Brief Report on Research Activities
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Cardio-pulmonary Responses to Exercise in Firefighters

This multi-year project began in July 2005 and will consist of a series of about eight sequential studies. This series of projects was commissioned following the final briefing of CFFM on the development of the selection standard for firefighter applicants.

The rationale was to allow more sophisticated exploration of some of the questions arising from our evaluation of the effects of fire protective equipment (specifically the SCBA) on human performance.

This is very innovative work and to date, the outcomes are very encouraging. However, since we are literally "going where no exercise physiologist has gone before", we are progressing slowly. That is, we are completing a study and then designing the next in the sequence based on the outcomes of the previous work. To date, we have completed five studies and have begun the sixth and seventh in the series.

The first study was our pilot investigation on developing a method to measure the work of breathing with the SCBA. We proved that the method was viable and we were actually able to measure what others have speculated on for decades. Our subjects completed a graded exercise protocol on a cycle ergometer with and without the SCBA. The main finding was that at higher ventilation rates, the work of breathing was significantly increased in the SCBA condition. The journal reference for this study is:

> Butcher, SJ, Jones, RL, Eves, ND, Petersen, SR. (2006) Work of breathing is increased during exercise with the self-contained breathing apparatus regulator. **Applied Physiology, Nutrition and Metabolism** 31 (6): 693-701.

In the second study, our subjects completed a more challenging exercise protocol that consisted of three 10-min bouts of stepping exercise, once again with and without breathing on the SCBA. In this protocol, the subjects were dressed in fire protective clothing and experienced significant increases in body temperature, which provided a secondary stimulus to increase ventilation. Once again, at higher ventilation rates, the work of breathing was significantly increased in the SCBA condition. We introduced a third condition where the subjects breathed heliox (21% oxygen and 79% helium). We have published other studies with helium and speculated that the impairment in ventilatory mechanics imposed by the SCBA might be at least partially reversed by breathing a lower density gas. This was shown to be correct.

This study provided a more mechanistic description of the breathing responses during exercise with the SCBA and provided evidence of a viable countermeasure. The study has been accepted for publication, and the journal reference is as follows:

> Butcher, SJ, Jones, RL, Mayne, JR, Hartley, TC, Petersen, SR (2007, in press) Impaired exercise ventilatory mechanics with the self-contained breathing apparatus are improved with heliox. **European Journal of Applied Physiology**, Volume 101. Published on-line in August 2007, journal publication expected in October 2007.

The third study in the Cardiopulmonary Series was designed to test the hypothesis that heart function might be influenced by the altered ventilatory mechanics and increased work of breathing during exercise with the SCBA.

In the two previous studies we have clearly documented higher esophageal pressures during heavy exercise with the SCBA. The combination of altered breathing pattern (longer expiration and shorter inspiration times) and the higher pressure required to exhale against the resistance of the SCBA regulator infer the potential to alter heart function in several ways. For example, venous return may be impaired by less favourable pressure gradients, heart filling may be affected by higher intrathoracic pressure, but the same condition could lead to more favourable conditions for emptying the heart.

Previous publications from our laboratory have documented decreases in VO_{2max} with the SCBA. We have reasoned that the majority of the decline in aerobic power is secondary to attenuated ventilation and perhaps altered gas exchange. However, part of the explanation may lie in altered heart function.

This project studied heart function during graded exercise on a stairmill, with and without SCBA. Our subjects exercised for four minutes at 50, 60, 70 and 80% of peak VO_2, and heart function was evaluated with 2-D echocardiography. During the two heavier workloads, we found evidence of reduced preload and increased contractility. In brief, it appears as though venous return is impaired by the

higher intrathoracic pressure on SCBA, but there is a compensatory effect in contractility to maintain cardiac output.

It is interesting to speculate how far this compensatory pattern might continue as exercise intensity increases towards VO_{2max}. We will explore this question in a future study.

The results of the first heart function study (#3 in the Cardiopulmonary series) will be presented at the annual conference of the Canadian Society for Exercise Physiology (CSEP) in London, ON, in November 2007. The abstract is shown below:

Effect of the Self-Contained Breathing Apparatus (SCBA) on Left Ventricular Function During Stairclimbing Exercise in Fire Protective Ensemble

JR Mayne[1], MJ Haykowsky[1], TC Hartley[1], SJ Butcher[2], RL Jones[1], SR Petersen[1]
[1]University of Alberta, [2]University of Saskatchewan

This study examined left ventricular function in 15 males (age 30.2 ± 8years) during exercise at 50, 60, 70 and 80% of VO_{2peak} on a motorized stepping treadmill. Subjects wore fire protective ensemble and data were collected in randomly ordered trials when breathing with and without the SCBA. Heart rate, blood pressure, ventilation (V_E), esophageal pressure (P_{ES}) and 2D echocardiography images (parasternal short-axis) were collected during the last minute of each 4-min work interval. Pressure swing (max-min P_{ES}) was greater ($p<0.05$) with SCBA during all work intervals despite similar V_E between conditions. There were no differences between conditions for HR, stroke area, cardiac (area) output or wall stress. However, at 70 and 80% VO_{2peak}, preload (end-disastolic cavity area) was lower and contractility (systolic pressure/end-systolic cavity area) was higher in the SCBA condition. During the submaximal exercise loads studied, left ventricular function was similar with or without the SCBA. The lower preload observed with the SCBA during the higher workloads was offset by increased contractility.

Supported by the Department of National Defence

Our two studies on the work of breathing with the SCBA follow numerous other publications (six refereed journal articles between 2000 and 2006) from our lab providing evidence that the SCBA impairs exercise performance secondary to attenuated ventilation. It was gratifying to see that a major manufacturer of SCBA, Scott Health and Safety, announced a modified secondary regulator that was specifically designed to reduce expiratory resistance. Information from Scott Health and Safety suggested that the new EZ-FLO™ II regulator would reduce expiratory resistance by up to 25%. We designed two studies to investigate the new regulator design on exercise performance.

The first study on regulator design (#4 in the Cardiopulmonary Series) compared peak exercise performance on a stairmill between the new EZ-FLO™ II regulator and its predecessor, the EZ-FLO™ regulator. In brief, we found that peak exercise performance was modestly improved with the new design.

The results of this study will be presented at the annual conference of the Canadian Society for Exercise Physiology (CSEP) in London, ON, in November 2007. The abstract is shown below:

Regulator Design Improves Peak Exercise Performance with the Self-Contained Breathing Apparatus (SCBA)

SR Petersen[1], JR Mayne[1], TC Hartley[1], SJ Butcher[2], RL Jones[1]
[1]University of Alberta, [2]University of Saskatchewan

We have previously reported that the SCBA reduces VO_{2max} secondary to attenuated peak ventilation (Eves *et al*, CJAP, 2005; Dreger *et al*, Ergonomics, 2006). Scott Health and Safety has recently modified the secondary regulator on the 4.5 model SCBA in an effort to reduce external expiratory resistance. The purpose of this study was to investigate the effects of the new design on aerobic performance at peak exercise. On separate days, sixteen males completed, in random order, graded exercise tests on a motorized stepping treadmill dressed in firefighting gear. The two test protocols were identical except for configuring the SCBA with either the previous design EZ-FLO™ or the new EZ-FLO II™ regulator. Respiratory gas exchange data were collected continuously during graded exercise to exhaustion. There were small but significant increases of approximately 3-4% in peak V_E (due to higher tidal volume) and peak VO_2 with the EZ-FLO II regulator. Total exercise time was also slightly longer ($p<0.05$) in the EZ-FLO II regulator condition. These results show that the altered regulator design reduces some of the impairment in peak exercise performance with the SCBA.
Supported by the Department of National Defence

The second study on regulator design (#5 in the Cardiopulmonary Series) compared the two regulators during submaximal exercise on a stairmill. We used the same exercise protocol as in the heart function study (four minutes of work at each of 50, 60, 70 and 80% of peak VO_2) and found evidence that the new design may reduce the work of breathing with the SCBA, but only during heavy exercise.

The results of this study will be presented at the annual conference of the Canadian Society for Exercise Physiology (CSEP) in London, ON, in November 2007. The abstract is shown below:

Effect of Regulator Design on Submaximal Exercise with the Self-Contained Breathing Apparatus (SCBA)

TC Hartley[1], JR Mayne[1], SJ Butcher[2], RL Jones[1], SR Petersen[1]
[1]University of Alberta, [2]University of Saskatchewan

The SCBA increases the work of breathing during exercise when ventilation (V_E) exceeds approximately 80 $L \cdot min^{-1}$ (Butcher *et al*, APNM, 2006). Scott Health and Safety has recently modified the secondary regulator on the 4.5 model SCBA in an effort to reduce external expiratory resistance. The purpose of this study was to investigate the effects of the new design on esophageal (P_{ES}) pressure during submaximal exercise. Fifteen males completed graded exercise protocols on a motorized stepping treadmill dressed in firefighting gear. The protocols consisted of 4 min of exercise at 50, 60, 70 and 80% VO_{2peak} and were identical except for randomizing the configuration of the SCBA with either the original EZ-FLO™ or the new EZ-FLO II™ regulator. P_{ES} and V_E data were collected in the final minute of each exercise load. Regulator condition had no effect on V_E during any of the workloads assessed. Peak inspiratory and expiratory P_{ES} differed only at 80% VO_{2peak} where both were lower ($p<0.05$) with the EZ-FLO II regulator. V_E was approximately 90 $L \cdot min^{-1}$ at 80% VO_{2peak}. These results show that the new design may reduce the work of breathing with the SCBA, but only during heavy exercise.
Supported by the Department of National Defence

We have recently begun work on the sixth and seventh studies in the Cardiopulmonary Series and these are described briefly in the following sections. The sixth study in the series will investigate the effects of the SCBA on heart function in older male subjects. The research design replicates the previous heart function (#3 described above) which found evidence of altered heart function during heavier exercise with the SCBA in *younger* males (mean age of

30 years). We have speculated that some of the normal age-related changes in cardiopulmonary function may lead to exaggerated responses in older males. We are actively enrolling middle-aged subjects and expect that the mean age of the older group will be approximately 50 years.

The seventh study in the series will investigate the effects of the SCBA on heart function during a more aggressive exercise protocol. In this study, subjects will complete three 10 minute bouts of treadmill exercise at approximately 75% of VO_{2peak}. This protocol has been designed to simulate the metabolic and thermal stress of prolonged fire suppression or rescue operations.

Our previous work suggests that we can expect a significant increase in body temperature (approximately 2°C), significant loss of body fluid (approximately 1.5 L), high levels of cardiovascular stress (near maximal heart rate) and a state of near exhaustion. Fluid intake will be restricted to maximize the cardiovascular strain. While the subjects will be carefully monitored throughout the protocol, we are attempting to simulate near "worst-case-scenario" conditions.

Pending the outcome of the 6th study with older firefighters, we may recruit a cohort of older subjects for this more aggressive protocol.

Future studies will explore the effectiveness of various counter-measures (e.g., plasma volume expansion) on the maintenance of heart function during similar exercise challenges.

In summary, the Cardiopulmonary Series is progressing well. We have been very productive despite the conservative approach of completing one study before starting the next. This series has resulted in the development of innovative techniques in work physiology that have allowed us to measure the work of breathing with the SCBA and undertake relatively sophisticated studies of heart function. It is noteworthy that previous descriptions of cardiovascular responses to exercise in firefighters has been limited primarily to heart rate. Our use of echocardiography during exercise is both innovative and informative.