

Comparison of Unmanned and Manned Test Measurements of Carbon Dioxide in the Breathing Zone of an Escape Air-Purifying Respirator

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ABSTRACT

Inhaled carbon dioxide concentrations ($F_{I}CO_2$) of an air-purifying escape respirator (APER) were measured using unmanned and manned test methods to compare results among test procedures. Unmanned experiments were performed according to National Institute for Occupational Safety and Health (NIOSH) procedures and two versions of the European (EN136) test method. $F_{I}CO_2$ data from manned test trials were obtained according to NIOSH human subject breathing gas (HSBG) procedures for chemical, biological, radiological, and nuclear APER standards, which include both resting and walking procedures. Bland-Altman statistics for determination of limits of agreement were applied to assess agreement between NIOSH unmanned and HSBG resting data, between standard EN136 (EN136S) unmanned and HSBG walking data, and between modified EN136 (EN136M) unmanned and HSBG walking data. No agreement between NIOSH unmanned and HSBG resting $F_{I}CO_2$ results or between EN136S unmanned and HSBG walking $F_{I}CO_2$ results was found. $F_{I}CO_2$ results of EN136M unmanned procedures were no more than 0.22% CO_2 higher than manned test results and the level of agreement between conditions was acceptable. These findings indicate that the EN136M unmanned and HSBG walking methods could be used interchangeably with regard to determination of respirator $F_{I}CO_2$ levels for APER certification testing.

Keywords: Carbon dioxide, escape respirator, manned and unmanned testing

INTRODUCTION

The potential for an increase of carbon dioxide (CO_2) concentration in the breathing zone of a respirator because of incomplete removal by the device during exhalation is well known (Johnson and Cummings, 1975; Raven *et al.*, 1979). With incomplete CO_2 removal upon exhalation, an amount of CO_2 above atmospheric levels may be re-inhaled during the following inhalation. Based upon an individual's sensitivity to CO_2 , elevated retention of CO_2 in the lungs can lead to subjective discomfort, headaches, increased anxiety, compensatory metabolic and ventilatory responses, and decreased mental and physical performance (Craig *et al.*, 1970; Shershow *et al.*, 1973; Cafarelli and Noble, 1976; Sayers *et al.*, 1987; Bishop *et al.*, 1999).

Standards for the certification of protective respirators attempt to alleviate potential CO_2 retention problems by defining acceptable inhaled CO_2 fractional concentrations for various respirator types. European Standards rely primarily on unmanned test methods to quantify respirator CO_2 retention (CEN, 1989; CEN, 1997; CEN, 1999). The National Institute for Occupational Safety and Health (NIOSH)

promulgates respirator standards that utilize either machine or human test procedures to quantify respirator inhaled CO₂ fractional concentrations dependent upon respirator type (CFR, 1995). The NIOSH chemical, biological, radiological and nuclear (CBRN) certification standard for air-purifying escape respirators (APER) is one standard that necessitates both unmanned and manned evaluations of inhaled CO₂ (NIOSH, 2003). The rationale for requiring both unmanned and manned testing of CBRN APER CO₂ levels with controlled (unmanned methods) and uncontrolled (manned methods) breathing parameters is not provided in the standard (NIOSH, 2003). One plausible reason for both is that unmanned procedures may serve as a screening test to ensure that an APER is designed for safe operation prior to subjecting individuals to mask wear trials. Nevertheless, the unmanned test parameters for the APER standard purportedly simulate human sedentary breathing and metabolic conditions, creating a significant challenge with regard to respirator CO₂ retention (Kloos and Lamonica, 1966). How well measures of inhaled CO₂ concentrations obtained under NIOSH unmanned test conditions compare with data acquired during the resting portion of the APER manned tests is unknown. If they are comparable, then the need for both unmanned and manned assessments of inhaled CO₂ fractional concentrations for APER systems is questionable. Additionally, if unmanned and manned test results agree for sedentary breathing conditions, why not adopt unmanned testing that simulates breathing and metabolic conditions found for the exercise portion of the APER manned testing requirements if they too prove to be identical?

This study compared in-mask CO₂ concentrations of an APER based on unmanned and manned test procedures. Results derived from published NIOSH and European unmanned test methods were compared with data acquired under manned test conditions of rest and exercise, respectively, as defined by the NIOSH CBRN APER standard (NIOSH, 2003).

MATERIALS AND METHODS

Unmanned Testing

Respirator CO₂ retention experiments were performed using both NIOSH and European unmanned test methods. Unmanned NIOSH data collection and analysis followed methods published in NIOSH Procedure No. RCT-APR-STP-0064 (NIOSH, 2005a) and all of these tests were performed by NIOSH personnel at the National Personal Protective Technology Laboratory (NPPTL). Details of the NIOSH procedures have also been published in related work performed by this laboratory (Caretti and Coyne, 2008). In brief, the NIOSH unmanned CO₂ test system used a headform and breathing machine with a sedentary cam adjusted to 14.5 revolutions per minute with a volume output of 0.72 L. Carbon dioxide supply was adjusted to provide a consistent exhalation gas CO₂ concentration of 5% by volume at the mouth of the headform. Supply and in-mask CO₂ concentrations were measured with a Beckman LB-2 CO₂ medical gas analyzer (Beckman Instruments, Inc., Fullerton, CA) from a sample line installed inside of the headform's breathing tube, terminating just inside the mouth. The sampling rate of the CO₂ analyzer was 500 mL·min⁻¹. Analog output signals from the CO₂ gas analyzer and a pressure transducer with a pressure-sensing tap installed just below the eye on the surface of the headform were monitored and recorded on-line at a rate of 40 Hz using customized LabVIEW (National Instruments Corp., Austin, TX) data acquisition software. Three replicates of unmanned CO₂ testing were completed for each of six test respirators. Respirators were doffed and re-donn'd on the headform between trials.

Unmanned tests according to EN136 procedures also delivered exhaled air with a CO₂ content of 5% by volume to the mouth of a head/torso simulator using a piston-type breathing pump set at a rate of 25 strokes per minute with a volume of 2 L (CEN, 1989). Since this study was part of a larger investigation (Caretti and Coyne, 2008), five additional breathing pump settings were also used to assess in-mask CO₂ concentration during inhalation under different volume and frequency conditions. However,

only the settings that most closely matched the ventilation parameters recorded during manned test trials will be reported in the current paper.

As described in the initial publication of results of the investigation performed by Caretti and Coyne (2008), the EN136S requires only one gas analyzer that measures inhaled CO₂. This study included the addition of a second gas analyzer (MGA model 1100, Perkin-Elmer, Inc., Pomona, CA) to measure CO₂ content of inhaled air from the test respirator's oro-nasal cavity on a breath-by-breath basis, thus providing CO₂ data similar to how it is acquired with NIOSH methods. With this modified set-up (EN136M), breath-by-breath sampling was obtained from a capillary drawing a small continuous gas sample (240 mL·min⁻¹) while placed inside the respirator with its end positioned just before the opening of the mouth of the head/torso. Simultaneous in-mask pressures were measured at the mouth of the head/torso with a differential pressure transducer (model DP15, Validyne Engineering, Northridge, CA). Data were sampled at 50 Hz and recorded on-line using data acquisition hardware controlled by a customized LabVIEW software application. Data were collected during one 30-sec increment for each minute of a five-minute test time following a three- to five-minute stabilization period of simulated breathing. Respirators were doffed and re-donned on the head/torso simulator between trials. All procedures associated with the EN136 unmanned test parameters were performed at the U.S. Army Edgewood Chemical Biological Center (ECBC).

Manned Breathing Gas Tests

Six non-smoking individuals, comprised of two females and four males without history of cardiorespiratory problems, volunteered to participate in this study after providing informed consent. Mean ($\pm$ SD) values for population demographics were as follows: age = 37 ± 8 yr, height = 174.4 ± 11.9 cm, and weight = 80.4 ± 8.8 Kg. Based on measurements of face length (Menton-Sellion) and face width (Bizygomatic breadth), subjects fit the Los Alamos National Laboratories universal respirator anthropometric fit test panel sizes three through ten.

Manned respirator wear trials followed NIOSH CBRN human subject breathing gas (HSBG) test methods published in NIOSH Procedure No. CET-APRS-STP-CBRN-0454 (NIOSH, 2005b). The HSBG test encompasses two ten-minute respirator wear periods, one while standing at rest and one during treadmill walking, separated by a ten-minute seated rest period of no mask wear. The standing rest and walk periods were randomly assigned for each subject. For each test condition, subjects donned the test APER unassisted in accordance with the manufacturer's instructions prior to beginning data collection. Subjects were permitted as much time as they needed to don the APER until they felt satisfied that they were wearing the system in compliance with the manufacturer's user's instructions. For the standing rest condition, subjects stood on the treadmill for ten minutes. In-mask samples of respired CO₂ and breathing volumes were collected during the last 30 sec of minutes six through ten of APER wear. Breath-by-breath sampling was obtained from a capillary drawing a small continuous gas sample (240 mL·min⁻¹) while placed within the breathing zone of the respirator with its end positioned midway between the subject's nose and upper lip approximately 0.64 cm from the surface of the face. Inspiratory airflow was measured with a Fleisch No. 3 pneumotachograph (OEM Medical, Richmond, Va.) connected to a pressure transducer (model MP45, Validyne Engineering) and carrier demodulator (Validyne Engineering). The pneumotachograph was mounted to the treadmill and connected to the respirator's filter cartridge via a 0.61 m length of 2.53 cm internal diameter flexible tubing permitting inhaled airflow to be measured continuously. Pneumotachograph pressure signals were integrated digitally to obtain volume measurements. Instrument calibrations were completed prior to each test using a 3 L calibration syringe and precision oxygen and carbon dioxide gas mixtures. Simultaneous in-mask pressures were measured at the mouth of the subject with a differential pressure transducer (model DP15, Validyne Engineering). Data were sampled at 50 Hz and recorded on-line using data acquisition hardware controlled by a customized LabVIEW software application.

For the walking portion of the HSBG test, volunteers walked at $1.56 \text{ m}\cdot\text{sec}^{-1}$ on a level grade (i.e., no incline) for ten minutes on the treadmill (Trackmaster TM 500E, JAS Manufacturing, Richardson, TX). Data collection procedures mimicked those utilized for the standing rest condition.

Experimental Conditions

The MSA Response™ NBC Escape Hood Respirator (MSA, Pittsburgh, PA) was utilized for all testing. The Response™ is a one-size-fits-all transparent hood respirator with a tight-fitting neck dam, a front mounted canister, and an internal oro-nasal mask. Six individual respirators were randomly tested. Test respirators were probed with two fit test probes (model 8025-N95, TSI Incorporated, St. Paul, MN) for in-mask sampling of CO_2 and breathing pressures at the mouth during test trials performed at the ECBC. Each APER was worn by only one test participant for each of his or her individual HSBG test days. Each respirator was subjected to all unmanned test methods one time. Therefore, each APER was used for three unmanned tests (NIOSH, EN136S, and EN136M) and two manned test trials (HSBG rest and HSBG walk).

Data Analysis

Data from three consecutive breathing cycles were analyzed per APER test performed with NIOSH unmanned procedures, providing a total of 18 data points. Breath-by-breath time-weighted average fractional concentration of in-mask CO_2 during inhalation ($F_{\text{I}}\text{CO}_2$) was calculated for each breath by averaging CO_2 from the start to the end of each inhaled breath as identified by in-mask pressure values and CO_2 decay curves after accounting for signal delays. Minimum and end-tidal fractional CO_2 ($F_{\text{ET}}\text{CO}_2$) readings from each inhaled breath were also identified (Figure 1). Values derived from each breath were then averaged to determine a mean $F_{\text{I}}\text{CO}_2$ for each mask fit according to NIOSH unmanned test methods, as well as mean minimum CO_2 and $F_{\text{ET}}\text{CO}_2$ results.

For EN136 unmanned test conditions, data from each inhaled breath completed in the 30 sec measurement period were used to determine breath-by-breath time-weighted average $F_{\text{I}}\text{CO}_2$ values. The beginning and ending points of each inhaled breath were identified by in-mask pressure values and the beginning and ending points of the inhaled CO_2 curves after accounting for signal delay of the medical gas analyzer. Minute averages of breath-by-breath $F_{\text{I}}\text{CO}_2$, minimum CO_2 and $F_{\text{ET}}\text{CO}_2$ were determined from all breath-by-breath values calculated in a single data collection period under standard and modified EN136 test conditions. Because data were collected during one 30-sec increment for each minute of a five-minute period, the maximum number of data points was 30 for each EN136 method of measurement.

Mean $F_{\text{I}}\text{CO}_2$ results were derived from HSBG data from both standing and walking test conditions using methods analogous to those used for EN136 data calculations. Again, the maximum number of data points for each HSBG test condition was 30. Tidal volume (V_{T}), breathing frequency (f_{B}), and

inhaled minute volume ($\dot{V}_{\text{I}}$) were determined from pneumotachograph recordings. Data for all flow conditions were at ambient temperature and pressure (ATPS) in environmentally-controlled laboratories.

The quantitative data reported herein are expressed as mean $\pm$ SD. Statistical comparisons of between group means were completed using t-tests; ANOVA were applied for comparisons among three or more groups and *post-hoc* comparisons were performed using Scheffe's multiple comparison test. To compare the $F_{\text{I}}\text{CO}_2$ results among methods, Bland-Altman statistics for determining measurement bias and limits of agreement between related unmanned and manned test methods were applied (Altman and Bland, 1983; Bland and Altman, 1986). For the Bland-Altman comparison test, there is no set acceptability level; it depends on the test methods of comparison and the difference between methods that are acceptable to the researcher. Therefore, to be consistent with our prior work (Carette and Coyne, 2008), the maximal acceptable difference between methods of measurement was set at 0.50% CO_2 .

Agreement between methods was tested using the null hypothesis that the largest level of agreement derived for each comparison of methods was less than 0.50%. Statistical significance was accepted at $p < 0.05$.

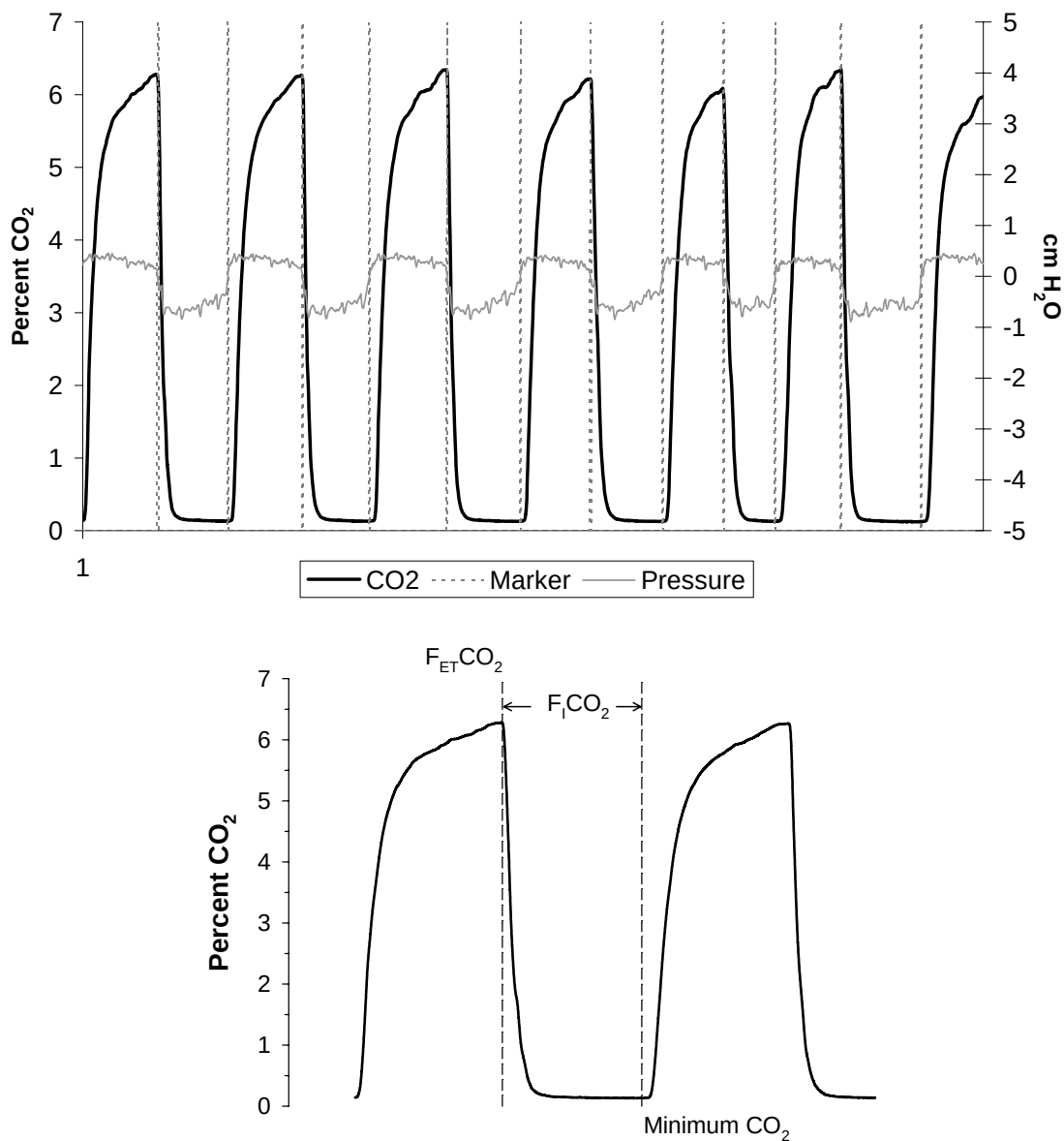


Figure 1. Sample of a breath-by-breath in-mask CO₂ recording obtained during a manned test trial with the ResponseTM APER. The top panel shows all CO₂ and pressure data in a 30 sec period. The bottom panel is an excerpt of a single breath and identifies data points derived from the different parts of the in-mask CO₂ curve during one inhalation. F_{ET}CO₂ and minimum CO₂ are single points on the curve and F_ICO₂ is the average of all data from F_{ET}CO₂ to minimum CO₂. The number of points analyzed per breath varied depending upon test participant breathing patterns.

RESULTS

HSBG Ventilation Parameters

Under HSBG resting conditions, V_T averaged 0.99 ± 0.32 L, f_B averaged 11.8 ± 2.3 min⁻¹, and $\dot{V}_I$ averaged 11.2 ± 3.0 L·min⁻¹ (N = 28). Taking into account the variability of the data, these HSBG resting ventilation rates provided a close approximation to NIOSH unmanned ventilatory conditions (i.e., $V_T =$

0.72 L, $f_B = 14.5$ min⁻¹, and $\dot{V}_I = 10.4$ L·min⁻¹). Thus, inhaled CO₂ results obtained under these breathing conditions were compared to NIOSH unmanned CO₂ results in subsequent analyses.

For HSBG walking conditions, $V_T = 1.81 \pm 0.42$ L, $f_B = 14.8 \pm 2.3$ min⁻¹, and $\dot{V}_I = 26.1 \pm 4.1$ L·min⁻¹ (N = 30). Human $F_{I\text{CO}_2}$ results obtained under these breathing conditions were compared to CO₂ results from

EN136S unmanned conditions (i.e., $V_T = 2.00$ L, $f_B = 25.0$ min⁻¹, and $\dot{V}_I = 50.0$ L·min⁻¹). In order to compare manned and unmanned $F_{I\text{CO}_2}$ results under like ventilatory conditions based on the HSBG walking ventilation rates, $F_{I\text{CO}_2}$ results were also compared to results obtained for EN136M unmanned

conditions of $V_T = 1.75$ L, $f_B = 17.0$ min⁻¹, and $\dot{V}_I = 29.8$ L·min⁻¹.

NIOSH Unmanned vs. HSBG Resting $F_{I\text{CO}_2}$

Mean values for minimum CO₂, $F_{E\text{T}\text{CO}_2}$, and $F_{I\text{CO}_2}$ values obtained under NIOSH unmanned and HSBG resting test conditions are presented in Table I. Results for all CO₂ measurements from unmanned testing with the APER were significantly ($p < 0.001$) greater compared to manned test results. Comparison of methods based on Bland-Altman analysis found a mean difference between NIOSH unmanned and HSBG rest data of 0.42% with a 95% confidence interval of 0.63% to 1.06%. These results indicate that $F_{I\text{CO}_2}$ measurements obtained using NIOSH unmanned procedures produced results between 0.63% and 1.06% higher than manned test results obtained under similar ventilatory conditions. Limits of agreement between conditions were 0.02% and 1.67%. The 95% confidence interval for the lower limit of agreement was -0.36% to 0.39%. For the upper limit of agreement the 95% confidence interval ranged from 1.29% to 2.04%. Agreement between NIOSH unmanned and resting HSBG methods was rejected because the largest limit of agreement (1.67%) was significantly greater than the maximal acceptable difference of 0.50% CO₂.

EN136 Unmanned vs. HSBG Walking $F_{I\text{CO}_2}$

No statistical differences in CO₂ measures were observed between EN136S test conditions with a $\dot{V}_I$ of 50.0 L·min⁻¹ and the EN136M conditions with a $\dot{V}_I$ of roughly 30.0 L·min⁻¹ (Table II). Human subject breathing gas results for minimum CO₂ and $F_{E\text{T}\text{CO}_2}$ were significantly greater than both unmanned EN136 conditions. Mean $F_{I\text{CO}_2}$ results differed significantly between EN136S and HSBG walk conditions. Although HSBG average $F_{I\text{CO}_2}$ values were lower compared to those found under EN136M test conditions, the difference between conditions did not reach significance ($p = 0.06$).

Bland-Altman analysis produced a mean difference in $F_{I\text{CO}_2}$ results between EN136S unmanned and HSBG walk data of 0.24% with a 95% confidence interval of 0.17% to 0.32%, signifying that $F_{I\text{CO}_2}$ values from EN136S unmanned procedures exceeded manned HSBG test results by 0.17% to 0.32%. Limits of agreement between conditions were -0.14% and 0.63%. The 95% confidence interval for the lower limit

of agreement was -0.27% to -0.01%, whereas the interval ranged from 0.50% to 0.76% for the upper limit of agreement. Since the largest limit of agreement (0.63%) was significantly greater than the maximal acceptable difference of 0.50% CO₂, agreement between EN136S unmanned and HSBG walk F_ICO₂ results was not found.

Table I. Mean (±SD) CO₂ Measures from NIOSH Unmanned and HSBG Resting Conditions

Test	N	Minimum CO ₂ (%)	F _{ET} CO ₂ (%)	F _I CO ₂ (%)
NIOSH Unmanned	17 [#]	1.53 ± 0.52	4.88 ± 0.20	2.06 ± 0.36
HSBG Rest	28 ^{\$}	0.52 ± 0.18 ^A	4.29 ± 0.38 ^A	1.22 ± 0.34 ^A

[#] = missing data for one simulated breath recording

^{\$} = blocked CO₂ sample line for one subject on 2 occasions

^A = significantly different from Unmanned

Table II. Mean (±SD) CO₂ Measures from Standard and Modified EN136 Unmanned Trials and HSBG Walking Conditions

Test	N	Minimum CO ₂ (%)	F _{ET} CO ₂ (%)	F _I CO ₂ (%)
EN136S	30	0.23 ± 0.05	5.08 ± 0.03	1.30 ± 0.13
EN136M	30	0.23 ± 0.02	4.95 ± 0.15	1.21 ± 0.26
HSBG Walk	30	0.43 ± 0.14 ^B	5.33 ± 0.32 ^B	1.08 ± 0.23 ^A

^A = significantly different from EN136S

^B = significantly different from both EN136 methods

The mean difference in F_ICO₂ values between EN136M unmanned and HSBG walk conditions was 0.13% with a 95% confidence interval of 0.05% to 0.22%. These results indicate that F_ICO₂ measurements obtained under EN136M unmanned procedures produced results that were only 0.05% to 0.22% higher than manned test results obtained under similar ventilatory conditions. The lower limit of agreement was -0.29% with a 95% confidence interval of -0.43% to -0.15%. The upper limit of agreement equaled 0.56% and the 95% confidence interval was 0.42% to 0.70%. Agreement between EN136M unmanned and HSBG walk F_ICO₂ results was accepted based upon the finding that the largest limit of agreement (0.56%) did not differ significantly from the maximal acceptable difference of 0.50% CO₂.

DISCUSSION

This study was implemented to compare in-mask CO₂ results obtained from unmanned and manned test methods for the same test respirator. As such, the main objective was to assess agreement between F_ICO₂ results of unmanned and manned measurement techniques. Utilization of unmanned testing for respirator certification is an obvious practical advantage compared to the time and effort required to implement human subject testing. Quantifying agreement between the unmanned and manned test methods would provide a clear understanding of proven differences between methods and determine whether or not they could be used interchangeably for respirator certification. Comparisons of

unmanned and manned test conditions required by the NIOSH CBRN certification standard for an APER were selected for study since both types of analysis are required to quantify respirator CO₂ retention (NIOSH, 2003). Given that the NIOSH unmanned test parameters utilize simulated breathing parameters associated with resting conditions, comparisons between NIOSH unmanned data and results from the HSBG wear trials that involved treadmill walking with breathing rates in excess of resting values were considered to be meaningless. Therefore, European unmanned test methods, which employ breathing parameters representative of human ventilation under moderate exercise (Johnson *et al.*, 1992; Caretti *et al.*, 2004), were used for comparing unmanned CO₂ results with data obtained under the HSBG walking test conditions.

Bland-Altman analysis showed that NIOSH unmanned testing produced F_ICO₂ results between 0.63% and 1.06% higher than manned testing and confirmed that the two methods did not agree for measures of F_ICO₂. Significantly higher values were also observed for minimum CO₂ and F_{ET}CO₂ parameters for unmanned compared to manned tests. The sedentary breathing rate employed by NIOSH assumes that respirator dead space is a fixed anatomical volume and an increase in tidal volume will dilute CO₂ concentration in the breathing zone (Kloos and Lamonica, 1966). As such, the larger average V_T associated with HSBG data compared to unmanned tests may explain differences in minimum CO₂ and F_ICO₂ values between conditions. However, subsequent data analysis with HSBG tidal volumes and breathing frequencies (V_T = 0.74 ± 0.08 L and fb = 13.3 ± 1.4 min⁻¹; N = 14) matched more precisely with the NIOSH simulated breathing parameters (V_T = 0.72 L and fb = 14.5) also found significantly greater values for minimum CO₂, F_{ET}CO₂, and F_ICO₂ for unmanned testing compared to manned tests. Since V_T effects on CO₂ parameters were not evident, these results suggest that the higher F_{ET}CO₂ levels of the NIOSH unmanned tests influenced differences in minimum CO₂ and F_ICO₂ values between conditions more than differences in V_T.

The similarities observed between EN136S and EN136M unmanned results for minimum CO₂, F_{ET}CO₂, and F_ICO₂ support the interchangeability of these test methods for quantifying respirator CO₂ retention as previously reported (Caretti and Coyne, 2008). However, comparisons between EN136S unmanned test data and HSBG walking test data were not in agreement. Unmanned average minimum CO₂ and F_{ET}CO₂ concentrations were significantly lower than HSBG walking results whereas F_ICO₂ levels obtained with EN136S unmanned procedures exceeded manned HSBG test results anywhere between 0.17% and 0.32%. Since ventilation parameters differed substantially between the two methods, similarity in results was not expected. The finding that F_ICO₂ results from the EN136S unmanned tests were substantially higher than HSBG results obtained with a much lower ventilation rate, but significantly higher average F_{ET}CO₂ concentration, also does not support the concept that respirator dead space is a fixed anatomical volume influenced by changes in V_T. A possible contributing factor for the observed differences may be related to the anatomical space occupied in the breathing zone of the test APER by the test headform compared to human subjects. In theory, the fixed anthropometrics of the test headform may have occupied less of the anatomical dead volume of the oro-nasal mask of the test APERs compared to that of the human test participants. With more oro-nasal mask space taken up by the nose, mouth, and chin, a lesser volume of air would be needed to fill and empty the dead space in the oro-nasal mask with every breath. Therefore, the smaller V_T found for the manned tests may have been more than enough to efficiently handle CO₂ exchange within the oro-nasal mask of the APER.

Even though minimum CO₂ and F_{ET}CO₂ values were significantly greater for manned compared to unmanned results, average F_ICO₂ values did not differ between EN136M unmanned and the HSBG walking procedures. Furthermore, F_ICO₂ results of EN136M unmanned procedures were no more than 0.22% higher than manned test results and the level of agreement between conditions was acceptable when tested against the maximal acceptable difference criterion. These findings indicate that the two methods are interchangeable with regard to determination of respirator F_ICO₂ levels. The close approximation of EN136M simulated ventilation rates to those of manned data from HSBG trials likely enhanced similarities in F_ICO₂ results between conditions.

At rest, $F_{ET}CO_2$ levels closely approximate those of lung alveolar air at the end of expiration (Jones *et al.*, 1979). Based upon reported values of alveolar CO_2 and $F_{ET}CO_2$ for healthy individuals at rest (Han *et al.*, 1997; Hansen *et al.*, 2007), the 5% $F_{ET}CO_2$ level utilized for NIOSH unmanned testing is plausible. However, the lower $F_{ET}CO_2$ levels recorded during HSBG test trials (mean = $4.29 \pm 0.38\%$; range = 3.60% to 4.83%) suggests that the NIOSH imposed $F_{ET}CO_2$ level may be somewhat high for the sedentary breathing conditions. In contrast, the $F_{ET}CO_2$ levels from HSBG walking test trials (mean = $5.33 \pm 0.32\%$) imply that the unmanned 5% $F_{ET}CO_2$ conditions of the EN136 methods may be a bit low for simulated exercise breathing conditions. Coupled with reported $F_{ET}CO_2$ data from similar exercising conditions (Jones *et al.*, 1979) and the observed range of HSBG walking $F_{ET}CO_2$ values of 4.65% to 5.82%, it is difficult to claim that the 5% set-point for the EN136 unmanned test methods was not representative of human data. Additional research is needed to assess comparisons of $F_{ET}CO_2$ results among unmanned and manned conditions matched for both ventilation and $F_{ET}CO_2$ values to determine if changes in unmanned $F_{ET}CO_2$ settings are warranted for enhancing interchangeability among methods.

CONCLUSIONS

The present study showed that NIOSH CBRN APER unmanned test methods for assessing respirator $F_{ET}CO_2$ produced results that were 0.63% to 1.06% higher than manned test results obtained under similar breathing conditions. Comparisons between $F_{ET}CO_2$ results from EN136S unmanned test procedures and HSBG walking test data were also not in agreement and resulted in higher $F_{ET}CO_2$ values on the order of 0.17% to 0.32%. Substantial differences in breathing conditions and $F_{ET}CO_2$ values between NIOSH unmanned and HSBG resting conditions, as well as between EN136S and HSBG walking conditions, accounted for the lack of agreement between methods. Agreement between $F_{ET}CO_2$ values from EN136M unmanned procedures and HSBG walking results was validated, suggesting that the two methods of $F_{ET}CO_2$ measurement could be used interchangeably. Since these methods were matched for breathing conditions, consideration should be given to redefining the EN136 test parameters to match the modified conditions of this study. Doing so would permit utilization of either the unmanned or manned procedures for APER certification testing.

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