Research article

INSPIRATORY MUSCLE FATIGUE FOLLOWING MODERATE-INTENSITY EXERCISE IN THE HEAT

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ABSTRACT

Heavy exercise has been shown to elicit reductions in inspiratory muscle strength in healthy subjects. Our purpose was to determine the combined effects of moderate-intensity endurance exercise and a thermal load on inspiratory muscle strength in active subjects. Eight active, non heat-acclimatized female subjects (23.5 ± 1.4 yr; VO2max = 39.8 ± 2.4 ml.kg⁻¹.min⁻¹) randomly performed two 40 min endurance exercise bouts (60% VO2max) in either a thermo-neutral (22°C/21% RH) or hot (37°C/33% RH) environment on separate days. Maximal sustained inspiratory mouth pressure (Plmax) was obtained pre and post exercise as an index of inspiratory muscle strength. Additional variables obtained every 10 min during the endurance exercise bouts included: rectal temperature (Tre), heart rate (HR), minute ventilation (VE), oxygen uptake (VO2), tidal volume (VT), breathing frequency (Fb), and ratings of perceived exertion and dyspnea (RPE/RPD). Data were analyzed with repeated measures ANOVA. Plmax was significantly reduced (p < 0.05) after exercise in the hot environment when compared to baseline and when compared to post exercise values in the thermo-neutral environment. Plmax was unchanged from baseline following exercise in the thermo-neutral environment. HR and Tre were significantly higher (p < 0.05) in the hot compared to the thermo-neutral environment. VE and VO2 were not significantly different between conditions. VT was unchanged between conditions whereas Fb was higher (p < 0.05) in the hot condition compared to thermo-neutral. RPE was not significantly different between conditions. RPD was significantly higher (p < 0.05) in the hot compared to the thermo-neutral environment. We conclude that moderate-intensity endurance exercise (60% VO2max) in a hot environment elicits significant reductions in inspiratory muscle strength in unfit females. This finding is novel in that previous studies conducted in a thermo-neutral environment have shown that an exercise intensity of >80% VO2max is required to elicit reductions in inspiratory muscle strength. In addition, dyspnea perception during exercise is greater in a hot environment, compared to thermo-neutral, at a similar level of VE and VO2.

KEY WORDS: Control of breathing, endurance, respiratory function, thermal load.

INTRODUCTION

Inspiratory muscle fatigue (IMF) has been demonstrated following maximal or near-maximal exercise in both trained and untrained subjects (Babcock et al., 1995a; 1995b; Coast et al., 1999; Johnson et al., 1996; Mador et al., 1993). In general, it appears that the intensity of exercise must be very high (>80% VO2max) and the duration of exercise lasting at least 10 min in order to elicit IMF in male and female subjects with a wide range of fitness levels (Babcock et al., 1996; 2002; Johnson et al., 1996). We have recently shown that IMF occurs in both male and female unfit subjects at an exercise intensity of >80% VO2max and that the magnitude of decrease in inspiratory muscle strength is similar
between genders (Gonzales et al., 2003). Likewise, it is generally accepted that the pulmonary system does not limit exercise performance in healthy subjects during prolonged submaximal exercise (Powers and Howley, 2004). However, limited data suggests that inspiratory muscle function may be compromised during submaximal exercise performed in various environmental conditions (e.g. heat or altitude) (Cibella et al., 1996; Romer et al., 2004).

Several hypotheses have been suggested as possible causes of IMF following heavy exercise. These include an accumulation of exercise-induced metabolites in the diaphragm (Babcock et al., 1995a; Yanos et al., 1993), reductions in available energy substrate (Ianuzzo et al., 1987), and competition for blood flow between respiratory and locomotor substrate (Ianuzzo et al., 1987), and competition for blood flow between respiratory and locomotor muscles (Babcock et al., 1995a; Babcock et al., 1995b Harms et al., 1997; Johnson et al., 1996). Babcock et al. (2002) have further suggested a dual cause of exercise-induced IMF. These authors postulated that the development of IMF during heavy exercise is related to the magnitude of both resistive and elastic inspiratory muscle work incurred and the adequacy of its blood supply. They further suggest that greater reductions in available inspiratory muscle blood supply would require less muscle work to produce IMF.

Exercise in a hot environment results in substantial alterations in cardiovascular function with a progressive increase in cutaneous blood flow as core temperature rises (Rowell, 1986). Consequently, blood flow to the inspiratory musculature may be further compromised during exercise in the heat which could exacerbate IMF, even at a moderate intensity of exertion. The purpose of this study was to test the hypothesis that the magnitude of IMF would be greater following moderate-intensity exercise in a hot environment compared to exercise at the same exercise intensity under a thermo-neutral environmental condition. We were interested in the effects of prolonged moderate-intensity exercise in a hot environment as this type of exercise is more typical of a daily training situation as opposed to an incremental exercise test to exhaustion. We chose to study females because: 1) considerably less exercise data, including that on inspiratory muscle function, has been collected in women (Sheel et al., 2004); 2) previous studies have demonstrated that women differ from men with respect to ventilatory control (White et al., 1983); and 3) women differ from men in the oxygen cost of breathing (Topin et al., 2003), which may influence inspiratory muscle function during exercise.

### Methods

Subjects
The study population consisted of eight females (age 23.5 ± 4.1 yr; height 1.66 ± 0.07 m; weight 59.2 ± 5.6 kg; mean ± SD) who were physically active but not engaged in competitive sports. Based on a detailed medical history questionnaire, all subjects were free of cardiopulmonary, metabolic or musculoskeletal disease and were nonsmokers. All subjects signed an informed consent form and the local institutional review board approved the study.

General testing procedures
Subjects reported to the laboratory on four separate occasions. On the first visit, the subjects practiced a maximal inspiratory mouth pressure maneuver (10-15 trials) (Larson et al., 1993) and were familiarized with the exercise testing equipment. Maximal inspiratory mouth pressure (PImax) has been commonly used as an index of inspiratory muscle fatigue (Chen et al., 1989; Inbar et al., 2000; Romer et al., 2002a; Sonetti et al., 2001; Volianitis et al., 2001; Williams et al., 2002). Though this measurement technique does not provide information as to the specific site of fatigue (central vs. peripheral) or to the specific inspiratory muscles involved, it is sufficient to determine global inspiratory muscle force generation. The second visit to the laboratory consisted of a spirometric screening test for normal pulmonary function and completion of a graded maximal exercise test (GXT). On the last two visits, the subjects performed an endurance exercise test (EET) in either a thermo-neutral or hot environment. Testing sessions for the GXT and EET were separated by 48 hours and the EET was randomized between environmental conditions. All testing was conducted during the follicular phase of the menstrual cycle (days 6-14 following menses) and at the same time of the day. Subjects were asked not to drink coffee or other caffeine-containing beverages on testing days and to refrain from strenuous exercise for 24 h prior to testing.

Graded maximal exercise and pulmonary function testing
All subjects performed a GXT on an electronically-braked cycle ergometer (Lode, Corival, Groningen, Holland). After a brief warm-up period, the exercise test began at 25 W and the subjects maintained a 70 rpm pace. The ergometer resistance was increased every 2 min by 25 W until the subjects were unable to keep the set pace or volitional fatigue. Ventilatory and gas exchange values were obtained on a breath-by-breath basis during the GXT and averaged over 30-sec intervals via an automated metabolic cart (MedGraphics, CPX/D, St. Paul, MN). Heart rate (HR) was monitored continuously throughout the GXT via electrocardiography (Quinton, Q4000,
Bothell, WA). Prior to the GXT, standard pulmonary function testing (Knudson et al., 1983) was performed to determine forced vital capacity (FVC), forced expired volume in one second (FEV₁) and the 12-second maximal voluntary ventilation (MVV₁₂) utilizing the automated metabolic/pulmonary function system described above. Calibration of the metabolic cart was performed prior to each testing session as per the manufacturer’s specifications. The system pneumotach was calibrated with a 3-L volume syringe and the gas analyzers were calibrated with certified gases of known concentration (5% CO₂; 12% O₂).

**Endurance exercise testing**

On separate days, all subjects completed a 40-min ride on the cycle ergometer in either a thermo-neutral (22°C-21% RH) or hot (37°C-33% RH) environment. The hot condition was performed in an environmental chamber. The endurance rides were randomized and performed at a work rate that corresponded to 60% of the subject’s VO₂max as determined from the GXT. Oxygen uptake (VO₂), heart rate (HR), minute ventilation (VE), tidal volume (VT), breathing frequency (Fb), and ratings of perceived exertion (RPE; Borg 6-20 scale) and perceived dyspnea (RPD; Borg 0-10 scale) were determined immediately before and at 10 min intervals during the endurance rides as described above. Additionally, rectal temperature (TRₑ) was continuously monitored and recorded at 10-min intervals during the endurance rides with a thermistor inserted to the depth of 12 cm (YSI, Yellow Springs, OH). Subjects were allowed to consume a commercial sports drink of their choice before and ad libitum during the endurance rides to prevent severe dehydration. FVC and PImax measurements were obtained before and immediately after the endurance exercise rides. As an index of effort and general motivation (Coast et al., 1990), hand grip strength (HG) was also obtained before and after the endurance rides with a standard handgrip dynamometer (Takei, Kogyo, Japan). Three attempts were allowed with the dominant hand and the single best value was used for analysis.

**Inspiratory muscle strength testing**

As an index of global inspiratory muscle strength, PImax generated at the mouth was recorded starting from residual volume as described previously (Black and Hyatt, 1969). Mouth pressures were recorded with a differential pressure transducer (Validyne, DP-45, Northridge, CA) that was calibrated with a certified pressure manometer prior to each test. A computer screen provided visual feedback of the pressure signal. Subjects sustained each inspiratory effort for at least 1 s. To ensure repeatable results, 3-5 trials were performed with at least 1 min of rest between each trial to prevent testing-induced fatigue. The greatest static negative inspiratory pressure recorded (cm H₂O) within 5% of three other trials was used for data analysis.

**Statistical analysis**

Data were analyzed with repeated-measures ANOVA. Significant main effects were further analyzed with Student-Newman post hoc tests. Results are presented as means (±SE). A p-value of < 0.05 was considered significant. Statistical analyses were conducted using SigmaStat for Windows (Jandel Scientific Software, SPSS Inc., Chicago IL).

**RESULTS**

Results from the GXT and pulmonary function testing are presented in Table 1. All subjects demonstrated essentially normal lung function and normal cardiopulmonary responses to graded exercise. The mean values for PImax before and after the EET for both environmental conditions are presented in Figure 1. Baseline values were not significantly different between environmental conditions. No significant reductions in PImax were observed following the EET in the thermo-neutral condition compared to baseline. PImax was significantly reduced (p = 0.001) following the EET in the hot condition compared to baseline and also when compared to the post EET value in the thermo-neutral condition (p = 0.003). All eight subjects showed a reduction in PImax following exercise in the hot condition. There were no significant differences in FVC or HG values before and after the EET for either environmental condition.

**Table 1.** Graded exercise test and spirometry values. Data are means (± SE).

<table>
<thead>
<tr>
<th>Variable</th>
<th>VO₂max (mL·kg⁻¹·min⁻¹)</th>
<th>% predicted VO₂max</th>
<th>HRmax</th>
<th>% predicted HRmax</th>
<th>RER</th>
<th>FVC (L)</th>
<th>% predicted FVC</th>
<th>FEV₁/FVC (%)</th>
<th>MVV (L·min⁻¹)</th>
<th>% predicted MVV</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>39.8 (2.4)</td>
<td>120.6 (9.3)</td>
<td>184 (2)</td>
<td>93.2 (1.3)</td>
<td>1.20</td>
<td>4.2 (2)</td>
<td>111.8 (4.4)</td>
<td>83.9 (2.3)</td>
<td>122.0 (5.9)</td>
<td>106.3 (5.2)</td>
</tr>
</tbody>
</table>

The TRₑ and HR responses during the EET for both environmental conditions are presented in Figure 2. Baseline values for both variables were not significantly different between environmental
conditions. Significant differences (p = 0.023) in T\textsubscript{RE} were detected between conditions at the 40-min measurement period during the EET. Significant differences in HR were detected between conditions at the 20-min (p = 0.008), 30-min (p = 0.003), and 40-min (p = 0.001) measurement periods during the EET.

**Figure 1.** Maximal sustained inspiratory mouth pressure (PI\textsubscript{max}) obtained pre and post endurance exercise during the thermo-neutral (closed circles) and hot (open circles) environmental conditions. Values are means ± SE. # significantly different from baseline (p = 0.001); * significantly different from the thermo-neutral condition (p = 0.003).

No significant differences were detected between conditions at any measurement time point for V\textsubscript{E} or VO\textsubscript{2}. The V\textsubscript{T} and F\textsubscript{b} responses during the EET for both conditions are shown in Figure 3. No significant differences between conditions were noted across time for V\textsubscript{T}. The F\textsubscript{b} tended to be higher at each measurement point during exercise in the hot condition compared to thermo-neutral and this reached statistical significance at the 30-min (p = 0.026) and 40-min (p = 0.005) measurement periods.

The reported values for RPE were not significantly different between conditions (Figure 4). RPD was statistically higher in the hot condition compared to the thermo-neutral condition at the 30-min (p = 0.012) and 40-min (p = 0.002) measurement time points.

**DISCUSSION**

The novel finding of this study was that moderate-intensity (60% VO\textsubscript{2max}) endurance exercise in a hot environment elicited significant reductions in inspiratory muscle strength in untrained female subjects. In contrast, previous studies (Babcock et al., 1996; 2002; Johnson et al., 1996) have shown that an exercise intensity of >80% VO\textsubscript{2max} is generally necessary to elicit significant IMF when exercise is performed in a thermo-neutral environment. In addition, dyspnea perception was greater in the hot compared to the thermo-neutral environment at a similar level of V\textsubscript{E} or VO\textsubscript{2}. Our measured handgrip strength data further suggest that the reductions in inspiratory muscle strength did not result from generalized fatigue or poor subject motivation.

**Figure 2.** Rectal temperature (T\textsubscript{RE}) and heart rate (HR) responses during the endurance rides for both thermo-neutral (closed circles) and hot (open circles) environmental conditions. Values are means + SE. * significantly different from the thermo-neutral condition (p < 0.01).

To the best of our knowledge, only one other study has investigated the combined effects of endurance exercise and a heat load on IMF. Results from this study (Romer et al., 2004) suggest that endurance exercise in the heat (66% maximal work rate/40 min) impaired a subsequent cycle time trial performance but did not exacerbate IMF when compared to exercise performed in a cool environment. Though direct comparisons between our study and the study of Romer et al. are difficult as their subjects were endurance trained males, the findings that inspiratory muscles are susceptible to fatigue following moderate-intensity endurance exercise in the heat are in partial agreement. However, our results suggest a significant difference
between environmental conditions, and we were unable to detect the presence of IMF following exercise in our thermo-neutral condition. This disparity in results may be the result of methodological differences between the studies. In the Romer et al. study (2004), inspiratory muscle strength was determined after a cycle time trial that was preceded by a constant load exercise bout. Thus, considerably more inspiratory muscle work was performed in this study compared to our study. In addition, the temperature was higher during both the heat (37° vs 35° C) and thermo-neutral (22° vs 15° C) conditions in the present study when compared to the study by Romer et al. (2004). This degree of a heat load coupled with our untrained subjects was adequate to result in a significant difference between environmental conditions in the present study.

Figure 3. Tidal volume (VT) and breathing frequency (Fb) responses during the endurance rides for both thermo-neutral (closed circles) and hot (open circles) environmental conditions. Values are means ± SE. * significantly different from the thermo-neutral condition (p < 0.05).

In both of our endurance exercise conditions, the exercise intensity was well below the previously reported threshold (>80% VO2max) for exercise-induced IMF (Babcock et al., 1996; 2002; Johnson et al., 1996). No evidence of IMF was present following exercise in the thermo-neutral environment whereas a significant reduction in inspiratory muscle strength was demonstrated following exercise in the hot environment. Harms et al. (1997) have demonstrated that locomotor muscles and the diaphragm compete for the available cardiac output during heavy exercise. Changes in inspiratory muscle work appear to effect limb muscle blood flow via a sympathetically mediated reflex arc originating from type III/IV receptors in the fatigueing inspiratory muscles (St Croix et al., 2000). With the addition of a heat load during exercise, it is not clear which vascular bed would be compromised as an additional portion of the cardiac output would now be directed to the cutaneous circulation for thermoregulation. Though indirect, our data suggests that inspiratory muscle blood flow was compromised during exercise in the heat as evidenced by a greater degree of IMF in this condition compared to the thermo-neutral exercise condition. These differences were present at a similar level of VE and VO2 and presumably a similar level of inspiratory muscle work. It is possible that the above mentioned reflex arc resulting in compromised limb blood flow also resulted in compromised inspiratory muscle blood flow which may have further exacerbated IMF.

Figure 4. Ratings of perceived exertion (RPE) and dyspnea (RPD) during the endurance rides for both thermo-neutral (closed circles) and hot (open circles) environmental conditions. Values are means ± SE. * significantly different from the thermo-neutral condition (p < 0.05).
Elevated $T_{RE}$ and HR responses to moderate-intensity exercise in a hot environment are well established and the magnitude of increase in the present study is comparable to those values previously reported (Powers et al., 1982; Romer et al., 2004). Elevated HR in a hot environment is the consequence of increased blood flow to the skin and a subsequent reduction in central blood volume resulting in a decreased stroke volume and a compensatory rise in HR. Our VO$_2$ values are also in agreement with a previous study demonstrating a small but insignificant increase in VO$_2$ in response to moderate-intensity exercise in a hot environment (Powers et al., 1982).

A progressive increase in $V_E$ occurs in response to prolonged constant-load exercise in a thermo-neutral environment (Martin et al., 1981) and increased $V_E$ has also been reported in a hot or humid exercise environment. This upward “drift” in $V_E$ in a hot environment may be the result of increased blood temperature influencing the respiratory control center (Powers et al., 1982). Altered ventilatory responses in the heat appear to be the result of an increase in $F_b$ and fall in $V_T$ (Martin et al., 1979) and this tachypneic pattern has also been observed after the induction of IMF (Mador, 1991). Our results are in agreement with these previous finding in that $V_E$ was slightly augmented at each measurement period in the hot condition compared to the thermo-neutral condition, and our subjects developed a tachypneic pattern toward the end of the EET in the hot condition. We view it likely that the significant increase in $F_b$ during the hot condition, with $V_T$ remaining constant, occurred in response to ensuing IMF (Mador, 1991; Mador and Acevedo, 1991; Syabhalo et al., 1994).

Previous studies have shown that experimentally induced IMF effects respiratory effort sensation (Gandevia et al., 1981). Our data are in agreement with these finding in that RPD was significantly elevated during exercise in the hot condition compared to thermo-neutral, at a similar level of $V_E$ and VO$_2$. We suggest that the elevated RPD is related to the ensuing IMF as evidenced by the reduction in PI$_{max}$ following the exercise bout. In addition, recent studies have demonstrated reductions in respiratory effort sensation during exercise following a period of specific inspiratory muscle training (Romer et al., 2002a; 2002b; Williams et al., 2002). In a recent review article (McConnell and Romer, 2004), evidence is presented suggesting that the contractile properties of the respiratory muscles modify the intensity of perceived dyspnea via changes in motor outflow to the respiratory muscles. Accordingly, in the presence of IMF, central motor outflow to the respiratory muscles would be increased to maintain a given level of mechanical output from the muscles and dyspnea would be enhanced (Gandevia et al., 1981). Alternatively, a peripheral hypothesis has been suggested involving enhanced muscle metaboreceptor afferent activity from respiratory muscles during IMF that is related to increased dyspnea (Jammes and Balzamo, 1992).

The reductions in PI$_{max}$ in the present study following exercise in the heat could be secondary to dehydration and/or substrate availability (Febbraio, 2000). However, we think this unlikely as our subjects consumed a commercial sports drink before and during the endurance rides and no significant reduction in body mass was noted following exercise in either condition. Exercise in a hot environment is associated with increased carbohydrate oxidation and lactate production (Gonzalez-Alonso et al, 1999). Lactate is one of several circulating metabolites of muscle metabolism that is associated with muscle fatigue. Though speculative as we did not measure blood lactate levels in our study, it is possible that increased blood lactate contributed to the reductions in inspiratory muscle strength observed following exercise in the heat condition whereas these reductions were not present in the thermo-neutral condition. Increases in core body temperature ranging from 38-40°C are associated with fatigue during exercise in the heat and may be related to central nervous system function (Gonzalez-Alonso et al., 1999; Nybo and Nielson, 2001). As all of the subjects in our study were able to complete the 40-min ride in the hot environment and RPE values were not significantly different between conditions, we feel that the contribution of central fatigue to the observed IMF in this study were minimal. Furthermore, our HG data suggest that subject effort and motivation were well preserved following exercise in both environmental conditions. In addition, changes in PI$_{max}$ are sensitive to changes in lung volume (Coast and Weise, 1990). FVC values were unchanged before and after the endurance rides in both environmental conditions suggesting that the reductions in PI$_{max}$ truly represented IMF and not an increase in residual volume.

**CONCLUSIONS**

Results from the present study suggest that moderate-intensity prolonged exercise in a hot environment with ad lib fluid intake results in significant reductions in global inspiratory muscle strength in untrained females. The mechanism whereby this reduction in inspiratory muscle function occurs may be related to compromised inspiratory muscle blood flow. The precise
mechanism whereby exercise-induced IMF occurs in a hot environment will require further research. In addition, the perception of dyspnea is augmented during exercise in the heat, compared to a thermoneutral condition, at a similar level of exercise $V_E$ and $VO_2$.

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KEY POINTS

- The combined effects of a heat load and exercise on inspiratory muscle strength were investigated in untrained female subjects.
- Previous studies have shown that a very high exercise intensity (> 80% VO$_2$max) is required to elicit reductions in inspiratory muscle strength.
- Prolonged submaximal exercise (40-min/60% VO$_2$max) in a hot environment significantly reduced inspiratory muscle strength in untrained females whereas the same intensity in a thermo-neutral environment had no effect on inspiratory muscle function.
- These reductions in inspiratory muscle strength may be related to competition for blood flow among the locomotor, inspiratory, and cutaneous circulations.

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