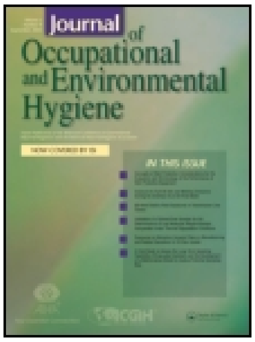

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: https://www.tandfonline.com/loi/uoeh20

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To cite this article: Aitor Coca , Raymond J. Roberge , W. Jon Williams , Douglas P. Landsittel , Jeffrey B. Powell & Andrew Palmiero (2009) Physiological Monitoring in Firefighter Ensembles: Wearable Plethysmographic Sensor Vest versus Standard Equipment, Journal of Occupational and Environmental Hygiene, 7:2, 109-114, DOI: 10.1080/15459620903455722

To link to this article: https://doi.org/10.1080/15459620903455722

Published online: 15 Dec 2009.

Journal of Occupational and Environmental Hygiene, 7: 109–114
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459620903455722

Physiological Monitoring in Firefighter Ensembles: Wearable Plethysmographic Sensor Vest versus Standard Equipment

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We evaluated the accuracy of a wearable sensor vest for real-time monitoring of physiological responses to treadmill exercise. Ten subjects in standard firefighter ensembles, treadmill exercising at 50% VO_2 max, had heart rate (HR), respiratory rate (RR), skin temperature (T_{sk}), oxygen saturation (SaO_2), tidal volume (V_T), and minute ventilation ($\dot{V}_E$) recorded concurrently by a wearable plethysmographic sensor vest and standard laboratory physiological monitoring equipment for comparison. A high degree of correlation was noted for most of the measured variables [HR (r = 0.99), RR (r = 0.98), T_{sk} (r = 0.98), $\dot{V}_E$ (r = 0.88), and SaO_2 (r = 0.79)]. V_T (r = 0.60) had a moderate correlation, although a paired differences analysis showed a mean paired difference of –0.03 L. This mean paired difference represents a 1.92% variation for V_T. Data from the wearable sensor vest is comparable to data captured from standard laboratory physiological monitoring equipment on subjects wearing standard firefighter ensembles while exercising at a moderate work rate. This study demonstrates the accuracy of the wearable sensor technology for these physiological parameters under these conditions and suggests that it could be useful for actual field studies of firefighters in traditional firefighting gear.

Keywords firefighter ensembles, physiological monitoring, wearable plethysmographic sensor vest

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

INTRODUCTION

Firefighters experience tremendous physical stresses in the course of their firefighting duties, both metabolically and environmentally.(1,2) The ability to monitor physiological variables in real-time in these individuals can offer valuable information that could be used to address the severity of these stressors. New devices with wearable sensors are being developed that allow for real-time monitoring of several physiological variables. These devices use new technologies, such as plethysmographic sensors incorporated into a vest, as well as other sensors.

Some of the physiological variables that these wearable devices monitor include heart rate (HR), respiratory rate (RR), skin temperature (T_{sk}), oxygen saturation (SaO_2), tidal volume (V_T), and minute ventilation ($\dot{V}_E$). Physiological data monitored by wearable plethysmographic sensors vests are usually stored onto a small, portable data recorder carried in a pouch attached to the vest and telemetered in real-time to a laptop computer. The wearable plethysmographic sensors vests have been used in research under high gravitational force environments,(3) with exercise,(4) and at rest with resistive loads.(5) These studies evaluated the system under different conditions, but they were not a comparison study wearing firefighting ensembles.

Comparison of simultaneously obtained physiological data from a wearable plethysmographic sensor vest and standard laboratory physiological monitoring equipment on subjects wearing firefighting ensembles could serve to verify the presumed accuracy of the wearable plethysmographic sensor vests for possible application in future field tests of firefighter protective equipment. Several studies have shown that firefighters engage in very heavy activities ($\dot{V}_E \sim 85\%$ maximal)(1,2,6) that can significantly affect their performance while wearing firefighting ensembles. However, it is difficult to measure these minute ventilation rates and other physiological parameters while wearing full firefighter ensembles and a self-contained breathing apparatus (SCBA).

Moreover, laboratory studies do not precisely mimic the activities and environment of the actual firefighting scenario. Therefore, this study examined the accuracy and efficacy of a wearable physiological sensor vest that could be worn under a full firefighter ensemble. Our goal was to establish that the sensor vest (1) could provide physiological information comparable to standard physiological monitoring equipment, and (2) could continue to provide this data to remote receivers while being exposed to the hot and humid microenvironment between the skin of the subject and the inside surface of the firefighter ensemble while the subject was physically active (working at 50% $\dot{V}O_{2max}$) on the treadmill.

Future studies will use wearable sensor vests under actual training or firefighting scenarios. We also anticipate that the sensor vest technology will have a broad application in occupations where heat stress is significant and physiological monitoring is useful (HAZMAT, mine rescue, logging community, agriculture, construction, roofing).

This study was undertaken by the National Personal Protective Technology Laboratory (NPPTL) of the National Institute for Occupational Safety and Health (NIOSH) to compare the accuracy of physiological data obtained from a wearable plethysmographic sensor vest worn by human subjects wearing a standard firefighter ensemble with data obtained concurrently from traditional, calibrated laboratory physiological monitoring equipment.

In addition to the goal of comparing the accuracy of a wearable plethysmographic sensor vest physiological measurements against standard physiological monitoring systems, we had a secondary goal of obtaining measurements of $\dot{V}_E$ from subjects during exercise while wearing a firefighter ensemble. $\dot{V}_E$ measurements while wearing firefighter ensembles are important for several reasons: (1) $\dot{V}_E$ measurements can be used to determine the work rate and, from that, an estimate of oxygen consumption based on published equations; (2) $\dot{V}_E$ can be used to determine how quickly the SCBA air pack will be drained; and (3) $\dot{V}_E$ against an increased breathing resistance has been shown to result in hypoventilation, a decrease in $\dot{V}O_2$ and an increase in $\dot{V}CO_2$. The increased $\dot{V}CO_2$ can further stimulate ventilation resulting in a decrease in respirator comfort and user acceptance.[7–9]

In our literature survey, we determined that there were no data regarding measurements of $\dot{V}_E$ from subjects wearing a wearable plethysmographic sensor vest under standard firefighter ensembles. Since a wearable plethysmographic sensor technology affords us the opportunity to derive $\dot{V}_E$ measurements from the product of RR and V_T, we decided to use a wearable plethysmographic sensor vest to make those measurements in the lab under controlled conditions during our study. We hypothesized that (1) the data obtained from a wearable plethysmographic sensor vest would not be significantly different from the data obtained from the standard physiological monitoring equipment, and (2) data on RR and V_T could be used to accurately derive $\dot{V}_E$ during exercise while wearing the firefighter ensemble.

MATERIALS AND METHODS

Participants

Ten healthy subjects (eight men, two women), ranging in age from 21–39 years and experienced in the use of standard firefighter gear, participated in the study. Subjects had passed a medical examination that included a 12-lead electrocardiogram (ECG), blood chemistries, complete blood count, urinalysis, drug testing, and (for women subjects) pregnancy testing. The subjects' characteristics were as follows (mean ± SD): age: 27.1 ± 6.6 yr; height: 1.76 ± 0.17 m; body mass: 77.4 ± 18.5 kg; BMI: 25.1 ± 5.7 kg/m^2; estimated percentage body fat: 13.8 ± 4.3 % (three skin folds method using Lange calipers); body surface area: 1.82 ± 0.29 m^2; $\dot{V}O_{2max}$: 48.6 ± 7.6 mL·kg^{-1}·min^{-1}; HR_{max} 190 ± 14.6 b·min^{-1}; $\dot{V}_{Emax}$, 135 ± 54.0 L·min^{-1}. The study was approved by the NIOSH Human Subjects Review Board, and both oral and written consent were obtained from all subjects prior to their participation in this study.

Participants (dressed in shorts, T-shirt, and athletic shoes) underwent a pre-study graded exercise test (GXT) to determine maximum oxygen consumption ($\dot{V}O_{2max}$). The GXT was performed on a TrackMaster motorized treadmill (model TMX 425CP; Full Vision Inc., Newton, Kan.) computer controlled by a Vmax Spectra metabolic cart (SensorMedics, Yorba Linda, Calif.). The Vmax Spectra metabolic cart was programmed to control the treadmill belt speed and incline incrementally in 3-min stages according to a modified Bruce protocol. Each 3-min stage of the modified Bruce protocol (1.7 mph, 0% grade; 1.7 mph, 10% grade; 2.5 mph, 12% grade; 3.4 mph, 14% grade; 4.2 mph, 16% grade; etc.) was continued until the subject reached volitional fatigue.

During the GXT, oxygen consumption ($\dot{V}O_2$, mL·kg·min^{-1}), carbon dioxide production ($\dot{V}CO_2$, mL·kg·min^{-1}), ventilation ($\dot{V}_E$, L·min^{-1}), respiratory exchange ratio (RER; $\dot{V}CO_2$/ $\dot{V}O_2$), respiratory rate (RR), arterial blood pressure, oxygen saturation (SaO_2), heart rate (HR), electrocardiogram (ECG), and subjective ratings of perceived exertion (Borg scale) were monitored. Maximal exercise capacity ($\dot{V}O_{2max}$) was considered to be reached when the subject experienced volitional fatigue, RER exceeded 1.15, and $\dot{V}O_2$ did not increase with increasing exercise intensity.

Once $\dot{V}O_{2max}$ was established for each subject, the exercise level predicted to yield 50% of $\dot{V}O_{2max}$ was calculated. The calculated 50% $\dot{V}O_{2max}$ took into consideration the contribution of the weight of the ensemble and SCBA for each specific subject to the 50% maximal effort. This calculation consisted of adding the weight of the ensemble and SCBA to the subject weight, then finding the 50% $\dot{V}O_{2max}$ that would correspond to the new weight. Thus, subjects exercised at 50% of their maximal aerobic capacity for the experimental portion of the study. The weight of the ensemble and SCBA was approximately 21 kg, which represented a range of 10 to 15% of $\dot{V}O_{2max}$ depending on each subject's body weight. Subjects walked on the treadmill at a speed (mean ± SD) of 3.9 ± 0.33 km/hr (2.4 ± 0.2 mph) and a grade of 8.6 ± 2.9%. All participants performed the evaluation study within a minimum of a 1-week and maximum of 2-week respite after the GXT.

Equipment and Measurements

The firefighter "standard" turnout gear (also known as bunker gear) used in this investigation included the coat, pants, boots, gloves, hood, and helmet. All firefighter turnout gear components meet the requirements of National Fire Protection Association (NFPA) 1971 Standard on Protective Ensembles for Structural Firefighting.[10] The SCBA assembly meets the NFPA-1981[11] requirements and is NIOSH chemical, biological, radiological, and nuclear (CBRN) approved.

For the purpose of this study, we used a commercially available wearable plethysmographic sensor vest known as the LifeShirt (VivoMetrics, Ventura, Calif.). The LifeShirt is a wearable spandex vest with various central and peripheral physiological sensors (i.e., ECG electrodes, respiratory inductance plethysmographic (RIP) bands, pulse oximeter fingertip sensor, skin temperature lead) incorporated into the garment. All the sensors and processing algorithms are approved by the Food and Drug Administration (FDA) for medical use.

The LifeShirt System is a continuous ambulatory monitoring system for collecting physiological data, such as HR, RR, T_{sk}, SaO_2, V_T, and $\dot{V}_E$. Physiological data monitored by the LifeShirt are stored onto a small, portable data recorder carried in a pouch attached to the vest, and telemetered in real-time to a laptop computer. The LifeShirt is a lightweight (8 oz), washable, breathable spandex vest, available in a range of sizes from XS to XXXL to best fit all sizes of individuals for the noninvasive monitoring of a number of physiological variables through the use of vest-impregnated sensors, electrodes, and plethysmography bands.

Three ECG electrodes provide a single lead that offers ECG waveform determinations and HR (determined by the ECG's R-R interval). A Nonin X-pod pulse oximeter (Nonin Medical Inc., Plymouth, Minn.) measures SaO_2 (70–100% accuracy [company brochure]) by means of a disposable, fingertip adhesive sensor. RIP bands embedded in the vest and encircling the rib cage just below the nipple (men) or breast (women), measure changes in the cross-sectional area of the rib cage that, with the use of proprietary algorithms, allow the determination of RR, V_T, and $\dot{V}_E$. T_{sk} is monitored with an Exacom DS18 thermistor (Exacom AS, Roskilde, Denmark; accuracy $\pm$ 0.1°C, between 25–50°C).

The clinically accurate physiological parameter measuring instruments utilized in this investigation, considered for the purposes of this study to be the reference standard, and their corresponding measurement variables are as follows: RR, $\dot{V}_E$, V_T, and HR (Vmax 29 Metabolic Measurement System; VIASYS/SensorMedics, Yorba Linda, Calif.); oxygen saturation (Nonin 8600 Pulse oximeter; SaO_2, 70–100% accuracy [company brochure]); and skin temperature (SQ2020-1F8 Skin Temperature Probe and Data Logger; accuracy [company brochure] 0.01% between –50° to 150°C (Grant Instruments Ltd., Cambridgeshire, U.K.).

All stationary laboratory monitoring equipment utilized in the study was calibrated according to established protocols (National Institute of Standards and Technology standards) prior to onset of the study. All volume measurements were reported using body temperature and pressure saturated (BTPS) units. All data were downloaded real-time onto data recorders and computers for storage and later retrieval.

Experimental Procedures

Prior to donning of the LifeShirt, subjects first removed their shirt (women subjects wore a sports bra beneath the T-shirt), and standard 12-lead ECG skin electrodes were placed. A standard skin temperature sensor (Grant Instruments) was affixed with adhesive to the right anterior upper chest wall (below the clavicle); the skin temperature sensor of the LifeShirt was similarly applied at the same anatomic location contralaterally. The three spot LifeShirt ECG electrodes were then placed at the upper left and upper right anterior chest wall and distal left lateral abdominal wall enabling ECG lead-II tracings.

The subjects then donned the LifeShirt vest and closed the inner of two zippers. Through available openings in the vest, the leads from the ECG electrodes were connected to a data collection cable, and the RIP band lead was also connected to the same cable. The LifeShirt pulse oximeter lead was attached with adhesive to the subject's left index finger, and its lead was connected to the data recorder cable. This data cable was then connected to the LifeShirt data recorder that is housed in a holding pouch located on the front of the vest. The standard pulse oximeter (Datex-Ohmeda) clip was placed onto the subject's right index finger. The subject then closed the outermost zipper of the vest, donned the T-shirt and firefighter ensemble with SCBA, and then placed the mouthpiece of the Metabolic Measuring System in his/her mouth, and a noseclip was applied to prevent nasal breathing.

All equipment was then examined to ensure that it was functioning properly. The treadmill speed started at a slow rate (2.4 km/hr [1.5 mph]) and the subject engaged in a warm-up period of 3 min. At that point, the treadmill was programmed at a rate and incline equivalent to the subject's predetermined 50% $\dot{V}O_{2max}$, and he/she was exercised at those settings for 20 min while continuous monitoring of the study physiological variables (HR, RR, T_{sk}, SaO_2, V_T, $\dot{V}_E$) was carried out.

Statistical Analysis

Data were averaged and stored every minute for HR, RR, T_{sk}, V_T, and $\dot{V}_E$, generating 20 data points for each subject. SaO_2 was recorded every 3 min creating 6 data points for each subject. To evaluate the correlation and magnitude of differences between systems (i.e., Vmax 29 system, LifeShirt), we calculated bootstrap estimates[12,13] and corresponding 95% confidence intervals (CI) for the correlations and paired differences. Bootstrapping is a flexible, nonparametric, resampling method that allows us to correctly account for correlations within-subject (e.g., across the 20 data points) without any assumptions about the underlying distribution.

For this approach, a single data point was randomly selected from each subject (retaining both the Vmax 29 and LifeShirt measurements at that data point) and then used to calculate the correlation and paired differences (based upon one observation from each subject). This process is then repeated 500 times, thus generating 500 correlations and paired differences. The subsequent mean (or bootstrap estimate) and standard deviation (across the 500 bootstrap samples) are

TABLE I. Bootstrap Estimates of the Correlation and Paired Differences Between the LifeShirt and Standard Laboratory Monitoring Equipment in Subjects Wearing Standard Firefighter Gear and SCBA While Treadmill Exercising at 50% $\dot{V}O_{2max}$

	Correlation Coefficient		Paired Differences	
Physiological Parameters	**Mean (SD)**	**95% CI**	**Mean (SD)**	**95% CI**
Heart rate (beats/min)	0.99 (0.01)	[0.96, >0.99]	0.33 (0.93)	[−1.45, 1.67]
Tidal volume (L)	0.60 (0.12)	[0.36, 0.78]	−0.03 (0.03)	[−0.09, 0.02]
Respiration rate (breaths/min)	0.98 (0.02)	[0.93, 0.99]	−0.15 (0.38)	[−0.80, 0.46]
Minute ventilation (L/min)	0.88 (0.03)	[0.82, 0.94]	−5.52 (0.92)	[−7.00, −4.08]
Skin temperature (°C)	0.98 (0.03)	[0.93, 0.99]	0.03 (0.09)	[−0.11, 0.18]
Oxygen saturation (%)	0.79 (0.11)	[0.58, 0.93]	0.81 (0.19)	[0.49, 1.13]

then used to calculate the 95% bootstrap CI (based on the 2.5th and 97.5th percentile of the bootstrap distribution). This bootstrap approach was used in favor of a random effects repeated measures model for its ease of interpretation and lack of underlying assumptions about normality and specific within-subject correlation structures.

RESULTS

All subjects successfully completed the 20-min duration of the comparison study. A high degree of correlation was observed for five out of six measurements by the two systems: HR (r = 0.99), RR (r = 0.98), T_{sk} (r = 0.98), $\dot{V}_E$ (r = 0.88), and SaO_2 (r = 0.79) (Table I). Although V_T showed only a moderate correlation (r = 0.60) (Table I), paired measurements showed very small differences on average, with a mean paired difference of only –0.03 L (or 1.92%).

To further illustrate the small within-subject differences, Figure 1 represents an individual example of the V_T measurements across the session. In this particular subject, differences between the two systems averaged 10.4% variation and had a high degree of correlation (r = 0.98). Figure 2 offers the time course of $\dot{V}_E$ for both systems throughout the session (n = 10) and again demonstrates a high degree of measurement concordance between both systems (r = 0.88). For RR, the mean paired difference across all subjects (again calculated via the bootstrap estimate) was –0.15 br/min, which represents a variability of only 0.52%. For $\dot{V}_E$, although it demonstrated a high degree of measurement concordance between systems (r = 0.88), the paired differences were substantially

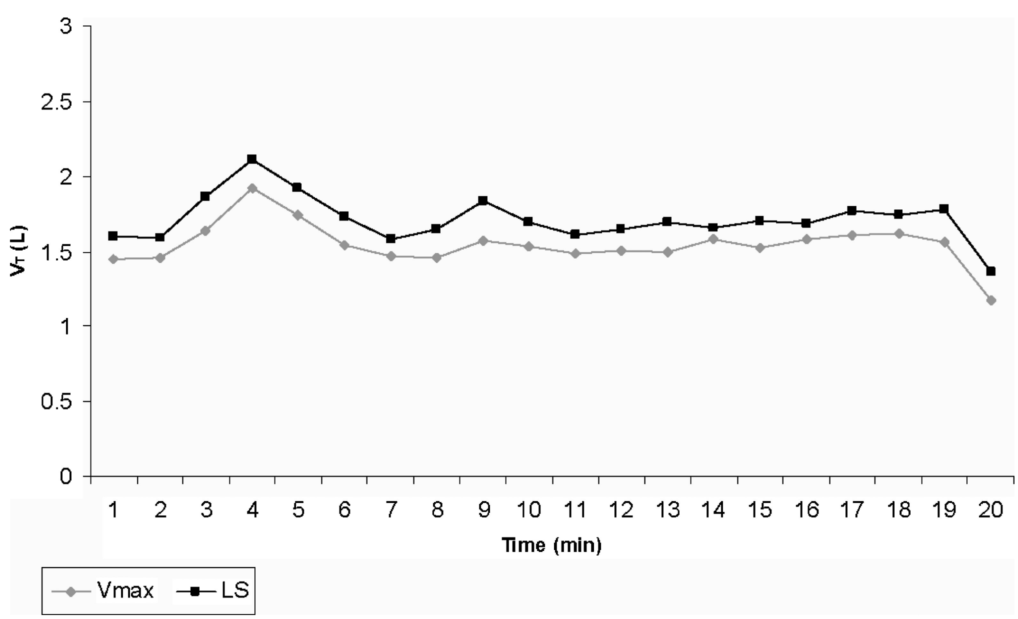

FIGURE 1. Time course of V_T in one subject as measured by both systems, LifeShirt (LS) and standard laboratory monitoring equipment (Vmax 29), during the 20-min validation period

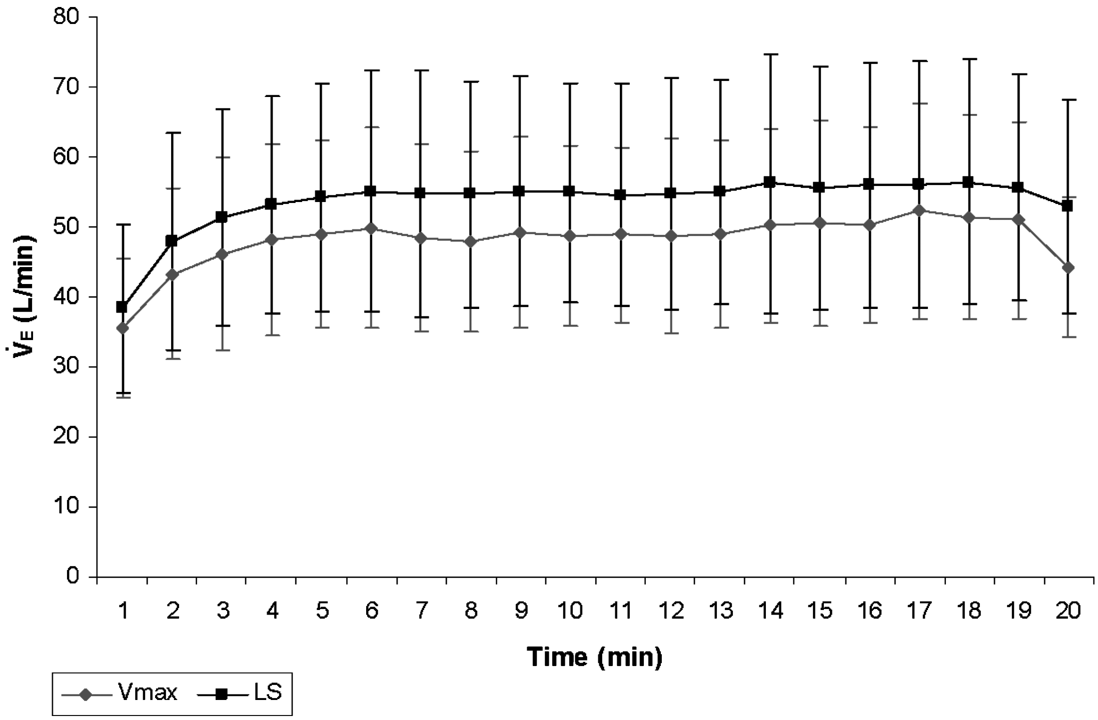

FIGURE 2. Time course of mean $\dot{V}_E$ (means ± SD) for LifeShirt (LS) and standard laboratory monitoring equipment (Vmax 29) during the 20-min validation period (n = 10)

greater, and the 95% CI did not include zero, with a mean of −5.52 L/min (10.3% variability). None of the subjects reported any discomfort associated with wearing the LifeShirt.

DISCUSSION

The current investigation determined high correlations between real-time physiological data measurements for HR, RR, T_{sk}, SaO_2, and $\dot{V}_E$, and moderate correlation for V_T captured concurrently by the LifeShirt and calibrated standard laboratory physiological monitoring equipment on subjects wearing a standard firefighter ensemble (bunker gear) and carrying, but not breathing through, a SCBA while treadmill exercising at a moderate work rate (50% $\dot{V}O_{2max}$). It was not unexpected that the data for HR, T_{sk}, and SaO_2 were similar (r = 0.99, 0.98, and 0.79, respectively), given that the equipment utilized by the two systems for these measurements are comparable in function and accuracy (as stated by company brochures).

However, RIP uses a significantly different technical approach from standard pneumotachograph determination of RR, V_T, and $\dot{V}_E$. The moderate-to-high correlations and relatively small paired differences for RR, V_T, and $\dot{V}_E$ measurements in the present study compare favorably with a prior investigation comparing the accuracy of LifeShirt and pneumotachograph recordings of these variables in healthy young males during rest and at treadmill exercise at various levels of energy expenditure, which ultimately found no significant differences ($p > 0.05$) in data from either system.[14]

It is important to mention the $\dot{V}_E$ measurement showed a paired difference CI that did not include zero, which would be considered significant. However, the high correlation shown by this measurement may explain that both systems show steady differences that are relatively small (a mean of –5.52 L/min) for the average values of this measurement while engaged in vigorous activity.

Our study noted a variation of 1.92% in LifeShirt V_T measurements that is in keeping with the manufacturer's assertion that the V_T is accurate to within 10% of changes estimated from spirometry when body position has not changed from the position in which calibration was carried out, and V_T is accurate to within 20% with large V_T variations (company brochure). Some of the LifeShirt variation is due to the fact that the RIP bands react not only to respiratory activity but also to postural changes; bending of the trunk; wrinkles in the garment; and vibrations of abdomen, chest, or breasts due to accelerative forces on the body.[14,15]

The V_T variation in the current investigation is comparable to a previous study[16] that compared respiratory variables from the LifeShirt with that from a pneumotachograph on healthy subjects and those with pulmonary and cardiac disease while exercising on a treadmill to exhaustion, and noted "no significant bias" (i.e., ± 7%) in V_T measurements between the two systems. The high correlation coefficients noted in the current study indicate that the two tested systems share a significant linear relationship, a finding that has been previously identified in a similar study comparing simultaneous LifeShirt and pneumotachograph recordings that noted r-values of 0.92, 0.87, and 0.90 for RR, V_T, and $\dot{V}_E$, respectively.[14]

Limitations of our study include the relatively small sample size (10 subjects) that may have been too undersized to detect a true difference (β-error) between the two test systems, although other LifeShirt studies have utilized similar numbers and achieved statistical significance.[4] Also, although we tested our subjects at 50% $\dot{V}O_{2max}$, firefighters often have short bursts of activity at much higher levels, and a prior comparison of the LifeShirt and pneumotachograph noted that discrepancies in $\dot{V}_E$ between the two systems grow larger with increasing exercise intensity.[17] Therefore, it is theoretically possible that had we employed a greater workload in the study, we might have noted greater variance in $\dot{V}_E$ measurements between the two systems.

CONCLUSION

Our study indicates that the LifeShirt system measures HR, RR, T_{sk}, SaO_2, V_T, and $\dot{V}_E$ somewhat accurately within the hot, moist environment of standard firefighter gear (bunker gear) during treadmill exercise at a moderate workload (50% $\dot{V}O_{2max}$) when compared with calibrated standard laboratory physiological monitoring equipment. LifeShirt V_T measurements displayed a variation of 1.92% that falls within the range of accuracy limits advertised by the manufacturer, though the range of our data included some values that were at the upper limit of the manufacturer's stated accuracy.

Our findings indicate that most physiological outcomes (i.e., HR, RR, T_{sk}, V_T) measured by the LifeShirt, worn under standard firefighter ensembles (bunker gear) at a moderate work rate, are not statistically different from physiological data recorded on standard laboratory equipment. The other two measurements ($\dot{V}_E$ and SaO_2) showed paired differences significantly different from 0.0 but showed high correlations (0.88 and 0.79, respectively). The investigators are aware that wearing the sensor vest while exercising upright on a treadmill does not mimic actual firefighting activities on the fire ground. The data obtained in this study are a preliminary assessment of the sensor vest under controlled lab conditions. Nevertheless, these data suggest that additional experiments to obtain LifeShirt data from firefighters in actual firefighting scenarios are warranted to determine accuracy in field settings.

ACKNOWLEDGMENTS

This research was performed while one of the authors (AC) held a National Research Council Resident Research Associateship at the National Personal Protective Technology Laboratory (NPPTL). The authors wish to thank Ronald Shaffer, Ed Sinkule, Bob Stein, and Ed Fries for their insightful reviews and excellent suggestions.

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