Safety and Health at Work 9 (2018) 468–472

Contents lists available at ScienceDirect

Safety and Health at Work

journal homepage: www.e-shaw.org

Original Article

Respiratory Responses during Exercise in Self-contained Breathing Apparatus among Firefighters and Nonfirefighters

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A R T I C L E I N F O

Article history:
Received 16 February 2017
Received in revised form
8 September 2017
Accepted 9 February 2018
Available online 17 February 2018

Keywords:
Carbon dioxide retention
Exercise
Protective equipment
Self-contained breathing apparatus

A B S T R A C T

Background: Firefighters are required to use self-contained breathing apparatus (SCBA), which impairs ventilatory mechanics. We hypothesized that firefighters have elevated arterial CO_2 when using SCBA.
Methods: Firefighters and controls performed a maximal exercise test on a cycle ergometer and two graded exercise tests (GXTs) at 25%, 50%, and 70% of their maximal aerobic power, once with a SCBA facemask and once with protective clothing and full SCBA.
Results: Respiratory rate increased more in controls than firefighters. Heart rate increased as a function of oxygen consumption ($\dot{V}_{O_2}$) more in controls than firefighters. End-tidal CO_2 ($ETCO_2$) during the GXTs was not affected by work rate in either group for either condition but was higher in firefighters at all work rates in both GXTs. SCBA increased $ETCO_2$ in controls but not firefighters.
Conclusions: The present study showed that when compared to controls, firefighters' hypoventilate during a maximal test and GXT. The hypoventilation resulted in increased $ETCO_2$, and presumably increased arterial CO_2, during exertion. It is proposed that firefighters have altered CO_2 sensitivity due to voluntary hypoventilation during training and work. Confirmation of low CO_2 sensitivity and the consequence of this on performance and long-term health remain to be determined.

1. Introduction

Firefighters are required to use self-contained breathing apparatus (SCBA) when working in immediately dangerous to life and health environments. Although essential for safe operations, breathing apparatus limits performance and work time [1,2]. SCBA impairs ventilatory mechanics and reduces the firefighters' maximal oxygen consumption ($\dot{V}_{O_2max}$) [1,3]. The finite air supply contained in the breathing cylinder limits the work interval by forcing the firefighter to disengage when the low air alarm sounds. Previous studies have reported that firefighters have different respiratory patterns when using SCBA to conserve breathing air [1,4], and another report concluded that "aggressive air management strategies are required" to operate in certain environments such as high-rise buildings [5]. Intentional hypoventilation while using respiratory protection also has physiologic consequences.

Previous studies have shown that scuba divers underventilate and thus have elevated arterial carbon dioxide [partial pressure carbon dioxide in arterial blood ($PaCO_2$)] as sensed by end-tidal carbon dioxide ($ETCO_2$) [6]. Additional studies have shown that some divers using scuba at depth have elevated $PaCO_2$, while the remaining maintain a normal $PaCO_2$ but develop dyspnea [7]. It has been suggested that the underventilation and subsequent elevation of $PaCO_2$ is due to the scuba diver's attempt to breathe slowly to conserve air and prolong dive time (skip breathing) [6]. It has further been shown that respiratory muscle fatigue occurs in divers during sustained exertion that leads to inadequate ventilation and increased $PaCO_2$ [7–9].

These studies among divers raise questions such as if similar skip breathing patterns among firefighters when breathing from SCBA during exertion lead to retention of carbon dioxide. The work of breathing using scuba and SCBA may be similar and thus have a negative impact on ventilation [3,8–11]. Firefighters are commonly

Abbreviations: IDLH, immediately dangerous to life and health; SCBA, self-contained breathing apparatus; $ETCO_2$, end-tidal carbon dioxide; RR, respiratory rate; HR, heart rate; V_{O2}, oxygen consumption; V_{O2max}, maximal oxygen consumption; V_E, ventilation; $PaCO_2$, partial pressure carbon dioxide in arterial blood.

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2093-7911/$ – see front matter
https://doi.org/10.1016/j.shaw.2018.02.002

taught to underventilate to conserve air and prolong work time due to the increased work of breathing and to extend the duration of the cylinder air supply. The elevation in $PaCO_2$ is likely increased further during exercise [12].

There are many short- and long-term negative effects of elevated $PaCO_2$. One of these is the inability to regulate acid–base status, particularly during exercise requiring anaerobic glycolysis that leads to lactic acid production and depressed pH (metabolic acidosis), which is common in firefighters. Metabolic acidosis typically results in respiratory compensation. If firefighters are voluntarily underventilating, however, $PaCO_2$ would be elevated and pH would be depressed. We hypothesized that (1) firefighters would have elevated $PaCO_2$ during exercise compared to nonfirefighters and (2) use of SCBA would result in underventilation and increased $PaCO_2$ as estimated from $ETCO_2$ [13] in both firefighters and nonfirefighters due to the increased work of breathing, with a greater affect in firefighters due to their voluntary underventilation during cycle exercise. We performed this pilot study to determine if there is a robust difference in respiratory responses during exercise between firefighters and nonfirefighters and the two conditions (SCBA vs. facemask alone) between firefighters and nonfirefighters.

2. Methods

2.1. Participants

The University at Buffalo Institutional Review Board approved this study. We recruited nonfirefighters control participants from the community and firefighters from the local fire service. Flyers were posted at the University and mailed to the fire departments in the immediate region around the university. Participants were recruited in the order in which they replied to the flyers and were not matched. Both men and women aged 18–49 years participated. To be eligible to participate, participants had to be free of diagnosed heart disease, stroke, hypertension, and not take medications that would be expected to blunt the physiologic response to exercise/stress, specifically, diuretics and/or antiarrthymic drugs. Female participants were screened with a urine pregnancy test. Participants could not use tobacco.

2.2. Procedures

After providing informed consent, participants had their height and mass assessed. Participants then performed a maximal exercise test on an electrically braked cycle ergometer while breathing into an open-circuit metabolic cart (TrueOne 2400, Parvomedics, Sandy UT). Participants pedaled at 60 rpm against a resistance of 50 W. The load was increased by 25 W every 2 minutes until the participant could no longer maintain the required rpm. During the test, heart rate and respiratory rate were recorded every minute and blood pressure every 2 minutes.

Nonfirefighter participants were provided instruction on how to don and use the SCBA. The participants wore the SCBA and breathed the compressed air for a minimum of 5 minutes. No participant displayed signs of hyperventilation, anxiety, or claustrophobia while wearing the SCBA. No breathing techniques were provided to any participant. Firefighter participants were aware of the purpose of the study but were not coached toward a particular breathing pattern.

After completion of the maximal test, participants returned to the lab on separate occasions to perform a submaximal graded exercise test (GXT) at 25%, 50%, and 70% $\dot{V}_{O_2max}$ on the cycle ergometer. Based on random assignment, participants completed the control condition (shorts, t-shirt, and athletic shoes) or the experimental condition where they wore a portion of a firefighters protective ensemble (heavy coat, fire resistant hood, and helmet) and SCBA. Participants were instructed to drink water equivalent to 1% of their mass in the 12 hours leading up to the study and to refrain from caffeine and exercise for 12 hours before the protocol. Upon arrival, the participant was weighed nude in a private room and was fitted with a Polar heart rate monitor.

During both protocols, the participant wore the SCBA facemask to ensure $ETCO_2$ was captured the same way in both conditions. A small sampling probe was introduced through the pliable nosecone of the facepiece approximately 2 cm in front of the participant's mouth and connected to a mass spectrometer (Perkin Elmer, Waltham, MA) to determine $ETCO_2$ which was used as an estimate of $PaCO_2$. The participant warmed up by pedaling for 2 minutes at 25 W. Participants were asked to pedal at 60 rpm for 15 minutes and consisted of three, consecutive five-minute, stages. Ergometer resistance for the three stages was set at 25%, 50%, and 70% of maximal effort based on the results of the maximal exercise test.

$ETCO_2$ was measured by the mass spectrometer continuously using data acquisition software (Acq*Knowledge* 4.0, Biopac Systems Inc, Goleta CA). Heart rate was obtained by telemetry (Polar Ectro, New Hyde Park, NY), and respiratory rate was calculated from the $ETCO_2$ tracing and recorded every minute during exercise. Perceived exertion was collected at the end of each 5-minute stage using the OMNI-cycle scale [14].

2.3. Statistical analyses

Data for men and women were combined due to the small *n* and to reflect firefighting scenarios. Participant demographics and morphometrics were compared by *t* test and represented by mean and standard deviation. The differences among groups and equipment (firefighter/nonfirefighter and control/SCBA, respectively) were examined during the maximal aerobic test for $\dot{V}_{O_2}$, heart rate, ventilation ($\dot{V}_E$), tidal volume, respiratory rate. Data at the three work rates (25, 50, 75% of $\dot{V}_{O_2max}$) during the GXT were checked for normality with a D'Agostino and Pearson Normality test and compared among groups and gear for heart rate, respiratory rate, and $ETCO_2$ with an analysis of variance conditioned by time and group combinations. A linear regression was performed for each group/variable collected during the maximal and GXTs. The line was extrapolated to the y-intercept to estimate resting heart rate, respiratory rate, and $ETCO_2$. Analyses were performed using SigmaStat 11.0 and graphed with SigmaPlot 11.0 (Systat Software, San Jose CA) and Prism 5.0f for Mac OS X (GraphPad Software, La Jolla CA).

3. Results

Ten firefighters and ten nonfirefighters completed all phases of the study. There were eight male and two female participants in each group. An eleventh firefighter completed one protocol visit and withdrew. There was no difference between control and firefighter groups in height, but the firefighters were heavier ($p = 0.003$) which resulted in a higher body mass index ($p = 0.002$) (Table 1). Firefighters were older than nonfirefighters ($p < 0.001$), but the relative $\dot{V}_{O_2max}$ did not differ between groups (Table 1).

All firefighter participants and nine control participants completed the entire 15-minutes graded exercise for both the facemask and SCBA conditions. One control participant only completed 14 minutes of the facemask condition and 12 minutes of the SCBA condition. The final recorded measurements for that participant were used in the analyses.

Table 1
Participant characteristics.

Participant type	Height (cm)	Mass (kg)	BMI	Age (yr)	$\dot{V}_{O_2max}$ (ml/kg/min)	Years of firefighting experience
Firefighters	177.2 ± 8.4	89.4 ± 10.4*	28.5 ± 3.2*	32.9 ± 7.6*	34.4 ± 6.6	11.7 ± 7.6
Controls	174.1 ± 8.1	73.4 ± 10.1	24.1 ± 1.9	20.8 ± 1.7	39.2 ± 7.9	–

* Groups are different, $p < 0.05$.
$N = 10$ per group. Data shown as mean ± SD.
BMI, body mass index; SD, standard deviation.

3.1. Maximal exercise test

Oxygen consumption during the maximal exercise test increased linearly as a function of work rate in both groups and was not different ($p = 0.843$). The average $\dot{V}_{O_2}$ was 0.94 ± 0.07 at 25% of $\dot{V}_{O_2max}$, 1.35 ± 0.08 at 50% of $\dot{V}_{O_2max}$, and 2.36 ± 0.18 L/min at 75% of $\dot{V}_{O_2max}$ (Table 2). Although no gear or facemasks were used during this test, firefighters had notable differences in respiratory responses to exercise when compared to control participants (Table 2). Expired $\dot{V}_E$ during the maximal test increased as a function of $\dot{V}_{O_2}$ 32.6 L/min body temeprature and pressure, saturated (BTPS) (intercept −6.65, $r^2 = 0.992$) for control participants and 26.38 L/min BTPS for firefighters (intercept −2.55, $r^2 = 0.994$) ($p = 0.024$). Breathing frequency increased as a function of $\dot{V}_E$ more in control participants than in firefighters (45%). Tidal volume increased as a function of $\dot{V}_E$, and was higher in firefighters (35%) than controls.

Heart rate during the maximal test increased as a function of $\dot{V}_{O_2}$ 50 bpm (intercept 56, $r^2 = 0.976$) for control participants and 43 bpm for firefighters (intercept 56, $r^2 = 0.976$) and were not different ($p = 0.079$). The $\dot{V}_{O_2}$ at the anaerobic threshold was 80% for control participants and 81% for firefighters of their respective $\dot{V}_{O_2max}$ determined during the maximal test.

3.2. Graded exercise test

$ETCO_2$ was not affected by work rate in either group for either condition (Fig. 1A). The $ETCO_2$ was higher in firefighters when compared to controls at all work rates ($p = 0.002$). Breathing with SCBA compared to the facemask alone resulted in a nonsignificant decrease in $ETCO_2$ in controls (4%) and firefighters (3%).

Respiratory rate increased linearly ($r = 0.97, 0.99, 0.98, 0.96$) as a function of the percentage of $\dot{V}_{O_2max}$ in both groups and conditions similarly (slope = 0.21, 0.22, 0.17, 0.17) (Fig. 1B). The respiratory rate was significantly higher in the control group in both the facemask (intercept = 15) and SCBA (intercept 17) conditions when compared to firefighters (intercept = 11 in both conditions) ($p = 0.004$). When breathing with SCBA, control participants had higher respiratory rates ($p = 0.01$). Firefighter participants did not significantly increase breathing frequency when using SCBA ($p = 0.18$) compared to the facemask alone, and their values were less than the control participants ($p = 0.005$).

Heart rate increased linearly as a function of work rate for controls and firefighters in the facemask and SCBA conditions ($r = 0.99$, 0.99, 0.99, 0.99, respectively) (Fig. 1C). However, the heart rate of the firefighter group was lower than the control group for both the facemask and SCBA conditions ($p = 0.032$). SCBA significantly increased heart rate compared to the facemask condition by 9% in control participants ($p = 0.04$) and 11% in firefighters ($p = 0.01$).

Cardiorespiratory responses during the GXT differed from the maximal test at comparable workloads (Table 2). In general, heart rates were higher in control participants at lower intensities both when wearing the facemask and when using the full SCBA. Firefighters had higher heart rates, compared to the maximal exercise test, in the SCBA condition. Both firefighters and control participants had lower respiratory rates in the facemask condition compared to the maximal test, but only firefighter participants had lower respiratory rates during the SCBA condition.

4. Discussion

The primary result of the present study was that firefighters had significantly higher $ETCO_2$ values than control participants when breathing on a mouthpiece ($\dot{V}_{O_2max}$ test), breathing apparatus facemask, and SCBA. In addition, breathing from an SCBA decreased

Table 2
Data from the maximal and GXT tests at comparable workloads.

Variable	Intensity	Maximal test		Graded exercise test			
		Control participants	Firefighters	Control participants		Firefighters	
				Facemask	SCBA	Facemask	SCBA
$\dot{V}_{O_2max}$	25% max	0.87 ± 0.11	0.94 ± 0.07				
	50% max	1.4 ± 0.1	1.4 ± 0.1				
	70% max	2.4 ± 0.2	2.4 ± 0.2				
$\dot{V}_E$	25% max	23.3 ± 2.7	22.4 ± 3.0				
	50% max	36.6 ± 4.0	32.4 ± 6.9				
	70% max	70.3 ± 20.2	61.0 ± 14.6				
TV	25% max	1.05 ± 0.21	1.32 ± 0.58				
	50% max	1.36 ± 0.22	1.47 ± 0.44				
	70% max	1.95 ± 0.17	2.10 ± 0.51				
RR	25% max	22 ± 6	17 ± 5	16 ± 7	23 ± 6	16 ± 6	16 ± 5
	50% max	27 ± 5	22 ± 6	18 ± 7*	27 ± 7	18 ± 6*	19 ± 5*
	70% max	36 ± 6	29 ± 9	24 ± 8*	34 ± 10	24 ± 5*	25 ± 7*
HR	25% max	98 ± 13	96 ± 10	117 ± 13*,†	127 ± 16*,†	107 ± 11	119 ± 14*,†
	50% max	126 ± 11	117 ± 13	140 ± 11†	149 ± 18*,†	126 ± 14	140 ± 16†
	70% max	170 ± 16	156 ± 16	164 ± 12	173 ± 15	149 ± 15*	163 ± 17

* Different from control participant maximal test.
† Different from firefighter participants maximal test.
All groups and variables increased with increasing intensity ($p < 0.001$).
GXT, graded exercise test; HR, heart rate (bpm); RR, respiratory rate (breaths per minute); SCBA, self-contained breathing apparatus; SD, standard deviation; TV, tidal volume (L); $\dot{V}_E$ ventilation (L/min); $\dot{V}_{O_2max}$, maximal oxygen consumption.
Data shown as mean ± SD.

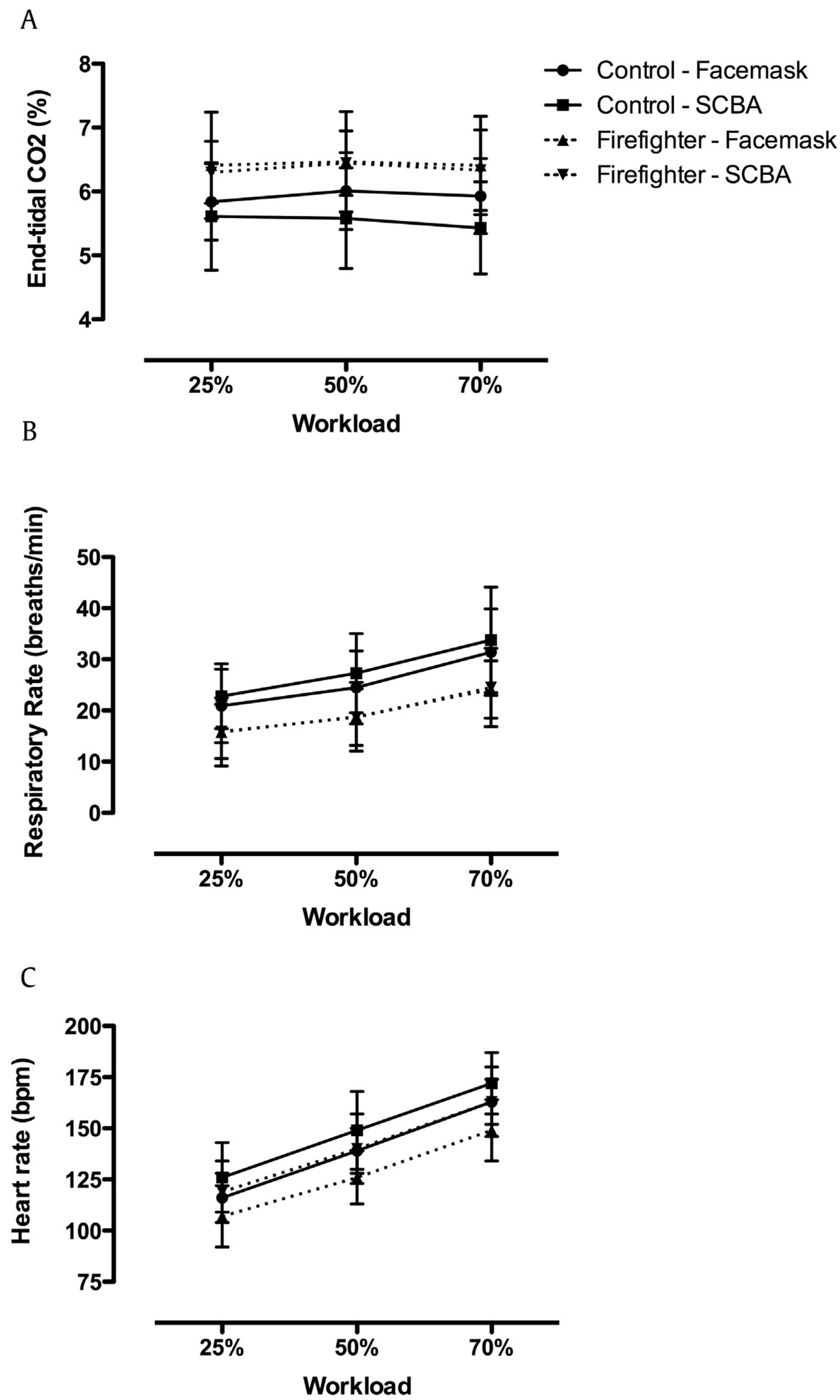

Fig. 1. The end-tidal CO_2, respiratory rate, and heart rate cycle exercise at 25%, 50%, and 70% of $\dot{V}_{O_2max}$. (A) End-tidal CO_2. (B) Respiratory rate. (C) Heart rate cycle exercise. Control (nonfirefighter) participants are represented by solid lines and firefighter participants by dashed lines. Circles = control participants-facemask condition, squares = control participants-SCBA condition, upright triangles = firefighter participants-facemask condition, upside-down triangles = firefighter participants-SCBA condition.
SCBA, self-contained breathing apparatus; $\dot{V}_{O_2max}$, maximal oxygen consumption.

$ETCO_2$ in control participants, but not in firefighters. During the $\dot{V}_{O_2max}$ test, the $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ were not different between control participants and firefighters; therefore, the differences in $ETCO_2$ during the GXT are likely not due to differences in $\dot{V}_{CO_2}$ and must be due to alveolar ventilation as reflected by $\dot{V}_E$. To protect the integrity of the facemask, $\dot{V}_E$ was not measured during the GXT. However, in the SCBA condition, the respiratory rate was lower in the firefighters compared to control participants. Supporting the lower $\dot{V}_E$, as suggested by the lower respiratory rate among firefighters, the $\dot{V}_E$ during the maximal test was lower at all time points in firefighters compared to control participants. These data suggest that firefighter's control of ventilation is depressed during exercise with SCBA and further suggests a depressed chemosensitivity to arterial CO_2.

Breathing with a full facemask and with SCBA may change the breathing pattern compared to breathing from a mouthpiece or free breathing [7]. This is seen in the present report for the control participants. It is known that breathing from SCBA increases the work of breathing, which alters breathing pattern. Previous studies have suggested that firefighters change their breathing pattern when using SCBA due to the increased work of breathing [1,3,11,15]. However, the firefighters in the present study also ventilated less during the maximal test, and their respiratory rate was similarly lower on the GXT in both conditions when compared to control participants. This suggests that the firefighter's control of ventilation changed during all three testing conditions and was not acutely due to the work of breathing from SCBA. The reduced ventilator pattern likely caused the increased $ETCO_2$ and arterial CO_2.

In support of the present data are previous data from our lab on breathing underwater with scuba where the work of breathing (measured as the area under the esophageal pressure and volume loop) is higher than on land [8–10]. Divers hypoventilate similarly to the firefighters in this study, and there is a similar increase in $ETCO_2$ [8–10]. In addition to laboratory studies, other studies have shown that active divers have reduced ventilation and increased $ETCO_2$ at rest and during exercise [6]. For individuals who cannot tolerate higher CO_2, protecting normal arterial CO_2 by increasing $\dot{V}_E$ leads to respiratory muscle fatigue, while having a lower $\dot{V}_E$ and allowing arterial CO_2 to increase may lead to dyspnea [7–9].

Intentional hypoventilation to conserve breathing gas could be understandable during periods of SCBA breathing. However, the firefighters in the present study demonstrated this adaptation during breathing on mouthpiece where there was not an increased work of breathing. To explain this, it is possible that their training with SCBA has altered their chemosensitivity to conserve $\dot{V}_E$ and allowed them to tolerate elevated arterial CO_2, as seen in this study. It has been shown that chemoreceptors exposed to elevated CO_2 become less sensitive and reset the exposure level where the brain would respond by increasing ventilation [16]. Although we are unaware of studies of CO_2 sensitivity in firefighters, these observations have been seen in scuba divers [17]. Based on the depressed $\dot{V}_E$ and elevated $ETCO_2$ seen among firefighters in the present study, it is reasonable to speculate that firefighters have depressed CO_2 sensitivity that results in elevated $ETCO_2$ during exercise, irrespective of the breathing gear. Although the acute elevation of CO_2 seen in the firefighter participants may not increase risk, chronic elevation may increase the risk of diseases, such as heart disease.

There are limitations to the interpretation of these data. Participants were not matched between groups resulting in the firefighter group being older and heavier than the nonfirefighters. Future studies should consider potential interactions of age, fitness, and body habitus on ventilatory responses when using breathing apparatus.

In conclusion, the present study showed that when compared to control participants, firefighters hypoventilate during a maximal and GXTs. The hypoventilation resulted in increased $ETCO_2$, and presumably increased arterial CO_2, during exertion. Firefighter $ETCO_2$ was not affected by using SCBA compared to the facemask alone while control participants lowered their $ETCO_2$ by hyperventilating. It is proposed that firefighters have altered CO_2 sensitivity due to voluntary hypoventilation during training and work. Confirmation of low CO_2 sensitivity and the consequence of this on performance and long-term health remain to be determined.

Conflicts of interest

None declared.

Funding

No extramural funding was obtained.

Ethical approval

This study was approved by the University at Buffalo Institutional Review Board.

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