO_{2max} allowed 44±10% [30-70%] completion, i.e. fatigue occurred after 7minutes:6seconds of the intended 16 minutes of high intensity, whereas HIIT at 95-80% of VO_{2max} was 100% sustainable ($p<0.01$). Measured intensity did not differ from intended intensity across the protocols ($p>0.05$). Blood La^- concentration [La^-] increased to 9.3±1.4mM during HIIT at 100% of VO_{2max}, whereas at 80-95% of VO_{2max} stabilised at 2-6mM in an intensity-dependent manner ($p<0.01$ vs 100% of VO_{2max} and $p<0.05$ vs baseline). Active recovery at 60-70% of LT *during* HIIT associated with steady-state blood [La^-] peaking at 6-7mM, whereas at 80-100% of LT, blood [La^-] accumulated to 10-13mM ($p<0.05$). *After* HIIT, active recovery at 80-90% of LT cleared blood [La^-] 90% faster than at 60-70% of LT ($p<0.05$).

CONCLUSIONS: To permit highest exercise stress during 4x4-minute HIIT, exercise intensity should be set to 95% of VO_{2max}, whereas active recovery should be set to 60-70% of LT *during* HIIT and 80-90% of LT *after* HIIT to most efficiently prevent excess La^- and aid recovery.

Key words: High-intensity interval training, Endurance, Active recovery, Fatigue, Lactate.

TEXT

Introduction

High-intensity interval training (HIIT) in the form of 4x4-minute intervals with interspersed recovery bouts, is a popular and effective form of exercise training that has been adopted widely by many different cohorts ranging from athletes to patients[1-3] and that in many instances accrues greater benefits than moderate-intensity exercise. 4x4-minute HIIT performed at 90-95% of maximum heart rate (HR) is significantly more effective for increasing maximal oxygen uptake (VO_{2max}) and cardiac contractile parameters,[3] as well as performance[2] than exercise at 70% of maximum HR, even after matching for energy consumption. For peripheral and skeletal muscle adaptations, similar intensity-dependence of effects has generally been observed, albeit to a lesser extent or with less confidence.[4] However, although the intensity-dependence of effect has been accepted as a principle, the highest intensity of HIIT that may be achieved and completed has not yet been reported.

Moreover, because the intensity of HIIT is above lactate (La^-) threshold (LT)[5,6] or critical velocity,[7] it is limited by early onset of fatigue that coincides with metabolite accumulation, including La^-. This is repelled by active recovery bouts interspersing the high-intensity intervals, which allow for accumulation of high intensity beyond that achieved by each individual 4-minute bout, but the optimal active recovery intensity during HIIT remains unknown.

Thus, the benefit of HIIT is firstly restricted by the balance between exercising at the highest sustainable intensity for the duration of the work period; too high intensity limits duration, and too low intensity, though sustainable, carries less adaptation. Secondly, the degree of recovery achieved during the active recovery bouts also affects the outcome. As such, finding this balance becomes important to optimize the outcome of HIIT.

Here, we determined the highest sustainable intensity that allows completion of a full 4x4-minute HIIT protocol, and subsequently assessed intensity-dependence of active recovery for removing La^- (La^- in this context being a marker of fatigue[5,6]) during HIIT to thereby identify if an optimal intensity of active recovery during 4x4-minute HIIT exists.

Materials and Methods

Subjects

14 moderately active males volunteered for participation, with characteristics as follows (mean±SD): 23.8±3.0 years, 180.2±5.7 cm and 70.5±7.0 kg; all were health screened and signed informed consent forms prior to commencement. Exclusion criteria were regular smoking, medication, drugs, and pre-existing medical conditions contraindicative to exercise testing, as well as avoidance of exhaustive exercise and alcohol within 48 hours and food and fluids except water within 2 hours of each test. The Institutional Review Board (University of Glasgow College of Medical Veterinary and Life Sciences Ethics Committee, Chair Professor W Martin, #1006, 13/09/2013) approved the study and it conformed to the Declaration of Helsinki.

Procedures

We designed 2 repetitive HIIT protocols to identify optimal intensity and recovery. To minimize training effects during participation of the study, each subject completed only 1 protocol following randomization. As such, subjects were randomized to either of the exercise intensity of HIIT (n=7) or the active recovery intensity of HIIT (n=7) protocols. Within each protocol, subjects completed 2 incremental exercise tests and 5 HIIT tests (see below for details), with at least 48 hours separating each test.

Incremental Exercise Tests

Subjects warmed-up by a 10-minute, 8km/h flat treadmill run (PPS55 Med, Woodway, Birmingham, UK). A ramped incremental exercise test measured VO_{2max}, with speed increasing 1 km/h/minute until volitional exhaustion, with VO_{2max} considered achieved with at least 3 of 4 criteria being met: oxygen uptake (VO_2) plateau, respiratory exchange ratio >1.15, post-exercise La^- concentration ($[La^-]$) >8mM, and HR within 10bpm of age-predicted maximum.[5,6]

After a similar warm-up, LT was measured with speed increasing 0.5km/h every 4 minutes, until blood $[La^-]$, measured at end of each 4-minute step, increased exponentially.[5-7] LT was determined by identifying the deflection point of blood La^- increase.[8]

La^- was sampled from finger prick capillary blood (Analox GM7 Lactate Analyzer, Analox, Hammersmith, UK), VO_2 measured by continuous 1-minute Douglas bag-collected expired gas samples (Servomex 4100 Gas Analyser, Servomex, Sussex, UK), and HR by a chest monitor (Polar Heart Rate FS1, Polar, Kempele, Finland).

Exercise Intensity of HIIT

To identify highest sustainable exercise intensity of HIIT, 7 subjects completed a series of 5 randomized HIIT protocols, whereby the 4-minute high-intensity intervals were set to correspond to 80%, 85%, 90%, 95%, or 100% of VO_{2max} (ON-transients; Figure 1A) for the entire session, with the subjects actively encouraged to complete each protocol as much as possible before volitional exhaustion. VO_2 and HR measurements in the last minute of each interval confirmed the intensity of each ON-transient. 4-minute active recovery bouts (OFF-transients), set to 60% of LT, interspersed the ON-transients (Figure 1A). Time sustained in the ON-transient was recorded.

Active Recovery Intensity of HIIT

To identify intensity-dependence of active recovery (OFF-transients) of a HIIT protocol, 7 subjects completed a series of 5 HIIT protocols, whereby the 4-minute high-intensity intervals were set to 95% of VO_{2max} (as it was identified as the optimal exercise intensity of the ON-transients in the above-mentioned experiments), and the 4-minute active recovery bouts were randomized to correspond to 60%, 70%, 80%, 90%, or 100% of LT (OFF-transients; Figure 1A) for the entire session, with the last OFF4-transient prolonged to allow full recovery. Blood La^- was sampled at the end of each ON-transient and every minute of OFF-transients, whereas ON-transient VO_2 was recorded to confirm intensity.

Statistics

Data are expressed as means±standard deviation (SD). One-way analysis of variance (ANOVA) and repeated measures general linear model (GLM) assessed differences between intensities; Scheffe post-hoc tests identified effects. Statistical significance was set to $p<0.05$. For analysis of La^- clearance during prolonged active recovery after the HIIT protocol, we normalized La^- removal curves and fitted exponential decay curves to derive time constants (2/3) and computed 1st derivatives for maximal rate of La^- clearance, whereby fitted curves were also compared to raw curves by regression.

Results

Incremental Exercise Tests

Subjects presented with VO_{2max} 60.5±6.0mL/kg/min, maximal HR 198±4bpm, and LT at running velocity 11.9±2.0km/h, VO_2 40.2±4.2mL/kg/min, %VO_{2max} 66.4±4.5%, HR 160±7bpm, and %HR maximum 79.3±6.0%. This corresponds with a moderate to good level of fitness and indicates subjects were regularly physically active.

Exercise Intensity of HIIT

First, we identified the optimal exercise intensity of the current 4x4-minute HIIT protocol, defining this to be the highest sustainable intensity that allowed completion of the 4x4-minute ON-transients of a given intensity protocol. We found that when the intensity of the ON-transients was set to 100% of VO_{2max}, only 44±10% of the protocol could be completed [range 30-70%] with intended intensity, before it dropped and irretrievable (for the session) onset of fatigue occurred (Figure 1B). Thus, fatigue occurred on average after 7 minutes 6 seconds, i.e. 3 minutes 6 seconds into the 2^{nd} ON-transient [range 4 minutes 57 seconds-10 minutes 51 seconds], of a maximum ON-transient exercise time of 16 minutes. Effectively, this means only 2-3 of 4 ON-transients could be sustained and completed at this intensity. In contrast, HIIT with ON-transients ranging 95-80% of VO_{2max} were all sustainable for the full duration of the HIIT protocol (Figure 1B).

Exercise intensity during HIIT protocols was measured in order to control that intended intensity was successfully achieved. By measuring VO_2 during the ON-transients, we found that the true intensities differed 0.24±1.1% from the intended intensities across the various HIIT protocols (80-100% of VO_{2max}), with no statistical differences between intended and measured intensities (one-way ANOVA $p>0.05$). Furthermore, although intensity was not set by HR, we found that HR during HIIT at 100% of VO_{2max} reached maximal HR (197±3bpm, range 195-202bpm), and in the lower intensities predictably reached values commensurate with the lower HIIT intensities of 80-95% of VO_{2max} (one-way ANOVA $p<0.05$ between intensities).

Finally, we measured blood [La^-] at the end of each ON- and OFF-transient (Figure 1C). This showed that blood [La^-] at HIIT intensity of 100% of VO_{2max} increased to 9.3±1.4mM (range 8.2-11.3mM) and did not decrease during OFF-transients. In contrast, [La^-] during HIIT intensities 80-95% of VO_{2max} increased to 2-6mM in an intensity-dependent manner, but significantly less compared to 100% VO_{2max}-intensity (Figure 1C). On further analysis, blood [La^-] decreased during active recovery OFF-transients at HIIT protocols 80-95% of VO_{2max}, whereas during HIIT at 100% of VO_{2max}, it continually increased until further exercise was unsustainable, including during the OFF1-transient. Thus, blood [La^-] accumulation occurred at a rate at least 140% higher during HIIT at 100% of VO_{2max} compared to the lower intensities of 80-95% of VO_{2max} (1.05±0.55mM/min vs. 0.23±0.10mM/min at 80% of VO_{2max} to 0.43±0.11mM/min at 95% of VO_{2max}; Figure 2A). In the 80-95% of VO_{2max} exercise intensity range, ON-transient blood [La^-] accumulation was matched by active recovery OFF-transient blood [La^-] clearance, whereas at 100% of VO_{2max}, no blood [La^-] clearance occurred; in fact, blood [La^-] continued to rise during the OFF-transient at this exercise intensity (Figure 2B), to the extent that the total rate of blood [La^-] accumulation (increase during ON-transients – clearance during OFF-transients) increased ~6 times when increasing HIIT exercise intensity from 95% to 100% of VO_{2max}; i.e. 0.24±0.11mM/min at 95% of VO_{2max} to 1.45±0.44mM/min at 100% of VO_{2max} (Figure 2C).

Active Recovery Intensity of HIIT

Next, we aimed to assess intensity-dependence of active recovery and possibly identify the optimal active recovery intensity during 4-minute OFF-transients of a HIIT protocol; i.e. that which removed blood [La^-] fastest. For this, ON-transient exercise intensity was set to 95% of VO_{2max}, as this was the highest sustainable exercise intensity that allowed completion of the HIIT protocol (see above); measured ON-transient intensity corresponded to 94.5±1.5% of VO_{2max}, $p>0.05$ vs intended intensity. ON-transient HR also corresponded with HR observed at this intensity in the previous set of experiments, whereas blood [La^-] increased from 0.97±0.24mM after warm-up to 5.68±0.81mM during ON1-transient (Figure 3), in line with the previous experiments.

On the basis of successful ON-transients that achieved the intended exercise intensity and the expected rise in blood [La^-], active recovery OFF-transients then varied 60-100% of LT, with VO_2 and HR measurements confirming that intended intensity of active recovery was achieved; measured VO_2 and HR during the OFF-transients differed 0.43±0.08% and 0.58±0.21%, respectively, from the intended values (one-way ANOVA $p>0.05$). These trials showed that blood [La^-] tended to increase during each HIIT protocol (in fact also during the first 1-2 minutes of active recovery); however, blood [La^-] continued to increase only significantly at HIIT with active recovery set to 80-100% of LT, but not 60-70% of LT (Figure 3). In particular, after the initial increase to 5-6mM during ON1, blood [La^-] continued to increase to reach a peak of 13mM, i.e. an increase of ~130%, after ON4 when active recovery was set to 80% of LT, whereas during active recovery at 60-70% of LT, blood [La^-] only increased insignificantly to 6-7mM. In other words, active recovery *during* HIIT is unable to prevent a continued increase of blood [La^-], but may mitigate if performed at 60-70% of LT. However, the situation was different during the prolonged OFF4-transient, where active recovery at 80-100% of LT tended to clear accumulated blood [La^-]

faster than at 60-70% of LT, though regardless, it took >20 minutes for blood [La^-] to return to baseline levels even under the best of circumstances (Figure 3).

To substantiate the latter observation, we investigated blood La^- clearance during the prolonged post-interval OFF4-transient closer. First, from the observed La^- clearance curves, we fitted exponential decay curves to assess time constants for 2/3 (67%) clearance. The fitted curves compared well with the observed curves, with R^2-values ranging 0.87-0.99 (p<0.01) and a coefficient of variation of 4%. From peak [La^-], the time constant for 2/3 La^- clearance was ~90% longer during active recovery at 60-70% of LT compared to higher intensities (Figure 4A). We then calculated the 1st derivative of the observed curves in order to assess the maximal rates of La^- clearance. In line with the above, this showed that the maximal rate was ~90% higher during active recovery at 80-100% of LT compared to lower intensities (Figure 4B).

Discussion

In this study, we aimed to first determine the highest sustainable exercise intensity relative to VO_{2max} that allows completion of a full 4x4-minute HIIT protocol, and secondly to assess the intensity-dependence of active recovery relative to LT for removing La^- during HIIT in order to determine if an optimal intensity of active recovery during HIIT exists, and if so, identify this intensity. Finding the optimal intensities of high-intensity intervals and active recovery bouts becomes important to optimize the outcome of HIIT. As such, the overarching aim was to inform strategies for designing optimal and practically sustainable protocols for high-intensity training by the use of HIIT.

From these experiments, we found:

- HIIT performed with interval intensities (ON-transients) corresponding to 95% of VO_{2max} permits completion of the full 4x4-minute protocol at the highest intensity, whereas in comparison, HIIT at 100% of VO_{2max} is not sustainable – only 44% of protocol was sustained on average and no subject sustained >70% of protocol at this intensity – and while exercise intensities <95% of VO_{2max} are therefore obviously sustainable, they associate with less exercise stimulus and stress.[4] Of note, active recovery during these trials was set to 60% of LT, as it allowed for steady-state active recovery conditions.
- Increasing HIIT ON-transient exercise intensity from 95% to 100% of VO_{2max} is associated with a substantial change in blood [La^-] dynamics; at the lower intensity it remains relatively steady-state during HIIT after an initial increase, whereas at the higher intensity, it accumulates >6 times faster and without any steady-state. This may at least partly explain why an exercise intensity of 100% of VO_{2max} cannot be sustained in the context of 4x4-minute HIIT protocols.
- Active recovery at 60-70% of LT in the OFF-transients *during* 4x4-minute HIIT (ON-transient intensity of 95% of VO_{2max}) allows for steady-state blood [La^-], whereas active recovery at higher intensities is associated with accumulation of blood [La^-]; however, this accumulation did still allow for continuation and successful completion of the HIIT protocol.
- For the prolonged OFF-transient *after* the 4x4-minute HIIT protocol, active recovery at 80-90% of LT, and to a lesser extent also 100% of LT, removed La^- faster than 60-70% of LT active recovery intensities; however, in all cases, at least 20 minutes of active recovery was required to fully remove excess blood La^-.

It should be pointed out that intensity of intervals (ON-transients) and active recovery bouts (OFF-transients) was always confirmed by continuous VO_2 and HR measurements; i.e. the intended intensity was truly achieved in the experiments. Moreover, when investigating the highest sustainable ON-transient exercise intensity of HIIT, active recovery OFF-transient intensity was set to 60% of LT as it ensured steady-state conditions during active recovery, while reciprocally, when investigating optimal active recovery OFF-transient intensity, ON-transient exercise intensity of HIIT was then set to 95% of VO_{2max}, as this had been identified as the highest sustainable exercise intensity of HIIT. Thus, we applied and confirmed optimum conditions where and when applicable throughout the study.

Thus, assuming i) the well-established concept of intensity-dependence of effects in both health and disease,[1-4,9,10] dictates that exercise intensity should be as high as achievable, and ii) the mode of exercise training is the also well-established 4x4-minute HIIT protocol,[1-3,9,10] these results are the first to suggest that the protocol should be carried out with an ON-transient exercise intensity of 95% of VO_{2max} and that interspersing active recovery bouts should be carried out with an OFF-transient intensity of 60-70% of LT *during* HIIT and 80-90% of LT *after* HIIT in order to most efficiently stimulate recovery and prevent and remove excess La^- that otherwise is generated by the HIIT protocol.

In the present study, we quantified exercise and active recovery intensities relative to the individual subjects' capacity (VO_{2max} and LT, respectively), as this or the corresponding energy expenditure converted from gas exchange VO_2 measurements (metabolic equivalents (MET)), is the preferred norm in the majority of studies and exercise programs, position stands and guidelines offered by professional and authoritative bodies such as the American College of Sports Medicine (ACSM), and in general the exercise and sports science community.[11] In this context, relative (%) rather than absolute quantification allows the intensity to be identified and individualized quickly and effectively, though we acknowledge that another appropriate strategy for setting the intensity especially during ON-transients would be by the velocity-tolerable duration relationship from the critical power or velocity concept;[7] however, since this relationship is hyperbolic, it requires a drastically greater laboratory testing effort, especially for running, which may not always be feasible.[12]

We acknowledge that La^- in itself may not fully cause or explain muscle fatigue during intense exercise, though it has been implicated in this process.[13-15] However, the rationale for the use of La^- as a biological marker of fatigue in the current study is that it correlates well with onset and generation of fatigue and therefore serves as an accessible, reproducible, and valid proxy measure of fatigue that may be obtained serially during and after exercise training.[5,6] La^- accumulates during intense exercise above LT with changes to the redox state of the exercising muscle that converts pyruvate to La^- that subsequently diffuses to the blood stream where it is measured.[13-16] We previously demonstrated this approach to be useful for assessing fatigue and recovery after single bouts of exercise and showed that blood La^- measurements could identify optimal intensity of active recovery during circumstances of both limited and excessive accumulations of La^-.[5,6] We now demonstrate the same is true for assessing the same parameters during HIIT, but in this case the repetitive accumulation and incomplete clearance due to the cyclical nature of the HIIT protocol adds complexity. As part of this, we observed a discrepancy of La^- clearance in this study compared to the previous studies, as after single bouts of exercise, active recovery at 80-100% of LT consistently cleared La- faster than lower intensities,[5,6] whereas in the current study, faster La^- clearance by active recovery was achieved at 60-70% of LT *during* HIIT and at 80-90% of LT *after* HIIT; the latter during prolonged active recovery and in line with the previous results, which as such confirms that during continued active recovery that exceeds the 4-minute bouts inside a HIIT protocol, La^- clearance occurs fastest when active recovery is set close to LT, where continued exercise and muscle contractile work metabolises La^- at the fastest rate, mainly by oxidation.[16] Thus, the observed intensity-dependence of La^- clearance during active recovery *after* HIIT is similar to previous observations,[5,6] whereas active recovery applied to OFF-transients *during* HIIT has not yet received scrutiny with respect to intensity-dependence of effect, though active recovery has been reported more beneficial than passive recovery.[17]

Conclusions

First, we aimed to determine the highest sustainable intensity relative to VO_{2max} that allows completion of a full 4x4-minute HIIT protocol. We found that a protocol with intervals at an exercise intensity of 95% of VO_{2max} is the highest sustainable intensity that allows completion of the protocol, whereas an exercise intensity above this level is not sustainable. Completing a HIIT protocol at an exercise intensity of 95% of VO_{2max} associates with elevated, but steady-state blood [La^-], whereas an intensity above this associates with continued accumulation of [La^-] until onset of fatigue. Secondly, we assessed intensity-dependence of interspersing active recovery bouts for removing La^- during and after a HIIT protocol. We found that active recovery intensities of 60-70% of LT *during* HIIT and 80-90% of LT *after* HIIT serve best to prevent and remove excess La. These findings therefore inform when designing efficient training programs that include 4x4-minute HIIT protocols.

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NOTES

Conflicts of interest.-The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contributions.-OJK conceived and designed research; all authors conducted experiments; OJK, EF, KM, DP, RS, and JW analysed data; OJK wrote the manuscript; all authors read and approved the manuscript.

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TITLES OF FIGURES

Figure 1.-A: Overview of high-intensity interval training (HIIT) protocols, with 4x4-minute high-intensity intervals (ON1-4, n=7) set to correspond to 80%, 85%, 90%, 95%, or 100% of maximal oxygen uptake (VO_{2max}) and 4x4-minute active recovery bouts (OFF1-4, n=7) set to correspond to 60%, 70%, 80%, 90%, or 100% of lactate (La^-) threshold (LT), with the last OFF4-transient prolonged to allow full recovery. Oxygen uptake (VO_2) and heart rate (HR) measurements in the last minute of each ON-transient interval confirmed intensity, whereas blood La^- was sampled at the end of each ON-transient and every minute of OFF-transients. B: Sustainable duration during HIIT protocols performed at exercise intensities 80-100% of VO_{2max}. C: Blood La^- concentration ([La^-]) during HIIT protocols performed at exercise intensities of 80-100% of VO_{2max}. Statistically significantly different from other exercise

intensities: ** $p<0.01$, * $p<0.05$. Statistically significantly different from baseline (BL): ## $p<0.01$, # $p<0.05$.

Figure 2.-Rate of blood lactate (La^-) concentration ($[La^-]$) rise during high-intensity intervals (ON-transients; A) and decrease (OFF-transients; B) of high-intensity interval training (HIIT) protocols, with ON-transients set to correspond to 80-100% of maximal oxygen uptake (VO_{2max}) of OFF-transients set to correspond to 60% of La^- threshold (LT). Statistically significantly different from other intensities: ** $p<0.01$.

Figure 3.-Blood lactate (La^-) concentration ($[La^-]$) during high-intensity interval training (HIIT) protocols, with 4x4-minute high-intensity intervals (ON1-4) set to correspond to 95% of maximal oxygen uptake (VO_{2max}), interspersed by 4x4-minute active recovery bouts set to correspond to 60%, 70%, 80%, 90%, or 100% of La^- threshold (LT; OFF1-4), with the last OFF4-transient prolonged to allow full recovery. BL: baseline. Statistically significantly different from OFF1 for active recovery intensities at 80-100% of LT, but not at 60-70% of LT: * $p<0.05$; statistically significantly different from other active recovery intensities: # $p<0.05$.

Figure 4.-Lactate (La^-) clearance of each active recovery intensity during the prolonged last post-interval active recovery bout (OFF4), with active recovery set to 60-100% of La^- threshold (LT); A: Time constants for 2/3 clearance, B: Maximal rate of La^- clearance. Statistically significantly different from other active recovery intensities: * $p<0.05$.