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Physiological Evaluation of Air-Fed Ensembles

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ABSTRACT

The goal of this study was to evaluate the respiratory and metabolic stresses of air-fed ensembles used by workers in the nuclear, chemical, and pharmaceutical industries during rest, low-, and moderate-intensity treadmill exercise. Fourteen men and six women wore two different air-fed ensembles (AFE-1 and AFE-2) and one two-piece supplied-air respirator (SA) at rest (REST) and while walking for 6 min at oxygen consumption ($\dot{V}O_2$) rates of 1.0 (LOW) and 2.0 l min^{-1} (MOD). Inhaled CO_2 ($FICO_2$), inhaled O_2 (FIO_2), pressure, and temperature were measured continuously breath-by-breath. For both LOW and MOD, $FICO_2$ was significantly lower ($\boldsymbol{P} < 0.03$) and FIO_2 was significantly greater ($\boldsymbol{P} < 0.008$) for SA compared with AFE-1 and AFE-2 in women, while in men, similar trends were observed. Significantly lower $FICO_2$ ($\boldsymbol{P} < 0.009$) and significantly greater FIO_2 ($\boldsymbol{P} < 0.04$) were consistently observed in AFE-1 compared with AFE-2 in men during LOW and MOD. For both men and women, average $FICO_2$ exceeded 2.0% in AFE-2 during MOD. During LOW and MOD, average FIO_2 in AFE-1 and AFE-2 dropped <19.5% in men and women. For men and women, average inhalation pressures (PIave) were significantly greater in both air-fed ensembles than SA ($\boldsymbol{P} < 0.001$) during REST, LOW, and MOD. Inhaled gas temperature was significantly lower in SA than in either air-fed ensemble ($\boldsymbol{P} < 0.001$). When the air supply was shut off during walking, the time taken for minimum $FICO_2$ to reach 2.0% was <38 s for all three ensembles in both men and women, an observation that has implications for the design of emergency escape protocols for air-fed ensemble wearers. Results show that inhaled gas concentrations may reach physiologically stressful levels in air-fed ensembles during moderate-intensity treadmill walking.

KEYWORDS: air-fed ensemble; oxygen consumption; protective suits; respirators; women

INTRODUCTION

An air-fed ensemble is an encapsulating suit with an external source of breathing air, which provides respiratory protection without the use of a tight-fitting face piece. Designed to be a full-body garment with integrated respiratory protection the air-fed ensemble must provide a flow of breathable air to the wearer and should maintain a positive pressure in the suit in relation to the outside environment during both inhalation and exhalation. In these ensembles, Grade D breathing gas is supplied to the suit at a manufacturer-recommended minimum flow rate at an inlet valve near the wearer's waist and is vented through valves on the head, back, and various other locations.

In emergency escape situations, air-fed ensemble wearers must disconnect their airlines, which can cause an increase in inhaled CO_2 and a decrease in inhaled O_2 concentrations. There is no estimate of the number of workers who wear air-fed ensembles; however, they are currently worn by government employees at the Department of Defense, Department of Energy, and the Centers for Disease Control and Prevention, as well as by workers in the nuclear, chemical, and pharmaceutical industries. The National Institute for Occupational Safety and Health (NIOSH, 2012) has proposed a concept paper for the certification of air-fed ensembles, which will include an evaluation of inhaled O_2 and CO_2 concentrations during human testing.

Research on the physiological burden of wearing air-fed ensembles, including the measurement of inhaled O_2 and CO_2 concentrations, is scarce. Crockford (1968) first reported on 'positive pressure suits', industrial suits designed to operate at a slight positive pressure of 5 cmH_2O. He concluded that during moderate-intensity exercise, an airflow of 5 ft^3 min^{-1} (141.5 l min^{-1}) would be required to maintain a respirable atmosphere with <2.0% inhaled CO_2 and >19% inhaled O_2 concentrations. Generalized requirements for a 'supplied-air bubble suit' for use in the nuclear industry were later outlined by Phillabaum and Adams (1974). A minimum airflow of 6 ft^3 min^{-1} (~170 l min^{-1}) into the suit was recommended, and the authors estimated that if the air supply failed, there would be 3–4 min of breathable air within the suit. It is unclear to what extent these early suits resemble modern air-fed ensembles, most of which have minimum airflow requirements of 250 l min^{-1}. Raven *et al.* (1979) published a review of the stresses imposed by PVC supplied-air suits, which focused almost exclusively on the heat stress incurred while wearing the suits in a hot ambient environment. An air flow of 140–980 l min^{-1}, depending on the ambient temperature, was recommended in order to provide sufficient evaporative cooling capacity. Since that review article, the only newer, published research available is a fit factor study of air-supplied blouses (Poirier, 1999). Inhaled gases were measured at the mouth, and inhaled CO_2 concentrations remained <2.0% while inhaled O_2 concentrations remained >19% when subjects ran in place for 2 min.

While previous research on wearing air-fed ensembles is rare, there is a significant body of literature in which the inhaled gas concentrations provided by supplied-air respirators (SAs), powered air-purifying respirators, or positive-pressure self-contained breathing apparatus (SCBA) were investigated. The most frequently used, generally accepted method for accurately measuring inhaled O_2 and CO_2 concentrations within respirator face pieces was reported by Dahlback and Fallhagen (1987). The technique has since been used to investigate inhaled gas concentrations within various types of respirators, including SCBA face pieces with and without oronasal cups (Warkander and Lundgren, 1995; Turner *et al.*, 1996). The measurement technique uses a capillary sampling tube, positioned between the nostrils and mouth, to draw inhaled and exhaled gases into fast response O_2 and CO_2 analyzers at a high flow rate. A second sample line is used to measure pressure at the same location, allowing for the precise determination of inhalation and exhalation periods. This technique has enabled the estimation of dead space within SCBA face pieces during actual use, providing evidence that dead space is relative, not fixed, and dependent on minute ventilation (Warkander and Lundgren, 1995). Data collected using this technique demonstrate that it is not sufficient to test air-supplied respirators at a single, resting minute ventilation; inhaled CO_2 concentrations may be greater at a minute ventilation produced during moderate- or high-intensity exercise than at a resting minute ventilation. Current NIOSH failure criteria for average inhaled CO_2 and average inhaled O_2 are >1.0 and <19.5%, respectively, for a 4-h open-circuit respirator (Code of Federal Regulations, Title 42, Part 84, 2004). The intensity of activities performed by workers wearing air-fed ensembles ranges from light (inspecting and calibrating equipment, seated laboratory bench work with the hands) to moderate (equipment repair, light material handling, walking while carrying tools) (Electric Power Research Institute, 1998). Decontamination work, which would require the use of SCBA with fully encapsulating suits instead of air-fed ensembles, would fall into the heavy-intensity category. Therefore, the appropriate exercise intensities for this study of air-fed ensembles are light and moderate. The goal of this study was to build on the research and measurement techniques described above in order to evaluate the metabolic and respiratory burden on wearers of air-fed ensembles at rest and during low- and moderate-intensity exercise on a treadmill.

METHODS

This study was approved by the NIOSH Human Subjects Review Board, and all subjects provided written informed consent. Fourteen men and six women between the ages of 18 and 44 who had prior experience wearing respirators completed baseline testing (Table 1) to determine the speed and grade required to elicit oxygen consumption ($\dot{V}O_2$) levels of 1.0 (LOW) and 2.0 (MOD) $l\ min^{-1}$ using the Cosmed K4b^2 Portable Metabolic Measurement System (Rome, Italy) functioning in breath-by-breath mode. To ensure that all women could complete the walking trials, investigators set the target $\dot{V}O_2$ levels at 0.85 (LOW) and 1.7 (MOD) $l\ min^{-1}$. It has been shown that subjects reach steady-state heart rate (HR), O_2 consumption, CO_2 production, and minute ventilation after 5–6 min of steady-state walking at low and moderate intensities even if inhaled CO_2 concentration is somewhat elevated (Jacobi *et al.*, 1987). Data from minute six of LOW and MOD baseline treadmill testing was used for setting speed and grade for ensemble testing. A nude body weight was obtained for each subject. To account for a typical range of body weights among a sample of human subjects, each individual subject was placed in one of three separate body weight categories, each with its own speed/grade combination selected to elicit a $\dot{V}O_2$ within 5% of the desired value (Sinkule *et al.*, 2002). For men, the categories were (i) 82–90 kg, (ii) 90.5–112 kg, and (iii) 112.5–125 kg. For women,

Table 1. Subject characteristics and baseline testing metabolic data (mean ± SD)

Variable	Men (n = 14)	Women (n = 6)
Age (years)	31.7 ± 7.9	26.7 ± 4.4
Body weight (kg)	90.38 ± 18.52	66.45 ± 4.55
Height (cm)	180.1 ± 6.7	161.0 ± 6.1
VO_2max		
Estimated, $l\ min^{-1}$, STPD	3.7 ± 0.7	2.5 ± 0.4
Estimated, $ml\ kg^{-1}\ min^{-1}$, STPD	41.0 ± 8.4	37.0 ± 6.2
VO_2 ($l\ min^{-1}$, STPD)		
REST (% VO_2max)	0.36 ± 0.07 (10%)	0.30 ± 0.04 (12%)
LOW (% VO_2max)	1.09 ± 0.10 (30%)	0.93 ± 0.09 (38%)
MOD (% VO_2max)	1.91 ± 0.06 (52%)	1.62 ± 0.11 (66%)
VE ($l\ min^{-1}$, BTPS)		
REST	13.0 ± 2.7	12.3 ± 1.2
LOW	28.7 ± 2.9	28.1 ± 3.7
MOD	47.7 ± 4.9	49.7 ± 4.8
HR (beats per minute)		
REST	74 ± 7	73 ± 11
LOW	92 ± 11	103 ± 13
MOD	120 ± 15	146 ± 15

VO_2max, maximal oxygen consumption; VO_2, absolute oxygen consumption; VE, minute ventilation; STPD, standard temperature, barometric pressure, dry; BTPS, body temperature, ambient barometric pressure, saturated.

the categories were (i) 61–78 kg, (ii) 78.5–102 kg, and (iii) 102.5–110 kg.

Subjects then wore two different air-fed ensembles (AFE-1 and AFE-2) from different manufacturers and one two-piece (combination of loose-fitting hood and containment suit) SA from a third manufacturer while standing still for 6 min (REST) and while walking for 6 min at LOW and 6 min at MOD (Fig. 1). Ensemble sizes were selected according to manufacturers' height and weight recommendations, and ensembles were worn in a counterbalanced order to control for order effects. Grade D breathing gas (Draeger Safety, Pittsburgh, PA, USA) was supplied to the air-fed ensembles and SA at the minimum manufacturer-recommended pounds per square inch (PSI) setting. The PSI settings were similar for all three respirators. Inhaled O_2 and CO_2 concentrations, pressure, and temperature were measured continuously breath-by-breath (60 Hz) at the mouth within an open oral-nasal nose cup 1–2 cm in front of the upper lip. As Dahlback and Fallhagen (1987) described, while seated subjects wore the nose cup, average inhaled CO_2 was ≤0.05% and average inhaled O_2 was ≥20.88%, demonstrating that the breath-by-breath system gave unobstructed, accurate measurements that were not different from those previously reported using sample lines that are taped in place on the face. Laboratory barometric pressure ranged from 734 to 745 mmHg, and room temperature ranged from 19.5 to 22.0°C (~50% relative humidity). Fast response O_2 and CO_2 analyzers (AEI Technologies, Pittsburgh, PA, USA) were used to make gas measurements, PhysiTemp thermocouples (Clifton, NJ, USA) were used to measure temperature, and a Setra 2239 manometer with a sensitivity of ±5 cm H_2O (Boxborough, MA, USA) was used to measure pressure at the mouth. Prior to each test, all instruments were calibrated, and response and transport times were measured for the gas analyzers. HR was continuously measured with a pulse oximeter (GE Healthcare, Waukesha, WI, USA). At the end of each 18-min ensemble test (6-min REST, 6-min LOW, and 6-min MOD), the air supply to each ensemble was shut off while the subject continued to walk on a level treadmill, and the time taken for minimum inhaled CO_2 concentration to reach 2.0% or maximum O_2 to drop <19% was measured. When these gas concentration limits were observed, the air supply was immediately restarted, and subjects stopped walking. Subjects rested while seated with the ensemble removed for ~10 min after each 18-min ensemble test, and it took ~10 min to don each ensemble. Including baseline and ensemble testing, each subject's total test time was ~130 min. To examine the effect on body weight of a prolonged period of exercising while wearing the three ensembles, nude body weight was measured again after each subject completed all three ensemble tests. All baseline and ensemble tests were completed in one visit.

Data were processed into individual breaths using LabView 8.2 software (National Instruments, Austin, TX, USA). Average inhaled O_2 and CO_2

1 A male subject walks on treadmill wearing (left to right) AFE-1, AFE-2, and SA.

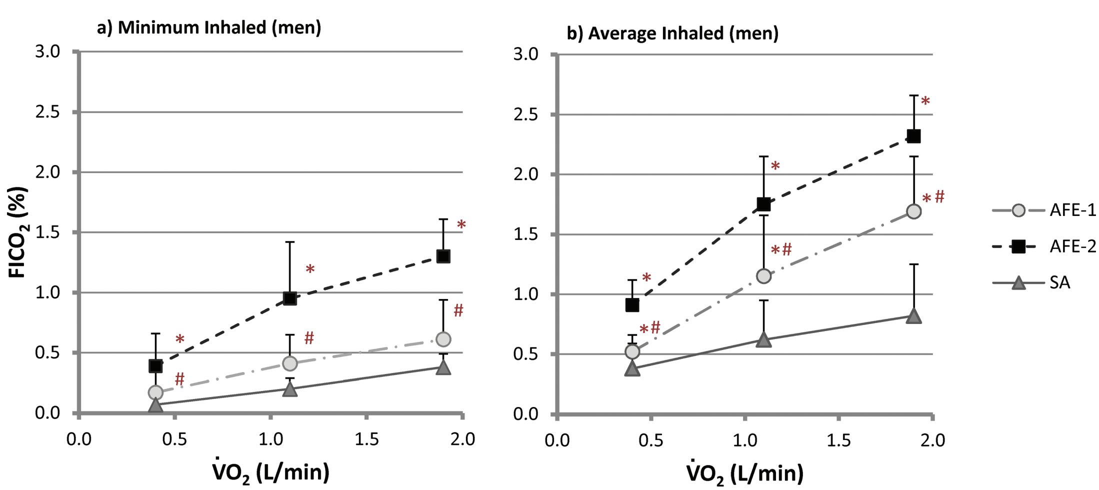
concentrations were calculated by integration over time. An average of data from the last 30 s of minute six for each period (REST, LOW, and MOD) was used for analysis. Men's and women's data were analyzed separately, and, following testing for normal distributions ($P > 0.05$) and equal variances ($P > 0.05$), comparisons of the effect of ensemble type on dependent variables were made using repeated measures analysis of variance (Systat Software, Inc., San Jose, CA, USA).

RESULTS

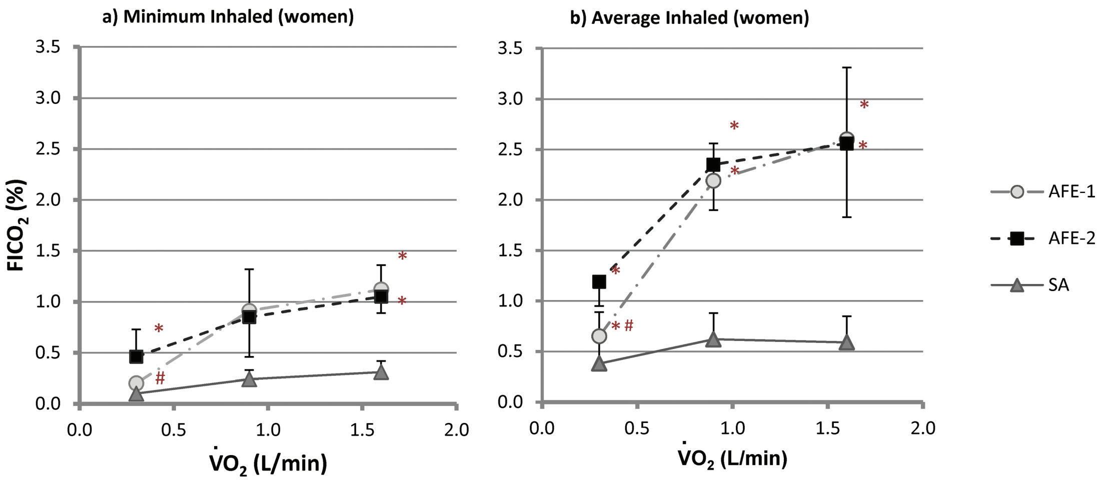
Subject characteristics, as well as control metabolic data, are shown in Table 1. Six men were in the lowest body weight category, three were from the middle category, and five were from the highest category. Four women were from the lowest body weight group, and two were from the middle group. For both men and women, control $\dot{V}O_2$ was within 10% of target for LOW and 5% of target for MOD. Based on an estimation of maximal $\dot{V}O_2$ (McArdle *et al.*, 2010), the LOW work rate was ~30% of maximum for men (38% for women), and MOD was 52% of maximum for men (66% for women).

Men's ($n = 14$) average and minimum inhaled CO_2 concentrations ($FICO_2$) during AFE-1, AFE-2, and SA testing at REST, LOW, and MOD are shown in Fig. 2. Minimum $FICO_2$ peaked at 1.3%, and average $FICO_2$ reached 2.3% during MOD for AFE-2. Across all metabolic rates, both minimum and average $FICO_2$ were significantly greater in AFE-2 than in AFE-1 ($P < 0.009$) and SA ($P < 0.001$). Average $FICO_2$ was significantly greater in AFE-1 than in SA ($P < 0.001$). Figure 3 shows women's ($n = 6$) average and minimum $FICO_2$ during ensemble testing. Minimum $FICO_2$ reached 1.1% for AFE-1 and 1.0% for AFE-2 during MOD, while average $FICO_2$ peaked at 2.6% for AFE-1 and 2.4% for AFE-2. Minimum $FICO_2$ was significantly greater ($P < 0.03$) than SA for both air-fed ensembles during MOD. Average $FICO_2$ was significantly greater ($P < 0.03$) than SA for both air-fed ensembles during REST, LOW, and MOD.

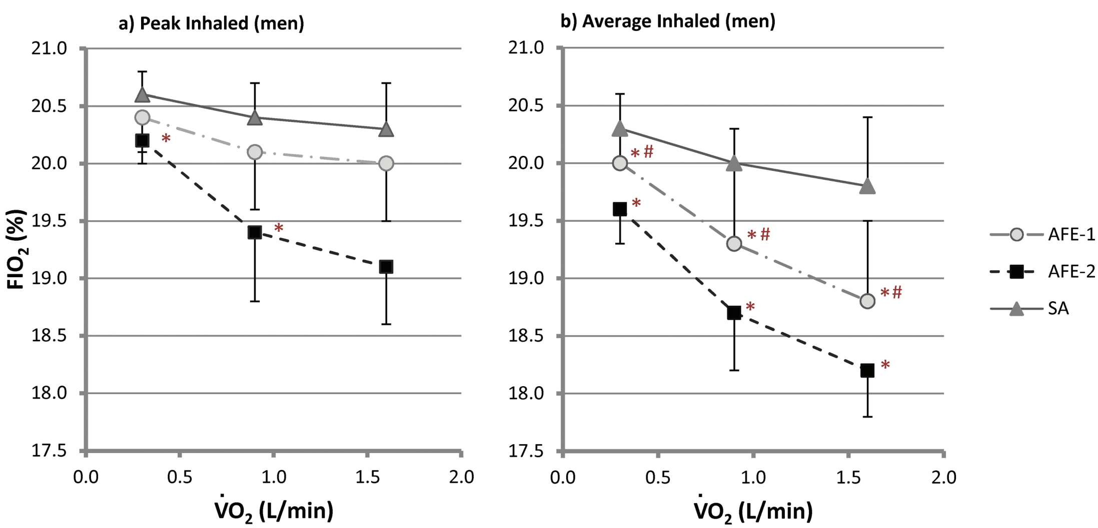
Men's ($n = 14$) average and peak inhaled O_2 concentrations (FIO_2) during AFE-1, AFE-2, and SA treadmill testing are provided in Fig. 4. Peak FIO_2 dropped to 19.1% for AFE-2 during MOD, while average FIO_2 reached lows of 18.8% (AFE-1) and 18.2% (AFE-2) during MOD. Peak and average FIO_2 were significantly lower ($P < 0.008$) in AFE-2 than SA across all metabolic rates. Average FIO_2 in AFE-1 was significantly lower than SA ($P < 0.008$) and significantly greater than AFE-2 ($P < 0.04$) across all metabolic rates. Women's ($n = 6$) average and peak FIO_2 during air-fed ensemble testing are shown in Fig. 5. Peak FIO_2 reached 19.6% for both AFE-1 and AFE-2 during MOD. Average FIO_2 fell to 18.0% for AFE-1 and 18.2% for AFE-2 during MOD. Peak FIO_2 was significantly lower ($P < 0.008$) in both air-fed ensembles than SA during LOW and MOD, while average FIO_2



2 Men's minimum (a) and average (b) inhaled CO_2 concentrations ($FICO_2$) versus oxygen consumption ($\dot{V}O_2$) for each work rate (mean ± SD). * denotes significantly different ($P < 0.001$) from SA; # denotes significantly different ($P < 0.009$) from AFE-2.



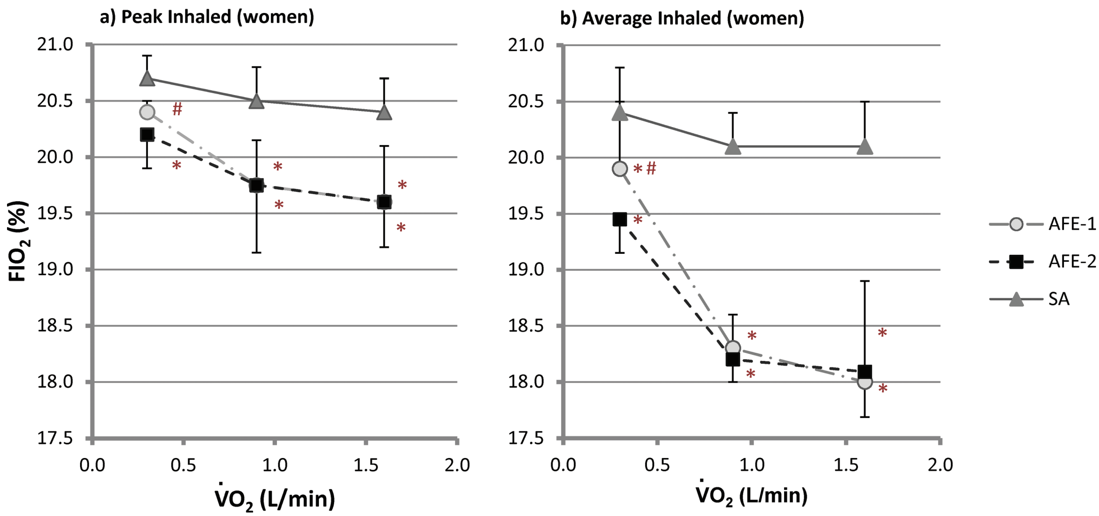
3 Women's minimum (a) and average (b) inhaled CO_2 concentrations ($FICO_2$) versus oxygen consumption ($\dot{V}O_2$) for each work rate (mean ± SD). * denotes significantly different ($P < 0.03$) from SA; # denotes significantly different ($P < 0.03$) from AFE-2.



4 Men's peak (a) and average (b) inhaled O_2 concentrations (FIO_2) versus oxygen consumption ($\dot{V}O_2$) for each work rate (mean ± SD). * denotes significantly different ($P < 0.008$) from SA; # denotes significantly different ($P < 0.04$) from AFE-2.

was significantly lower ($P < 0.008$) in both air-fed ensembles than SA during REST, LOW, and MOD. At rest, both peak and average FIO_2 for AFE-1 were significantly greater ($P < 0.008$) than for AFE-2.

Men's mean pressure, temperature, and HR data are presented in Table 2, and women's data are shown in Table 3. The following statistically significant differences were found for both men and women. For AFE-1, average exhalation pressures (PEave) and average inhalation pressures (PIave) were significantly greater than SA ($P < 0.001$) and AFE-2 ($P < 0.05$) during REST, LOW, and MOD. For AFE-2, PIave was significantly greater than SA ($P < 0.001$) during REST, LOW, and MOD. For both AFE-1 and AFE-2, end inhalation temperatures were significantly greater than SA ($P < 0.001$) during REST, LOW, and MOD. There were no significant differences in HR among AFE-1, AFE-2, and SA for any metabolic rate.



5 Women's peak (a) and average (b) inhaled O_2 concentrations (FIO_2) versus oxygen consumption ($\dot{V}O_2$) for each work rate (mean ± SD). * denotes significantly different ($P < 0.008$) from SA; # denotes significantly different ($P < 0.001$) from AFE-2.

Table 2. Men's pressure, temperature, and HR results ($n = 14$) for AFE-1, AFE-2, and SA (mean ± SD)

Model	Work rate	PEave (mmH_2O)	PIave (mmH_2O)	End inhalation temperature (°C)	HR (beats per minute)
AFE-1	REST	14 ± 2[a,b]	12 ± 2[a,b]	25.2 ± 1.3[a]	91 ± 14
	LOW	14 ± 2[a,b]	9 ± 3[a,b]	25.9 ± 0.8[a,b]	115 ± 9
	MOD	15 ± 3[a,b]	8 ± 2[a,b]	26.3 ± 1.2[a,b]	138 ± 19
AFE-2	REST	4 ± 1[a]	4 ± 1[a]	25.5 ± 1.3[a]	90 ± 14
	LOW	5 ± 1	2 ± 1[a]	26.9 ± 0.7[a]	112 ± 14
	MOD	7 ± 2	0 ± 1[a]	27.3 ± 0.8[a]	138 ± 20
SA	REST	3 ± 2	1 ± 1	22.3 ± 1.4	92 ± 14
	LOW	5 ± 3	1 ± 2	22.8 ± 1.6	111 ± 12
	MOD	7 ± 3	−1 ± 2	23.2 ± 1.4	139 ± 19

PEave, average exhalation pressure at mouth; PIave, average inhalation pressure at mouth.
[a]Denotes significantly different ($P < 0.001$) from SA.
[b]Denotes significantly different ($P < 0.05$) from AFE-2.

Table 4 shows ensemble weights, time to reach 2.0% minimum $FICO_2$ after shutting off the flow of breathing gas, and mean loss in body weight during control, AFE-1, AFE-2, and SA testing for men and women. The slightly greater weight of SA is due to its belt/hose assembly, which is worn on the torso. For each respirator ensemble, time to reach 2.0% minimum $FICO_2$ after shutting off the air flow was between 29 and 38 s; the time was ~3–8 s shorter for women than for men. The loss in body weight during all testing, including control testing, was almost equal for men (0.46 kg) and women (0.44 kg) (Table 4). The total time between nude body weight measurements was ~130 min, with subjects walking or standing for 72 min and wearing the three protective ensembles for ~54 min of that time period.

Table 3. Women's pressure, temperature, and HR results ($n = 6$) for AFE-1, AFE-2, and SA (mean ± SD)

Model	Work rate	PEave (mmH_2O)	PIave (mmH_2O)	End inhalation temperature (°C)	HR (beats per minute)
AFE-1	REST	14 ± 1[a,b]	12 ± 2[a,b]	25.1 ± 0.5[a]	98 ± 10
	LOW	13 ± 2[a,b]	10 ± 1[a,b]	26.6 ± 0.4[a]	122 ± 14
	MOD	14 ± 1[a,b]	9 ± 3[a,b]	27.6 ± 0.8[a,b]	162 ± 10
AFE-2	REST	5 ± 2[a]	4 ± 3[a]	24.2 ± 0.5[a]	95 ± 14
	LOW	6 ± 1	3 ± 1[a]	25.7 ± 0.7[a]	125 ± 11
	MOD	7 ± 1	2 ± 2[a]	26.1 ± 0.5[a]	163 ± 8
SA	REST	2 ± 1	1 ± 1	21.7 ± 1.3	94 ± 15
	LOW	3 ± 1	0 ± 0	22.1 ± 0.8	129 ± 11
	MOD	5 ± 2	−2 ± 1	22.7 ± 0.9	165 ± 12

PEave, average exhalation pressure at mouth; PIave, average inhalation pressure at mouth.
[a]Denotes significantly different ($P < 0.001$) from SA.
[b]Denotes significantly different ($P < 0.05$) from AFE-2.

Table 4. Ensemble weights, time to reach 2.0% minimum $FICO_2$ after shutoff of breathing gas, and mean loss in body weight for men and women (mean ± SD)

Variable	Men ($n = 14$)	Women ($n = 6$)
Ensemble weight (kg)		
AFE-1	1.72 ± 0.14	1.54 ± 0.12
AFE-2	1.49 ± 0.12	1.26 ± 0.11
SA	1.96 ± 0.15	1.91 ± 0.13
Time to 2% minimum $FICO_2$ (s)		
AFE-1	37.8 ± 11.1	30.0 ± 9.4
AFE-2	32.5 ± 9.6	30.0 ± 9.4
SA	33.6 ± 10.7	28.8 ± 11.8
Loss in body weight (kg)	0.46 ± 0.19	0.44 ± 0.19

While there were no significant differences in HR among ensembles, the additional weight and movement effects of the three protective ensembles had a substantial impact on HR compared with baseline testing. For men, mean HR was 23, 23, and 15% greater with the ensembles versus the baseline test without an ensemble for REST, LOW, and MOD, respectively. For women, mean HR was 29, 21, and 12% greater with the ensembles versus the baseline for REST, LOW, and MOD, respectively.

DISCUSSION

SAs typically supply breathing gas only to the head of the wearer, while air-fed ensembles' whole-body encapsulation results in much larger dead space volumes and, as confirmed in the present study, lower inhaled O_2 and greater CO_2 concentrations. The findings of the present study support the conclusion that these breathing gas concentrations rarely reach stressful levels in wearers of air-fed ensembles during rest while seated or standing. However, during LOW and MOD, gas concentrations in the air-fed ensembles approached the NIOSH limits for average inhaled CO_2 and average inhaled O_2, which are >1.0 and <19.5%, respectively, for a 4-h open-circuit respirator (Code of Federal Regulations, Title 42, Part 84, 2004). Significantly greater FIO_2 and lower $FICO_2$ values were consistently observed in AFE-1 compared with AFE-2 in men only. AFE-1 has tubing that directs air to the arms and legs, which may account for the observed differences in men. The arm and leg tubing may assist with flushing the dead space in the ensemble extremities; however, this design feature did not produce the same effects in women, possibly due to women's smaller body volume relative to the AFE-2 volume. While gender results could not be compared directly due to differing absolute metabolic rates, a trend was apparent: greater average $FICO_2$ and lower average FIO_2 concentrations were seen in women's air-fed ensemble results compared with men's. This trend may be due to ensemble sizing that does not adequately match the body volumes of women users.

Slightly negative average inhalation pressures were observed in SA during MOD; however, these measurements were made at the mouth (not at a potential leak site for this hood) and may not represent a significant risk of inward leakage for this respirator. The significantly 3–4°C greater inhalation temperatures observed in AFE-1 and AFE-2 compared with SA were the result of the exposure of the breathing gas to the wearer's warm body surface. However, in a neutral ambient environment, the inhalation temperatures observed in the two air-fed ensembles should not cause any significant degree of heat strain for the wearer. The weight loss measured during the entire 2-h test period represents a sweat loss of approximately half a liter. Mild dehydration may lead to decrements in exercise performance, and it is generally recommended that workers drink 16 ounces of fluid for every pound of weight they lose (Sawka *et al.*, 2007). Use of these ensembles for a prolonged duration may necessitate that the wearers periodically rehydrate.

The mean times for minimum inhaled CO_2 concentrations to increase to 2% after the air supply was shut off were all <40 s. During these short periods, the ensembles collapsed around the subjects and the visors fogged, making it difficult for the subjects to continue to walk. For these reasons, emergency escape protocols for wearers of air-fed ensembles may need to include a portable supply of breathing gas for use during egress.

Limitations of study

A potential limitation of the study is in the ensemble selection: the two ensemble models that were tested may not be representative of all air-fed ensemble models. Another potential limitation was the somewhat small sample size of women participants.

CONCLUSIONS

The findings of the current study expand the limited body of literature on the physiologic burden of wearing air-fed ensembles, including the measurement of inhaled O_2 and CO_2 concentrations during low- and moderate-intensity exercise. In general, $FICO_2$ trended lower, FIO_2 trended greater, and inhaled gas temperature was lower in SA than in either air-fed ensemble. Significantly greater FIO_2 and lower $FICO_2$ were consistently observed in AFE-1 compared with AFE-2 in men, possibly due to differences in ensemble design. For both men and women, average $FICO_2$ concentration was ≥2.0% during MOD for AFE-2, and average FIO_2 dropped <19.5% during LOW and MOD for both AFE-1 and AFE-2. These observed $FICO_2$ and FIO_2 concentrations are instructive for the development of criteria for the certification of air-fed ensembles. When the air supply was shut off during walking, the time taken for minimum $FICO_2$ to reach 2.0% was <38 s for all three ensembles, an observation that may have implications for the design of emergency escape procedures for air-fed ensemble wearers.

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DISCLAIMER

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of company names or products does not imply endorsement by the National Institute for Occupational Safety and Health.

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