Development of *Bona Fide* Pre-Employment Physical Fitness Standards for Canadian Forces (CF) and Department of National Defence (DND) Firefighters:

Sub-study of Cardiopulmonary Responses to Exercise in Firefighters

Final Report

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BACKGROUND

In 2000, the University of Alberta entered into a contractual agreement with the Canadian Forces Personnel Support Agency to conduct research into the development of physical fitness standards for Canadian Forces (CF) and Department of National Defence (DND) firefighters. The previous stages of this research project included the following steps:

1. To identify the problem
2. To review the related literature
3. To identify appropriate methodology
4. To brief the Canadian Forces Fire Marshall (CFFM) on the findings
5. To prepare a research proposal summarizing the work necessary to develop appropriate tests and standards
6. To conduct the research to develop appropriate tests and standards
7. To conduct sub-studies on the aerobic demands of simulated firefighting work in males and females
8. To submit a final report and brief the CFFM

Steps 1 – 8 have been completed according to the original contract and the subsequent amendments. The CFFM and CFPSA were briefed on the selection standards project in November 2004. At that meeting, the need for additional research on the cardiopulmonary responses to exercise in firefighters was identified. This report summarizes the research that was undertaken in the sub-study.

Firefighters must normally wear a personal protective ensemble (PPE) in order to work safely in hazardous work environments. Previous research, by our laboratory and others, has identified some of the physiological effects of exercise in PPE. Briefly summarized, it is known that the modern self-contained breathing apparatus impairs ventilation during heavy exercise. The impairment in ventilation ultimately attenuates maximal oxygen consumption (VO_{2max})

secondary to the reduction in peak ventilation. The weight of modern firefighting PPE is typically about 24 kg and this load imposes a significant metabolic cost even at low levels of exercise. The metabolic cost is exacerbated by what is often referred to as the “hobbling effect’ where the additional layers of clothing increase the energy cost of movement by reducing efficiency.

The PPE is designed to protect the firefighter from environmental hazards, but it also traps metabolic heat produced during exercise. Numerous research reports have documented the increases in body temperature during exercise in PPE. On the other hand, virtually no attention has been paid to the interaction between body temperature, ventilation, heart function and work output.

When heat is gained (through metabolic heat production and/or from the environment) faster than it can be lost, this situation is referred to as uncompensable heat stress (UHS). Because of the properties of PPE, the incidence of UHS is common in firefighting, even when the work is done in a thermo-neutral environment. In a failing attempt to regulate body temperature, firefighters sweat profusely and increase ventilation. The loss of body water decreases plasma volume, which theoretically will have a negative effect on heat tolerance, maximal cardiac output, VO_{2max}, and work output. The effects of the increased ventilation are less well understood, but equally important. Our research shows a disproportionate increase in the energy cost of breathing with the SCBA at higher ventilation rates. For example, increasing ventilation rate from 100 to 120 $L \cdot min^{-1}$ requires a far more energy than increasing from 60 – 80 $L \cdot min^{-1}$. The functional outcomes of heavy exercise in PPE and SCBA include increased metabolic demand, the potential for respiratory muscle fatigue and altered cardiac function. One of the most noticeable effects during fire operations would be an elevated rate of air consumption from the SCBA. During continuous or repeated bouts of treadmill exercise at a constant work-rate, the rate at which air is consumed can increase up to 30 – 40% after about 30 minutes of work because of thermal stress.

It is well accepted that the self-contained breathing apparatus (SCBA) and fire protective ensemble (PPE) reduce maximal exercise capacity (Louhevaara et al. 1995; Eves et al. 2005; Dreger et al. 2006). It is also well known that exercise in PPE accelerates the storage of heat and potentially leads to a state of fatigue and/or heat-related stress. However, many questions remain unanswered with respect to the short and long-term effects of these conditions on firefighters. The main purpose of this research program was to investigate the interaction between thermal stress and cardiopulmonary responses during exercise with PPE and SCBA.

RESEARCH SUMMARY

Five research projects were completed. The results have been presented at scientific conferences and four have been published in scientific journals as follows:

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.

Butcher, SJ, Jones, RL, Mayne JR, Hartley TC, Petersen, SR. (2007) Impaired ventilatory mechanics with the self-contained breathing apparatus are improved with heliox. **European Journal of Applied Physiology**, 101(6): 659-69.

Mayne JR, Haykowsky MJ, Nelson MD, Hartley TC, Butcher SJ, Jones RL Petersen SR. (2009) Effects of the self-contained breathing apparatus on left-ventricular function at rest and during graded exercise. **Applied Physiology, Nutrition and Metabolism**, 34 (4): 625-631.

Nelson MD, Haykowsky MJ, Mayne JR, Jones RL, Petersen SR (2009) Effects of the self-contained breathing apparatus on ventricular function during strenuous exercise. **Journal of Applied Physiology**, 106: 395-402.

The fifth project resulted in two presentations at the 2007 annual scientific conference of the Canadian Society for Exercise Physiology (CSEP) and the references for the published abstracts are as follows:

Petersen SR, Mayne JR, Hartley TC, Butcher SJ, Jones RL, (2007) Regulator Design Improves Peak Exercise Performance with the Self-Contained Breathing Apparatus. **Applied Physiology Nutrition and Metabolism**, 32:S71.

Hartley TC, Mayne JR, Butcher SJ, Jones RL, Petersen SR, (2007) Effect of Regulator Design on Submaximal Exercise with the Self-Contained Breathing Apparatus (SCBA). **Applied Physiology Nutrition and Metabolism**, 32:S42.

Copies of the four articles are appended to this report (see Appendices A – D) and each of the five projects is summarized briefly below. In each case, an abstracted version of the study is presented, followed by brief comments on the significance of the work.

STUDY 1

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.

Abstract

Background: The self contained breathing apparatus (SCBA) increases the expiratory pressure required to maintain high rates of ventilation, suggesting that the expiratory work of breathing (WOB) is increased; however, this has never been reported.

Objective: To determine if the WOB is increased with the SCBA regulator (BA condition) compared with a low resistance breathing valve (RV condition) during exercise.

Research Design and Methods: Twelve healthy male subjects underwent two randomized exercise trials, consisting of cycling at 150, 180, 210, and 240 watts. Inspired and expired tidal volumes were measured using a body plethysmograph while esophageal pressures were measured with an esophageal balloon. Modified Campbell diagrams were created in order to calculate the resistive and elastic components of WOB during inspiration and expiration.

Results: There were no differences in WOB between BA and RV conditions at 150 W. End-inspiratory and end-expiratory lung volumes were elevated ($p<0.05$)

in the BA condition at higher ventilation rates, which increased inspiratory elastic work and decreased expiratory elastic work at 180 and 210 W ($p<0.05$). At 240 W (V_E = 112 ± 17 L·min^{-1} in the BA condition), active expiratory resistive work was increased by 59 ± 51%, inspiratory elastic work by 26 ± 24%, and total WOB by 13 ± 12% with the BA ($p<0.05$).

Conclusions: The SCBA regulator causes an increase in the active expiratory resistive work to maintain high ventilatory rates and an increase inspiratory elastic work through an elevation in lung volumes.

Comments

The term "work of breathing" (WOB) is used in pulmonary physiology to describe the amount of work that is done in order for the lung to change volume. Work of breathing is properly defined as the respiratory muscle effort required to change lung volume and is expressed as the integral of pressure and volume throughout a single breath (Roussos and Campbell, 1986). It can be thought of in terms of the energy cost of breathing. The respiratory muscles (e.g., the diaphragm, the chest wall muscles) must do some work in order to move air in and out of the lung. At rest, this is minimal but during exercise, ventilation rate (liters of air per minute) can increase by up to 20-fold and this translates to a significant increase in the energy cost of breathing.

The SCBA presents a resistance to breathing (especially during expiration) and this also can increase WOB. Research from our laboratory (e.g., Eves et al, 2005) and others has inferred that the work of breathing should be higher with the SCBA during exercise but this had not actually been measured before.

In order to do this experiment, we built a body plethysmograph (body box) to allow measurement of lung volumes during exercise and modified the facemask to allow the passage of an esophageal pressure catheter to determine respiratory muscle effort. Changes in lung volume were plotted against esophageal pressures to create pressure-volume loops to calculate work of breathing.

Results of the experiment showed that expiratory resistive work (the work done to overcome airway and external resistances on expiration) is increased at ventilation rates greater than about 80-90 L/min, (equivalent to a workload on the cycle ergometer of about 210 W). These findings show that the modern SCBA imposes a limitation on ventilation during heavy exercise.

In practical terms, it is important to bear in mind that the increase in WOB starts when ventilation approaches about 80 L/min and increases in an exponential fashion as ventilation increases. When ventilation is lower than about 80 L/min, WOB is not significantly different. We should also bear in mind that this experiment only involved the SCBA facepiece and regulator, not the backpack. We speculate, as have others, that the weight of the pack may interfere with normal chest wall movement, and this would also tend to increase WOB. Finally, there was no heat stress in this experiment, so the ventilation rate was determined by the exercise load. Since ventilation tends to increase secondary to higher body temperature, these factors could lead to higher WOB at lower exercise loads.

STUDY TWO

Butcher, SJ, Jones, RL, Mayne JR, Hartley TC, Petersen, SR. (2007) Impaired ventilatory mechanics with the self-contained breathing apparatus are improved with heliox. **European Journal of Applied Physiology**, 101(6): 659-69.

Abstract

The effect of the self-contained breathing apparatus (SCBA) with compressed air (BA-A) on ventilatory mechanics, work of breathing (WOB), pulmonary function and respiratory muscle fatigue was compared with that of a low resistance Rudolph breathing valve (RV). Also, the effect of unloading the respiratory muscles with heliox while using the SCBA (BA-H) was compared with BA-A and RV. Twelve men completed three randomized exercise trials on separate days, each consisting of three 10 minute bouts of stepping exercise separated by 5 minutes recovery. Subjects wore firefighter protective equipment including the

SCBA. At rest, FEV_1 and peak expiratory flow were lower with BA-A than RV, but were higher with BA-H than either BA-A or RV. After 30 minutes of exercise, end-expiratory lung volume, expiratory resistive WOB, and inspiratory elastic WOB were increased in BA-A compared to RV but these were lower with BA-H compared to BA-A. After exercise, maximal inspiratory and expiratory pressures were reduced with BA-A, but not RV or BA-H. In summary, we found that the SCBA reduces resting pulmonary function, and increases end-expiratory lung volume, work of breathing, and respiratory muscle fatigue during stepping exercise, and these changes can be moderated with the use of heliox.

Comments

This experiment built on what we learned in the first study in this series. While the focus was still on understanding the effects of the SCBA on work of breathing during exercise, there were several significant differences. First, the subjects wore complete fire protective ensemble which included the SCBA backpack. Second, the exercise mode was stair-climbing rather than cycling. Third, the exercise intensity was high (80% of peak step-rate) and prolonged (3 x 10 min with 5 min breaks for bottle changes). Fourth, we added an experimental condition where the respiratory muscles were "unloaded" by using heliox (21% oxygen, 70% helium). Fifth, we evaluated resting pulmonary function with the SCBA which had not been previously reported in the scientific literature. Finally, we evaluated respiratory muscle fatigue to explore the functional outcomes of the higher WOB with the SCBA.

The results of this experiment showed that the SCBA alters resting pulmonary function. This was perhaps not surprising given what we know about expiratory resistance with this respirator, however it had never been reported before. The exercise protocol was extremely challenging and led to the kind of ventilation rates that we would expect during initial attack fire suppression. While we could not simulate the environmental heat that would be experienced in a structural fire, it is important to note that core temperature increased by approximately 2° C from the exercise alone as metabolic heat was trapped by the protective clothing. The change in body temperature led to higher ventilation than would be expected from the exercise alone, which of course was then manifest as higher work of breathing. Not surprisingly, this challenge led to significant levels of respiratory muscle fatigue. Unloading the respiratory muscles with helium resulted in reductions in WOB and no respiratory muscle fatigue in spite of similar ventilation rates and body temperature. We believe that this study presents a much clearer representation of the effects of the SCBA on the pulmonary system during exercise in protective clothing.

STUDY THREE

Mayne JR, Haykowsky MJ, Nelson MD, Hartley TC, Butcher SJ, Jones RL Petersen SR. (2009) Effects of the self-contained breathing apparatus on left-ventricular function at rest and during graded exercise. **Applied Physiology, Nutrition and Metabolism**, 34 (4): 625-631.

Abstract

The purpose of this study was to examine the effects of the self-contained breathing apparatus (SCBA) on left-ventricular (LV) function at rest and during mild- to moderate intensity exercise using two-dimensional echocardiography. Twenty-three healthy male volunteers exercised on a stair-climber at work rates equivalent to 50%, 60%, 70% and 80% VO_{2peak}. Esophageal pressure, LV diastolic and systolic cavity and myocardial areas were acquired during the final minute of each stage of exercise. As expected, the esophageal pressure response during SCBA breathing revealed significantly lower (more negative) inspiratory pressures and higher (more positive) expiratory pressures, and consequently, higher pressure swings compared to free-breathing (FB). End-diastolic cavity area (EDCA) and end-systolic cavity area (ESCA) were lower with the SCBA compared to FB. Left ventricular contractility was higher ($p < 0.05$) with the SCBA which can partially be explained by decreases in end-systolic wall stress. Therefore, the SCBA was found to decrease LV preload during moderate

intensity exercise but did not negatively affect stroke area (SA) due to a similar reduction in ESCA.

Comments

This is the first study to report the effects of the SCBA on heart function during exercise. By way of introduction, it is important to remember that the higher WOB values that have were reported in the first two studies result from the respiratory muscles generating more pressure in the thoracic cavity in order to change lung volumes. The altered pressure environment has the potential to influence how the heart functions, since the heart and lungs occupy the same space.

At the risk of oversimplification, there is a positive pressure in the chest cavity during expiration. The first two studies showed clearly that during heavy exercise with the SCBA, a higher than normal pressure is required to move the same amount of air out of the lung. This higher positive pressure may impede diastolic filling of the heart and could possibly assist emptying of the heart during systole. We have also shown that under these conditions the way we breathe is altered so that we spend proportionately more time exhaling and proportionately less time inhaling. The former is mostly due to the need to overcome the expiratory resistance from the regulator while the latter is probably due to the positive pressure in the SCBA face-piece. However, the net effect is a shift towards the higher positive pressure for a greater fraction of the time it takes to complete a breathing cycle (inhaling and exhaling). It is also worth bearing in mind that within each cardiac cycle, the heart spends much more time filling (diastole) than it does emptying (systole).

Therefore, we reasoned that as expiratory resistive WOB increases (as shown clearly in the first two studies), that the more dominant positive pressure environment in the chest cavity might start to impede stroke volume.

The third study utilized ultrasound (echocardiography) techniques to evaluate heart function during exercise with the SCBA. We employed a graded exercise protocol on a stair treadmill (“stairmaster”). Our subjects wore fire protective ensemble and completed brief (4 min) bouts of exercise at intensities equivalent to 50, 60, 70 and 80% of VO_{2peak}. There were rest periods between work bouts to avoid accumulation of fatigue, thermal stress and dehydration, all of which have the potential to further alter heart function (these factors were introduced in Study Four).

The heart function measures could not be done in the body box, and therefore, it was impossible to *measure* WOB and heart function simultaneously. The first two experiments on work of breathing did however show us that changes in esophageal pressure were strongly associated with WOB. In this study, we used esophageal pressure measurements to *infer* the WOB. The changes in esophageal pressure were consistent with what we had seen previously.

The results of this study showed that during lower intensity exercise with the SCBA, when WOB would not be expected to be significantly greater than normal, heart function was also not affected. However as exercise intensity increased to 80% of peak, we began to see a decrease in “preload”, or in simpler terms, blood returning to the heart. We reasoned that the higher intrathoracic pressure during heavy exercise with the SCBA would impede venous return. This effect was not seen during the same exercise without the SCBA.

Despite the reduction in blood volume returning to the heart, cardiac output was maintained by enhanced left ventricular function. Therefore, it appears that the healthy heart can, at least in the short term, compensate for reduced venous return by possibly more forceful contractions to ensure that cardiac output is not compromised. Whether the heart can continue to compensate at higher exercise loads, or when faced with significant heat stress and dehydration remains unanswered by this study, however we began to investigate those factors in Study Four.

STUDY FOUR

Nelson MD, Haykowsky MJ, Mayne JR, Jones RL, Petersen SR (2009) Effects of the self-contained breathing apparatus on ventricular function during strenuous exercise. **Journal of Applied Physiology**, 106: 395-402.

The purpose of this study was to investigate left-ventricular function during strenuous exercise with the self-contained breathing apparatus (SCBA). Using two-dimensional echocardiography, images of the left ventricle (LV) were acquired during sustained exercise (3 x 10-min) under two conditions: (1) SCBA, or (2) a low resistance breathing valve. Twenty healthy men volunteered for the study and in each condition subjects wore fire protective equipment. Heart rate, systolic blood pressure, cavity areas during systole and diastole (ESCA and EDCA, respectively), esophageal pressure, ventilation rate, oxygen consumption, perceived physical, thermal and respiratory distress and core temperature were measured at regular intervals. Urine specific gravity (< 1.020 g mL^{-1}) and haematological variables were used to infer hydration status. All subjects began both trials in a euhydrated state. No differences were found between conditions for heart rate, systolic blood pressure, ventilation rate, oxygen consumption, perceived distress, or any haematological variables. Peak expiratory esophageal pressure was always higher ($P < 0.05$) while EDCA and stroke area (SA) were significantly lower ($P < 0.05$) with the SCBA. ESCA, end-systolic transmural pressure (ESTMP), and LV contractility (ESTMP/ESCA) were similar between conditions. Sustained exercise with fire protective equipment resulted in significant reductions in EDCA, ESCA and SA from the start of exercise, which was associated with a 6.3 ± 0.8% reduction in plasma volume, increase in core temperature (37.0 ± 0.4 to 38.8 ± 0.3°C) and a significant increase in heart rate (146.9 ± 2.1 to 181.7 ± 2.4 bpm) throughout exercise. The results from this study support research by others showing that increased intrathoracic pressure reduces LV preload (EDCA); however, the novelty of the present study is that when venous return is compromised by sustained exercise and heat stress, SA cannot be maintained.

Comments

This study was designed to continue the investigation of the effects of the SCBA on heart function. Some important changes were made to the methods following Study Three, where heat stress, dehydration and fatigue were deliberately avoided. In Study Four, we introduced a "prolonged" exercise model with three bouts of exercise, each lasting 10 minutes and separated by a five minute break for changing the SCBA tank. Previous studies (e.g., Study Two) has shown that this type of exercise leads to high levels of fatigue as well as a state of uncompensable heat stress (UHS) and significant dehydration. All of these factors are likely to be present during fire suppression work and therefore, we felt that it was important to simulate those conditions in our studies.

In brief, the exercise challenge in Study Four was significantly more demanding than in Study Three and the resulting heat stress and dehydration led to conditions where the heart was unable to compensate for the reduction in venous return.

At rest, passive heat stress increases cardiac output by as much as 8 L/min, with between 50 – 75% of this blood flow directed toward the skin. During exercise, the demand for available blood flow increases to meet the additional metabolic demand. In young, healthy hearts, this cardiovascular challenge is met through large increases in systolic function (more specifically, ejection fraction) to support the reduction in cardiac preload secondary to the redistribution of blood flow (unpublished results from current studies our laboratory).

However, the combination of heavy exercise, heat stress and dehydration presents a scenario in which a healthy heart may not be able to offset the reduction in preload by increased contractility. In this case, stroke volume may be reduced such that any change in cardiac output is met by additional increases in heart rate. Since heart rate is already at a very high percentage of maximum during strenuous work, the potential exists for reductions in cardiac output if heart rate can no longer be increased. Mean arterial pressure (MAP) is the triple product of heart rate x stroke volume x total peripheral resistance (TPR). The above scenario would support the rationale that a failure to augment heart rate or stroke volume requires an increase in TPR to maintain MAP. This has previously been experimentally shown (Gonzalez-Alonso et al. 2003) to lead to reduced skeletal muscle blood flow, oxygen delivery, and work performance.

Age may also influence the cardiovascular response to exercise during uncompensable heat stress (for example, firefighting). Age is associated with increased ventricular stiffness and reduced maximal ejection fraction. The inability to fill the ventricle under reduced filling pressures (associated with heat stress) or to offset this reduction in preload through augmented systolic function could lead to a reduction in work performance, or even increase the risk of heart related incidents in older firefighters. More research is needed to test this hypothesis.

STUDY FIVE

This project was undertaken to evaluate the influence of SCBA regulator design on submaximal and maximal exercise performance.

Petersen SR, Mayne JR, Hartley TC, Butcher SJ, Jones RL, (2007) Regulator design improves peak exercise performance with the self-contained breathing apparatus (SCBA). **Applied Physiology Nutrition and Metabolism**, 32:S71.

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.

Hartley TC, Mayne JR, Butcher SJ, Jones RL, Petersen SR, (2007) Effect of regulator design on submaximal exercise with the self-contained breathing apparatus (SCBA). **Applied Physiology Nutrition and Metabolism**, 32:S42.

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.

Comments

A significant body of research work has been produced in our laboratory demonstrating the effects of the SCBA on various aspects of human performance. By far, the most significant aspect is the external breathing resistance, inherent to the SCBA regulator, which tends to affect respiratory effort (or work of breathing) during expiration when ventilation approaches and exceeds about 80 L/min. Once the effect appears, WOB continues to increase in an exponential fashion. We have not measured WOB with the SCBA at peak exercise, however we do not from several experiments that peak ventilation is reduced because of this breathing resistance. In young (~30 years), healthy, physically active males peak ventilation is reduced by about 15% (typically from approximately 180 L/min with a standard exercise testing breathing valve to about 150 L/min with the SCBA). We have consistently reported similar reductions in peak oxygen uptake (VO_{2peak}) which we reason is secondary to the reduction in pulmonary ventilation. While we have shown conclusively that physiological countermeasures (e.g., breathing hyperoxic and helium-based gases) can very effectively restore or even enhance normal function during exercise, we have been extremely careful never to alter the breathing apparatus. In every experiment conducted in our laboratory, the SCBA have been continuously checked by qualified technicians to ensure normal function, despite any modifications we have made to allow collection of physiological data.

This study became possible when Scott Health and Safety introduced a modification to the regulator on the 4.5 system in an effort to reduce external breathing resistance. While we have discussed the possible merits of such a modification for years, the appearance of the EZ-FLO II™ regulator provided the opportunity to investigate the effect of improved regulator design on performance.

During graded submaximal exercise (50 – 80% VO_{2peak}), esophageal pressure was lower in the EZ-FLO II™ condition once ventilation reached about 90 L/min. As might be expected from the results of our previous work, below that level of work and ventilation, the SCBA has no significant effect on WOB. Therefore, it is very encouraging to note that regulator design can reduce, we would predict from our indirect measurements, work of breathing during heavy exercise. This, we predict, would during prolonged operations involving high intensity work, reduce the incidence of respiratory muscle fatigue.

During graded exercise to exhaustion, peak ventilation was slightly but significantly higher in the EZ-FLO II™ condition, indicating that the new design does partially reduce the impairment in breathing during maximal exercise. As expected, the higher ventilation was accompanied by a corresponding increase in peak oxygen uptake. While the improvements (~3-4%) were small it is important to note that they were achieved through a relatively simple modification to the apparatus.

We believe that these findings provide important ammunition that the fire service can use to lobby the manufacturers to improve the expiratory airflow characteristics of their products. At this time, a manuscript is in preparation for publication in a scientific journal.

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Nelson MD, Haykowsky MJ, Mayne JR, Jones RL, Petersen SR (2009) Effects of the self-contained breathing apparatus on ventricular function during strenuous exercise. **Journal of Applied Physiology**, 106: 395-402.

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Appendix A

Publication Reprint

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.

Appendix B

Publication Reprint

Butcher, SJ, Jones, RL, Mayne JR, Hartley TC, Petersen, SR. (2007) Impaired ventilatory mechanics with the self-contained breathing apparatus are improved with heliox. **European Journal of Applied Physiology**, 101(6): 659-69.

Appendix C

Publication Reprint

Mayne JR, Haykowsky MJ, Nelson MD, Hartley TC, Butcher SJ, Jones RL Petersen SR. (2009) Effects of the self-contained breathing apparatus on left-ventricular function at rest and during graded exercise. **Applied Physiology, Nutrition and Metabolism**, 34 (4): 625-631.

Appendix D

Publication Reprint

Nelson MD, Haykowsky MJ, Mayne JR, Jones RL, Petersen SR (2009) Effects of the self-contained breathing apparatus on ventricular function during strenuous exercise. **Journal of Applied Physiology**, 106: 395-402.