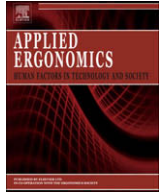




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Air management and physiological responses during simulated firefighting tasks in a high-rise structure

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ABSTRACT

Air consumption, oxygen uptake (VO_2), carbon dioxide output (VCO_2) and respiratory exchange ratio ($\text{RER} = \text{VCO}_2/\text{VO}_2$) were measured directly from the self-contained breathing apparatus (SCBA) as 36 professional firefighters (three women) completed scenarios of high-rise stair climbing and fifth floor search and rescue. During stair climbing VO_2 was $75 \pm 8\% \text{VO}_{2\text{max}}$ (mean \pm SD), $\text{RER} = 1.10 \pm 0.10$, and heart rate = $91 \pm 3\%$ maximum (based on maximum treadmill data). Firefighters stopped climbing on consuming 55% of the air cylinder then descended. In the fifth floor search and rescue VO_2 was slightly lower than stair climbing but RER remained elevated (1.13 ± 0.12) reflecting high anaerobic metabolism. The first low air alarm sounded, indicating 25% of the air remaining in a “30-min cylinder”, during the stair climb at 8 min with 19 of 36 sounding before 12 min. Aggressive air management strategies are required for safety in high-rise firefighting.

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1. Introduction

Firefighters will encounter emergency situations in high-rise buildings in which it is necessary to enter the fire while breathing from their self-contained breathing apparatus (SCBA), climb several flights of stairs, perform fire suppression or emergency search and rescue operations and then safely exit the building. To date, only one study has actually measured oxygen uptake (VO_2) directly while breathing through the SCBA but they did not report on air consumption for different tasks (Sothmann et al., 1991) and the data were not able to inform on an air management strategy. Other recent studies of firefighters (Bilzon et al., 2001; Holmér and Gavhed, 2007; von Heimburg et al., 2006) replaced the SCBA with a portable metabolic measurement system and observed rates of air consumption that exceed by 2–3 fold the nominal 40 l/min the National Institute for Occupational Safety and Health (NIOSH) standards for designating air cylinder volumes (e.g. “30-min” cylinder).

It is well known that the demands of firefighting are strenuous (Bilzon et al., 2001; Gledhill and Jamnik, 1992; Holmér and Gavhed, 2007; Lemon and Hermiston, 1977; Romet and Frim, 1987; Sothmann et al., 1991; von Heimburg et al., 2006). Further, within the firefighting profession it is recognized that the actual duration

for work while wearing an SCBA could be considerably less than the nominal values and time for a safe exit is limited after the low air alarm sounds (Bernzweig, 2004).

We undertook the current study to obtain quantitative data from professional firefighters who first performed laboratory testing of fitness then completed two different high-rise emergency simulations while breathing from their SCBA. We selected stair climb while carrying a pack with two lengths of hose as a task that might be performed under extreme conditions that could be encountered if elevators were inoperative. Firefighters climbed to 55% of their air supply then dropped the high-rise pack and descended the stairs to an exit on the ground floor. In the second scenario we had firefighters climb five floors then perform a search and rescue. Based on recent observations by von Heimburg et al. (2006), we anticipated that experienced firefighters might perform the search and rescue more quickly and that they would use less air from their SCBA cylinder.

2. Methods

2.1. Subjects

Thirty-three men and three women (age from 30 to 53 years, mean 40.7 ± 6.6 years, with 0.5–30 years of service, mean 12.0 ± 8.5 years) were recruited from the Toronto Fire Services. This research was approved by the Office of Research Ethics at the University of Waterloo, informed written consent was obtained

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prior to participation in the study, and each person was informed that he or she could withdraw from the study at any time without penalty.

2.2. Materials and methods

During the maximal treadmill tests and simulated firefighting scenarios, breath-by-breath pulmonary gas exchange and heart rate were measured using the Cosmed K4b² portable metabolic system (Cosmed, Italy). Prior to each test, the O₂ and CO₂ gas analyzers were calibrated using a precision-analyzed gas mixture. The volume flowmeter was calibrated using a 3.0 L hand-pumped syringe. Heart rate was recorded during the tests using the Polar monitoring system. For the simulated firefighting scenarios the Cosmed K4b² was integrated with a Mine Safety Appliances (MSA™) SCBA system. There were no modifications to the inspired side of the SCBA, a small gas sample line was introduced through the voice box to a position close to the mouth, and a *t*-shaped adapter was placed on the expired port from the SCBA. This *t*-shaped adapter allowed the volume turbine of the Cosmed system to be placed so that it did not interfere with normal activities and volume was measured accurately. Volume measurements agreed within ±1% between the volume turbine and the change in weight of the air cylinder. VO₂ values were compared with a mechanical calibrator and shown to be accurate within ±4%.

2.3. Experimental design

Testing was conducted on 2 separate days, 1 day for the maximal treadmill test and predictive muscular strength and endurance tests, and the other for the simulated firefighting scenarios. A minimum of 2 h separated the two randomly ordered firefighting scenarios to minimize carryover effects.

An incremental exercise test was conducted on a motorized treadmill (Quinton, Washington) to determine VO_{2max}. Following a 4 min warm-up at a brisk walking pace, speed was increased 1.6 km/h every 2 min until a comfortable running speed was reached and this was followed by 2% increases in grade every 2 min. The test was terminated when participants were unable to continue and reached volitional fatigue. VO_{2max} was taken as the highest 20-s average during the final minute.

Muscular strength measures were obtained using a predictive one-repetition maximum (1-RM), as previously described (Kraemer and Fry, 2006):

$$\text{Predicted } 1 - \text{RM} = \text{Load Lifted} / (1 - 0.025 * \text{reps})$$

Subjects completed a warm-up of five repetitions with a load ~40% of their 1-RM. After a 1 min rest period, they performed a maximal effort with a load predicted to cause fatigue in fewer than 10 repetitions (Kraemer and Fry, 2006). A 3–5 min rest period preceded the next 1-RM test. The order of muscle testing was: maximal handgrip dynamometer (Takei Co. Ltd., Tokyo, Japan), flat bench press, seated 45° incline leg press, military shoulder press, and standing bicep curls. Upper body endurance was assessed with a bench press of 30 kg at 30 repetitions/min. Lower body endurance was measured with an absolute load of 123 kg on the incline leg press at a cadence of 25 repetitions/min. Subjects were required to lift the load until they were unable to maintain cadence.

2.4. Firefighting scenarios

Two different high-rise scenarios were developed through discussions with training officers, Commanders, and District Chiefs within the Toronto Fire Services. One was designed to determine

physiological responses and air demands during a “maximal” stair climb, and the second was developed as a typical search and rescue operation. The firefighters performed the tasks singly to allow for completion of the tasks at the pace self-selected to be their normal work effort. During both scenarios, subjects wore full personal protective equipment (PPE, bunker pants and jacket, flash hood, gloves, helmet, and boots) that weighed approximately 9.2 kg and integrated Cosmed K4b²-SCBA system (weight 9.5 kg). Prior to each test subjects stood for 2 min while breathing room air through the SCBA facemask to collect pre-exercise data. All testing took place in Toronto City Hall which had a total of 23 floors for a vertical climb of 73.14 m.

The high-rise stair climb scenario was implemented to determine the total number of flights of stairs firefighters were capable of climbing, while carrying an additional 18 kg high-rise pack (consisting of two 38 mm hose bundles). Vertical ascent was terminated when firefighters had consumed 55% of the air in their cylinder allowing 20% for exit before their low air alarm sounded, or on reaching the top (23rd) floor. At the point of 55% depletion, the subjects were requested to drop the high-rise pack and descend the stairs in order to achieve a safe exit. The SCBA cylinders were filled each day using the standard protocol for the fire services with actual pressure averaging ~4300 psi. The testing was based on depleting 55% of this constant pressure. Prior to each test the gauge reading of each cylinder was determined and 55% of 4300 was subtracted to give the actual pressure at turn around. A research assistant walked with the firefighter to time progress and to monitor the pressure gauge and signal the turn around point. Eight firefighters reached the 23rd floor turnaround point without depleting 55% of the cylinder air.

The fifth floor search and rescue scenario was implemented to simulate an actual fire scenario in a high-rise structure. Firefighters were requested to complete the following protocol:

1. Ascend five stories while carrying an additional 18 kg high-rise pack. Five stories were chosen as this is normally the maximum number of floors climbed without the use of an elevator in a high-rise structure.
2. On arriving at the fifth floor, the firefighter dropped the high-rise pack and crawled on hands and knees in order to advance an uncharged 38 mm hose line a distance of 18.3 m. At intervals throughout the hose advance each firefighter completed three separate room searches (average area 15.6 m²) that simulated a scan for a victim.
3. After the search, the firefighter used a sledge hammer to hit a forcible entry simulator in order to breach a door (simulator set to a resistance between 700 and 800 psi [4826–5516 kN/m²], requiring at least four solid strikes).
4. Enter the room and rescue a 75 kg mannequin a distance of 23 m back to the stairwell.
5. Descend five stories in order to achieve a safe exit.

For both high-rise scenarios, each firefighter was requested to perform at a work rate that he or she would utilize at a typical fire scene.

2.5. Data analysis and statistics

For the high-rise stair climb scenario, performance time was recorded for each flight that was completed by the firefighter. During the fifth floor high-rise scenario, performance time was recorded for individual tasks separately. Breath-by-breath gas exchange variables were averaged for V_E, VO₂, VCO₂, RER, and HR to obtain single values for each stage of testing with the exception of the five floor stair climb in the search and rescue task where the

final 25 s was taken as representative of the demands. Data are presented as both the individual responses and as the mean and standard deviation (SD). Comparisons between phases of the tasks were made by repeated measures ANOVA using SigmaStat 3.1. Regressions were performed to determine the relationship between experience and air consumption and total time during the fifth floor scenario.

3. Results

3.1. Anthropometric and maximal exercise testing

Anthropometric data and results from the maximal treadmill test are depicted in Table 1. Data from the one-repetition maximal strength tests and muscular endurance tests are displayed in Table 2. The firefighters' average age and years of service in the present study were similar to the statistics obtained for individuals with the rank of firefighter within the City of Toronto Fire Services (41.5 years of age and 13.2 years of service) and the proportion of women was approximately the same as in the Fire Services.

3.2. High-rise stair climb scenario

The average duration of the stair climb plus descent was 10:22 (min:s) with a range from 8:14 to 14:11. Average number of floors climbed while consuming 55% of a typical air cylinder was 20 ± 2.5 flights (range 14.5–23 flights, six men and two women were turned around on reaching the maximum number of floors). The individual subject values for V_E , VO_2 and RER are shown in Fig. 1. Each of V_E , VO_2 , and HR increased rapidly over the first five to six floors of the stair climb then reached relatively stable levels until the turn around point and decreased slightly during the descent (Figs. 1 and 2). There were considerable between subject variations in response but the individual subject values that were relatively constant after the 6th floor coincided with the sustained lower velocity after an initial rapid ascent (Fig. 3). Mean V_E during the stair climb was 85.3 l/min (range 56.8–113.6 l/min). Mean VO_2 after passing the fifth floor in the stair climb was 3165 ± 518 ml/min (range 2015–4249 ml/min) which correspond to 38.3 ± 5.2 ml/kg per min (range 25.2–47.0 ml/kg per min) and $75 \pm 8\%$ VO_{2max} (range 58–91% VO_{2max}). Mean VCO_2 was 3777 ± 664 ml/min (range 2320–4889 ml/min). Mean respiratory exchange ratio for the stair climb was 1.10 ± 0.10 (range 0.92–1.39). Heart rate averaged $91 \pm 3\%$ HR_{max} (range 83–96%).

The descent portion of the scenario required a mean VO_2 of 2482 ± 480 ml/min, corresponding to 27.6 ± 4.4 ml/kg per min and $54 \pm 9\%$ VO_{2max} , mean VCO_2 of 2755 ± 594 ml/min, and RER of 1.11 ± 0.10 . The heart rate response decreased slightly to $85 \pm 5\%$ HR_{max} , but indicates that even during an average descent duration of 3:53 (min:s) (range 2:29–5:30), cardiorespiratory responses remained elevated.

3.3. Fifth floor search and rescue scenario

The fifth floor high-rise scenario required an average completion time of $5:27 \pm 1:01$ (min:s), with a range from 4:11 to 9:38. Taken across the full fifth floor scenario expired ventilation

averaged 90.7 ± 14.6 l/min (61.6–118.5 l/min, Fig. 4), with a mean VO_2 of 3015 ± 469 ml/min (2213–4118 ml/min), corresponding to 34.1 ml/kg per min (range 23.2–41.7 ml/kg per min, Fig. 4), VCO_2 of 3385 ± 528 ml/min (range 2216–4217 ml/min), RER of 1.13 ± 0.12 (range 0.94–1.29, Fig. 4), and HR of 160 ± 13 bpm (range 127–189 bpm). The fifth floor scenario required $67 \pm 10\%$ VO_{2max} (range 46–87%) and $88 \pm 5\%$ HR_{max} (range 80–94%) (Fig. 5).

The VO_2 was significantly greater during the five floor stair climb compared to any of the tasks after the first room search ($p < 0.05$). VO_2 increased significantly during the victim rescue task compared to the hose drag and forcible entry tasks that preceded it ($p < 0.05$). The heart rate response continued to increase after the stair climb into the first room search before declining then increasing again during the victim rescue ($p < 0.05$).

3.4. Air management

The air consumption as a percentage of the nominal “30-min” cylinder is shown as a function of time for each individual in Fig. 6 during the stair climb (Fig. 6A) and search and rescue scenario (Fig. 6B). Mean air consumption during the stair climbing scenario that required from 8:14 to 14:11 min:s was 71% of the cylinder, with a range from 55 to 81%. Of the 36 firefighters studied 19 (53%) had their low air alarm activated indicating less than 25% of their air remaining prior to achieving a safe exit. On reaching a relatively constant level of ventilation between the fifth and 14th floors the average air consumption for the entire group was 2.4% of the air cylinder per floor, with the maximum individual value 3.5% and the minimum level 1.6% per floor of high-rise climbed.

In comparison during the fifth floor scenario that was completed in 4:11 to 9:38 min:s average air consumption was 37% of the air cylinder, with a range from 24 to 50%. Air consumption for the individual components of the task was determined as the group average along with minimum and maximum. The five floor stair climb carrying the high-rise pack with two lengths of hose from a standing start required 6.5% (4% minimum, 10% maximum). The hose drag (total distance 18.3 m) plus three room search (average surface area per room 15.6 m^2) required an average of 17% of the air cylinder (10% minimum, 29% maximum). The forcible entry required an average of 1.4% (0.7% minimum, 3.4% maximum). The rescue of the 75 kg mannequin a distance of 23 m required an average of 5.8% of the air cylinder (2.8% minimum, 7.3% maximum). Finally, descent of the five floors to the safe exit required an average of 6% of the air cylinder (4% minimum, 10% maximum).

To test whether age or experience had any relationship to speed of completing the fifth floor scenario or to air consumption during the tasks, Pearson product-moment correlations were calculated. Time to complete the search and rescue scenario was positively related to age ($r = 0.47$, $P = 0.005$) and to years of experience ($r = 0.47$, $P = 0.009$) suggesting slower times in older, more experienced firefighters. Completion time was not related to body mass ($r = -0.09$, $P = 0.61$). Total air consumption increased with age ($r = 0.61$, $P < 0.001$), with years of experience as a firefighter ($r = 0.47$, $P = 0.004$), and was positively correlated with body mass ($r = 0.36$, $P = 0.03$).

Table 1

Anthropometric and maximal treadmill test data for all firefighters.

Age (years)	Service (years)	Height (m)	Body mass (kg)	V_E (l/min)	VO_2 (ml/min)	VO_2 (ml/kg per min)	VCO_2 (ml/min)	RER	HR (bpm)
40.7 ± 6.6	12 ± 8.5	178.3 ± 6.4	87.5 ± 12.2	144.8 ± 22.0	4470 ± 696	51.4 ± 6.5	4455 ± 590	1.01 ± 0.10	183 ± 9

Data are presented as mean \pm SD.

Table 2
Data from the predicted one-repetition maximal strength testing and muscular endurance tests.

Predicted 1-RM					Muscular endurance	
Handgrip (kg)	Bench press (kg)	Shoulder press (kg)	Biceps curls (kg)	Leg press (kg)	Leg press (reps)	Bench press (reps)
56.5 ± 7.9	94.6 ± 27.6	66.3 ± 14.8	49.8 ± 8.5	349.4 ± 70.3	52.0 ± 34.7	41.8 ± 14.3

Data are presented as mean ± SD.

4. Discussion

This study provides new information to assist in planning strategies for air management by professional firefighters performing tasks in a high-rise structure while breathing from their SCBA. Previous research has reported either $\dot{V}O_2$ but no air consumption information while breathing through the SCBA (Sothmann et al., 1991) or $\dot{V}O_2$ and \dot{V}_E but not while breathing through the SCBA (Bilzon et al., 2001; Holmér and Gavhed, 2007; von Heimburg et al., 2006). Our data showed the anticipated high $\dot{V}O_2$ and heart rate for both high-rise scenarios. In addition, we report for the first time the markedly elevated VCO_2 during high-rise tasks, which provides through the respiratory exchange ratio insight into the magnitude of lactic acid production and the contribution of anaerobic metabolism to energy supply. As well, we have the important applied observation during the high-rise stair climb that 53% of firefighters had their low air alarms sound in 8–12 min on their so-called “30-min” air cylinders before they reached a safe exit from the stairs. Further, linear extrapolation of the rate of air consumption during the fifth floor search and rescue suggested that the low air alarm could be activated in as little as

9 min. Thus, high-rise tasks performed at work rates self-selected by professional firefighters as typical of their normal activities clearly demonstrate the need for aggressive air management strategies to ensure the health and safety of all firefighters.

4.1. High-rise stair climb scenario

Rationale for performing the stair climb scenario can be found in the fire in the 45 storey LaSalle Bank Building December 6, 2004 in which firefighters had to climb up to 14 floors while breathing from their SCBA. Smoke inhalation due to exhausting the air supply was responsible for many of the 23 injuries. In our study we arbitrarily set the turn around point for stair climbing with the 18 kg high-rise pack to be at 55% air consumption. The lowest turn around point was 14.5 floors and eight (six men, two women) of 36 individuals reached the top 23rd floor before turning around. Under these conditions, 19 of 36 firefighters had their low air alarm sound before reaching the exit (Fig. 6A).

After starting from a standing position the $\dot{V}O_2$ and heart rate increased rapidly during the first five floors of the high-rise stair climb as expected with the onset of heavy work (Hughson et al., 2000;

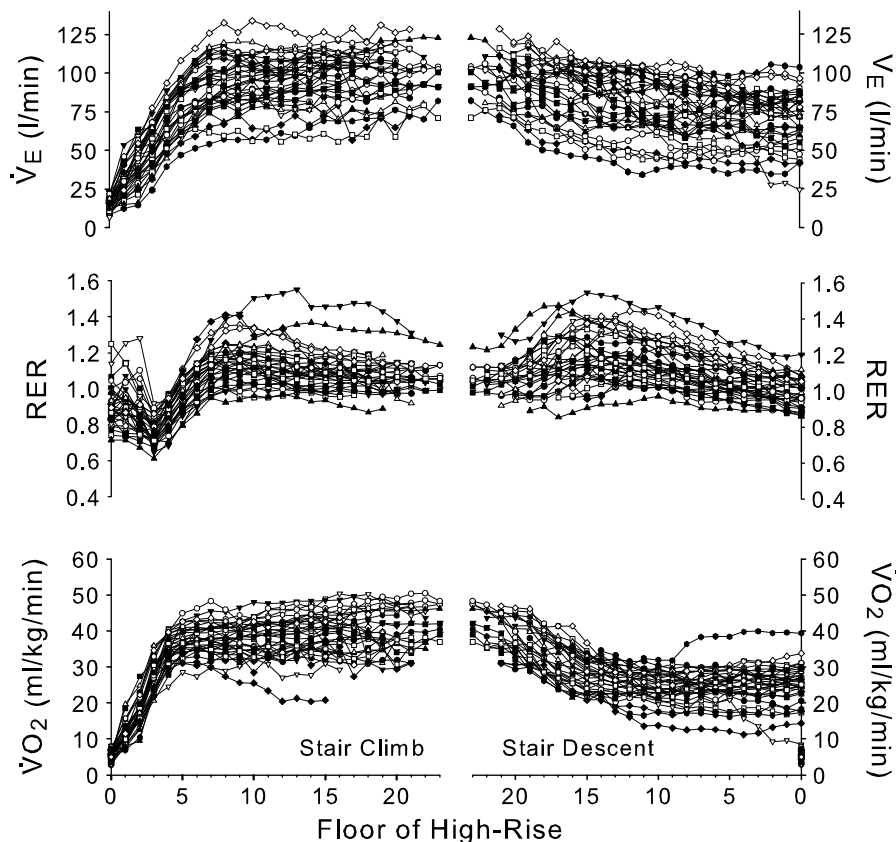


Fig. 1. Individual firefighter data are shown for expired ventilation (\dot{V}_E), respiratory gas exchange ratio ($RER = VCO_2/\dot{V}O_2$), and relative oxygen uptake ($\dot{V}O_2$, ml/kg per min) during the stair climbing task with extra weight of two hose lengths in a high-rise pack. Firefighters turned around when their SCBA was reduced to 55% of its volume or when they reached the top 23rd floor. Firefighters who stopped before the maximum 23rd floor have their first data point during descent at the floor below where they stopped.

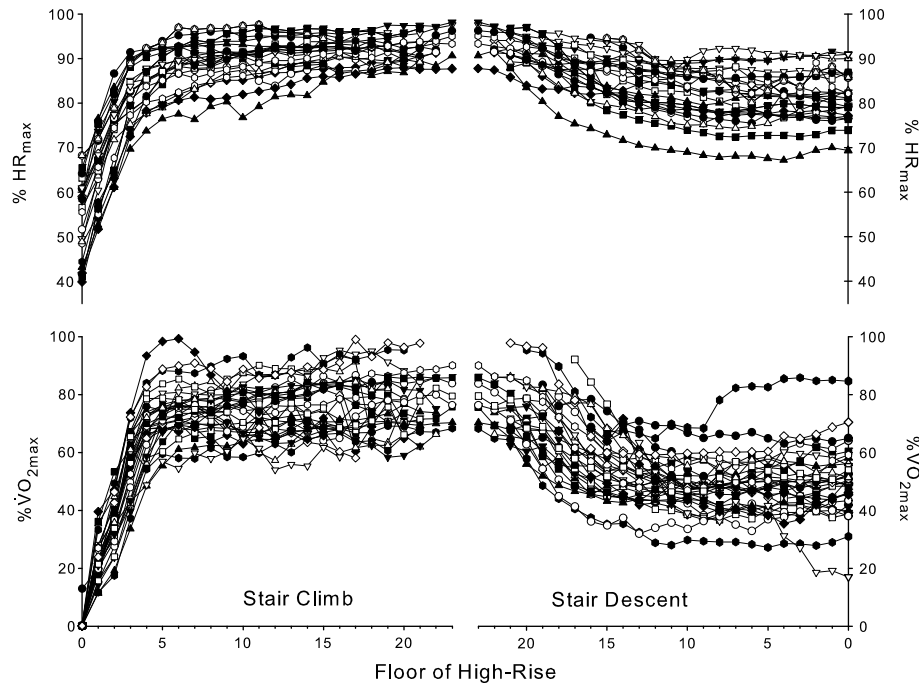


Fig. 2. Individual firefighter data are shown for heart rate and oxygen uptake as percentage of the maximum value observed during treadmill exercise (HR_{max} and VO_{2max} , respectively) during the stair climbing task with extra weight of two hose lengths in a high-rise pack. Firefighters turned around when their SCBA was reduced to 55% of its volume or when they reached the top 23rd floor. Firefighters who stopped before the maximum 23rd floor have their first data point during descent at the floor below where they stopped.

Tordi et al., 2003) such as stair climbing while carrying additional weight (Manning and Griggs, 1983; O'Connell et al., 1986; von Heimburg et al., 2006). The firefighters in our study began climbing at a rate of 0.31 ± 0.05 m/s and slowed to 0.20 ± 0.05 m/s by the fifth floor. This was similar to other studies in which the average velocity was 0.23 m/s over six floors (von Heimburg et al., 2006), step mill climbing was completed at 0.20 m/s for 5-min (O'Connell et al., 1986).

Beyond the sixth floor the firefighters in our study slowed a bit more to a velocity of 0.16 ± 0.05 m/s at the 15th floor but in spite of this their VO_2 (38 ml/kg per min, 75% VO_{2max}) and heart rate (91% of maximum) remained elevated until the turn around point. During the descent portion of the scenario oxygen requirements decreased to approximately 28 ml/kg per min or 54% VO_{2max} , while heart rate remained high at 86% of maximum. The rate of stair descent varied

considerably between individuals probably reflecting several factors including fatigue.

The plot of RER reveals a range of responses while standing on the ground floor that reflects variable levels of normal versus hypoventilation that caused RER to be elevated in some individuals. On starting to climb the stairs, there was an initial decrease reflecting a brief lag for the increase in VCO_2 relative to VO_2 as CO_2 was stored in the tissues and blood (Hughson and Inman, 1985). However, by the eighth floor RER exceeded 1.0 in the majority of subjects, with a group mean of 1.10. This high level of RER would not be expected if these individuals were exercising at the same relative VO_2 (75% VO_{2max}) on a cycle ergometer or walking on a treadmill (Linnarsson, 1974). RER would be expected to increase above 1.0 only when VO_2 exceeded $\sim 90\%$ VO_{2max} (Perrey et al., 2003; Tordi et al., 2003). The sustained

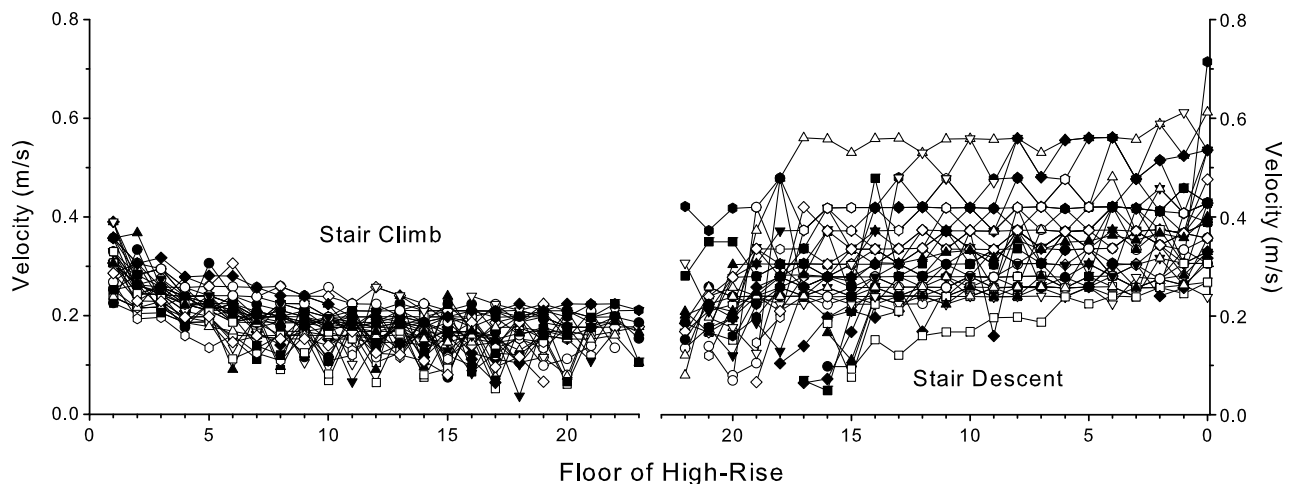


Fig. 3. Individual firefighter values are shown for the absolute vertical velocity during the stair climb (left side) and stair descent (right side). Firefighters who stopped before the maximum 23rd floor have their first data point during descent at the floor below where they stopped.

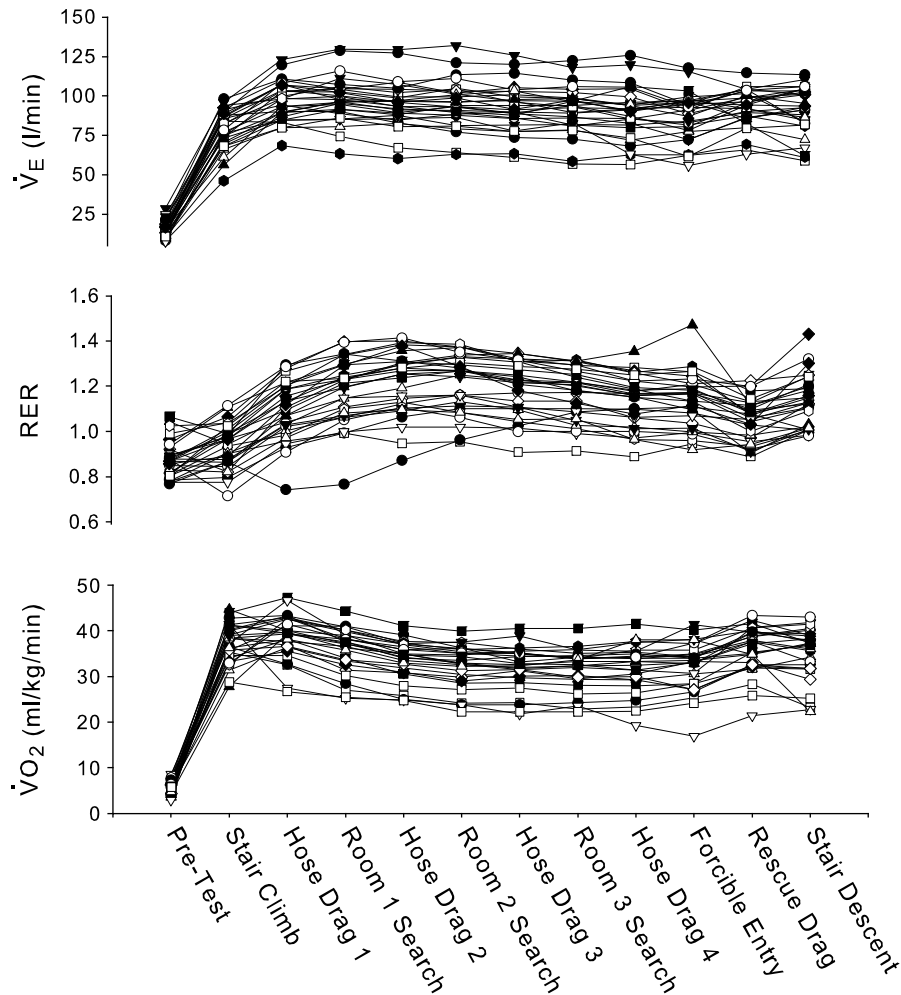


Fig. 4. Expired ventilation (\dot{V}_E), respiratory gas exchange ($RER = \dot{V}CO_2/\dot{V}O_2$), and relative oxygen uptake ($\dot{V}O_2$, ml/kg per min) during the fifth floor search and rescue simulation. Individual subjects are shown with separate symbols and lines for each of the individual tasks. Values during stair climbing are from the final 20 s of the five floor climb, the floor-by-floor responses were very similar to those presented in Fig. 1. Firefighters crawled and dragged a hose to three separate rooms where they conducted a search before reaching the forcible entry simulator, rescuing a 75 kg “victim” and descending five floors to a safe exit.

high RER reflects an important difference between firefighting and typical aerobic exercises. We speculate that high levels of muscle tension required to lift not only body mass but the weight of the personal protective gear plus the 18 kg high-rise pack impaired muscle blood flow and oxygen delivery causing increased reliance on anaerobic metabolism. The small increase in RER as the firefighters descended the stairs probably reflects some CO_2 coming out of body stores at the relatively lower work rate of descent versus ascent.

4.2. Fifth floor scenario

The fifth floor high-rise scenario was selected as representative of fire suppression and victim search and rescue situations encountered by most firefighters. Standard operating procedures for this fire service require firefighters to walk up to the fire if the climb is five floors or less. This scenario which lasted $5:27 \pm 1:01$ (min:s) with a range from 4:11 to 9:38, was rated as 7.9 ± 1.0 out of 10 when the firefighters were asked on completion of the task how they would “rate the simulation in comparison to actual fire scene activities?” This rating was relatively high in spite of the fact that the simulations were performed without smoke or visual obstruction.

This research is the first to report full details of respiratory gas exchange during search and rescue tasks while breathing through

an SCBA. Sothmann et al. (1991) measured $\dot{V}O_2$ and HR from a system integrated with the SCBA; however, that system was technically limited because it measured only ventilation and O_2 with an assumption that $RER = 1.0$ which could lead to non-trivial errors under extreme conditions. Recent research has utilized portable gas exchange measurement systems during performance of simulations of firefighting activities but did not integrate the systems with the SCBA (Bilzon et al., 2001; Holmér and Gavhed, 2007; von Heimburg et al., 2006), while older studies collected gas in bags for later analysis (Gledhill and Jamnik, 1992; Lemon and Hermiston, 1977). Given observations of the impact of breathing through the SCBA on exercise performance with possible alterations in the pattern of breathing and reductions in $\dot{V}O_{2max}$ (Donovan and McConnell, 1999; Dreger et al., 2006; Louhevaara et al., 1985) our data provide new insight into the physiological stress of firefighting under conditions that replicate as closely as possible the actual breathing situation encountered.

Based on data from von Heimburg et al. (2006), we anticipated that larger and more experienced firefighters might perform the tasks more quickly and use less air. We found the opposite that the older more experienced and heavier firefighters consumed more total air from their cylinders during the fifth floor search and rescue task. There was wide variation between individuals but perhaps

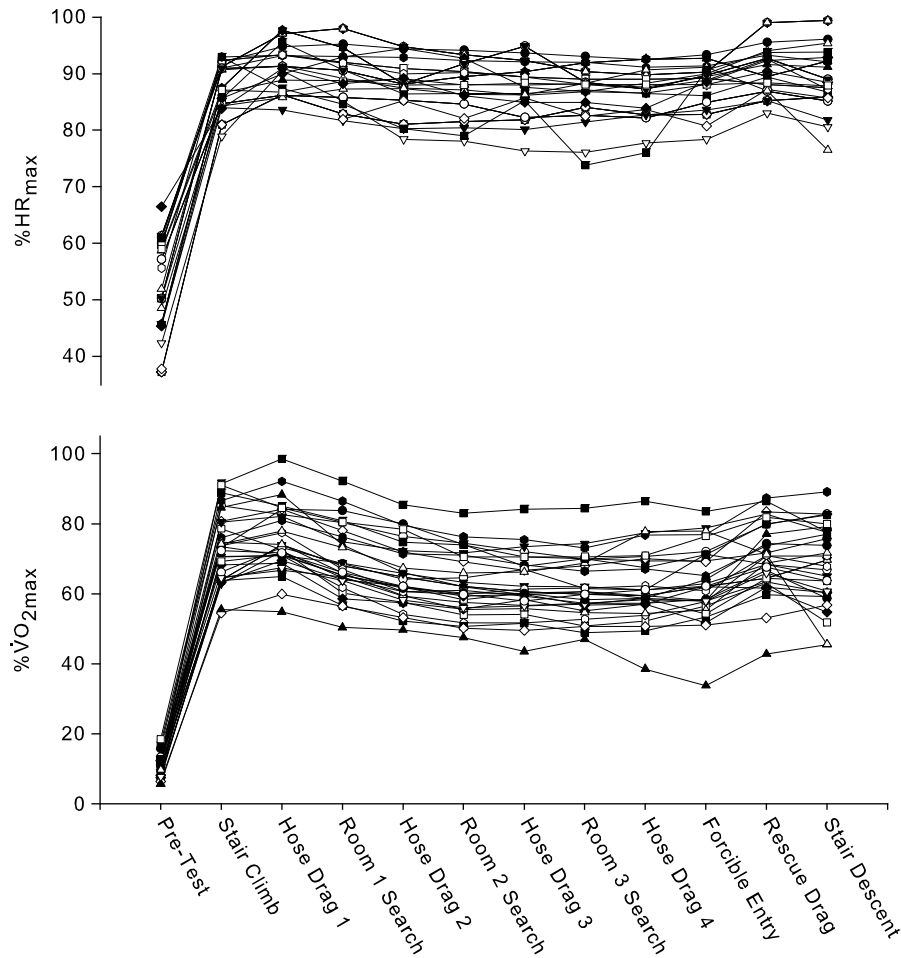


Fig. 5. Individual firefighter data are shown for heart rate and oxygen uptake as percentage of the maximum value observed during treadmill exercise (HR_{max} and VO_{2max} , respectively) during the fifth floor search and rescue simulation. Individual subjects are shown with separate symbols and lines for each of the individual tasks. Values during stair climbing are from the final 20 s of the five floor climb. Firefighters crawled and dragged a hose to three separate rooms where they conducted a search before reaching the forcible entry simulator, rescuing a 75 kg “victim” and descending five floors to a safe exit.

more importantly our firefighters worked at their own pace and the older firefighters who took somewhat longer to complete the tasks might have been more thorough in their room searches. In contrast, von Heimburg et al. asked their firefighters to perform the task as quickly as possible. The overall physical characteristics including VO_{2max} , body mass and upper body strength measurements were similar between these two studies, while the difference in leg press strength reflects different equipment.

The relatively long period of advancing a hose and searching while crawling on hands and knees is a typical task in a high-rise structure fire, but previous research has not isolated this activity. Holmér and Gavhed (Holmér and Gavhed, 2007) mention crawling as part of one task but give no specific data. The energy cost of the crawling search technique was high with VO_2 between approximately 47–82% VO_{2max} . Importantly, the level of ventilation sustained during this crawling activity was very high ranging from 63 to 131 l/min while the firefighters were in the second room. Although we did not measure maximal exercise capability in these individuals while wearing the SCBA, previous findings by Louhevaara et al. (1985) and recent results from Dreger et al. (2006) showed limitations in V_E and VO_2 while wearing the SCBA. Dreger et al. (2006) reported a 17.3% reduction in VO_{2max} from 52.4 to 43.0 ml/kg per min due in part to a 14.5% reduction in peak ventilation from 167 to 143 l/min while breathing from the SCBA. There are major implications for the work of breathing and possible

ventilatory limitations during the current study especially considering the crawling position in which the arms and back were used to support movement. It might be anticipated that this could further restrict ventilation while wearing the SCBA. Future research is required to quantify the impact of body position as well as breathing from the SCBA on peak V_E and VO_2 to put the measured values during the high-rise scenario into perspective.

The data on RER measured throughout a simulated work task by firefighters breathing from an SCBA provide unique insight into metabolic demands. The only previous study to report RER during firefighting tasks by Lemon and Hermiston (1977) were confined to observations of very brief work periods (30–90 s) so the RER values were low and appeared unimportant. RER during treadmill testing while breathing through the SCBA was reduced (Louhevaara et al., 1985) or unchanged (Dreger et al., 2006), so it does not appear that the SCBA per se was responsible for the high values. Rather, the sustained increased RER reflected a major contribution to energy supply by anaerobic metabolism as considered in more detail in the next section.

4.3. Air management for firefighters

The duration of the search and rescue scenario was relatively brief (from 4:11 to 9:38 min:s for the individual firefighters). As a consequence, average air consumption was only 37% of the

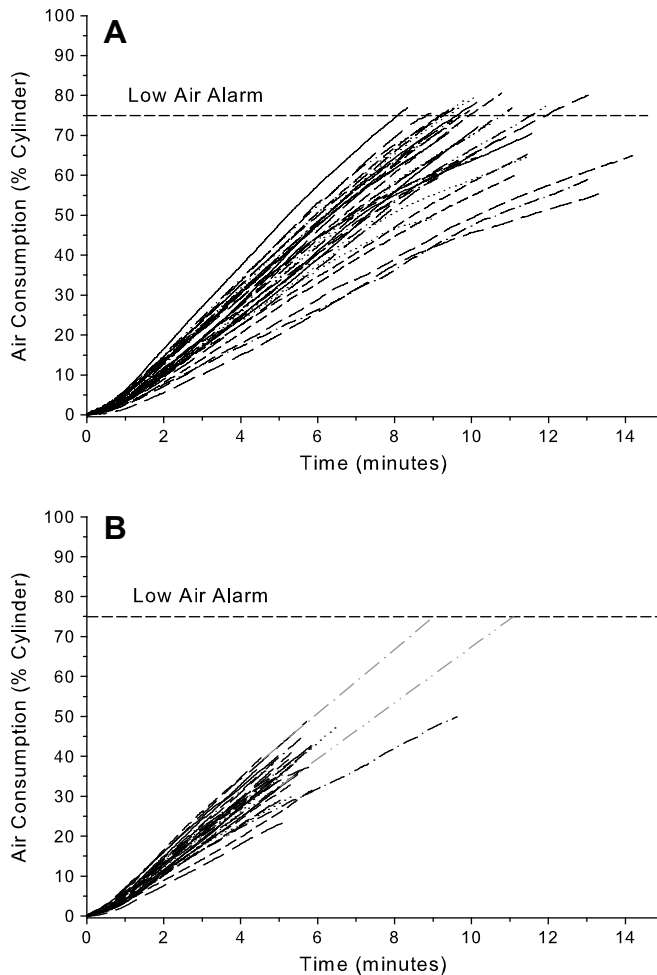


Fig. 6. Individual firefighter air consumptions are shown as a % of the cylinder volume for a standard “30-min” cylinder during the stair climb with added weight of high-rise pack (A) and during the fifth floor search and rescue task (B). In the stair climb (A), 19 of 36 firefighters consumed greater than 75% of the air in their cylinders and had their low air alarms sound. In the fifth floor search and rescue, the task duration was sufficiently short that no firefighter had his/her low air alarm sound. However, the gray lines in B show that at the existing rate of air consumption the low air alarm could have sounded as early as 9 min (dash single dot line) or approximately 11 min (dash double dot line) for the group average.

cylinder (range from 25 to 51%) and no low air alarms were activated. However, Fig. 6B shows with two gray lines added as linear extrapolations of the air consumption what might have happened if the firefighters had been required to continue to search more rooms before finding the victim. The line to the left (dash, single dot) is an extrapolation of firefighters who used air at the highest rates. For these individuals, it was predicted that the low air alarm could sound in 9 min. The other gray line (dash, double dot) is an extrapolation based on the average rate of air consumption. This line predicts that 50% of firefighters would have had their low air alarm activated if they had continued to work to a total time of 11 min.

It is important to recognize that the extrapolations presented in Fig. 6B are simply predictions based on a linear model of air consumption. Indeed, it is unknown if the firefighters would have been able to sustain the level of activity required to demand ventilation at the measured rate. However, the data on air consumption taken together with the measured metabolic requirements of the search and rescue can be utilized to consider a frequently asked question in the fire services as to whether

firefighters should use a larger cylinder to increase the level of safety? The current data and other recent evidence argue strongly against this practice.

The energy demands of firefighting have been described for many years as approximately 60–70% VO_{2max} and our data are consistent with this in firefighters who are breathing through their SCBA. However, if the data of Dreger et al. (2006) can be extrapolated to all SCBA systems then it is likely that the value normally taken to be 100% VO_{2max} (from treadmill VO_{2max} with standard laboratory equipment) should be reduced by ~17% due to the impact of breathing through the SCBA. This would increase the relative intensity of work when expressed as a percentage of VO_{2max} (in the current case to about 76% from 62% during the search of the second room). Yet, even at 76% VO_{2max} , we would not anticipate a major anaerobic contribution to energy supply as reflected by the high RER. The consistent excess CO_2 output during this scenario must reflect a large net accumulation of lactic acid. We can calculate based on the average values of VO_2 (~3000 ml/min), a work duration of 5.5 min and the RER of 1.13 that the body produced at total of 1950 ml of excess CO_2 which reflects the depletion of bicarbonate (87 mmol) as a buffer of an equivalent amount of hydrogen ion dissociated from lactic acid. This calculation gives an estimated increase in blood lactate concentration similar to the 13 mmol/l measured by von Heimburg (2006) after stair climbing and victim rescue. It is probable that climbing stairs with the added weight of the high-rise pack and the personal protective gear in addition to activities such as crawling, forcible entry and victim drag caused sustained high levels of muscle tension that restricted blood flow forcing the muscles to produce more lactate.

Our data reflecting the extremely strenuous nature of firefighting suggest that any attempt to have firefighters work longer by supplying larger cylinders for the SCBA would simply result in greater levels of fatigue from which it would be extremely difficult to recover. It is well known that the maximum total high intensity work is accomplished by short periods of activity with rest intervals (Astrand and Rodahl, 1985). Therefore under conditions where firefighters perform active duty cycles at a fire scene, it is best to keep the work period relatively short for two key reasons. First, longer cycles will cause greater fatigue with increased likelihood of injury. Second, as we have demonstrated, individual firefighters can consume air at such a rate that their low air alarms are activated in less than 10-min. Firefighters should be safely out of emergency fire situations before their low air alarm sounds allowing for unexpected emergencies including the possible need for self-rescue (Bernzweig, 2004).

4.4. Limitations

A major limitation in the current study was that the activities were performed under non-emergency situations. There was no smoke nor was vision intentionally impaired by black out and there were no obstructions. It is impossible to predict how actual emergencies might alter the work rate and the physiological response to any given work rate. The firefighters were asked to perform the activities at their normal working pace. They might have performed a bit faster knowing that they were in a research project, and knowing the specific task might have prompted them to perform the task a bit faster because they anticipated the end point.

The current study was conducted on professional firefighters who volunteered to participate in the research project. Even though the study population reflected very well the average age, years of experience, and sex distribution in the City’s Fire Service and they had similar physical characteristics to other study groups (von Heimburg et al., 2006), it is likely that we obtained a relatively fitter

population. It could be anticipated that less fit individuals would not volunteer for this study. Therefore, the current data should be used with some caution; it is possible that larger, less fit individuals might consume air at a greater rate than the study subjects. Approximately 10% of the firefighters in the City's Fire Service are women and we had three of 36 but it is not possible to extrapolate from this small sample size. The women were generally smaller than the average man but they successfully completed these tasks. Two of the eight firefighters who reached the 23rd floor in the stair climbing task that involved carrying an additional 18 kg hose pack in addition to the personal protective gear were women.

5. Conclusions

We observed in two high-rise firefighting simulations of continuous stair climbing plus exit and a fifth floor search and rescue task that individual firefighters could use air at a rate causing their low air alarms to sound in as little as 8:14 (min:s) and that approximately 50% of firefighters could have their alarms sound within 11–12 min when working at a rate they self-selected as their normal effort. We presented evidence based on the respiratory exchange ratio ($RER = \dot{V}CO_2/\dot{V}O_2$) that the intensity of the effort of firefighting is much greater than running or cycling exercise that has an equivalent $\dot{V}O_2$. There is a major anaerobic energy contribution with strong evidence for large increases in blood lactate concentration. Our data on the high physical demands of firefighting in combination with our observations of the rapid utilization of the air supply in the SCBA cylinder point not to increasing the size of the air cylinder but to different strategies for air management. The terminology "30-min" cylinder is misleading and potentially dangerous. Instead, cylinders should be designated by their nominal volume (e.g. 1200 l). Knowledge of maximum rates of air consumption (in % of air cylinder or l/min) for specific tasks can enable incident commanders to develop strategies for air management to insure that firefighters can safely exit a burning structure before the sounding of their low air alarms.

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