The Partial Pressure of Inspired Carbon Dioxide Exposure Levels in the Extravehicular Mobility Unit

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ABSTRACT: NASA has been making efforts to assess the carbon dioxide (CO_2) washout capability of spacesuits using a standard CO_2 sampling protocol. This study established the methodology for determining the partial pressure of inspired CO_2 (P_ICO_2) in a pressurized spacesuit. We applied the methodology to characterize P_ICO_2 for the extravehicular mobility unit (EMU). We suggested an automated and mathematical algorithm to find the end-tidal CO_2 and the end of inspiration. We provided objective and standardized guidelines to identify acceptable breath traces, which is essential to accurate and reproducible calculation of the in-suit inhaled and exhaled partial pressure of CO_2 (PCO_2). The mouth guard-based method for measurement of inhaled and exhaled dry-gas PCO_2 was described. We calculated all individual concentrations of P_ICO_2 inhaled by 19 healthy subjects classified into 3 fitness groups. The transcutaneous PCO_2 was monitored as a secondary measure to validate washout performance. Mean and standard deviation values for the data collection performance and the CO_2 metrics were presented (e.g., minimum time weighted average PCO_2 at suited workloads of resting, 1000, 2000, and 3000 (BTU/h) were 4.75 ± 1.03, 8.09 ± 1.39, 11.39 ± 1.26, and 14.36 ± 1.29 (mmHg*s). All CO_2 metrics had a statistically significant association and all positive slopes with increasing metabolic rate. No significant differences in CO_2 metrics were found between the 3 fitness groups. A standardized and automated methodology to calculate P_ICO_2 exposure level is presented and applied to characterize CO_2 washout in the EMU. The EMU has been operated successfully in over 400 extravehicular activities (EVAs) and is considered to provide acceptable CO_2 washout performance. Results provide a basis for establishing verifiable PCO_2 requirements for EVA spacesuits.

Keywords: Inspired carbon dioxide (CO_2), CO_2 washout, extravehicular mobility unit (EMU) spacesuit, transcutaneous monitor.
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1. INTRODUCTION

Exposure to carbon dioxide (CO_2) during spaceflight is of primary concern for NASA toxicologists, flight surgeons, and astronauts as the effects of exposure to elevated levels can negatively affect astronaut performance and long-term health.[7,8] The exact duration, dose, and attributable physiologic effects, however, are highly variable and difficult to accurately predict. This uncertainty has led to a progressive lowering of vehicle and habitat exposure levels to help relieve some of the symptoms being reported by crewmembers that may be attributed to rising levels. These limits are intended to apply only to long-duration chronic exposures, in large habitat and vehicle volumes, and thus should not be applied to spacesuit exposures, where crewmembers may be acutely exposed to high levels of CO_2 in a confined helmet space.

Providing adequate CO2 washout is essential to the reduction of risk in performing suited operations. Washout capability refers to the ability of the suit ventilation system design to remove expired air from the vicinity of the oronasal area and helmet before being inspired by the crewmember. Efforts were undertaken by the NASA Johnson Space Center's (JSC) Human Physiology, Performance, Protection, and Operations (H-3PO) Laboratory to aid in the definition of a spacesuit specific exposure requirement and to characterize the CO_2 exposure environment of the extravehicular mobility unit (EMU) spacesuit, which is the longest continually operating United States spacesuit design, enabling safe execution of hundreds of in-flight extravehicular activities (EVAs), training sessions in neutral buoyancy environments, and ground-based tests. Specifically, we developed a simulated breathing technique to determine the effects on measured CO_2 data integrity of various hardware portions of a proposed standard test set up for in-suit measurement of CO_2.[6,9,12] Testing was then performed using this standard method to quantify the crewmember partial pressure of inspired CO_2 (P_ICO_2) in the EMU.[1,2] The level of the measured P_ICO_2 indicates whether the suit ventilation system to wash out the expired air in the helmet before being inspired by the crewmember.

In this paper, we provided the standardized description of testing requirements, conditions, and procedures necessary to acquire inhaled and exhaled dry-gas partial pressure of CO_2 in a pressurized EMU spacesuit which is used to calculate P_ICO_2. To determine the P_ICO_2 exposure level experienced by persons in the spacesuit, we proposed the optimization-based algorithm that automatically and accurately identify acceptable breath traces from the respiratory waveform. The CO_2 waveform displays changes in the CO_2 concentration during the respiratory cycle. The shape of the CO_2 waveform has also diagnostic value, but is currently assessed qualitatively, by visual inspection.[13] While visual inspection of the highest or lowest points in the waveform can discern gross changes, it cannot reliably recognize and therefore systematically leverage small gradations in shape that may have diagnostic value. Computational and quantitative analysis of the CO_2 waveform was also considered to define phases and related metrics using the characteristics of the rectangular-shaped waveform, including curved plateau and sloping regions.[11,14] However, the guidelines for selecting acceptable breath traces to calculate P_ICO_2 exposure level must be robust and consistent enough to exclude erratic breath traces during suited operations but not exclude true results from a spacesuit design that results in poor washout. No automated method for calculating inhaled and exhaled dry-gas P_ICO_2 concentration during exercise has been described in the literature nor has its usage been applied to provide the actual results of the EMU CO_2 washout. Our standardized testing protocol and automated analyzing process were designed to accurately and consistently test the interaction between the suit and a human test subject as a dynamic system and generate repeatable results under defined laboratory conditions.

This paper is organized as follows: Section 2 delineates the methodology and experimental design. Section 3 and Section 4 present the results and includes a discussion of our findings. The standard testing procedure proposed in this study may be used to measure the in-suit P_ICO_2 as well as calculating the average P_ICO_2 during the inhalation portion of the respiratory cycle while a human test subject is performing work at levels anticipated during suited operations in ground and flight environments.

2. METHODS

2.1. Subjects

This study protocol, reviewed and approved by the NASA JSC's Institutional Review Board (IRB), included a total of 19 healthy individuals (7 female and 12 male) who could exercise using an arm ergometer wearing an EMU spacesuit participated.

Intersubject variability due to respiratory variability between subjects (e.g., ventilation rates, breathing frequency, tidal volume, and respiratory exchange ratio at an absolute metabolic rate) may result in different PCO_2 measurements for similar flow rates and work rates. To define the subject population needed for this study, a separate study was completed characterizing expired ventilation, tidal volume, and respiratory rate trends across increased metabolic rates by subjects demographics using the VO_2peak tests. Based on the result, 19 test individuals were sought to evaluate the washout performance of the EMU across a range of subject fitness levels. Specifically, the lower end contained 7 persons with VO_2peak of less than 2.5 L/min (3000 BTU/h). The middle group contained 6 persons with 2.5-3.75 L/min, and the upper group contained 6 persons over 3.75 L/min (4500 BTU/h). Mean and standard deviation (SD) values of the absolute VO_2peak of subjects used in this study are shown in Table 1. As subjects work at a greater relative workload (% VO_2peak), expired ventilation increases and above ventilatory threshold, this increase is primarily driven by an increase in respiratory rate. It was hypothesized that a greater respiratory rate would lead to increased dead space ventilation, rebreathing of exhaled gas, and poorer CO_2 washout results.

Table 1. Group characteristics.

Group	Criterion	Number of subjects	VO_2peak ($L_{(STPD)}$/min)
1	≤ 2.5 L/min	7 (Male: 1, Female: 6)	2.21 (0.39)
2	2.5-3.75 L/min	6 (Male: 5, Female: 1)	3.12 (0.34)
3	≥ 3.75 L/min	6 (Male: 6, Female: 0)	4.07 (0.12)

* Mean (SD)

2.2. Equipment

A sample probe for the proposed standardized method is a commercial mouthguard (Battle Sports Oxygen Mouthguard) with an open hole at the front (Figure 1a). The sample line is placed through the roof of the mouth guard opening by puncturing the material and compression fitting the tubing. The mouth guard material provides secure placement. This places the sample line directly at the center of the subject's breathing airflow path, and the mouth guard is kept flush against the subject's face (Figure 1b). A 3.05 m (10ft) long, 0.159 cm (1/16 in) inner diameter flexible Tygon tubing was used, with no intermediate connectors (e.g., threaded adapters) between the probe end in the suit and the CO_2 sensor to minimize the error resulting from mixing caused by turbulent flow (Figure 1c). A sample flow rate of 1000 mL/min was used to result in a minimal error due to gas mixing, which was identified from our prior study. A sampling of air from within the spacesuit is driven by the pressure of the suit, which is tested at 19 psia (4.3 psid, which is the EMU nominal working pressure). To maintain laminar flow as closely as possible and control the flow rate to the sensor, an orifice (Bird Precision, Waltham, MA) was placed between the CO_2 sensor and the sample tubing (Figure 2). A flow and pressure meter was placed on the exhaust of the CO_2 sensor to verify that 1000 mL/min was being passed through the CO_2 sensor and that the sensor was not inadvertently pressurized during testing. In the cases where suit testing is performed at the ventilation loop pressure, which is typically less than 1 psid, removing the orifice and placing a vacuum pump at the exhaust port of the CO_2 sensor is acceptable for minimizing sampling configuration induced errors. All data were sampled at 50 Hz, which provides sufficient breath-by-breath resolution for accurate characterization of expired and inspired CO_2. Finally, the transcutaneous PCO_2 ($TcpCO_2$, TCM TOSCA®, Radiometer America, Brea, CA) sensor was affixed to the subject's cheek as a secondary measure of washout performance of the spacesuit (Figure 1c).

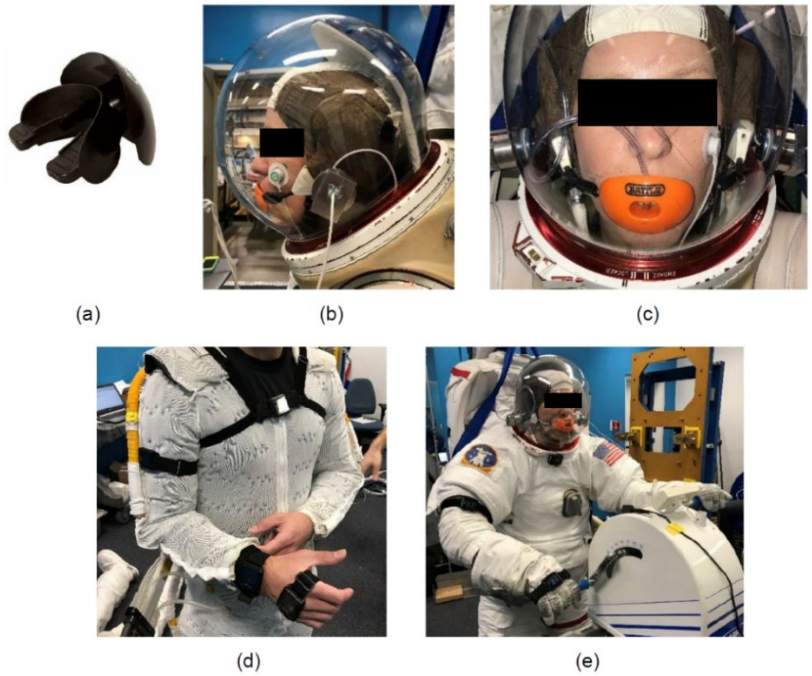
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Figure 1. (a) Bite style mouth guard. (b) Subject side profile with the mouth guard sample probe and the $TcpCO_2$ sample probe affixed to the subject's left cheek. (C) Front view of subject with sample line placed through the roof of the mouth guard opening, protruding ~5 mm into the mouth guard's breathing hole for direct air sampling of expired and inspired air. (d) Unsuited condition (LCVG and TCU worn), (e) Suited subject working on the arm ergometer.

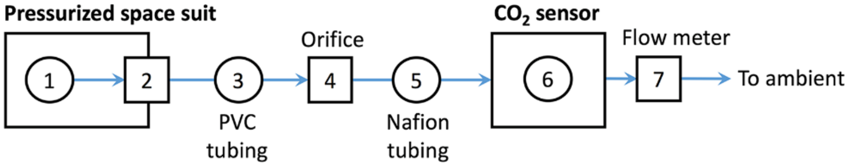


Figure 2. Air sampling configuration. (1) Mouth guard sample probe; (2) Suit pass-through port, open port potted with room temperature vulcanizing silicone (3) 10ft, 1/16 in ID Tygon® PVC tubing; (4) Orifice sized to achieve 1000mL/min to sensor; (5) Nafion tubing; (6) Infrared CO_2 sensor, AEI Technologies CD-3A; (7) Flow meter for sample flow rate verification.

2.3. Procedure

Subjects performed 2 components in this study: (1) an unsuited (liquid cooling and ventilation garment (LCVG) and thermal comfort undergarment (TCU) worn. (Figure 1d) characterization of respiratory performance at workloads of rest, 1000 British thermal unit per hour (BTU/h, 293 watts (W)), and 2000 BTU/h (586 W); (2) a suited (Mark-III spacesuit, Figure 1e) characterization of the EMU washout performance at workloads of standing rest, 1000 BTU/h, 2000 BTU/h, and, if achievable by the subject, 3000 BTU/h (879 W). Suit pressure was maintained at 4.3 psid and a flow rate of 6 ACFM, the nominal in-flight EMU EVA configuration. Test subjects wore the suit while weight relief was provided via an overhead trolley, during which time they exercised using an arm ergometer (Monark 881, HealthCare International, Langley, WA) placed on a test stand in front of the subject (Figure 1e). Metabolic rate was calculated in real-time from the total CO_2 production as measured by a gas analyzer (CD-3A, AEI Technologies, Bastrop, TX) at the air outlet from the suit using methods consistent with previous studies.[1,2]

Additionally heart rate was monitored to ensure that the suited subjects stayed within a safe exertion level. This study also investigated incorporation of a $TcpCO_2$ sensor within the suit for transcutaneous gas monitoring of CO_2 levels. An Apollo-era EMU helmet with dual feed ports on either side of the face, as shown in Figure 1b, was used to pass both the CO_2 sampling tubing (held in place by the mouth guard) and the $TcpCO_2$ sensor. The ports were filled with room temperature vulcanizing silicone adhesive to ensure no leaks occurred at the pass-through ports. A suit leak check also was performed before each test to verify pressure and flow were maintained at expected levels.

2.4. Data Processing

We have established the testing equipment and setup to get high resolution breath-by-breath trace data during suited operations for accurate characterization of expired and inspired CO2.[2] We have also shown that in-suit sampled respiratory traces via the simplified and controlled air sampling configuration (see Equipment and Procedure sections) were most reflective of physiologic characteristics. The peak PCO_2 during exhalation is known as the end-tidal CO_2 ($EtCO_2$) and normally occurs at the end of the alveolar plateau (see the in-suit sampled respiratory waveform in appendix). At the end of inspiration, the CO_2 trace generally reaches minimum, which is called the inspiration end. The total concentration of CO_2 inhaled by the subject is the area under the inspiration portion of the breath trace, which is defined by the $EtCO_2$ and inspiration end. The criteria for identification of the $EtCO_2$ and inspiration end points must be broad and robust enough to exclude erratic breath traces but not exclude true results from a suit design that results in poor washout. Likewise, identification of acceptable breath traces from within a data set is essential to accurate calculation of PCO_2 because the inhalation portion of the respiratory trace is the only component necessary for calculation of inspired CO_2 and washout performance. Due to the variability associated with human-in-the-loop (HITL) testing (e.g., subject size, suit fit, physiology, etc.), ventilation designs, and suit configuration there is a need to standardize this breath trace selection methodology. Several factors resulting from human-induced errors (e.g., talking, swallowing, coughing, etc.) also could affect the performance when calculating the inspired CO_2 concentration and building the standardized acceptable breath criteria. Therefore, it is important to create a guideline and methodology to accept potentially noisy expiratory data if it has not interfered with the inspiration portion of the breath trace. The criteria for identification of the start and end of inspiration points for calculating the suit CO_2 washout performance and identification of an acceptable inspiratory breath trace are described in appendix.

The time weighted average (TWA) PCO_2 represents the quantity of CO_2 inspired by the subject, excluding adjustments for pressure and water vapor saturation. The TWA PCO_2 calculation is the total acceptable area between the $EtCO_2$ and inspiration end points.[1,2,5] There are 2 PCO_2 values reported for this calculation: (1) Maximum TWA PCO_2, defined as the TWA PCO_2 calculated without accounting for any sampling hardware induced measurement uncertainty; and (2) Minimum TWA PCO_2, defined as the TWA PCO_2 calculated after scaling of the breath traces to account for sampling hardware induced measurement uncertainty.[10] The procedure for calculating maximum TWA PCO_2 and minimum TWA PCO_2 is described in appendix.

2.5. Statistical Analysis

Linear mixed-effects regression models were developed to characterize CO_2 response across metabolic rates within the Suit. The dependent variables of interest included maximum and minimum TWAs, $EtCO_2$, and $TcpCO_2$. All analyses and graphs were created in R. The *lme*() function within the *nlme* package was used to fit the mixed models. The form of the fixed effects within the models was CO_2 variable of interest ~ Average Metabolic Rate. Subject-specific random intercepts and slopes (random = ~1 + Average Metabolic Rate | Subject) were included to adjust for the repeated measures within individuals, allowing for individualized response. The overall relationship between in-suit PCO_2 metrics and other factors (e.g., metabolic rate) was assumed to be linear based on visual displays of the data. Graphs include both the subject-specific predictions and the overall estimated average response across the population. Analysis on whether fitness group (Group 1, Group 2, or Group 3) changes intercept or slope of the regression models were provided by incorporating group as a main effect and as an interaction term with Average Metabolic Rate. Visual inspection of model residuals showed conformity to normality requirements.

3. RESULTS

Mean and SD values for the data collection performance (e.g., metabolic rate, heart rate, acceptable breath, data collection time) are presented in Table 2. At the suited testing state, each average of the metabolic rate at workloads of 1000, 2000, and 3000 (BTU/h) was higher than the target metabolic rate, respectively. Each average of the metabolic rate at unsuited workloads of resting, 1000, and 2000 were lower than that at suited workloads. Heart rate was increased depending on the increment of the metabolic rate. At each unsuited and suited testing state, we collected data for about 1 minute and 2 minutes, respectively. We could retain at least 80% of the acceptable breath ratio at unsuited testing states and suited high metabolic rates (2000, 3000). However, at lower metabolic rates (suited resting and 1000), we collected data up to about 160 seconds because we could not have enough acceptable breath traces for reliable characterization of performance due to measurement artifact at the early stage of testing. Table 2 also includes summary statistics of the CO_2 metrics (e.g., maximum TWA, minimum TWA, $EtCO_2$, $TcpCO_2$). We compared calculated TWAs, detected $EtCO_2$ and measured $TcpCO_2$ to determine if there is any evidence for increasing the amount of CO_2 dissolved in the blood with increasing PCO_2 levels in the suit as metabolic rate increases. Table 3 and Figure 3 shows that $TcpCO_2$, TWAs, and $EtCO_2$ have a statistically significant positive association ($P < 0.005$) with metabolic rate; furthermore, they appear to be linear, supporting our choice of a linear mixed-effects model.

Table 2. Overall result (n = 19).

Variable, unit	Target metabolic rate unsuited (BTU/h)			Target metabolic rate suited (BTU/h)			
	Resting	1000	2000	Resting	1000	2000	3000
Metabolic Rate, BTU/h	385.88 (43.44)	1002.75 (53.42)	1783.63 (86.23)	672.79 (63.79)	1161.67 (95.13)	2104.77 (140.94)	3184.13 (178.81)
Heart Rate, bpm	81.85 (2.85)	114.12 (2.28)	139.08 (3.14)	76.66 (4.84)	98.94 (4.58)	122.83 (4.16)	133.90 (5.39)
Acceptable breath, %	88.16 (16.20)	99.38 (2.62)	98.25 (3.53)	50.13 (24.21)	68.55 (20.93)	81.85 (12.29)	87.02 (8.53)
Data collection time, s	62.99 (6.97)	61.36 (2.11)	59.94 (3.15)	164.54 (85.34)	164.28 (82.75)	122.45 (20.63)	115.96 (16.88)
Maximum TWA, mmHg*s	5.10 (1.16)	4.21 (1.02)	3.81 (0.85)	5.68 (1.17)	9.46 (1.62)	13.31 (1.55)	16.56 (1.47)
Minimum TWA, mmHg*s	3.86 (1.03)	2.75 (0.82)	2.15 (0.60)	4.75 (1.03)	8.09 (1.39)	11.39 (1.26)	14.36 (1.29)
$EtCO_2$, mmHg	37.04 (1.66)	38.94 (2.17)	39.15 (2.18)	34.05 (3.43)	38.05 (3.84)	44.00 (3.35)	49.29 (3.14)
$TcpCO_2$, mmHg	.	.	.	36.80 (0.39)	38.16 (0.43)	40.23 (0.44)	43.30 (0.46)

* Mean (SD)

Table 3. Fixed effects: F-tests and Coefficient tests.

Variable, unit	Test	numDF	denDF	F-value	p-value
Maximum TWA, mmHg*s	Intercept	1	1939	768.9	<0.0001
	Slope	1	1939	309.4	<0.0001
Minimum TWA, mmHg*s	Intercept	1	1939	692.0	<0.0001
	Slope	1	1939	335.9	<0.0001
$EtCO_2$, mmHg	Intercept	1	1939	1399.2	<0.0001
	Slope	1	1939	320.3	<0.0001
$TcpCO_2$, mmHg	Intercept	2	1939	1144.9	<0.0001
	Slope	2	1939	202.5	<0.0001

* F-tests

Variable, unit	Test	Coefficient	STD.Error	DF	t-value	*p*-value
Maximum TWA, mmHg*s	Intercept	4.35	0.31	1939	14.02	0.00
	Slope	0.00	0.00	1939	17.59	0.00
Minimum TWA, mmHg*s	Intercept	3.61	0.25	1939	14.45	0.00
	Slope	0.00	0.00	1939	18.33	0.00
$EtCO_2$, mmHg	Intercept	32.05	1.32	1939	24.27	0.00
	Slope	0.01	0.00	1939	17.90	0.00
$TcpCO_2$, mmHg	Intercept	35.91	1.21	1939	29.74	0.00
	Slope	0.00	0.00	1939	14.23	0.00

* Coefficient tests

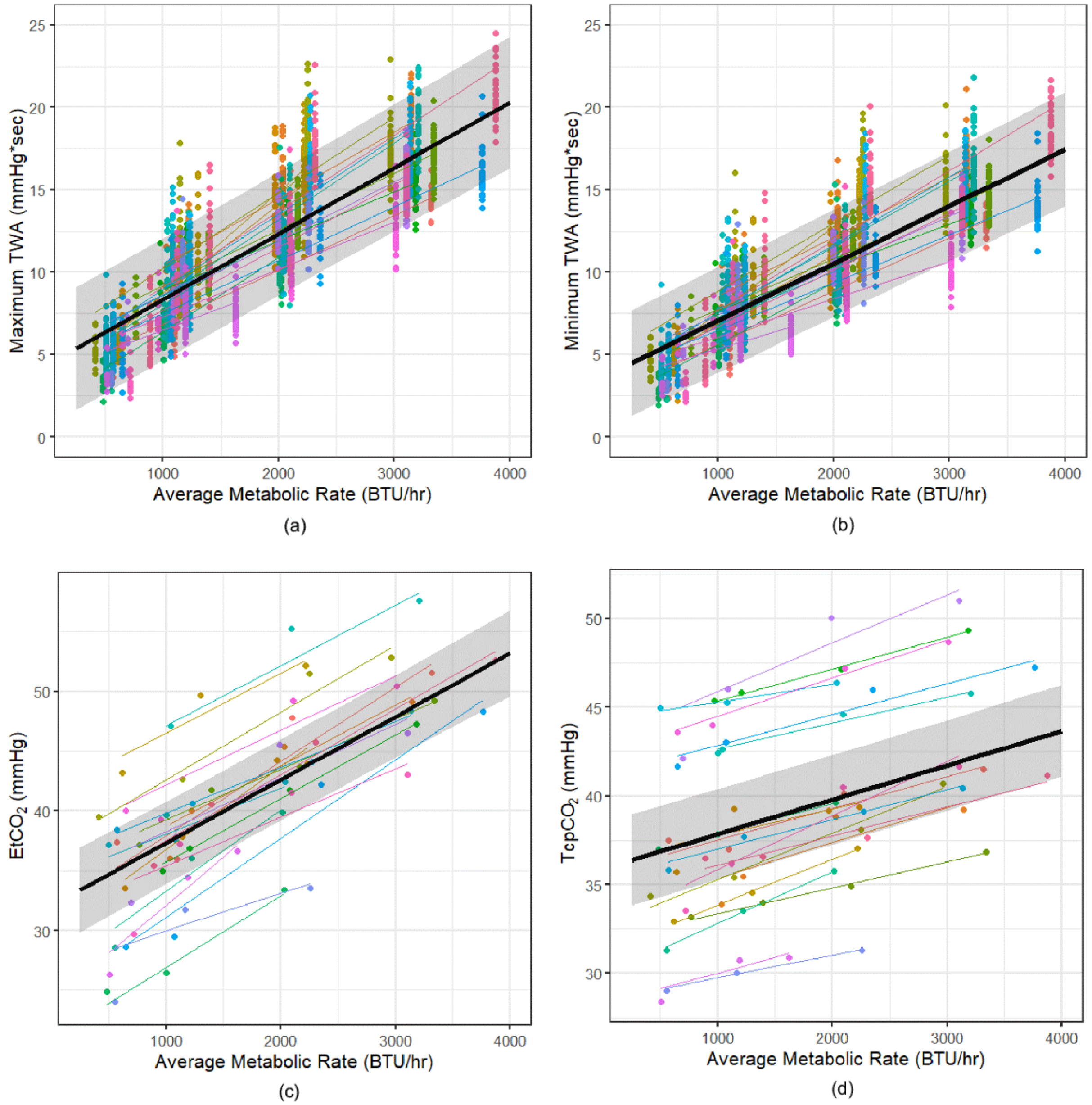


Figure 3. (a) Maximum TWA, (b) Minimum TWA, (c) $EtCO_2$, and (d) $TcpCO_2$ values both increased as a function of metabolic rate. The bold black line and the gray area are the modeled population response and the 95% confidence limits on the linear prediction line, respectively. All other colors reflect individual subject responses.

Finally, we investigated whether the physiology-related factors influence washout performance. Mean and SD values for the data collection performance (e.g., metabolic rate, heart rate, acceptable breath, data collection time) and the CO_2 metrics (e.g., maximum TWA, minimum TWA, $EtCO_2$, $TcpCO_2$) in all groups are presented in Table 4. Table 5, and Figure 4 shows the comparison results by fitness group in Table 4. Although sex was associated with the fitness groupings, none reached statistical significance for inclusion in the models of CO_2 variables (e.g., maximum and minimum TWAs, $EtCO_2$, $TcpCO_2$) or for differences in CO2 variables between groups ($P > 0.1$). Subjects in Group 1 could not achieve the higher metabolic rates in the spacesuit due to our study termination criteria. This study was classified as NASA level 3 medical monitoring, which limits subjects to submaximal aerobic effort. Therefore, the trial is terminated if the subject exceeds 85% of the age-predicted heart rate maximum for greater than 2 minutes. Using this trial termination criteria, the lower fitness subjects in Group 1 were not able to complete all target metabolic ranges.

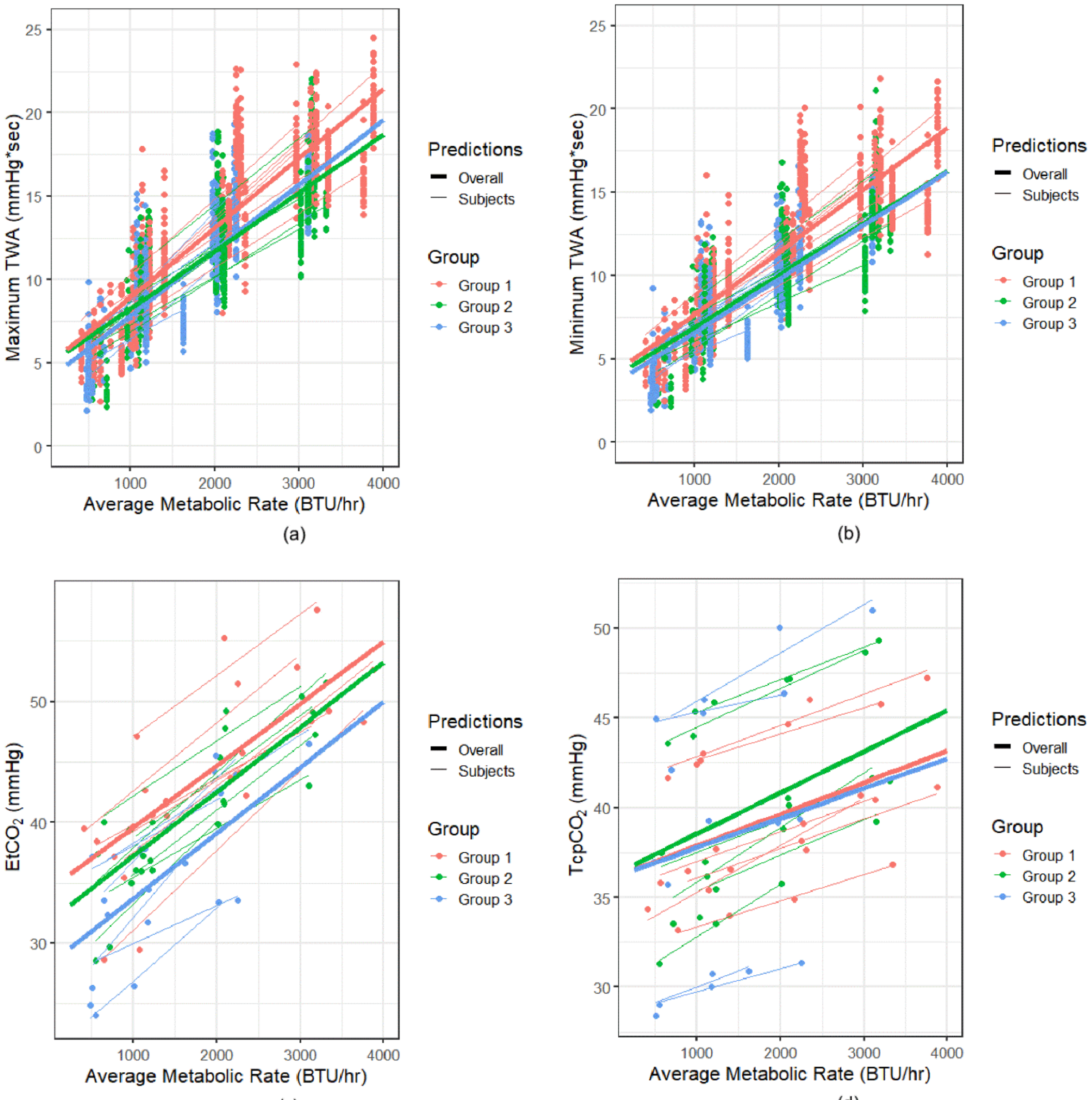
Table 4. Group results.

Variable, unit		Target metabolic rate unsuited (BTU/h)			Target metabolic rate suited (BTU/h)			
		Resting	1000	2000	Resting	1000	2000	3000
Group 1 (n = 7)	Metabolic Rate,	362.41	1019.59	1557.14	572.16	1139.45	2017.73	2669.75
	BTU/h	(41.05)	(52.17)	(82.80)	(55.43)	(82.89)	(154.73)	(118.59)
	Heart Rate,	89.88	134.66	151.40	66.04	110.81	139.07	126.72
	bpm	(3.20)	(2.53)	(3.80)	(4.10)	(3.95)	(3.76)	(3.17)
	Acceptable breath,	92.65	100.00	98.89	53.50	71.45	84.07	74.97
	%	(7.72)	(0.00)	(2.48)	(24.66)	(18.65)	(10.24)	(14.78)
	Data collection time,	60.72	60.55	60.69	163.82	164.31	111.89	90.83
	s	(0.74)	(0.60)	(0.69)	(96.46)	(96.85)	(22.39)	(43.85)
	Maximum TWA,	6.89	4.10	4.12	4.83	9.06	12.30	15.53
	mmHg*s	(1.81)	(1.05)	(0.89)	(1.07)	(1.34)	(1.54)	(1.61)
	Minimum TWA,	5.19	2.49	2.03	3.97	7.76	10.27	12.88
	mmHg*s	(1.61)	(0.80)	(0.58)	(0.96)	(1.15)	(1.27)	(1.51)
	$EtCO_2$,	38.65	35.40	34.71	31.64	36.50	41.15	45.22
	mmHg	(1.97)	(1.67)	(1.89)	(4.33)	(3.82)	(3.35)	(3.63)
	$TcpCO_2$,	.	.	.	35.73	37.67	39.20	45.19
	mmHg				(0.32)	(0.39)	(0.34)	(0.27)
Group 2 (n = 6)	Metabolic Rate,	366.71	983.36	1827.51	748.50	1136.77	2071.16	3152.53
	BTU/h	(41.14)	(65.10)	(84.62)	(65.37)	(121.97)	(117.15)	(174.08)
	Heart Rate,	84.84	116.08	143.25	93.03	108.00	127.74	150.16
	bpm	(2.24)	(1.74)	(2.16)	(6.07)	(5.20)	(4.17)	(3.67)
	Acceptable breath,	82.50	100.00	95.96	49.83	63.77	82.01	89.89
	%	(23.63)	(0.00)	(4.95)	(26.33)	(20.76)	(16.90)	(4.62)
	Data collection time,	60.28	62.17	60.68	112.34	120.52	124.43	120.70
	s	(1.01)	(3.39)	(0.90)	(25.67)	(0.55)	(8.04)	(0.43)
	Maximum TWA,	4.63	4.55	3.83	5.96	9.35	12.26	15.32
	mmHg*s	(0.95)	(1.08)	(0.94)	(1.17)	(1.59)	(1.52)	(1.18)
	Minimum TWA,	3.47	2.98	2.25	4.94	7.89	10.54	13.29
	mmHg*s	(0.75)	(0.85)	(0.66)	(0.99)	(1.36)	(1.19)	(0.96)
	$EtCO_2$,	37.47	39.01	38.67	34.45	37.57	44.26	48.28
	mmHg	(1.29)	(2.60)	(2.36)	(2.92)	(4.32)	(3.41)	(3.14)
	$TcpCO_2$,	.	.	.	37.52	38.67	41.58	44.08
	mmHg				(0.36)	(0.45)	(0.41)	(0.38)
Group 3 (n = 6)	Metabolic Rate,	415.30	1002.50	1935.80	714.50	1212.50	2239.91	3391.92
	BTU/h	(46.71)	(43.21)	(90.43)	(71.97)	(82.56)	(148.64)	(202.83)
	Heart Rate,	74.64	88.19	125.33	72.68	76.03	98.98	122.73
	bpm	(3.13)	(2.52)	(3.39)	(4.46)	(4.69)	(4.61)	(7.57)
	Acceptable breath,	90.00	97.78	100.00	46.49	69.93	79.09	88.65
	%	(14.91)	(4.97)	(0.00)	(25.60)	(26.21)	(10.78)	(6.67)
	Data collection time,	66.53	61.51	58.58	217.57	208.00	132.80	120.40
	s	(10.28)	(1.37)	(5.21)	(88.03)	(93.83)	(24.00)	(0.31)
	Maximum TWA,	4.40	3.98	3.54	6.38	10.02	15.52	17.94
	mmHg*s	(0.94)	(0.92)	(0.72)	(1.29)	(1.95)	(1.60)	(1.67)
	Minimum TWA,	3.37	2.85	2.16	5.48	8.69	13.56	15.75
	mmHg*s	(0.90)	(0.81)	(0.56)	(1.16)	(1.69)	(1.33)	(1.48)
	$EtCO_2$,	35.72	43.81	43.32	36.47	40.35	47.07	51.50
	mmHg	(1.77)	(2.35)	(2.24)	(2.88)	(3.39)	(3.30)	(2.98)
	$TcpCO_2$,	.	.	.	37.32	38.22	40.07	42.03
	mmHg				(0.51)	(0.45)	(0.58)	(0.59)

* Mean (SD)

Table 5. Group comparison.

Variable, unit	Test	numDF	denDF	F-value	p-value
Maximum TWA, mmHg*s	Intercept	2	15	0.49	0.62
	Slope	2	1862	1.20	0.30
Minimum TWA, mmHg*s	Intercept	2	15	0.63	0.55
	Slope	2	1862	1.53	0.22
$EtCO_2$, mmHg	Intercept	2	15	0.63	0.55
	Slope	2	1862	1.53	0.22
$TcpCO_2$, mmHg	Intercept	2	15	0.14	0.87
	Slope	2	1862	2.35	0.10



(a) (b) (c) (d)

Figure 4. Group comparisons: (a) maximum TWA, (b) minimum TWA, (c) $EtCO_2$, and (d) $TcpCO_2$.

4. DISCUSSION

A standardized methodology for measuring PCO_2 in spacesuits is important to verify if ventilation designs maintain safe levels of CO_2 during all suited operations. In this study, we proposed an objective and quantitative framework from which acceptable breath traces are identified and then analyzed. An example of breath trace data is to illustrate initial identification of the acceptable breath traces for analysis (see Figure 4 in Appendix). The guidelines for selecting acceptable breath traces must be robust and consistent enough to exclude erratic breath traces but not exclude true results from a spacesuit design that results in poor washout. For example, a high-velocity ventilation inlet jet into the helmet may create significant turbulence and result in a single breath sample having both low content CO_2 gas and high CO_2 gas as it mixes within the helmet. We minimized this artifact by placing the sample probe directly in the flow path of the expiration/inspiration; however, it is not entirely unavoidable and ultimately governed by suit design. For this reason, we cannot discard all erratic traces as they may be a result of poor washout. Therefore, the guideline we proposed aimed to capture potential washout effects while ensuring that measurement noise and human-induced error should not affect the calculation of TWAs.

The measurement or human-induced errors are not representative of normal steady-state breathing and thus should be deemed unacceptable for accurate characterization of PCO_2. In our previous study, we mentioned that the breath trace in Phase I is acceptable if the concentration trend during the expiration phase and plateau is "continually increasing" to the peak $EtCO_2$ point. In this study, we accepted the breath if the amplitude of inspiration start is greater than 90% of the amplitude of the starting point in the plateau period during Phase I (see Figure 3b in Appendix) to accept potentially noisy expiratory data if it has not interfered with the inspiration portion of the breath trace. Likewise, we provided the objective and quantitative guidelines to robustly exclude erroneous data resulting from human-induced errors during Phase II and Phase III (see Figure 3c and Figure 3d in Appendix), respectively. We can determine the number of acceptable breath traces by using the guidelines for the acceptable breath trace and the data collection time. Mean (SD) of the number of acceptable breath traces in unsuited and suited conditions were 15.72 (4.52) and 28.72 (10.55), respectively. Future work should explore the minimum data collection time at each testing condition to retain enough acceptable breath traces for accurate characterization of performance with several types of spacesuits.

In this study, the PCO_2 in each subject also was determined by transcutaneous monitoring. A transcutaneous monitor measures the blood-gas CO_2 ($TcpCO_2$) to provide an estimate of the partial pressure of arterial CO_2. We compared $TcpCO_2$ with our CO_2 variables (TWAs and $EtCO_2$) to determine if there is any evidence for increasing blood-gas CO_2 levels with increasing PCO_2 levels in the suit as metabolic rate increases. No slope differences between $TcpCO_2$, TWAs, and $EtCO_2$ were found when evaluated the significance of fixed effects (Table 3). Figure 3 showed the slopes of $TcpCO_2$, TWAs, and $EtCO_2$ were all positive, which means that all CO_2 measurements and the metabolic rate are positively correlated. NASA pursues a standardized methodology of the PCO_2 quantification in spacesuits to verify if ventilation designs maintain safe levels of CO_2 during suited operations.

The EMU has been used 449 times during flight EVAs from 1983 to 2019, as well as for training at the Neutral Buoyancy Laboratory (NBL). The major objectives of flight EVAs are consistently accomplished and the authors are aware of reported symptoms consistent with high CO_2 during EVAs performed in the EMU spacesuit. Metabolic rates obtained in the EMU are typically measured between 800 and 1200 BTU/h and rarely exceed 1500 BTU/h during flight EVAs and NBL runs. Our assumption was that the performance of EMU CO_2 washout has been operationally acceptable for the metabolic rates generated during both during NBL training and flight EVA. However, the new design for the exploration EMU (xEMU) allows astronauts to move around much more dynamically, probably with higher metabolic rates. NASA initially defined Spacecraft Maximum Allowable Concentrations (SMACs) for habitats based on data from ambient wall-mounted sensors. However, within a spacesuit, the precise location at which gas is sampled significantly affects the measured PCO_2 values. Therefore, the level of PCO_2 measured from the gas being inspired by users of the xEMU should be quantified and defined using a valid and reliable methodology. This is the first methodology that demonstrated a quantitative and standardized methodology necessary for calculating PCO_2 concentration experienced by persons in a pressurized spacesuit. The EMU CO_2 washout data described herein was a primary consideration in the subsequent development of the inspired CO_2 requirements for the new xEMU spacesuit, which will be detailed in our future work. Future work also will introduce the EMU/xEMU requirements about the acceptable limit on the TWA, provide a way to compare in suit CO_2 values of the EMU/xEMU, and develop exposure standards for suited EVA exposures.

The present study involved several limitations. First, our result for each group is limited to the small sample sizes inherent to research involving NASA personnel. Thus, our results should not be generalized beyond the testing environment in this study. The physiologic measures (e.g. heart rate) may further clarify with a large number of qualified subjects. Next, the current NASA Standard Testing Procedure recommends that all data will be visually assessed prior to final data reporting to verify any automated computational errors did not occur.[4] Due to noise effects resulting from the human-in-the-loop nature, it is likely that fully automating the analysis in a way that accounts for all subject differences in breathing patterns and data may not be possible. In the case of disagreement with identification, it is recommended that multiple reviewers manually interpret the data and a consensus is reached. Though we could not find any computational errors with the current dataset for this study, future work using crewmembers data is needed to fully validate and understand the potential benefits of the proposed automated approach.

CONFLICT OF INTEREST

The authors have no competing interests to disclose.

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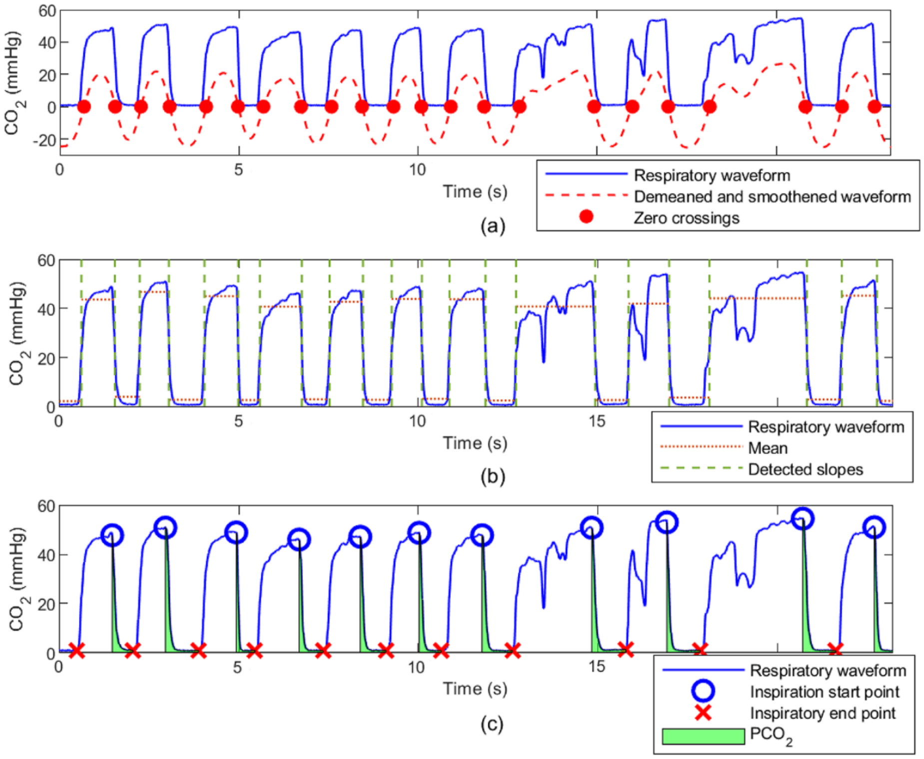
APPENDIX

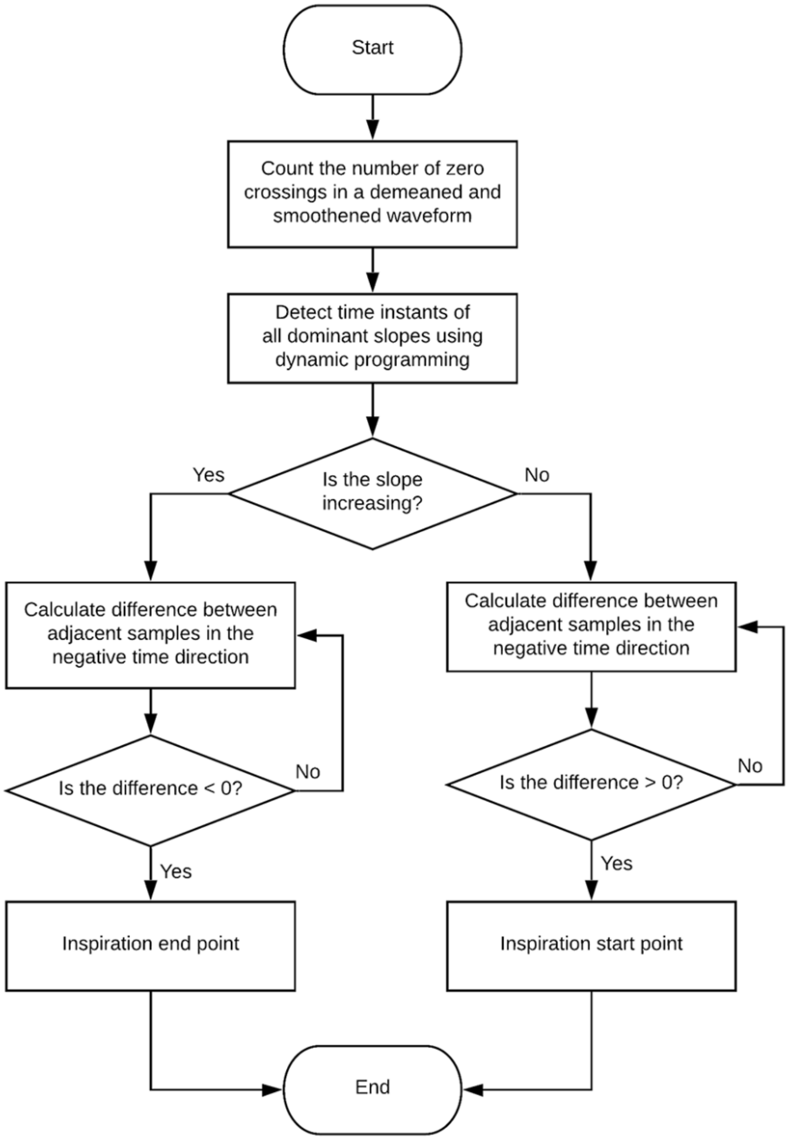
This appendix is aimed to introduce the standardized criteria 1) to quantitatively detect the $EtCO_2$ and inspiration end, 2) to objectively determine acceptable breath traces, and 3) to automatically calculate P_ICO_2 from the accepted inspiratory breath traces in a consistent and accurate manner.

The respiratory waveform has a sloped decrease and increase after the $EtCO_2$ (blue circle: ○) and inspiration end (red cross: ×), respectively (see Figure 1). Detection of such abrupt changes has been considered as one of the important practical problems arising in various applications.[1] In this study, we have considered a mathematical optimization method which is commonly used to find the best solution to a problem by maximizing or minimizing an objective function with respect to constraints. Specifically, we applied a parametric global optimization method based on a penalized contrast to automatically find all the dominant slopes in the respiratory waveform.[5] In the parametric method, the procedure becomes straightforward when the number of changes is known. When the number is unknown a penalty term, which is responsible for over- or under-fitting, should be added to the contrast function. For example, if the number of change points was over or underestimated, less drastic changes could be possibly missed out or unnecessarily added. In the extreme case, the most drastic change or every point could be considered as a change point, respectively. To create a guideline to accept potentially noisy expiratory data, we counted the number of zero crossings (red filled circles in Figure 1a) in a demeaned and smoothened waveform (a red dashed line in Figure 1a). Specifically, we subtracted a mean of the waveform and smoothened the demeaned waveform with a moving average using a Gaussian window of length 100 at the 50 Hz sampling rate. In Figure 1a, 22 zero-crossings were counted that are matched with the number of dominant slopes. Given the number of zero-crossings, an optimization algorithm based on dynamic programming with early abandonment was used to minimize the contrast function.[4] Figure 1b shows all the detected slopes (green dashed lines) in the respiratory waveform as a result of the optimization algorithm.



Appendix Figure 1. Procedure for calculating PCO_2: (a) a simple method for counting the number of change points, (b) detected slopes, (c) PCO_2 inspiration start and end points.

A step-by-step flow chart for automatically detecting the inspiration start and end is presented in Figure 2. As described in the flow chart, we detected the inspiration start and end by tracking differences between adjacent samples in the negative time direction based on time instants of dominant slopes. Figure 1c shows the inspiration start (blue circles: ○) and end (red crosses: ×) in the respiratory waveform. Even though significant noise is present during the expiration phase and plateau (Figure 1c), we were successful in automatic detection of the inspiration start and end by choosing a point clearly on the inspiratory down- and up-slope. Finally, P_ICO_2 concentration was calculated by integrating the area underneath the inhalation portion of the curve as shown in Figure 1c (green areas). Traditional investigations on the detection of change-points could be affected by small amounts of signal noise. However, Figure 1 shows that our method robustly detected the $EtCO_2$ and inspiration end points.



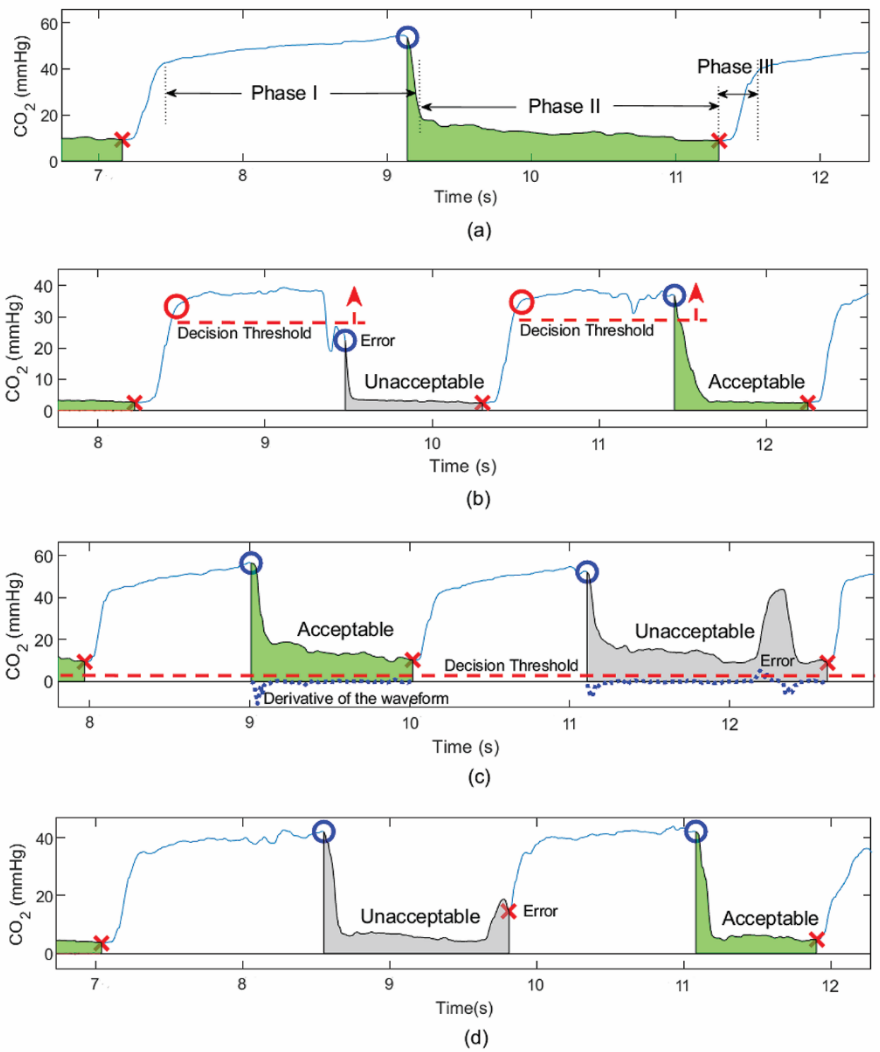
Appendix Figure 2. Flow chart of the procedure for detecting inspiration start and end points.

Identification of acceptable breath traces from within a data set is essential to accurate calculation of the in-suit P_ICO_2. Due to the variability associated with HITL testing (e.g., subject size, suit fit, physiology, etc.), ventilation designs, suit configuration, there is no single method that can be applied across all suit configurations and tests. Considering this, guidelines for determining acceptable traces for analysis have been established to provide a consistent method by which this analysis can be completed. The following are descriptions of acceptability criteria at each phase of the breath (see Figure 3a):

i. Phase I (plateau during the expiration phase and sloped decrease after inspiration start): Breath is acceptable if the amplitude of inspiration start (blue circle: ○) is greater than 90% of the amplitude of the starting point in the plateau period (red circle: ○) as shown in Figure 3b. The knee point detection algorithm[6] provides the point of maximum curvature (red circle: ○) after the inspiration end (red cross: ×) that is a mathematical measure of how much a function differs from a straight line.[3,7] If the amplitude of inspiration start (blue circle: ○) is less than 90% of the amplitude of the starting point in the plateau period (red circle: ○) (Figure 3b), the breath is unacceptable. The shape of the plateau between the inspiration end and the next inspiration start is variable depending on the type of suit. This guideline provides a consistent and mathematically justifiable answer regardless of the shape of the plateau during Phase I.

ii. Phase II (plateau during the inspiration phase): Breath is acceptable if the plateau during Phase II is maintained flat without an error in measurement. To detect an unexpected error during Phase II, a decision threshold derived from the first derivative of the waveform of Phase II is set (Figure 3c). If the amplitude of the first derivative of the waveform is greater than 3 (mmHg/s), the breath is unacceptable.

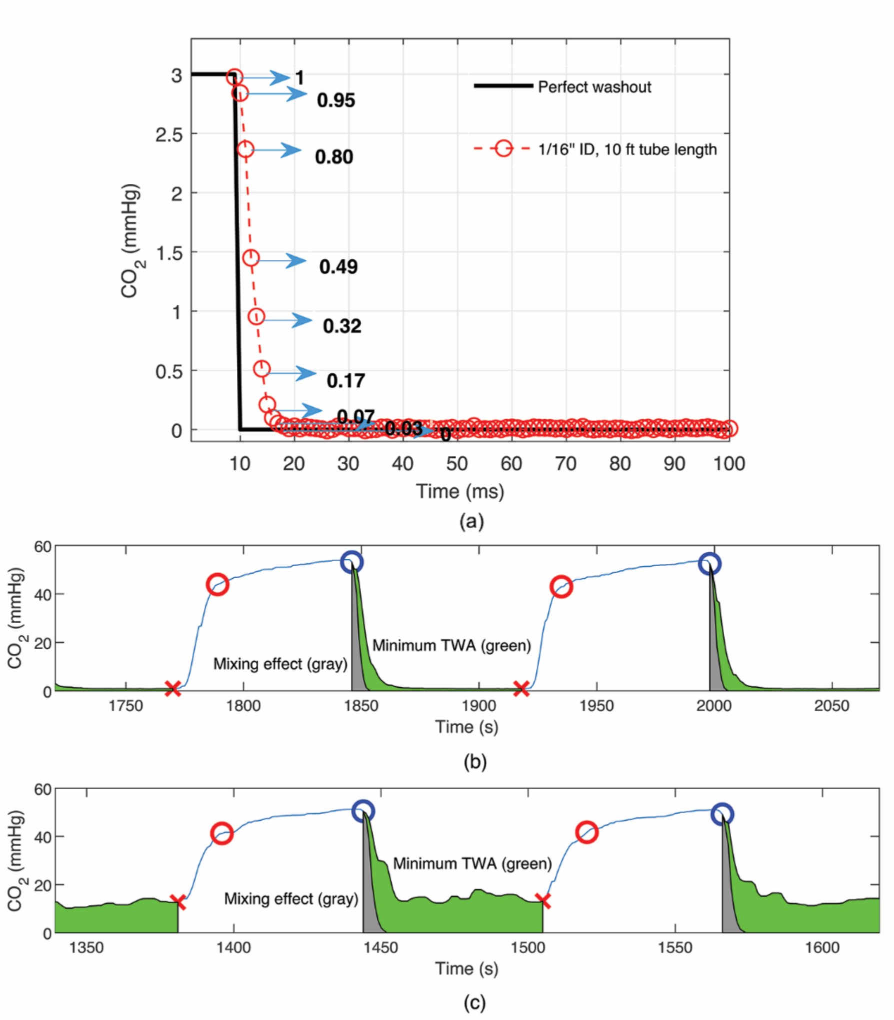
iii. Phase III (sloped increase after inspiration end): Breath is acceptable if the inspiration slope is continuously increasing without an error in measurement. During the process to find an inspiration end point from a sloped increase, this unwanted peak (Figure 3d) can be detected as a fake inspiration end point before reaching the start point of Phase III. The inspiration end point is, therefore, a wrong choice and the breath unacceptable if 90% of the amplitude at the inspiration end point is greater than the average of adjacent inspiration end points.



Appendix Figure 3. Identification of acceptable breath traces: (a) Three phases of a breath, examples of acceptable breaths: (b) Phase I, (c) Phase II, (d) Phase III.

The maximum TWA PCO_2 is calculated for each breath as identified above. The total area between the identified inspiration start and inspiration ends calculated using an approximate integral via the trapezoidal method with unit spacing. This total area per breath is divided by the time duration between the $EtCO_2$ and inspiration end points for that breath to result in the maximum TWA PCO_2. All individual PCO_2 maximum TWAs are reported as individual breath data points, which can then be used to characterize the spacesuit performance.

Benchtop testing demonstrated that even if pure sources of gas are used, mixing effects remain as a result of the measurement hardware.[2] If no mixing effects were present, switching a valve from 3% to 0% would result in an immediate drop in CO_2 value measured, however, a square wave during testing was not observed. The scale of the mixing can be found for each data point before measurement of 0% gas is observed as each data point should report 0% in a perfect washout case. The percentage difference between gas 1 (3%) and gas 2 (0%) during this transition is the degree of uncertainty in the measurement. Each acceptable breath collected is scaled with these percentage differences to identify the area of inspiration that is affected by hardware induced mixing effects. These inspired data are considered real; however, it is not possible to definitively state what portion is attributable to the suit washout performance versus the sampling hardware. This only serves to bound the potential minimum (excluding uncertainty) and maximum PCO_2 value. Both values are reported. Figure 4a plots an "inspiration trace" collected in the benchtop testing between 2 known gasses illustrating the mixing effect and indicating the scaling factors for each data point between gas 1 and gas 2. Figure 4b and Figure 4c illustrate the area that is removed from the maximum calculation when these scaling factors are applied to calculate the minimum PCO_2.



Appendix Figure 4. (a) Perfect washout versus actual measurement using the benchtop system. Area of mixing uncertainty (gray) is subtracted from total breath trace area when calculating minimum PCO_2 (green): (b) example minimum TWA unsuited, (c) example minimum TWA suited.

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