Acute Cardiorespiratory Responses to Inspiratory Pressure Threshold Loading

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ABSTRACT

MCCONNELL, A. K. and L. A. GRIFFITHS. Acute Cardiorespiratory Responses to Inspiratory Pressure Threshold Loading. *Med. Sci. Sports Exerc.*, Vol. 42, No. 9, pp. 1696–1703, 2010. **Purpose**: We tested the acute responses to differing pressure threshold inspiratory loading intensities in well-trained rowers. The purpose of this study was to evaluate 1) how the magnitude of inspiratory pressure threshold loading influences repetition maximum (RM), tidal volume (V_T), and external work undertaken by the inspiratory muscle; and 2) whether the inspiratory muscle metaboreflex is activated during acute inspiratory pressure threshold loading. **Methods**: Eight males participated in seven trials. Baseline measurements of maximal inspiratory pressure (P_{Imax}), resting tidal volume (V_T), and forced vital capacity (FVC) were made. During the remaining sessions, participants undertook a series of resistive inspiratory breathing tasks at loads corresponding to 50%, 60%, 70%, 80%, and 90% of P_{Imax} using a pressure threshold inspiratory muscle trainer. The number of repetitions completed at each load, V_T, heart rate (f_c), and measures of arterial blood pressure was assessed continuously during each trial. **Results**: A standardized cutoff of 10% FVC was used to define the RM, which decreased as loading intensity increased ($P < 0.05$). This response was nonlinear, with an abrupt decrease in RM occurring at loads ≥70% of P_{Imax}. The most commonly used inspiratory muscle training regimen of 30RM corresponded to 62.5% ± 4.6% of P_{Imax} and also resulted in the highest external work output. Tidal volume (V_T) decreased significantly over time at 60%, 70%, and 80% of P_{Imax} ($P < 0.05$), as did the amount of external work completed ($P < 0.05$). **Conclusions**: Although all loads elicited a sustained increase in f_c, only the 60% load elicited a sustained rise in mean arterial blood pressure ($P = 0.016$), diastolic blood pressure ($P = 0.015$), and systolic blood pressure ($P = 0.002$), providing evidence for a metaboreflex response at this load. **Key Words:** RESPIRATORY MUSCLE LOADING, REPETITION MAXIMUM, INSPIRATORY MUSCLE METABOREFLEX, VENTILATORY TASK FAILURE

Several studies have now shown that moderate-intensity (50%–60% of maximal inspiratory pressure) pressure threshold of inspiratory muscle training (IMT) improves inspiratory muscle strength, power, and endurance (18). Those studies undertaking IMT using inspiratory pressure threshold loading, and with the appropriate outcome measures (17), have also demonstrated improvements in exercise tolerance in healthy young athletes (17) and in patients with respiratory (7) and cardiovascular (5) disease. Furthermore, recent evidence points to attenuation of the inspiratory muscle metaboreflex as an important mechanism underlying post-IMT improvements in exercise tolerance (4,16,26).

The inspiratory muscle metaboreflex has typically been examined using flow-resistive loading, and its activation is manifest as a time-dependent increase in mean arterial blood pressure (MAP) and heart rate (f_c) (16,20,22,26). However, it is unclear whether the metaboreflex is activated during acute inspiratory pressure threshold loading (of the type used during IMT) or, indeed, whether this is an obligatory stimulus to the adaptations that result in changes to the activation of this reflex after pressure threshold IMT.

One of the unique features of pressure threshold loading is its fixed-magnitude, flow-independent load. Although this characteristic offers advantages in the reliability of the training stimulus, it is not without its drawbacks, the principal of which is the interaction of the fixed load with the inspiratory muscle length–tension (pressure–volume) relationship. This interaction is such that, the greater the magnitude of the inspiratory pressure threshold load, the smaller the tidal volume excursion that can be achieved. Thus, not only do higher loads result in a smaller number of repetitions to task failure, they may also be associated with a reduction in the amount of external work undertaken by the inspiratory muscles. The latter may have important implications for the design of IMT protocols because there may be a minimum amount of inspiratory work required to elicit the changes in function, which underpin increases in the metaboreflex threshold.

Thus, the purpose of this study was to characterize the acute physiological responses to pressure threshold loading

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across a range of inspiratory loads. Specifically, we sought to evaluate 1) how the magnitude of the inspiratory pressure threshold load influences repetition maximum (RM), tidal volume (V_T), and inspiratory muscle work; and 2) whether the inspiratory muscle metaboreflex is activated during acute inspiratory pressure threshold loading. We hypothesize that 1) the limit of tolerance (T_{lim}) will decrease with increasing loads, 2) V_T will decrease with increasing loads, and 3) one or more of the loading protocols will activate the inspiratory muscle metaboreflex.

METHODS

Participants. Eight healthy competitive male rowers volunteered to participate in this study that was approved by the Brunel University Ethics Committee. Before testing, all participants completed a health questionnaire and gave written informed consent.

Participants were requested to maintain their normal diet in the few days that preceded testing. Participants were also requested to avoid alcohol and vigorous exercise 2 d before testing and to avoid caffeinated beverages on test day. To minimize the effects of inspiratory muscle fatigue, participants were limited to one test session per day.

General design. Each participant attended six testing sessions. During session 1, maximal inspiratory mouth pressure (P_{Imax}), resting V_T, and forced vital capacity (FVC) were assessed. During the subsequent sessions, participants undertook a series of loaded breathing tasks at five loads (50%, 60%, 70%, 80%, and 90% of P_{Imax}) using a pressure threshold inspiratory muscle trainer. Participants breathed against each load to the T_{lim} at a breathing frequency of 15 breaths per minute, which was paced by metronome. Ventilatory and cardiovascular responses were monitored throughout each breathing task.

Participant characteristics. Stature, body mass, and respiratory function were assessed at session 1, and these are presented in Table 1.

Inspiratory warm-up. Before inspiratory muscle strength testing, participants were instructed on the proper usage of the pressure threshold loading device for the inspiratory "warm-up" (POWERbreathe; HaB International Ltd, Southam, UK). Participants were instructed to perform two sets of 30 breaths at a resistance equivalent to 40% P_{Imax}. This protocol has been shown to attenuate the effect of repeated measurement on P_{Imax} and to improve within-day and between-day reliability, as quantified by limits of agreement, coefficient of variation, and intraclass correlation coefficients (15,24).

TABLE 1. Descriptive characteristics of the participants (mean ± SD).

	Participants (n = 8)
Anthropometry	
Age (yr)	22.0 ± 2.1
Stature (m)	1.8 ± 0.1
Body mass (kg)	86.0 ± 11.9
Respiratory function	
P_{Imax} (cm H_2O)	193.4 ± 26.7
FVC (L)	5.2 ± 1.0
Resting V_T (L)	1.3 ± 0.3

Inspiratory muscle strength. Maximal inspiratory pressure was assessed using a portable handheld mouth pressure meter (Morgan Medical, Hertford, UK) according to the American Thoracic Society guidelines (1). The assessment of P_{Imax} required a sharp, forceful effort maintained for a minimum of ~2 s. The pressure meter incorporated a 1-mm leak to prevent glottic closure (2). Measurements were repeated until three technically acceptable maneuvers were achieved within 5 cm H_2O; the best of these three was recorded.

Pulmonary function. FVC and loaded breath volumes were assessed using an online computer software package (BIOPAC MP30; BIOPAC Systems, Inc., Goleta, CA) according to the American Thoracic Society guidelines (1). Participants breathed through a flow meter that measured flow using a differential pressure transducer and integrated this signal to derive volume.

Participants undertook a series of inspiratory loaded breathing tasks using a pressure threshold training device (POWERbreathe; HaB International Ltd.). The breathing tasks consisted of loads of 50%, 60%, 70%, 80%, and 90% of P_{Imax} performed in a randomized order. Participants were requested to undertake each load to the T_{lim}, but no encouragement was provided during the task, and no indication was provided as to how many breaths they should perform. A metronome was used to regulate breathing frequency to 15 breaths per minute. The target duty cycle was 0.5, but in practice, this ranged from 0.3 to 0.5 because of the inertial properties of the threshold load and the influence of the force–velocity relationship of the inspiratory muscles. After 15 min, any participant who was able to maintain the resistive breathing load was stopped. Participants were not informed of the cutoff time of 15 min until they reached that point. All participants were encouraged to perform the tasks to their own T_{lim} and not to a target time or number of breaths. The duration from the onset of the task to the point the participant removed the mouthpiece was termed T_{lim}, and this is presented in seconds (s). We did not attempt to control arterial P_{CO_2} (Pa_{CO_2}) during the loaded breathing tasks because of the uncertainty relating to the relationship between end-tidal P_{CO_2} and Pa_{CO_2} during loaded breathing. Our previous experience is that mild hypocapnia (>30 mm Hg) develops during the low loads, whereas eucapnia prevails during the heavy loads. Previous research has demonstrated that, in humans, mild hypocapnia does not elicit any changes in either forearm vascular resistance or blood pressure (10). These authors also demonstrated that responses to lower body negative pressure were unaffected by this mild hypocapnia, suggesting that mild hypocapnia does not influence resting vessel tone or reflex responses to baroreceptor stimulation. Furthermore, we have

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TABLE 2. Average total repetitions, number of repetitions with V_T > 10% FVC (T), and average time at each load (n = 8).

	Mean (Breaths)	Minimum (Breaths)	Maximum (Breaths)	T_{lim} (s)
Total repetitions				
50%	134.6 ± 66.9	57	217	537 ± 268
60%	84.6 ± 85.4	14	217	339 ± 342
70%	19.5 ± 24.4*	6	76	78 ± 96*
80%	8.9 ± 6.0*	4	21	32 ± 24*
90%	7.1 ± 3.3*	2	12	28 ± 13*
Repetitions >10% FVC				
50% T	133.6 ± 68.2	54	217	534 ± 270
60% T	84.5 ± 85.5	14	217	334 ± 335
70% T	17.3 ± 25.5**	0	76	72 ± 95**
80% T	7.1 ± 7.0**	2	21	28 ± 28**
90% T	4.6 ± 3.7**	2	11	18 ± 15**

* Significantly different compared with 50% P_{Imax} load ($P \leq 0.05$).
** Significantly different compared with 50% T ($P \leq 0.05$).

also demonstrated activation of the inspiratory muscle metaboreflex in the presence of mild hypocapnia (16).

Tidal volume (V_T) was measured during each loading task and was predicted to decline with increasing load and with increasing repetitions (because of the effects of the pressure–volume relationship and fatigue, respectively). Because the time course of the within-test change in V_T was unknown, an objective V_T threshold was determined retrospectively to define the RM for each load. A V_T threshold of 10% of FVC was used to define the RM at each load; breaths occurring after V_T that had fallen below 10% FVC were excluded (for RM determination purposes).

Assessment of cardiovascular responses. Measures of f_c and arterial blood pressure were made noninvasively during the loaded breathing tasks using an automated combined continuous blood pressure monitor (Colin CBM-7000; Scanmed, Moreton in Marsh, UK). Blood pressure was measured using arterial tonometry; a solid-state blood pressure transducer sensor was attached to the participant's left wrist over the radial artery. An oscillometric brachial cuff provided calibration for the pressure transducer sensor. Measures of MAP and systolic and diastolic blood pressures (SBP and DBP, respectively) are presented in millimeters of mercury (mm Hg). Continuous f_c was recorded and presented as beats per minute (bpm).

Data analysis. Temporal data were analyzed using two methods. First, to account for differences in the number of repetitions achieved and changes in V_T, each breathing task was divided into isotime quartiles. Second, pulmonary and cardiovascular data were also analyzed every 30 s for the first 3 min at loads of 50% and 60% and every 15 s for the first minute at loads of 70%, 80%, and 90% to determine the onset, if present, of the inspiratory muscle metaboreflex. Mean values were calculated for each outcome variable and were subjected to statistical analysis. Participants not achieving four breaths for a given task were excluded from the analysis at that particular load. In addition, an approximation of inspiratory work was made to determine whether the combination of load and volume resulted in more or less external work at any given inspiratory load. The average external work of breathing was calculated for each resistive load using the following equation:

$$\text{Work} = \text{force (pressure)} \times \text{distance (volume)}$$
$$\text{External work of breathing} = \text{inspiratory threshold load (cm } H_2O) \times V_T \text{ (L)}$$

A repeated-measures ANOVA was used to determine physiological changes over time. Violations of the assumption of sphericity were measured using the Mauchly sphericity test and corrected using the Greenhouse–Geisser adjustment. Planned pairwise comparisons were made to analyze significant interaction effects using the Bonferroni adjustment. Pearson correlation coefficients were performed to determine relationships between physiological and performance variables. Probability values <0.05 were considered significant. Statistical and mean data were calculated using the statistical software SPSS V16.0 for Windows (SPSS, Inc., Chicago, IL). All results are expressed in mean ± SD unless stated otherwise.

RESULTS

Repetition maximum at each load. Data for average total number of repetitions, the number of repetitions performed at a V_T > 10% FVC threshold load, and average T_{lim} at each load are presented in Table 2. There was a statistically significant within-participant effect for the total number of breaths (P = 0.001, Greenhouse–Geisser), indicating a difference in the number of repetitions performed at differing loads. As shown in Table 2, there was a statistical difference between total repetitions performed at 50% P_{Imax} compared with those performed at 70% (P = 0.011), 80% (P = 0.009), and 90% P_{Imax} (P = 0.010). Similarly, when the objective V_T criterion was applied to determine RM, there was a statistical difference within participants (P = 0.001, Greenhouse–Geisser) at 50% compared with 70% (P = 0.013), 80% (P = 0.010), and 90% (P = 0.011).

Participants completed the various breathing tasks at different time points. As shown in Table 2, there was an abrupt drop in T_{lim} at loads >70% P_{Imax}. During the 50% and 60% loads, there were a few participants (n = 3 and n = 2, respectively) who maintained the task to the 15-min cutoff

TABLE 3. Mean V_T and V_T %FVC across isotime quartiles (Q) at each load.

	50% P_{Imax} (n = 8)	60% P_{Imax} (n = 8)	70% P_{Imax} (n = 6)	80% P_{Imax} (n = 6)
V_T (L)				
Q1	2.4 ± 1.0	2.3 ± 0.8	1.6 ± 1.1*	1.4 ± 0.6*
Q2	2.3 ± 0.8	2.2 ± 0.8	1.4 ± 1.2	1.1 ± 0.5**
Q3	2.1 ± 0.7	2.0 ± 0.8***	1.4 ± 1.2	1.0 ± 0.4**
Q4	2.0 ± 0.9***	1.9 ± 0.8**,***	1.0 ± 0.8**	0.8 ± 0.4**
V_T %FVC (%)				
Q1	44.8 ± 16.1	43.7 ± 12.5	30.7 ± 4.2*,****	29.6 ± 8.1****
Q2	44.0 ± 14.8	41.5 ± 12.1	26.4 ± 7.8	20.5 ± 5.6
Q3	42.6 ± 15.7	38.3 ± 15.2	24.1 ± 9.9	18.5 ± 4.3**
Q4	41.7 ± 18.9	36.2 ± 14.7***	21.6 ± 8.3	14.4 ± 4.9**

* Significantly different compared with 60% load ($P \leq 0.05$).
** Significantly different from Q1.
*** Significantly different from Q2.
**** Significantly different compared with 50% load ($P \leq 0.05$).

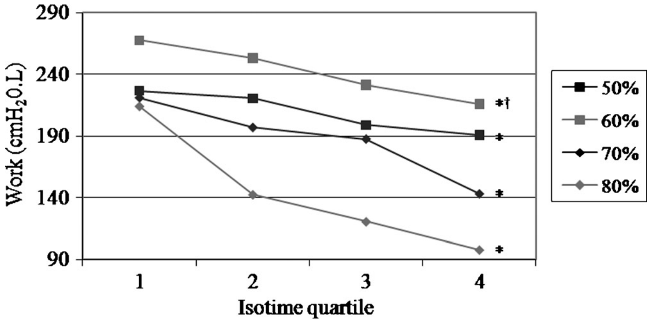

FIGURE 1—Comparison of estimated average work completed for each resistive load. *Significantly different over time (P < 0.05). †Significantly different compared with other loads (P < 0.05).

point. On average, the 30RM corresponded to 62.5% ± 4.6% P_{Imax} (60% in six participants and 70% in two participants).

Significant correlations were found between FVC and the number of repetitions completed at 70% P_{Imax} (r = 0.806, P = 0.016) and 90% P_{Imax} (r = 0.841, P = 0.009). Although these relationships were significant, this significance was attributable primarily to one or two outliers. There were no significant correlations between the number of repetitions performed and stature, body mass, V_T, or P_{Imax} at any load.

Within task changes in tidal volume and tidal volume expressed as a percent of forced vital capacity. Significant differences were detected in V_T between participants at 60% (P = 0.039) and within participants over time at 50% (P = 0.023), 60% (P = 0.006), 70% (P = 0.041), and 80% (P = 0.000; Table 3). No analysis was performed for the 90% load because the number of participants (n = 2) who were able to sustain breathing above the 10% FVC tidal volume threshold was insufficient. When tidal volume was expressed as a percentage of FVC (V_T %FVC), there was also a significant within-participant effect at 60%, 70%, and 80% (P < 0.05) but not at 50%.

Estimation of average external work. There was a significant within-participant effect over time (P = 0.006, Greenhouse–Geisser) when comparing the estimated average work completed at each load (Fig. 1). Estimated average work was highest during the 60% load compared with that during the 50% (13.6% difference, P = 0.012), 70% (22.5% difference, P = 0.023), and 80% loads (40.6% difference, P = 0.043). Inspiratory work undertaken at all loads was highest within the first quartile, decreasing progressively over time at all loads (P < 0.05). Bivariate correlations were performed to compare the relationship between average work completed to average f_c at each load and to the number of repetitions at each load; no significant correlations were found at any load.

Cardiovascular response. Because of the large reduction in the number of repetitions completed at loads >70% P_{Imax} (Table 2), differing temporal analyses were undertaken for data <70% and >70% P_{Imax}. Analysis of loads at 50% and 60% P_{Imax} was undertaken at 30-s bin intervals for the first 3 min of loading. Loads >70% P_{Imax} were analyzed at 15-s bin intervals for the first min because some participants were unable to maintain breathing for >30 s.

Temporal analysis of the cardiovascular response at 50% and 60% P_{Imax}. Repeated-measures ANOVA did not reveal any significant differences between loads for MAP (P = 0.343), SBP (P = 0.314), and DBP (P = 0.313); however, there was a clear and sustained difference in blood pressure between the 60% and 50% loads (Table 4 and Figs. 2A–C). Therefore, planned pairwise comparisons were undertaken, with Bonferroni correction, to determine whether there were any significant changes within loads (P set at <0.016) and between loads (P set at <0.025) at the 30-, 60-, and 90-s time intervals compared with baseline. Comparisons were not made beyond 90 s because of the decreasing number of participants able to sustain the 60% load beyond this time point. Using the critical P values above, there was a significant increase from baseline to the 60-s time interval in MAP (P = 0.016) and DBP (P = 0.015) at the 60% load. The 60% load also

TABLE 4. Comparison of physiological responses at 30-s intervals for the first 3 min at loads of 50% and 60%.

	V_T (L)	MAP (mm Hg)	SBP (mm Hg)	DBP (mm Hg)	f_c (bpm)	Work (cm H_2O·L)
50% (n = 8)						
Pretest	1.3 ± 0.5	87.9 ± 11.3	136.0 ± 19.8	69.8 ± 10.5	73.3 ± 11.4	
30 s	2.3 ± 1.0	90.2 ± 13.4	133.0 ± 20.5	71.4 ± 14.1	86.7 ± 12.6*	225.6 ± 107.6
60 s	2.4 ± 1.1	87.1 ± 13.9	132.9 ± 21.8	67.6 ± 14.4	88.6 ± 17.7*	234.5 ± 123.8
90 s	2.5 ± 1.1	90.8 ± 13.1	135.9 ± 20.8	71.0 ± 13.4	88.2 ± 17.0*	241.2 ± 119.8
120 s	2.3 ± 1.0	90.0 ± 13.2	135.0 ± 20.1	70.2 ± 13.6	89.4 ± 18.8	226.5 ± 113.8
150 s	2.4 ± 1.0	87.5 ± 12.2	131.9 ± 18.8	68.0 ± 12.9	87.4 ± 15.0	228.2 ± 116.6
180 s	2.2 ± 0.9	87.3 ± 12.8	131.8 ± 20.7	67.9 ± 12.5	88.9 ± 16.0	214.3 ± 103.7
60%						
Pretest (n = 8)	1.3 ± 0.5	92.3 ± 7.9	139.0 ± 16.8	70.6 ± 7.4	70.1 ± 13.2	
30 s (n = 8)	2.3 ± 0.8	94.6 ± 9.7	142.8 ± 15.2**	73.5 ± 10.7	88.9 ± 18.5	269.1 ± 118.8
60 s (n = 8)	2.1 ± 0.8	99.7 ± 10.1*	145.3 ± 20.0*	77.7 ± 8.1*	92.0 ± 20.8*	249.3 ± 112.3
90 s (n = 7)	2.1 ± 0.8	103.3 ± 12.2	151.7 ± 22.4*	80.4 ± 11.1	98.0 ± 22.8*	250.1 ± 131.8
120 s (n = 6)	2.1 ± 0.8	104.3 ± 16.7	149.1 ± 26.5	82.6 ± 13.5	95.8 ± 24.9	255.6 ± 134.6
150 s (n = 4)	2.2 ± 1.0	109.2 ± 18.4	151.8 ± 29.4	87.7 ± 14.3	95.6 ± 29.2	271.3 ± 141.1
180 s (n = 4)	2.3 ± 1.0	109.1 ± 20.1	153.8 ± 31.5	87.7 ± 15.0	100.7 ± 23.8	237.2 ± 145.0

Pairwise comparisons were only made at 30, 60, and 90 s because there were insufficient participants at later times for the 60% load.
* Significantly different compared with baseline ($P \leq 0.016$).
** Significantly different compared with 50% load ($P \leq 0.025$).

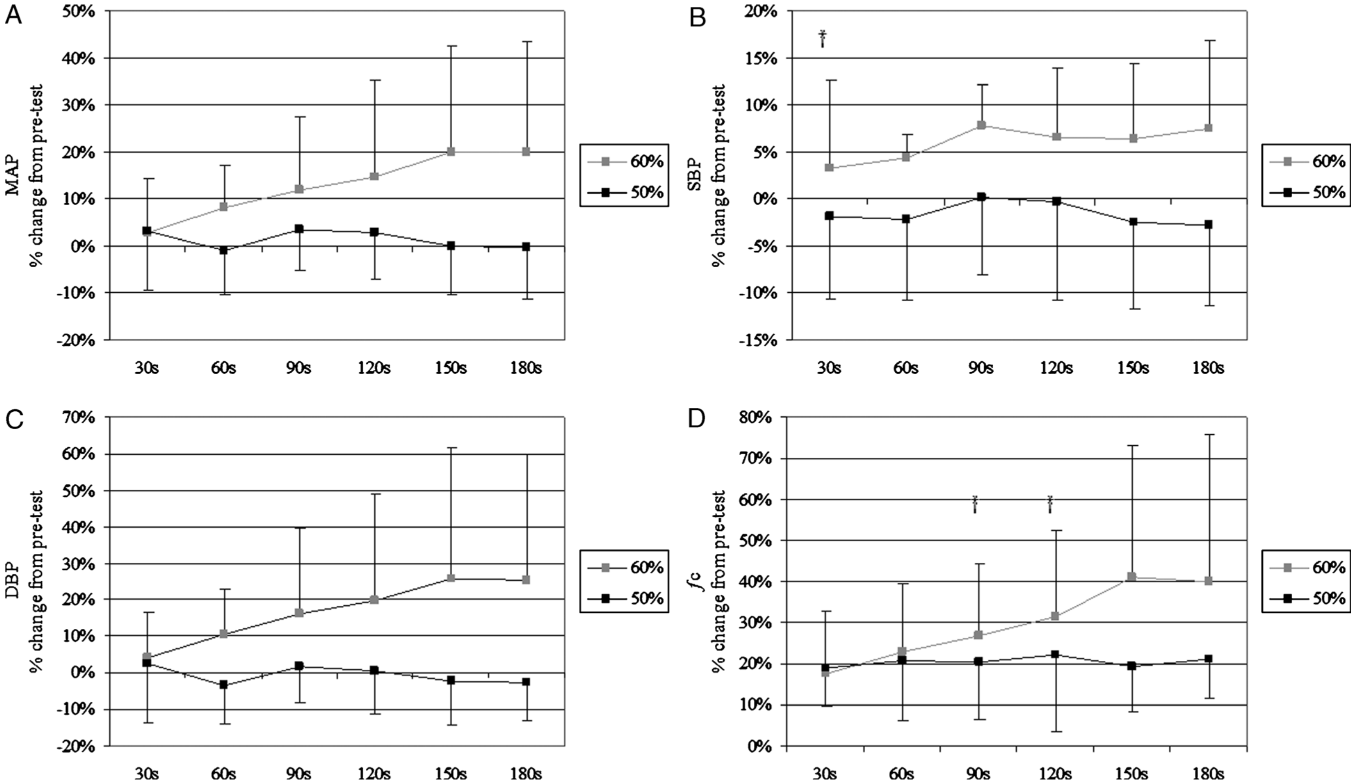

FIGURE 2—Comparison of percentage change from pretest values for MAP (A), SBP (B), DBP (C), and f_c (D) at 50% and 60% loads. MAP, SBP, and DBP were measured in millimeters of mercury (mm Hg). †Significantly different compared with 50% load (P < 0.025).

elicited a rise in SBP from baseline to the 60-s (P = 0.002) and 90-s (P = 0.002) time interval; furthermore, there was a significant difference in SBP at the 30-s time interval compared with the 50% load (P = 0.020). Importantly, changes in arterial blood pressure were consistent between participants at the 60% load, i.e., all participants showed an increase. No change in blood pressure was evident over time during the 50% load.

Repeated-measures ANOVA revealed significant between-participant (P = 0.002) and within-participant (P = 0.001) effects over time for f_c when comparing the 50% and 60% loads. Heart rate (f_c) also exhibited a sustained increase from baseline during the 60% load (P = 0.000). Pairwise comparisons with Bonferroni correction (P set at < 0.016) revealed significant differences at 30-s (P = 0.013), 60-s (P = 0.015), and 90-s (P = 0.002) time intervals compared with baseline during the 50% load (Fig. 2D).

There was a significant difference in average work completed at the 50% and 60% loads (13.6%, P = 0.012), such that the average work completed during the first 2 min at the 60% load was 10.7% higher (255.4 ± 12.9 cm H_2O·L) compared with that at 50% (228.4 ± 9.1 cm H_2O·L). No

TABLE 5. Comparison of cardiovascular responses at 15-s intervals for the first 45 s at loads of 70%, 80%, and 90% P_{Imax}.

	V_T (L)	MAP (mm Hg)	SBP (mm Hg)	DBP (mm Hg)	f_c (bpm)
70% P_{Imax}					
15-s intervals					
Pretest (n = 8)	1.3 ± 0.5	91.0 ± 14.3	131.4 ± 20.9	74.2 ± 13.0	76.2 ± 10.3
15 s (n = 8)	1.0 ± 0.6	94.8 ± 25.5	133.7 ± 33.5	75.8 ± 19.7	89.3 ± 14.9*
30 s (n = 8)	0.8 ± 0.6	98.7 ± 26.0	136.4 ± 39.0	77.2 ± 19.5	91.8 ± 16.5*
45 s (n = 3)	1.0 ± 0.8	95.2 ± 16.0	122.7 ± 15.9	75.0 ± 10.8	98.7 ± 17.5*
80% P_{Imax}					
15-s intervals					
Pretest (n = 8)	1.5 ± 0.5	90.5 ± 9.6	133.1 ± 15.8	72.1 ± 11.4	73.4 ± 11.6
15 s (n = 8)	1.3 ± 0.9	89.4 ± 6.9	126.0 ± 18.1	67.7 ± 9.8	92.2 ± 11.0*
30 s (n = 6)	0.9 ± 0.8	97.3 ± 15.2	140.5 ± 24.8	78.3 ± 13.8	87.9 ± 11.7*
45 s (n = 2)	1.5 ± 0.6	96.2 ± 0.2	142.2 ± 9.8	68.6 ± 4.0	109.4 ± 7.9
90% P_{Imax}					
15-s intervals					
Pretest (n = 8)	1.3 ± 0.5	92.1 ± 7.9	133.1 ± 7.9	74.4 ± 7.9	70.6 ± 6.4
15 s (n = 8)	0.8 ± 0.3	94.1 ± 11.5	129.5 ± 13.2	75.1 ± 10.0	86.3 ± 13.9*
30 s (n = 5)	0.5 ± 0.3	101.0 ± 15.9	139.8 ± 19.6	82.3 ± 13.9	96.0 ± 19.2*
45 s (n = 1)	0.5	100.1	139.3	76.7	87.5

* Significantly different compared with baseline ($P \geq 0.05$).

statistical analysis was performed from 120 to 180 s because of the small number of participants (n = 4) able to continue the task for 3 min at the 60% load.

Temporal analysis of the cardiovascular response at loads >70%. Only those participants able to complete at least 30 s of breathing were included in the temporal analysis at loads >70%. Table 5 compares the cardiovascular responses at 15-s intervals for loads of 70%, 80%, and 90%. Although there was a significant within-participant effect for all variables ($P < 0.05$), there were no significant differences between loads. All loads elicited a significant increase in f_c over time compared with baseline ($P < 0.05$), but planned pairwise comparisons revealed no significant changes in any other cardiovascular variable.

DISCUSSION

The main purpose of this study was to characterize the acute cardiorespiratory responses to a range of pressure threshold inspiratory loads (50%–90% P_{Imax}). Although inspiratory pressure threshold loading is the most widely used method for training the inspiratory muscles, the characteristics of inspiratory pressure threshold loading remain largely unstudied. This dearth of knowledge for inspiratory pressure threshold loading is in stark contrast to the widely studied technique of inspiratory flow-resistive loading (16,20–22,26). The most important findings of our study were as follows: 1) during inspiratory pressure threshold loading, external work is compromised at high loading intensities because of the interaction of the load with the pressure–volume relationship of the inspiratory muscles; 2) external work was maximized at the 60% load; and 3) although all loads elicited a sustained increase in f_c, only the 60% load elicited a sustained rise in SBP and MAP, providing evidence for a metaboreflex response at this load. These observations have important practical implications for the successful implementation of pressure threshold IMT.

Load magnitude and RM. To our knowledge, this is the first study to examine the training characteristics across a range of loads using inspiratory pressure threshold loading. There was little difference between the total number of repetitions completed to task failure and the number of repetitions defined objectively using the V_T %FVC threshold (Table 2). At 50% and 60% P_{Imax}, participants were able to complete an average of 134 ± 68 repetitions (537 ± 268 s) and 85 ± 85 repetitions (339 ± 342 s), respectively. Direct comparison with previous studies using flow-resistive inspiratory loading is problematic because not only the method of loading but also the breathing frequency, duty cycle (15 breaths per minute and 0.5, respectively, in the present study), and V_T differed in the present study. For example, Witt et al. (26) observed that T_{lim} during inspiratory flow-resistive loading at 60% P_{Imax} occurred after 535 ± 52 s, which corresponded to ~133 repetitions at their breathing frequency of 15 breaths per minute and duty cycle of 0.7. On the face of it, the tolerance to moderate (60% P_{Imax}) inspiratory flow-resistive loading seems much greater than to pressure threshold loading. However, V_T in the study of Witt et al. (26) was less than half that in the present study (~1.l vs ~2.l, respectively), reducing the external work associated with each breath. In addition, the inertial properties of a pressure threshold load tend to lead to higher inspiratory flow rates and a reduction in inspiratory time (6), despite the imposed duty cycle. In theory, the associated reduction in duty cycle should reduce the likelihood of fatigue of the inspiratory muscles, but in practice, the higher inspiratory flow rate increases the relative load on the inspiratory muscles due to functional weakening at higher velocities of shortening (14). These factors may collectively hasten T_{lim} during pressure threshold loading, compared with flow-resistive loading.

There was a nonlinear inverse relationship between the number of repetitions completed and the magnitude of the inspiratory load. The break point of this relationship occurred at the 70% P_{Imax} load (Table 2). Our results showed a broadly similar relationship between the relative inspiratory muscle load and the number of repetitions to that of limb muscles, in that participants performed an average of 1–7 repetitions at training loads >80% P_{Imax}, 7–17 repetitions between 70% and 80% P_{Imax}, and >18 repetitions at loads <60% P_{Imax}. In traditional whole-body resistance training, loads >80%–85% of the 1RM are typically associated with regimens of 1–6 repetitions, loads of 70%–80% 1RM with ~6–12 repetitions, and loads of <60% 1RM with 12–15 repetitions (13). Our data suggest that the relationship between the relative load and the number of repetitions to task failure is similar to that of limb muscles at high loading, but that the ability to tolerate low to moderate loads may be greater for the inspiratory muscles, e.g., 84 repetitions at 60% P_{Imax}, compared with 12–15 repetitions for whole-body resistance training at a similar relative load. This may be a reflection of the more aerobic phenotype typical of inspiratory muscles (8) as well as the absence of an eccentric phase to the inspiratory muscle loading.

Previous studies of pressure threshold IMT in healthy young people have typically used loads equivalent to the 30RM (3,9,11,16,19,23,25). Our participants showed marked differences in their individual tolerance to inspiratory loading (Table 2). For example, at the lowest load of 50% P_{Imax}, some participants (n = 3) were able to continue to the maximum 15-min cutoff, whereas others reached task failure in less than 4 min (n = 2). To explore the relationship of the 30RM to the relative P_{Imax} load, we identified the load that induced task failure as close as possible to 30 breaths for each participant, which corresponded to 60% for six participants and 70% for the remaining two. Thus, for our participants, the load most closely corresponding to the 30RM was 62.5% P_{Imax}. Interestingly, a recent study investigating pressure threshold IMT in elite oarsmen (12) showed no IMT-induced change in P_{Imax} using a load of 50% P_{Imax}, whereas they found a significant 21% increase in P_{Imax} after 6 wk of IMT using a load of

BASIC SCIENCES

~62% ± 3% P_{Imax}. These data suggest that, in trained individuals at least, a pressure threshold load in excess of 60% P_{Imax} is required to elicit improvements in P_{Imax}, and the present data indicate that this can be approximated by using the 30RM.

Tidal volume and external work during pressure threshold loading. Participants were instructed to maximize V_T during inspiratory loading to explore how loading influenced V_T. It was assumed that the interaction of the fixed pressure threshold load with the pressure–volume relationship of the inspiratory muscles would influence the starting V_T and that progressive fatigue would lead to a reduction in V_T during loading. As seen in Table 3, these assumptions were confirmed. However, it is notable that V_T during the 50% and 60% loads was disproportionately larger than that seen at the 70% and 80% loads. We speculate that this may be due to the nonlinearity of the pressure–volume relationship, such that high loads are on a steeper portion of this relationship than moderate loads are. Hence, smaller changes in volume result in larger reductions in force-generating capacity at higher loads. It seems that the breakpoint for this relationship occurs between 60% and 70% of P_{Imax}. There was also a significant effect of time on V_T at loads >60% of P_{Imax}. This temporal decline in V_T during flow-resistive breathing has been shown previously (20), and it is most likely a manifestation of the onset of fatigue. The absence of this phenomenon at the 50% load suggests that loads <50% of P_{Imax} fail to provide adequate overload to the inspiratory muscles in well-trained young men.

These observations have important implications for external inspiratory muscle work undertaken at a given load (Fig. 1) because external work is the product of the pressure load and the volume change achieved at that load. This was found to decline significantly over time at all loads and to be significantly greater during the 60% load than at any other load. Counterintuitively, external work was lowest at the 80% load, and this was a direct effect of the lower V_T at this load. During resistance training of limb muscles using inertial loads, external work is a direct function of the external load because the distance over which the load is moved does not differ between loads or within a given set. Our data indicate that this is not the case for inspiratory pressure threshold loading. If one accepts the premise that it is desirable to maximize the amount of external work completed while minimizing the time taken to achieve this during a given training session, our data suggest that achieving adequate training overload during pressure threshold loading demands a careful balance of maximizing load and number of repetitions while minimizing the influence of loading on V_T. These findings may also shed light on the cardiovascular responses that were observed (see below).

Cardiovascular response to inspiratory resistive loading. One of the purposes of this study was to evaluate whether the inspiratory muscle metaboreflex was activated during pressure threshold loading. At the 50% P_{Imax} load, there was a significant increase in f_c, but no change in any index of blood pressure, compared with baseline (Table 4). In contrast, at the 60% P_{Imax} load, there was not only an increase in f_c but also increases in MAP, SBP, and DBP, compared with baseline, as well as to the responses at the 50% P_{Imax} load. This observation is consistent with those of both Sheel et al. (20,21) and Witt et al. (26) during flow-resistive inspiratory loading at 60% P_{Imax}. Both studies observed a time-dependent increase in both f_c and MAP within 2–3 min of the start of loaded breathing. Our data show an earlier onset of these changes (60 s), which have been attributed to the activation of the inspiratory muscle metaboreflex and were only present at the 60% P_{Imax} load. The question then arises as to why metaboreflex activation occurred at the 60% load but not at any other load. As indicated above, the 60% load was also associated with the greatest external work; thus, it is possible that there is a threshold intensity of work that is required to activate the inspiratory muscle metaboreflex. A threshold phenomenon has been shown previously using inspiratory flow-resistive loading, and at a similar loading intensity (21), but these authors characterized the loading in its propensity to induce diaphragm fatigue, rather than its mechanical properties. They concluded that only flow-resistive loads that induced diaphragm fatigue were associated with metaboreflex activation. Our data are entirely consistent with this notion because one would predict that the accumulation of metabolites within the inspiratory muscles would be associated with a minimum threshold of inspiratory muscle work and that this accumulation would also elicit contractile fatigue of the inspiratory muscles.

Previous studies of the influence of pressure threshold IMT on the inspiratory muscle metaboreflex threshold have shown that training at loads equivalent to the 30RM (16) and at 50% P_{Imax} for three sets of 75 breaths (26) elicit an increase in the threshold for activation of this reflex. Data from the present study suggest that 30RM protocol is associated with the activation of the inspiratory muscle metaboreflex during IMT. In the case of the protocol used by Witt et al. (26), the present study suggests that a continuous set of 134 ± 66.9 breaths at 50% P_{Imax} is insufficient to elicit the metaboreflex. However, it is possible that accumulating a total of 225 breaths (3 × 75 breaths) may be sufficient for activation. Further studies are required to identify whether metaboreflex activation during IMT is an obligatory feature of the IMT-induced increase in metaboreflex threshold.

SUMMARY

As expected, there was a nonlinear inverse relationship between load magnitude and T_{lim} when breathing against inspiratory pressure threshold loads, and there was large interindividual variation in tolerance to such loading. In our participants, the 30RM load that has been used in previous studies of IMT corresponded to a load of 62.5%

P_{Imax}. Most importantly, the pressure–volume relationship of the inspiratory muscles exerted a potent influence on V_T during loading, which had a corresponding influence on the amount of external work undertaken by the inspiratory muscles during each load. Unexpected paradoxical reductions in external work were present at loads above 60%, which may have implications for the efficacy of high-intensity IMT with respect to its influence on inspiratory muscle function. Metaboreflex-induced increases in the indices of arterial blood pressure were evident within 60 s during inspiratory pressure threshold loading at 60% P_{Imax} (our participants' 30RM) but not at other loads. This may also have important implications for the ergogenic efficacy of IMT, but further research is needed to determine whether activation of the metaboreflex during IMT is obligatory for increasing its threshold for activation after IMT.

A.K.M. declares a beneficial interest in the POWERbreathe inspiratory muscle trainer in the form of a share of license income to the University of Birmingham, as well as acting as a consultant to HaB International Ltd. L.A.G. has no potential conflicts of interest.

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