Loading of Trained Inspiratory Muscles Speeds Lactate Recovery Kinetics

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ABSTRACT

BROWN, P. I., G. R. SHARPE, and M. A. JOHNSON. Loading of Trained Inspiratory Muscles Speeds Lactate Recovery Kinetics. *Med. Sci. Sports Exerc.*, Vol. 42, No. 6, pp. 1103–1112, 2010. **Purpose**: The purpose of this study was to investigate the effects of inspiratory threshold loading (ITL) and inspiratory muscle training (IMT) on blood lactate concentration ($[lac^-]_B$) and acid–base balance after maximal incremental cycling. **Methods**: Eighteen subjects were divided into a control (n = 9) or an IMT group (n = 9). Before and after a 6-wk intervention, subjects completed two maximal incremental cycling tests followed by 20 min of recovery with (ITL) or without (passive recovery (PR)) a constant inspiratory resistance (15 cm H_2O). The IMT group performed 6 wk of pressure threshold IMT at 50% maximal inspiratory mouth pressure. Throughout recovery, acid–base balance was quantified using the physicochemical approach by measuring the strong ion difference ($[SID] = [Na^+] + [K^+] - [Cl^-] + [lac^-]$), the total concentration of weak acids ($[A_{tot}^-]$), and the partial pressure of carbon dioxide (PCO_2). **Results**: After the intervention, maximal inspiratory mouth pressure increased in the IMT group only (+34%). No differences in lactate clearance were observed between PR and ITL before the intervention in both groups and after the intervention in the control group. After IMT, relative to PR, $[lac^-]_B$ was reduced throughout ITL (minutes 2–20) by 0.66 ± 1.28 mmol·L^{-1} ($P < 0.05$), and both the fast (lactate exchange) and the slow (lactate clearance) velocity constants of the lactate recovery kinetics were increased ($P < 0.05$). Relative to pre-IMT, ITL reduced plasma $[H^+]$, which was accounted for by an IMT-mediated increase in [SID] due almost exclusively to a 1.7-mmol·L^{-1} reduction in $[lac^-]_B$. **Conclusions**: After maximal exercise, ITL affected lactate recovery kinetics only after IMT. Our data support the notion that the inspiratory muscles are capable of lactate clearance that increases [SID] and reduces $[H^+]$. These effects may facilitate subsequent bouts of high-intensity exercise. **Key Words:** INSPIRATORY MUSCLE TRAINING, WORK OF BREATHING, BLOOD LACTATE CONCENTRATION, ACID–BASE REGULATION

BASIC SCIENCES

Recent evidence suggests that the respiratory muscles become net producers of lactate when the work of breathing exceeds a critical threshold level (2,16,40) and that specific training of these muscles reduces their rate of lactate production and/or increases their rate of consumption (2,40). Reductions in blood lactate concentration ($[lac^-]_B$) have also been reported during exercise after specific respiratory muscle training (RMT [23,35,38]), suggesting that at moderate levels of pulmonary ventilation the respiratory muscles may become net lactate consumers (10). These findings are surprising given the small muscle mass (approximately 0.5% total body mass) of the respiratory muscles and collectively suggest an important, previously underestimated role for the respiratory muscles in the regulation of whole-body lactate kinetics.

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This theme was recently extended by Chiappa et al. (3), who found that adding an inspiratory resistance (15 cm H_2O) during recovery from maximal incremental cycling exercise significantly reduced $[lac^-]_B$ (~2.5 mmol·L^{-1}) compared with a passive recovery (PR). This intriguing finding suggests that inspiratory muscle work accelerates lactate clearance by a similar magnitude to that achieved with an active recovery involving locomotor muscles but with the benefit of sparing intramuscular energy stores (6). Given that lactate consumption and/or reduced production by the inspiratory muscles is enhanced by training (23,35,38), it is attractive to speculate that the finding of Chiappa et al. (3) would be magnified after RMT, and this was the focus of the present study.

It is unlikely that increases in $[lac^-]$ *per se* result in metabolic acidosis and cause skeletal muscle fatigue (34), particularly at physiological temperatures (43). However, according to the integrated physicochemical systems approach, with which it is possible to quantify the mechanisms accounting for disturbances in acid–base balance during and after exercise, the $[lac^-]$ may indirectly affect $[H^+]$ (38). Within a given compartment (e.g., muscle, plasma, erythrocyte), the dependent variables, $[H^+]$ and $[HCO_3^-]$, are determined by the independent variables, strong ion difference ($[SID] = [Na^+] + [K^+] - [Cl^-] + [lac^-]$), the partial pressure of carbon dioxide (PCO_2), and the total concentration of weak acids ($[A_{tot}^-]$). Therefore, a reduction in $[lac^-]$ in the

systemic circulation may affect the $[H^+]$ by causing a positive shift in [SID] (for reviews, see Kowalchuck and Scheuermann [17] and Lindinger [20]). This is especially important given the associations between elevated $[H^+]$ and/or $[lac^-]$ on some intramuscular processes (8) and subsequent exercise performance (30,40).

Accordingly, the purpose of the present study was to test the hypothesis that inspiratory pressure threshold loading during recovery from maximal exercise would speed lactate clearance and that this would be further increased after specific inspiratory muscle training (IMT). To determine the effect of changes in $[lac^-]_B$ on plasma $[H^+]$, we quantified the contribution of associated physiological variables to the regulation of plasma acid–base homeostasis using the integrated physicochemical approach.

METHODS

Participants. After ethical approval and written informed consent, 18 healthy nonsmoking participants with normal lung function volunteered for the study (Table 1). Throughout, subjects were instructed to adhere to their normal training regimen and not to engage in any strenuous exercise the day preceding and the day of a trial. Both habitual training and IMT were recorded throughout the intervention using a training diary. Each subject completed a 24-h diet record before their first trial, and this was repeated before subsequent tests. Subjects arrived at the laboratory 2 h postprandial having abstained from alcohol and caffeine in the 24 h before testing. All exercise trials were performed on an electromagnetically braked cycle ergometer (Excalibur Sport; Lode, Groningen, The Netherlands), at a similar time of day, separated by 48 h and in similar laboratory conditions (temperature = 21.1°C ± 2.7°C, relative humidity = 46.6% ± 14.4%).

Experimental design. Subjects attended the laboratory three times before a 6-wk intervention; each laboratory visit was separated by a minimum of 48 h. During the first laboratory visit, subjects completed pulmonary function and maximal inspiratory mouth pressure (MIP) tests and were subsequently familiarized with all testing procedures including maximal incremental exercise. Pulmonary function was assessed using a pneumotachograph (Pneumotrac; Vitalograph, Buckingham, UK) calibrated using a 3-L syringe. Measurement of FVC and FEV_1 was repeated until the difference between the largest and the next largest value was less than 100 mL. A minimum of three maneuvers and a maximum of eight maneuvers were performed, and the highest value used for subsequent analysis (28,32). With the exception of peak inspiratory flow, lung function is unchanged after IMT (22) and therefore was not measured postintervention. A hand held mouth pressure meter (MicroRPM; Micro Medical, Kent, UK) measured MIP as an index of global inspiratory muscle strength. The mouthpiece assembly incorporated a 1-mm orifice to prevent glottic closure during inspiratory efforts. Maneuvers were performed in an upright standing posture, were initiated from residual volume, and sustained for at least 1 s. To ensure a true maximal effort, a minimum of five maneuvers were performed. Efforts were repeated every 30 s until three serial measures differed by no more than 10% or 10 cm H_2O, whichever was smallest (21). The highest value recorded during repeat measurements was used for subsequent analysis (21). MIP values were compared with predicted values using the equation of Wilson et al. (44), where $MIP_{predicted} = MIP_{measured} / (142 - (1.03 \times age) \times 100)$. MIP was reevaluated throughout the intervention after 2 and 4 wk. After IMT, MIP was assessed 48 h after the final training session and on a separate day to any exercise testing.

On two separate occasions, subjects completed a maximal incremental exercise test. Immediately after exercise, subjects breathed against either a constant pressure threshold inspiratory resistance (15 cm H_2O) for 20 min (inspiratory threshold loading (ITL)) or recovered passively with spontaneous breathing for 20 min (no inspiratory resistance; PR); the order of these trials was randomized and separated by 48 h. After the preintervention trials, subjects were matched for $\dot{W}_{max}$ and divided in to an IMT group ($n = 9$) or a control group ($n = 9$). After a 6-wk intervention (IMT or no IMT), subjects repeated the preintervention trials. Given the increase in MIP expected after IMT, the IMT group completed a third maximal incremental exercise test in which the absolute intensity of ITL during recovery was increased so that the same fraction of MIP was used before and after the intervention. This subsequent trial was defined as ITL%. The order of the postintervention trials was randomized and separated by 48 h. For each subject, all trials before and after the intervention period were performed at a similar time of day (±1 h).

Passive recovery. Subjects performed a maximal incremental cycling test in which the initial power was 0 W and was increased by 20 $W \cdot min^{-1}$ until exercise could no longer be tolerated ($\dot{W}_{max}$) (3). The highest oxygen uptake ($\dot{V}O_2$) recorded in any 30-s period defined $\dot{V}O_{2max}$. $[lac^-]_B$ was determined at the cessation of exercise and every 2 min

TABLE 1. Descriptive characteristics of the subjects.

	Control ($n = 9$)	IMT ($n = 9$)
Age (yr)	27.1 ± 3.7	32.2 ± 6.3*
Body mass (kg)	81.3 ± 8.0	78.9 ± 16.6
Height (cm)	183.3 ± 6.6	177.0 ± 9.5
FVC (L)	6.03 ± 0.92 (109 ± 14)	5.22 ± 1.03 (107 ± 9)
FEV_1 (L)	4.77 ± 0.63 (103 ± 11)	4.11 ± 0.76 (101 ± 7)
FEV_1/FVC (%)	79.5 ± 5.2 (97 ± 7)	79.3 ± 6.7 (96 ± 7)
MVV_{10} ($L \cdot min^{-1}$)	198.5 ± 23.2 (105 ± 14)	176.6 ± 29.4 (109 ± 9)
MIP (cm H_2O)	148.0 ± 35.7 (114 ± 4)	120.1 ± 27.3 (109 ± 7)
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	4.27 ± 0.49	4.13 ± 0.83
$\dot{W}_{max}$ (W)	386 ± 44	378 ± 57

Values are expressed as mean ± SD. Values in parentheses represent the percent of predicted values (28,44).

* $P < 0.05$ control group vs IMT group.

FVC, forced vital capacity; FEV_1, forced expiratory volume in 1 s; MVV_{10}, maximal voluntary ventilation in 10 s; MIP, maximal inspiratory mouth pressure; $\dot{V}O_{2max}$, maximal oxygen consumption; $\dot{W}_{max}$, maximal power output.

thereafter; PCO_2 and $[H^+]$ were determined at volitional intolerance and every 5 min thereafter. At the cessation of exercise and after 10 and 20 min, physicochemical variables were determined. Subjects wore a face mask (model 7940; Hans Rudolph, Kansas City, MO) connected to an online expired gas analyzer (ZAN 600USB; Nspire Health, Oberthulba, Germany). Breath-by-breath respiratory variables were averaged over the final 30 s of every 2-min interval. Heart rate (HR) was recorded continuously during exercise using short-range telemetry (Polar S610; Polar, Kempele, Finland).

Inspiratory pressure threshold loading. The ITL trial was identical with PR; however, immediately after exercise, a 1.5-m length of wide-bore (35-mm internal diameter) corrugated tubing (Clean-bor tubes; Vacumed, Ventura, CA), which provided minimal additional resistance (0.16 cm $H_2O \cdot L^{-1} \cdot s^{-1}$), was attached to the inspiratory port of a two-way nonrebreathing valve (model 2730; Hans Rudolph) and connected distally to a custom-built weighted plunger pressure threshold inspiratory muscle loading device identical to that used previously (13,14). The 1.5-m length of tubing permitted the subject to remain in the same body position on the cycle ergometer when breathing through the device and provided a small degree of freedom to move the head comfortably and safely. The pressure threshold loading system was previously shown to be flow independent over the physiological range (see ref. 13); a full description of the device is provided elsewhere (14). During ITL, weights were added to the plunger to adjust the threshold opening pressure that was fixed at 15 cm H_2O (3). For the IMT group and the control group, this represented 13% ± 3% and 11% ± 3% MIP (pooled data, n = 18, 12% ± 3% MIP), respectively. After 6 wk of IMT and due to the training-induced increase in MIP, the opening pressure of 15 cm H_2O represented a smaller resistance relative to MIP (10% ± 2% MIP). Thus, in the ITL% trial, the absolute resistance was increased to 20 ± 2 cm H_2O, which achieved the same relative resistance as the pre-IMT ITL trial (i.e., 13% ± 3%). The measurement accuracy of the online expired gas analyzer during ITL was investigated before commencement of the study. Comparisons were made with the Douglas bag method at rest and over a range of exercise intensities. The mean bias ± 95% limits of agreement (2 SD) were -1.91 ± 2.19 $L \cdot min^{-1}$ for $\dot{V}_E$, -0.08 ± 0.14 $L \cdot min^{-1}$ for $\dot{V}O_2$, and -0.07 ± 0.14 $L \cdot min^{-1}$ for $\dot{V}CO_2$. These data show that the online expired gas analyzer performed satisfactorily despite the negative pressures generated during ITL.

Intervention. IMT was performed using an inspiratory pressure threshold device (POWERbreathe®, Gaiam, UK). The IMT group performed 30 dynamic inspiratory efforts twice daily for 6 wk against a pressure threshold load of approximately 50% MIP. The initial training load was determined by inserting a 0.8-mm hypodermic needle into the mouthpiece of the device that was attached distally to a mouth pressure meter (MicroRPM; Micro Medical). During repeated maximal efforts, identical with that performed throughout IMT, the opening pressure of the valve was adjusted to 50% MIP. Throughout 6 wk of IMT, subjects were instructed to periodically increase the load to a level that would permit them to only just complete 30 breaths. In addition, the resistance of the device was also confirmed using the protocol outlined above after 2 and 4 wk of IMT to ensure that the training load did not exceed 50% MIP. Each inspiratory maneuver was initiated from residual volume and subjects strove to maximize V_T. This protocol is known to be effective in eliciting an adaptive response (2,15,22,23,35,36,42). Subjects completed a training diary to record IMT adherence and habitual training, which the control group also recorded. The control group continued with its habitual physical training schedule and was not exposed to an intervention. A placebo treatment was not applied to the control group because the study outcome measures could not be influenced by either motivation or expectation. Subjects were informed that they belonged to a control group before commencement of the study and were afforded the opportunity to undertake 6 wk of IMT after completion of the study to avoid any possible disadvantage.

Blood sampling and analysis. During all exercise trials, arterialized venous blood was drawn from a dorsal hand vein via an indwelling 21-G cannula (9,25). Arterialization was achieved by immersing the hand in water at approximately 40°C for 10 min before cannulation and by warming the hand during exercise using an infrared lamp. Blood samples were analyzed immediately for $[lac^-]_B$ (Biosen; EKF Diagnostics, Barleben, Denmark), PCO_2, and pH (ABL520; Radiometer, Copenhagen, Denmark).

To elucidate the mechanisms accounting for acid–base disturbance, the integrated physicochemical systems approach was used (39). At rest, the cessation of maximal exercise, and every 10 min thereafter, a 5-mL blood sample was drawn and centrifuged immediately for 10 min at 3000*g*. Plasma $[Na^+]$ and $[K^+]$ were measured using inductively coupled plasma optical emission spectrometry (1200DV ICP OES; PerkinElmer, Waltham, MA). Plasma $[Cl^-]$ was measured by ion chromatography (DX120; Dionex, Sunnyvale, CA), and the total concentration of plasma proteins $[PPr^-]$ was assayed in duplicate according to the method of Lowry (19). The total concentration of weak acids ($[A_{tot}^-]$) was subsequently calculated as $2.45[PPr^-]$ (24). Plasma strong ion difference ([SID]) was calculated as the sum of the strong cations minus the sum of the strong anions (39):

$$[SID] = ([Na^+] + [K^+]) - ([Cl^-] + [lac^-]) \quad [1]$$

Plasma $[H^+]$ along with the contributions of each independent variable (PCO_2, [SID], and $[A_{tot}^-]$) to changes in arterialized venous plasma $[H^+]$ was calculated according to the method of Putman et al. (31).

Lactate recovery kinetics. The individual $[lac^-]_B$ recovery curves before and after the intervention were

TABLE 2. Preintervention responses to maximal incremental cycling exercise before 20 min of passive recovery (PR) and 20 min of inspiratory threshold loading (ITL).

	Control Group		IMT Group	
	PR	ITL	PR	ITL
$\dot{W}_{max}$ (W)	387 ± 44	387 ± 41	378 ± 57	376 ± 57
$\dot{V}O_{2max}$ (L·min^{-1})	4.21 ± 0.66	4.23 ± 0.52	4.10 ± 0.92	4.20 ± 0.75
$\dot{V}_E$ (L·min^{-1})	166.6 ± 22.5	170.1 ± 14.0	163.1 ± 32.3	158.8 ± 34.8
f_R (breaths·min^{-1})	61 ± 13	60 ± 8	60 ± 11	58 ± 11
V_T (L)	2.83 ± 0.62	2.93 ± 0.47	2.90 ± 0.94	2.86 ± 0.93
T_i/T_{tot}	0.50 ± 0.02	0.50 ± 0.01	0.47 ± 0.04	0.50 ± 0.01
HR (beats·min^{-1})	177 ± 9	178 ± 11	181 ± 10	181 ± 11

Values are expressed as mean ± SD.
$\dot{W}_{max}$, maximal power output; $\dot{V}O_{2max}$, maximal oxygen uptake; $\dot{V}_E$, minute ventilation; f_R, respiratory frequency; V_T, tidal volume; T_i/T_{tot}, inspiratory time divided by total breath time (duty cycle); HR, heart rate.

fitted to the following biexponential time function using an iterative nonlinear regression technique (11):

$$\mathrm{Lac}^-(t) = \mathrm{Lac}^-(0) + A_1(1 - e^{\gamma_1 t}) + A_2(1 - e^{\gamma_2 t}) \quad [2]$$

where $\mathrm{Lac}^-(t)$ (mmol·L^{-1}) denotes the $[\mathrm{lac}^-]_B$ for a given time (t; min) of the recovery period and $\mathrm{Lac}^-(0)$ (mmol·L^{-1}) being the $[\mathrm{lac}^-]_B$ at the onset of the recovery period. This equation illustrates that blood lactate kinetics after exercise can be described by two mathematical and physiological processes: one with a fast velocity constant (γ_1; min^{-1}) describing the appearance of lactate in the arterialized blood ($A_1 > 0$; mmol·L^{-1}) and an increased $[\mathrm{lac}^-]_B$ and a second with a slow velocity constant (γ_2; min^{-1}) describing lactate clearance ($A_2 < 0$; mmol·L^{-1}) and a reduction in $[\mathrm{lac}^-]_B$. The parameters of the biexponential nonlinear regression were calculated using SYSTAT (Version 12; Systat Software Inc., San Jose, CA) with the regression method of least mean squares.

Statistical analyses. Statistical analyses of the dependent variables were performed using the Statistical Package for the Social Sciences for Windows (Version 15; SPSS, Chicago, IL). Preintervention and postintervention results and group interactions were assessed using one- or two-way repeated-measures ANOVA across groups (IMT vs Control), trials (PR vs ITL), and time (20-min recovery duration or preintervention vs postintervention). After a significant F ratio, Tukey's HSD *post hoc* analysis was performed.

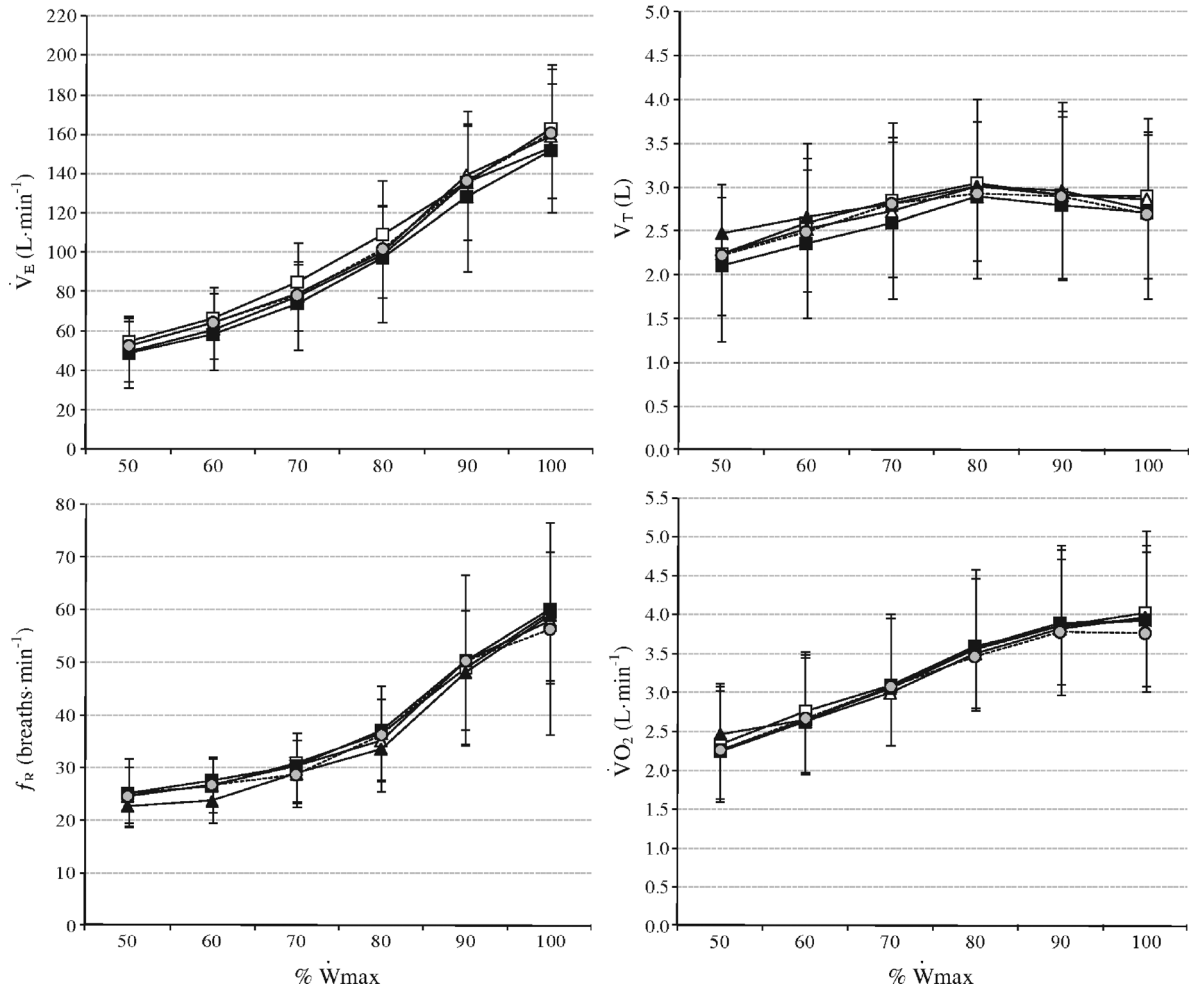

FIGURE 1—Respiratory responses to maximal incremental cycling exercise for the IMT group only before and after the 6-wk intervention. ▲, PR trial preintervention; □, inspiratory pressure threshold loading trial at 15 cm H_2O preintervention; ■, PR trial after the intervention; Δ, ITL trial after the intervention; ●, inspiratory pressure threshold loading trial postintervention at a higher absolute resistance but the same relative resistance as preintervention (ITL%).

Pearson product-moment correlation coefficients assessed the relationship between selected variables. Statistical significance was set at $P \leq 0.05$. Results are presented as mean ± SD.

RESULTS

Training compliance was excellent in the IMT group (92% ± 2%), and inspection of training diaries revealed that habitual training remained constant in both groups. MIP was unchanged after the intervention in the control group (preintervention vs postintervention = 148.0 ± 35.6 vs 148.4 ± 37.7 cm H_2O). In contrast, MIP increased from 120.1 ± 27.3 cm H_2O at baseline to 140.0 ± 26.7, 154.8 ± 36.2, and 159.8 ± 34.8 cm H_2O (+34%) ($P < 0.001$) after 2, 4, and 6 wk of IMT, respectively.

$\dot{W}_{max}$, $\dot{V}O_{2max}$, breathing pattern, and HR responses to maximal exercise before the intervention are shown in Table 2 for the control and the IMT groups, respectively. These responses were similar between trials (PR vs ITL) and between groups (IMT vs control) before and after the intervention. Before and after the intervention, the coefficient of variation of $\dot{W}_{max}$ in the IMT group was 0.4% ± 1.3% and 0.3% ± 1.0%, respectively, and in the control group was 0.7% ± 1.4% and 1.2% ± 1.9%, respectively. Transient changes in breathing pattern and $\dot{V}O_2$ throughout incremental exercise and recovery from maximal exercise in PR, ITL, and ITL% for the IMT group are shown in Figures 1 and 2, respectively. There were no within- or between-group differences in $\dot{V}_E$, f_R, V_T, and $\dot{V}O_2$ during incremental exercise both before and after the intervention (Fig. 1). During recovery from maximal exercise, $\dot{V}_E$ was similar between trials and between groups. With ITL, V_T was increased by 0.32 ± 0.16 L and f_R was decreased by 4.5 ± 1.6 breaths per minute, which increased T_i/T_{tot} in both IMT (absolute increase = 0.020 ± 0.031) and control groups (absolute increase = 0.044 ± 0.047) (Fig. 2). These responses were similar after the intervention in both groups and also during the ITL% trial. HR recovery was similar between trials and between groups. Maximal HR was

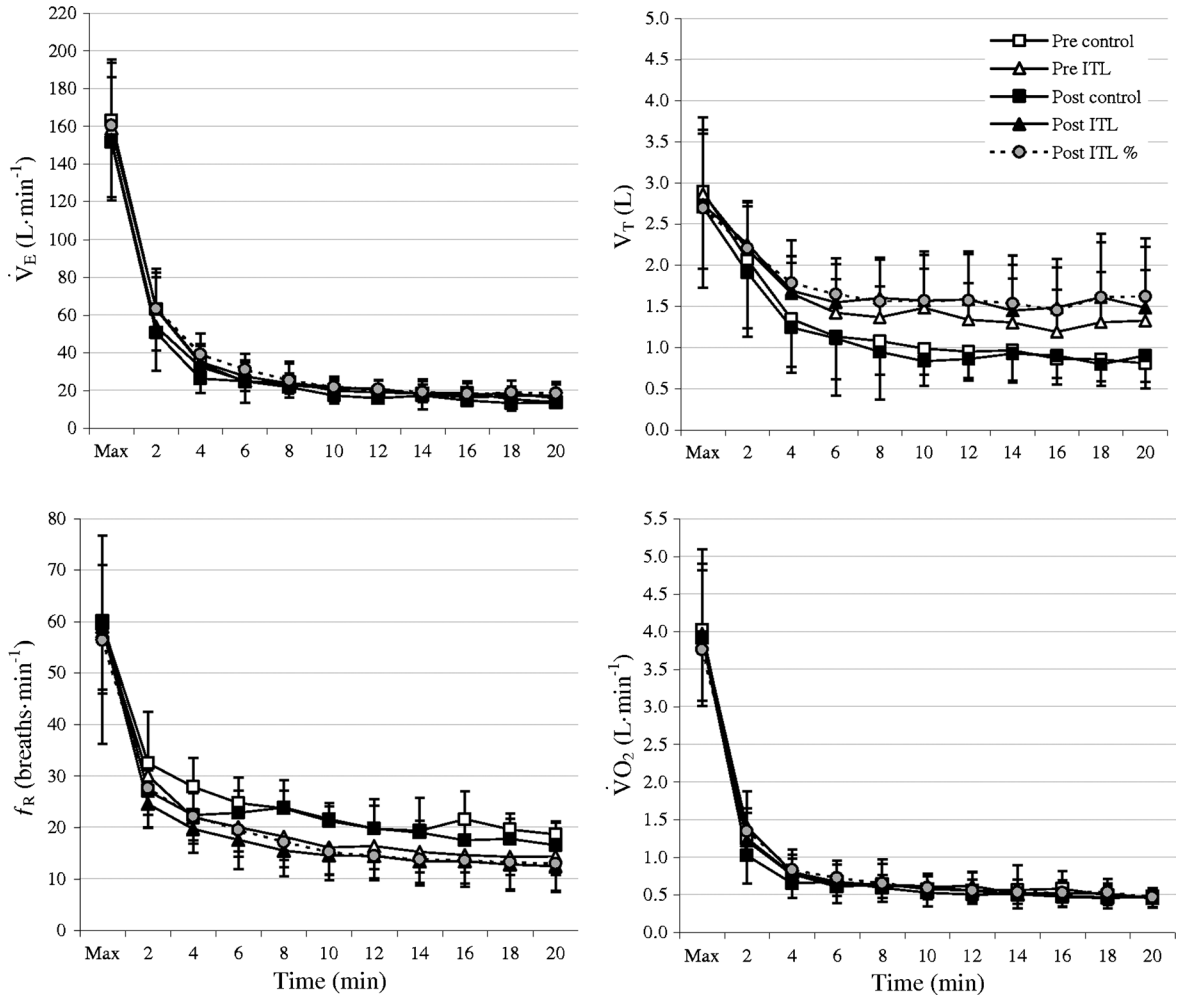

FIGURE 2—Respiratory responses to 20 min of recovery from maximal incremental cycling exercise in the IMT group only before and after the 6-wk intervention. "Max" is defined as the point of exercise intolerance. ▲, PR preintervention; □, inspiratory pressure threshold loading at 15 cm H_2O (ITL) preintervention; ■, PR after the intervention; Δ, ITL after the intervention; ●, ITL%.

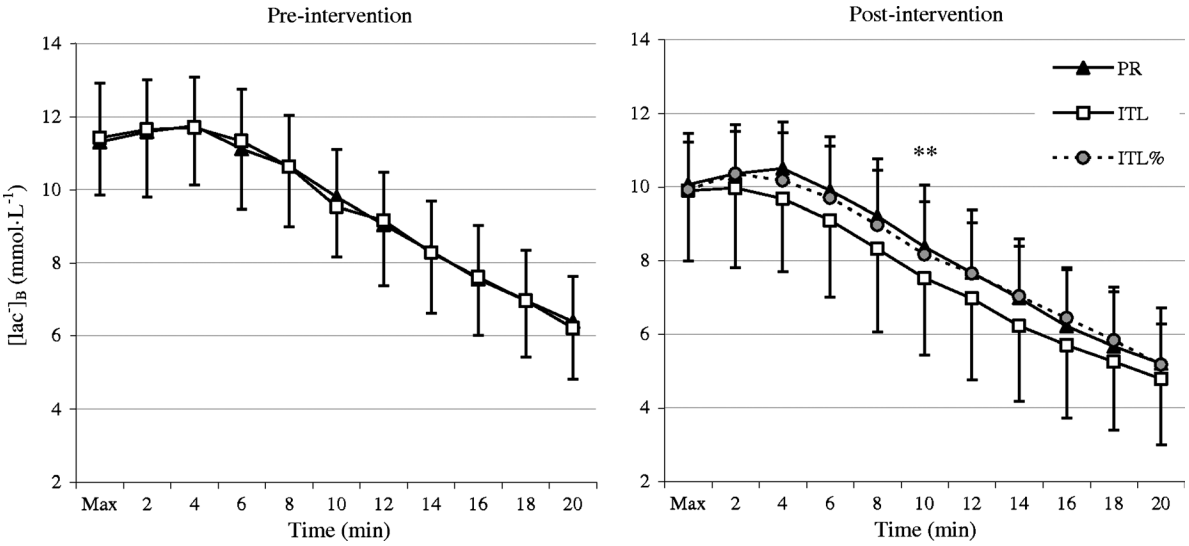

FIGURE 3—Blood lactate concentration ($[lac^-]_B$) during 20 min of recovery from maximal incremental cycling exercise in the IMT group only before and after the 6-wk intervention. "Max" is defined as the point of exercise intolerance. ▲, PR; □, inspiratory pressure threshold loading at 15 cm H_2O (ITL); ●, ITL%. **Postintervention: ITL different to PR ($P < 0.05$).

approximately 180 beats·min^{-1} and decreased to approximately 100 beats·min^{-1} after 8 min of recovery, which was not different from 20 min.

Preintervention, peak, and minimum $[lac^-]_B$ were similar in PR and ITL in both groups (Fig. 3) and were unchanged in the control group after the intervention. After IMT, the exercise-induced peak and the minimum $[lac^-]_B$ after 20 min of recovery were reduced by 1.24 ± 1.32 mmol·L^{-1} ($P < 0.05$) and 1.18 ± 1.22 mmol·L^{-1} ($P < 0.05$) in PR, by 1.52 ± 1.26 mmol·L^{-1} ($P < 0.05$) and 1.42 ± 1.60 mmol·L^{-1} ($P < 0.05$) in ITL, and by 1.50 ± 1.00 mmol·L^{-1} ($P < 0.05$) and 1.02 ± 1.01 mmol·L^{-1} ($P < 0.05$) in ITL%, respectively; these reductions were not different between the PR, the ITL, or the ITL% trials. After IMT only, ITL throughout the 20-min recovery period (mean = 2–20 min) reduced $[lac^-]_B$ by 0.66 ± 1.28 mmol·L^{-1} (trial × time interaction effect, $P < 0.01$). When ITL was performed with the same relative inspiratory pressure threshold load as preintervention (ITL%), lactate clearance was not different from the post-IMT PR trial (Fig. 3).

The amplitudes and the velocity constants for the lactate recovery curves are shown in Table 3. Before the intervention, there were no differences between groups or between trials in any parameter; thus, ITL throughout recovery failed to affect either lactate exchange or lactate clearance. After the intervention, all parameters remained unchanged in the control group. After IMT, relative to the equivalent preintervention trial, $Lac^-(0)$ and A_2 were reduced in PR ($P < 0.05$). In ITL, there was a decrease in A_1 and A_2 and an increase in γ_1 and γ_2 ($P < 0.05$); the reduction in A_2 and the increase in γ_2 exceeded those of the control group (group × time × trial interaction effect, $P < 0.05$). In ITL%, relative to the preintervention ITL trial, there was a reduction in $Lac^-(0)$ and A_2 and an increase in γ_1 ($P < 0.05$), although relative to the postintervention ITL trial, γ_2 was slower ($P < 0.05$). In the ITL trial, lactate clearance was not correlated with the relative intensity of inspiratory muscle loading (%MIP) before the intervention (γ_2; $n = 18$; see Fig. 3, left panel). After IMT, there was no correlation between the relative intensity of inspiratory loading and γ_2 when data from both the ITL and the ITL% trials were combined ($n = 9$; see Fig. 4, right panel).

At rest, $[Cl^-]$ was 101.2 ± 3.6 mmol·L^{-1}, $[Na^+]$ was 138.4 ± 5.9 mmol·L^{-1}, and $[K^+]$ was 3.9 ± 0.3 mmol·L^{-1} in

TABLE 3. Parameters of the biexponential nonlinear regression model for both the control and the IMT groups, respectively.

	Control Group ($n = 9$)		IMT Group ($n = 9$)				
	Preintervention		Preintervention		Postintervention		
	PR	ITL	PR	ITL	PR	ITL	ITL%
La(0)	10.97 ± 1.22	11.11 ± 1.44	11.25 ± 1.53	11.50 ± 1.52	10.12 ± 1.58*	9.91 ± 2.04*	9.94 ± 1.32‡
A_1	4.387 ± 1.443	4.383 ± 1.561	3.933 ± 0.391	3.992 ± 1.900	3.368 ± 0.919	2.554 ± 0.666*,†	3.209 ± 1.516
γ_1	0.270 ± 0.246	0.313 ± 0.182	0.296 ± 0.084	0.235 ± 0.076	0.308 ± 0.168	0.463 ± 0.266*,†	0.377 ± 0.199‡
A_2	−21.765 ± 7.988	−19.166 ± 6.847	−20.624 ± 5.503	−20.172 ± 3.827	−15.161 ± 4.425*	−13.132 ± 3.958*,†	−14.723 ± 3.588‡
γ_2	0.031 ± 0.014	0.037 ± 0.015	0.031 ± 0.011	0.034 ± 0.009	0.036 ± 0.012	0.056 ± 0.025*,†	0.038 ± 0.014§

Data from the control group were not different after the intervention and have been omitted.
Values are presented as mean ± SD. For abbreviations and units, see Methods section.
* Different to the same trial preintervention ($P < 0.05$).
† Different to PR ($P < 0.05$).
‡ Different to ITL preintervention ($P < 0.05$).
§ Different to ITL postintervention.

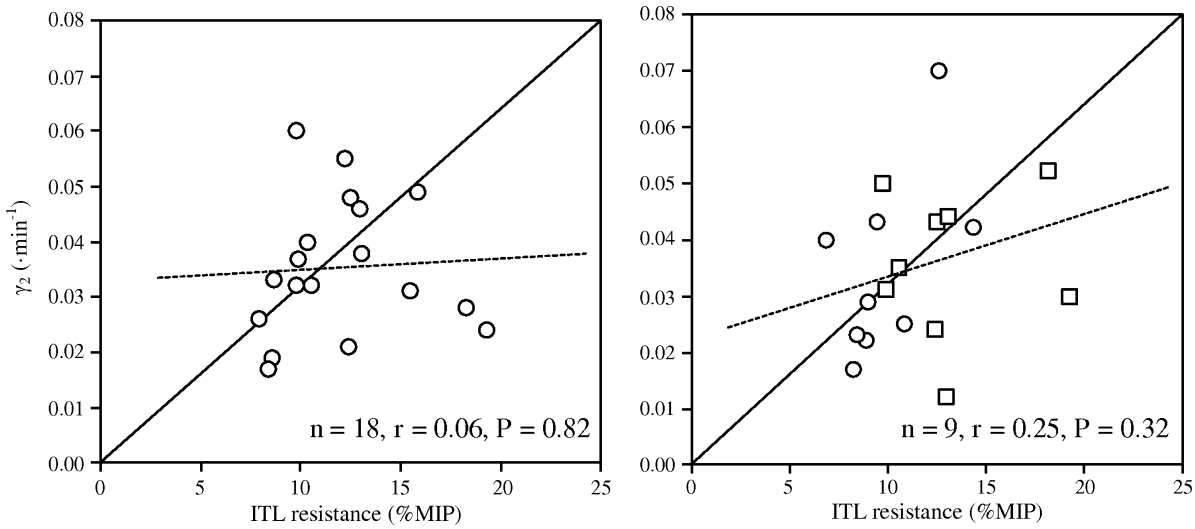

FIGURE 4—Inspiratory pressure threshold load relative to the maximal inspiratory mouth pressure (MIP) versus the slow velocity constant (γ_2; min^{-1}), which describes lactate clearance ($A_2 < 0$; mmol·L^{-1}). *Left panel*: preintervention pooled data of both control and IMT groups. *Right panel*: post-IMT data from the ITL and ITL% trials; ○, ITL data; □, ITL% data. Note: regression line reflects the pooled data from both the ITL and the ITL% trials.

the IMT group, which was not different from the control group. In PR immediately after maximal exercise, [Cl^-] and [K^+] increased by 4.4 ± 0.8 and 1.4 ± 0.5 mmol·L^{-1} in the IMT group and by 4.2 ± 0.6 and 2.5 ± 1.3 mmol·L^{-1}, respectively, in the control group ($P < 0.05$); these increases were similar between groups and between trials (PR vs ITL). These increases in [Cl^-] and [K^+] were unchanged after the intervention in both groups. [Na^+] remained unchanged after maximal exercise and throughout recovery in both groups and in all trials before and after the intervention. During recovery from maximal exercise, [K^+] returned to resting values after 10 min. [Cl^-] remained higher than rest after 10 min of recovery but had returned to resting concentration after 20 min. These patterns were similar in both groups during both PR and ITL trials and were largely unaffected by the intervention period. The pattern observed in ITL% was not different to that observed after the intervention in the PR trial. After 20 min of the post-IMT ITL trial, [K^+] was 0.3 ± 0.3 mmol·L^{-1} greater ($P < 0.05$) than at the same time point of the pre-IMT ITL trial.

Tables 4 and 5 illustrate the contributions of the independent variables ([SID], [A_{tot}^-], and PCO_2) to changes in plasma [H^+]. Before IMT, [H^+] increased significantly from rest (37.3 ± 2.2 nmol·L^{-1}) to maximal exercise (PR = 60.4 ± 7.9 nmol·L^{-1}, ITL = 63.0 ± 7.3 nmol·L^{-1}, $P < 0.01$). Similar changes were observed in the control group. During the final 10 min of the recovery period of the PR trial,

TABLE 4. Independent and dependent acid–base variables before and after maximal exercise (Max) and after 10 and 20 min of recovery in the IMT group only.

	IMT Group (n = 9)									
	PR				15 cm H_2O ITL			ITL%		
	Rest	Max	10 min	20 min	Max	10 min	20 min	Max	10 min	20 min
Independent variables										
[SID]										
Before	40.4 ± 6.2	28.7 ± 7.3	26.2 ± 7.2*	35.8 ± 7.5	33.2 ± 14.4	32.0 ± 13.3	34.0 ± 6.6	–	–	–
After	–	32.3 ± 6.7	28.7 ± 6.7*	36.2 ± 11.0	33.1 ± 9.7	28.7 ± 10.1	40.8 ± 11.8‖	31.8 ± 5.4	28.8 ± 6.5*	34.3 ± 4.5
[A_{tot}^-]										
Before	16.2 ± 8.2	20.5 ± 5.4	23.3 ± 3.6	19.5 ± 4.3	23.6 ± 9.7	22.9 ± 3.4	18.7 ± 6.9	–	–	–
After	–	21.1 ± 3.2	23.7 ± 3.1	21.3 ± 7.1	26.7 ± 13.2§	21.5 ± 8.0	22.2 ± 3.3‖	22.4 ± 4.2	24.6 ± 3.8	21.5 ± 6.1
PCO_2										
Before	39.5 ± 4.1	42.2 ± 8.0	34.4 ± 3.0*	36.1 ± 3.2	44.0 ± 7.7	33.9 ± 4.8	33.2 ± 6.0	–	–	–
After	–	42.4 ± 9.0	34.4 ± 2.9	35.7 ± 2.7	42.3 ± 7.4	32.5 ± 4.7*	32.4 ± 5.5	44.2 ± 7.6	34.0 ± 5.0	33.8 ± 6.6*
Dependent variables										
[H^+]										
Before	37.3 ± 2.2	60.4 ± 7.9*	53.8 ± 5.8*	45.2 ± 4.2*,†,‡	63.0 ± 7.3*	51.1 ± 3.8*	41.5 ± 4.0†,‡	–	–	–
After	–	57.0 ± 8.7*	50.6 ± 5.4*	43.2 ± 4.6*,†,‡	59.0 ± 10.0*	48.8 ± 7.9†,‡	40.4 ± 6.3†,‡	60.2 ± 8.1*	50.2 ± 5.2*,†	42.3 ± 6.3*,‡
[HCO_3^-]										
Before	25.3 ± 1.8	16.7 ± 2.0*	15.6 ± 2.1*	19.2 ± 2.4*,‡	16.7 ± 2.1*	15.8 ± 2.0*	19.0 ± 2.4*,‡	–	–	–
After	–	17.8 ± 2.5*	16.4 ± 2.1*	19.9 ± 1.9*,‡	17.2 ± 2.1*	16.2 ± 3.0*	19.3 ± 2.7*,‡	17.6 ± 2.4*	16.2 ± 1.9*	18.8 ± 2.3*

Data from the control group have been omitted because they were not different from the IMT group preintervention and remained unchanged after the intervention. Values are expressed as means ± SD.

Within trials: * significantly different from rest ($P < 0.05$); † significantly different from max ($P < 0.05$); ‡ significantly different from 10 min ($P < 0.05$). Between trials: § time point significantly different from PR ($P < 0.05$); ‖ significantly different from pre-IMT ($P < 0.05$).

[SID], strong ion difference; [A_{tot}^-], total concentration of weak acids; PCO_2, partial pressure of carbon dioxide; [H^+], hydrogen ion concentration; [HCO_3^-], bicarbonate concentration.

TABLE 5. Contributions of the independent variables PCO_2, [SID], and $[A_{tot}^-]$ to changes in plasma $[H^+]$ after maximal exercise with 20 min of passive recovery (PR) and inspiratory threshold loading (ITL) before (pre-IMT) and after IMT (post-IMT).

	Concentration			Contribution of Independent Variables $[H^+]$ (nmol·L^{-1})		$\Delta[H^+]$ = Exercise − Rest (nmol·L^{-1})		Percentage Contribution to $\Delta[H^+]$ (%)	
Variable	Rest	PR	ITL	PR	ITL	PR	ITL	PR	ITL
Pre-IMT									
$[H^+]$ meas. (nmol·L^{-1})	37.3	49.3	46.4	–	–	+12.0	+9.1	–	–
$[H^+]$ calc. (nmol·L^{-1})	36.1	52.0	44.8	–	–	+15.9	8.7	–	–
PCO_2 (mm Hg)	39.5	35.2	33.5	32.2	30.9	−3.9	−5.2	−21	−37
[SID] (mmol·L^{-1})	40.4	31.0	33.0	51.9	47.5	+15.8	+11.4	+84	+81
$[A_{tot}^-]$ (mmol·L^{-1})	16.2	21.4	20.8	39.2	38.8	+3.1	+2.7	+16	+19
Post-IMT									
$[H^+]$ meas. (nmol·L^{-1})	37.3	46.9	44.6	–	–	+9.6	+7.3	–	–
$[H^+]$ calc. (nmol·L^{-1})	36.1	49.7	40.8	–	–	+13.6	+4.7	–	–
PCO_2 (mm Hg)	39.5	35.1	32.5	32.2	29.6	−3.9	−6.5	−24	−56
[SID] (mmol·L^{-1})	40.4	32.5	34.8	48.8	44.5	+12.7	+8.4	+77	+72
$[A_{tot}^-]$ (mmol·L^{-1})	16.2	22.5	21.9	39.8	39.4	+3.7	+3.3	+23	+28

Data are the average of minutes 10–20. For abbreviations, see Table 4.
meas., measured $[H^+]$; calc., calculated $[H^+]$ using the method of Putman et al. (27).

84% of the increase in $[H^+]$ above rest was accounted for by a 9.4-mmol·L^{-1} reduction in [SID] with the remaining 16% because of a 5.2-mmol·L^{-1} increase in $[A_{tot}^-]$. During the recovery period, $[H^+]$ was lower by approximately 3 nmol·L^{-1} in the ITL trial compared with the PR trial, although this difference was accounted for by the greater hypocapnia (lower PCO_2) observed during the ITL trial. Similar findings were observed in the control group both before and after the intervention. After IMT, responses in the ITL% trial were similar to those observed in the post-IMT PR trial (Table 4).

Compared with preintervention values, after IMT plasma, $[H^+]$ was lower in recovery from maximal exercise in both PR (main effect trial, $P < 0.05$) and ITL (main effect trial, $P < 0.05$). In the same analysis, PCO_2 and $[A_{tot}^-]$ after exercise and throughout recovery were not different after IMT. Therefore, the reduction in $[H^+]$ was accounted for exclusively by an increased [SID]. The increase in [SID] during PR was accounted for by the reduction in $[lac^-]_B$ and during ITL by the significant 1.7-mmol·L^{-1} ($P < 0.05$) and 0.3-mmol·L^{-1} ($P < 0.05$) decrease and increase in $[lac^-]_B$ and $[K^+]$, respectively.

DISCUSSION

The primary finding of this study is that the addition of a pressure threshold inspiratory resistance (15 cm H_2O) during recovery from maximal incremental exercise accelerated blood lactate clearance but only after 6 wk of specific IMT.

Our finding that pressure threshold loading of untrained inspiratory muscles immediately after maximal exercise failed to affect systemic lactate clearance (Fig. 3) disagrees with the findings of Chiappa et al. (3). An explanation for this disagreement is not readily forthcoming as the experimental protocols were broadly similar (including breathing pattern). However, it must be acknowledged that although the same inspiratory resistance was used, the methods of inspiratory muscle loading were somewhat different. The valve opening characteristics of the ITL device may have differed, and an additional 1-m length of tubing was used in the present study to connect the device to the subject. Chiappa et al. (3) found that during recovery with an inspiratory resistance, $[H^+]$ was unaffected by a large (~2.5 mmol·L^{-1}) decrease in $[lac^-]_B$ with no change in PCO_2. The authors suggest that flux in other strong ions (not measured) may explain the unaltered blood acid–base balance despite the large reduction in $[lac^-]_B$. We found no such changes either before or after IMT. Also, lactate clearance is well described by a biexponential function after exercise at different intensities (11), with respiratory muscle loading ([29]; this study) and after both whole-body training (26) and IMT (this study). That this pattern was not observed by Chiappa et al. (3) is also difficult to resolve.

Although methodologically disparate, our (preintervention) findings are similar to those of Perret and Mueller (29), who reported unchanged lactate recovery kinetics after exercise with low-intensity isocapnic volitional hyperpnea ($\dot{V}_E$ = 61.6 ± 9.3 L·min^{-1}, 30% ± 1% of MVV) compared with PR. Therefore, the issue of whether increasing the work of breathing offers a method of accelerating lactate clearance remains equivocal. It is possible that the intensity of inspiratory muscle loading is influential: when ITL was performed at the same relative intensity (an absolute pressure threshold of 20 ± 2 cm H_2O; i.e., ITL%) after IMT, lactate clearance was not accelerated relative to PR and ITL. This finding is similar to previous work where relative to high-intensity leg exercise (65% $\dot{V}O_{2max}$), low-intensity leg exercise (35% $\dot{V}O_{2max}$) performed immediately after maximal exercise increased lactate clearance (5). The blood flow characteristics of different exercise intensities were proposed as an explanation for their findings (5). Notwithstanding this, the lack of relationship between %MIP of ITL (range = 10%–19%) and rates of lactate clearance (Fig. 4) does not support the notion that the ITL intensity is influential. However, it is interesting to speculate whether a lower inspiratory resistance (<15 cm H_2O) before the intervention

would have accelerated lactate clearance, and further work is warranted to reveal the effects of ITL intensity on lactate recovery kinetics.

We also report that IMT reduced peak $[lac^-]_B$ by approximately 1 mmol·L^{-1} after completion of the maximal incremental exercise test despite no change in the incremental or maximal exercise breathing pattern (Fig. 1). This agrees with previous RMT studies showing a lower $[lac^-]_B$ after both maximal incremental (38) and steady-state exercise (23) without a change in the exercise $\dot{V}_E$ and lends further credence to the hypothesis that RMT affects lactate clearance rather than lactate production (2). When comparing $[lac^-]_B$ during the ITL trial pre-IMT and post-IMT, the difference was maximal (2.30 mmol·L^{-1}) after 8 min. Chiappa et al. (4) recently reported that 10 min of ITL accelerated lactate recovery and increased peak power during subsequent 30-s all-out maximal exercise. Whether IMT magnifies such effects also remains an intriguing question.

We are the first to report that ITL after specific IMT can significantly speed lactate clearance after maximal incremental cycling exercise. After IMT, A_2, which reflects the amplitude concentration of lactate clearance, was reduced during PR from maximal exercise; however, because the velocity constants were unchanged, this is likely to reflect the lower absolute $[lac^-]_B$ throughout recovery relative to preintervention (Table 3 and Fig. 3). Conversely, increasing the work of breathing with ITL immediately after exercise at the same intensity increased the velocity constants and decreased the amplitudes of both exponential terms (Table 3). We observed a significant reduction in PCO_2 throughout the ITL trial, and respiratory alkalosis is known to elevate the $[lac^-]_B$ (2). Thus, whether controlling breathing pattern throughout recovery would further lower $[lac^-]_B$ and accelerate lactate recovery kinetics remains to be confirmed. Previous studies have reported similar changes in these parameters after whole-body training (26,27). After IMT, we observed a 68% increase in γ_1 during ITL, indicating an improved capacity for lactate exchange between the previously worked muscle(s) and the systemic circulation (11). Because of the specific nature of IMT, this was probably achieved by increasing the concentration gradient between the locomotor muscles and the systemic circulation, most likely because of increased lactate clearance by the inspiratory muscles (as confirmed by the 71% increase in γ_2). The increase in γ_2 is similar to that found in whole-body exercise training studies in which it was associated with an increase in lactate transport capacity (MCT1 and MCT4) and oxidative enzyme activity (26,27). It has been argued that such adaptations may occur after IMT (cf. McConnell and Sharpe [23]). In support, oxidative enzyme adaptations occurred in sheep diaphragm after intense resistive RMT (1), and an increased proportion of Type I muscle fibers was observed in the external intercostal muscles of chronic obstructive pulmonary disease patients after 5 wk of IMT (33).

We used the physicochemical approach (39) to quantify the relative contribution of each of the independent variables to changes in acid–base disturbance (31,39). Similar to a previous study (31), we observed excellent agreement between the measured and the calculated $[H^+]$ ($r = 0.925$, $P < 0.001$). After IMT, the smaller disturbance of $[H^+]$ during ITL compared with PR was due to an increase in [SID]. With the exception of a small increase in $[K^+]$, no other strong ion was affected. Therefore, the increase in [SID] was almost exclusively accounted for by the reductions in $[lac^-]_B$. The defense of plasma acid–base homeostasis is considered of great importance during and after exercise (31); therefore, IMT and ITL may provide a favorable systemic metabolic environment for subsequent bouts of exercise (4,7).

$\dot{W}_{max}$, peak $[lac^-]_B$, acid–base balance, and lactate recovery kinetics were unaltered in the control group after the intervention period. With the exception of one study (37), evidence suggests that placebo effects associated with RMT interventions are minimal (12,15,18,35,36,41); thus, we feel that the physiological changes observed after IMT in this study are unlikely to be the result of greater subject expectation and/or motivation. Notwithstanding this, a limitation of our study is that a placebo was not used, which may have influenced outcome measures in the control group.

CONCLUSIONS

In stark contrast to the findings of Chiappa et al. (3,4), we observed no effect of ITL on lactate recovery kinetics. The novel finding of this investigation is that after IMT, ITL accelerates the capacity for whole-body lactate exchange and clearance. Furthermore, IMT also reduced plasma $[H^+]$, which was accounted for by the increase in [SID] due almost exclusively to the IMT-mediated reduction in $[lac^-]_B$. The potential mechanisms affecting lactate recovery kinetics after IMT appear similar to those observed after whole-body endurance training. The effects of ITL during recovery from intense exercise on subsequent performance after IMT present novel avenues for future study.

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