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Characterization of Carbon Dioxide Washout Measurement Techniques in the Mark-III Space Suit

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A space suit must provide adequate carbon dioxide (CO_2) washout inside the helmet to prevent symptoms of hypercapnia. In the past, an oronasal mask has been used to measure the inspired air of suited subjects to determine a space suit's CO_2 washout capability. While sufficient for super-ambient pressure testing of space suits, the oronasal mask fails to meet several human factors and operational criterion needed for future sub-ambient pressure testing (e.g. compatibility with a Valsalva device). This paper describes the evaluation of a nasal cannula as a device for measuring inspired air within a space suit. Eight test subjects were tasked with walking on a treadmill or operating an arm ergometer to achieve target metabolic rates of 1000, 2000, and 3000 British thermal units per hour (BTU/hr), at flow rates of 2, 4, and 6 actual cubic feet per minute (ACFM). Each test configuration was conducted twice, with subjects instructed to breathe either through their nose only, or however they felt comfortable. Test data shows that the nasal cannula provides more statistically consistent data across test subjects than the oronasal mask used in previous tests. The data also shows that inhaling/exhaling through only the nose provides a lower sample variance than a normal breathing style. Nose-only breathing reports better CO_2 washout due to several possible reasons, including a decreased respiratory rate, an increased tidal volume, and because nose-only breathing directs all of the exhaled CO_2 down and away from the oronasal region. The test subjects in this study provided feedback that the nasal cannula is comfortable and can be used with the Valsalva device.

Nomenclature

ACFM = actual cubic feet per minute
BTU = British thermal unit
C = Celsius
CO_2 = carbon dioxide
EMU = extra-vehicular mobility unit
EVA = extra-vehicle activity
Hr = hour
Hz = hertz
kcal = kilocalorie
LCG = liquid cooling garment
lO_2 = liter of oxygen
mmHg = millimeters of mercury
NASA = National Aeronautics and Space Administration
$ppCO_2$ = partial pressure of carbon dioxide
psia = pounds per square inch absolute
psig = pounds per square inch gauge
$\dot{q}_{met}$ = metabolic rate
RER = respiratory exchange ratio

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RR = respiratory rate
SCFM = standard cubic feet per minute
$\dot{V}_{gas}$ = standard volumetric flow rate

I. Introduction

It is essential to provide adequate carbon dioxide (CO_2) washout in a space suit to reduce the risks associated with manned operations in space suits. CO_2 toxicity symptoms can include reduced cognitive performance, dyspnea, fatigue, dizziness, faintness, visual disturbances, and headache[5]. To maintain the health and safety of test subjects and astronauts NASA imposes limits on inspired CO_2 levels for space suits when they are used in space and for ground testing.

Testing and/or analysis must be performed to verify that a space suit provides adequate CO_2 washout. Previous testing of developmental space suits[1,2] has used an oronasal mask that funnels all exhaled and inhaled air from the nose and mouth through a single opening, where samples are collected at the left and right sides (Figure 2, b). However, there are several concerns with this approach. The oronasal mask cannot be used with a Valsalva device, which is required for sub-ambient pressure testing with space suits. Additionally, the mask may alter the nominal air flow path inside the helmet because the mask protrudes from the subject's face. This could divert air to the sides of the test subject's face. The oronasal mask also has dead space volume at the front of the mask, which could alter the washout characteristics of the helmet and appears to compress the respiratory waveform leading to elevated local minimums and diminished peak values. To mitigate these concerns, a nasal cannula was investigated as a method for measuring inspired CO_2 based on the hypotheses that the low profile design will not interfere with the nominal helmet air flow path, the placement directly in the nasal cavity will reduce any dead space effects, and the construction with compressible material will make it compatible with a Valsalva device.

Specific objectives of this test were to: (1) compare data collected from the nasal cannula to data collected from past oronasal mask evaluations; (2) determine if a particular breathing style (nose only vs. unrestricted) affects the measurement characteristics of the nasal cannula; and (3) determine if the nasal cannula meets the needs of human factors criteria, such as comfort and being able to use the Valsalva device.

II. Test Methodology

Eight test subjects were used in this study. The test subjects used a treadmill or an arm ergometer to achieve the metabolic rates listed in Table 1. The flow rate was set at 2, 4, or 6 ACFM. Suit pressure was maintained at 4.3 psig for all test points. Subjects were instructed to breathe either exclusively through their nose, or however they felt comfortable (referred to as "Normal" in Table 1). Samples were collected over two minute intervals where possible. In some cases, however, typically at lower suit flow rates, CO_2 partial pressure safety limits were reached and the test point was terminated early.

Table 1. Test matrix.

		Flow Rate (ACFM)		
Metabolic Rate (BTU/hr)	**Breathing Technique**	**6**	**4**	**2**
500 (Resting)	Nose-Only	x	x	
1000	Unrestriced (Mouth + Nose)	x	x	x
	Nose-Only	x	x	x
2000	Unrestriced (Mouth + Nose)	x	x	x
	Nose-Only	x	x	x
3000	Unrestriced (Mouth + Nose)	x	x	

A. Quantitative Data

The metabolic rate was measured to ensure that each test subject experienced the same work rate and produced equivalent CO_2 at each test point. Metabolic rate was calculated based on CO_2 measurements at the suit exhaust. The supply air for the suit was maintained at a very low (<0.05%) CO_2 concentration. Therefore, the only significant source of CO_2 inside the space suit was the subject. This method of metabolic rate measurement assumes that the suit ventilation design ensures proper mixing of gas throughout the suit, and that gas sampled at the exhaust is representative of gas in the overall suit. This method has been used in previous CO_2 washout tests[1, 2]. In addition to CO_2 concentration at the outlet, the flow rate of breathing air was also measured and a constant respiratory exchange ratio (RER) of 0.85 was assumed. Equation 1 shows how metabolic rate was calculated, where $\dot{\mathrm{q}}_{\mathrm{met}}$ is the metabolic rate, $\dot{\mathrm{V}}_{\mathrm{gas}}$ is the standard volumetric flow rate of gas, $\%\mathrm{CO}_2$ is the percentage of CO_2 as measured in the CO_2 exhaust, and RER is the respiratory exchange ratio. RER is the ratio between the amount of CO_2 produced and oxygen consumed, This RER value has been used in previous space suit CO_2 washout tests[1,2].

$$\dot{q}_{met} = 4.8\frac{kcal}{lO_2} * \dot{V}_{gas} * \frac{\%CO2_{out}}{RER} \quad (1)$$

The metabolic rate data acquisition system consisted of a CO_2 analyzer (AEI Technologies CD-3A CO_2 sensor) at the suit exhaust and a flow meter (Kurz 500-series) at the suit inlet. The Kurz flow meter output is flow rate in SCFM based on a standard temperature of 25°C and a pressure of 14.7 psia. Small variations in suit pressure were not recorded; the pressure was assumed to be constant at 4.3 psig.

Inspired CO_2 was measured to quantify the CO_2 washout in the suit's helmet. As with previous space suit CO_2 washout tests[1,2], the inspired CO_2 was assumed to be the minimum (trough) CO_2 value in each breath cycle. While this does not completely capture the full inhalation profile, Ref. 4 shows that the trough CO_2 value accurately approximates the inspired CO2. In addition to inspired CO_2, the expired (peak) CO_2 values were monitored. Normal partial pressures of end tidal CO_2 ($P_{ET}CO_2$) ranges from 34-42mmHg and tends to increase with exercise and decrease with hyperventilation[8]. $P_{ET}CO_2$ is often used as an index of arterial CO2 values, so significant increases in $P_{ET}CO_2$ would indicate accumulation of CO_2 in the blood, which should be avoided. Peak CO_2 values different from this range could indicate a problem with the test setup, therefore a normal peak CO_2 was confirmed prior to the start of data collection. An example respiratory profile is shown in **Error! Reference source not found.**.

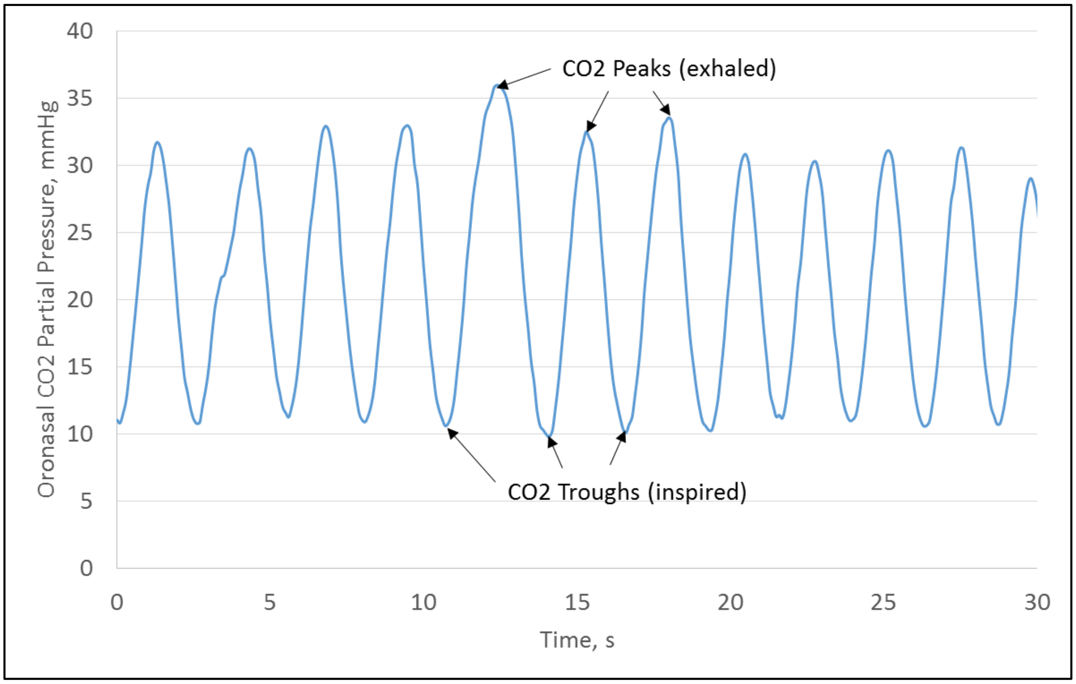


Figure 1. Inspired CO_2 was estimated by measuring the respiratory CO_2 troughs. End Tidal CO_2 was estimated by measuring the respiratory CO_2 peaks.

To measure inspired CO_2, a high-speed CO_2 sensor is needed to measure the full respiratory profile of the test subject. This test used an AEI Technologies CD-3A infrared CO_2 sensor which outputs at 25 Hz, which then was reduced to 10 Hz via the customized LabVIEW computer program because 10 Hz has been sufficient to capture the full respiratory cycle. The sensor was calibrated at 0.03% CO_2 (ambient air concentration) and 4% CO_2 (span gas) at the beginning of each test day.

B. Subjective Data

Test subject feedback was solicited to determine the overall comfort of the nasal cannula and the cannula's compatibility with the Valsalva device. At the beginning of each test day, test subjects were asked if they could use the Valsalva device to clear their ears when the nasal cannula was installed. A “yes” or “no” response was recorded, along with any relevant comments. After each set of metabolic rate test points, test subjects were asked to rate the comfort and security (ability to stay in place) of the nasal cannula. These questions and ratings are summarized in Table 2.

Table 2. Test subject questions.

Question	Rating		
Able to Use Valsalva Device?	Yes	No	
Comfort of Nasal Cannula?	Unacceptable	Acceptable but Needs Improvement	Acceptable
Security of Nasal Cannula?	Unacceptable	Acceptable but Needs Improvement	Acceptable

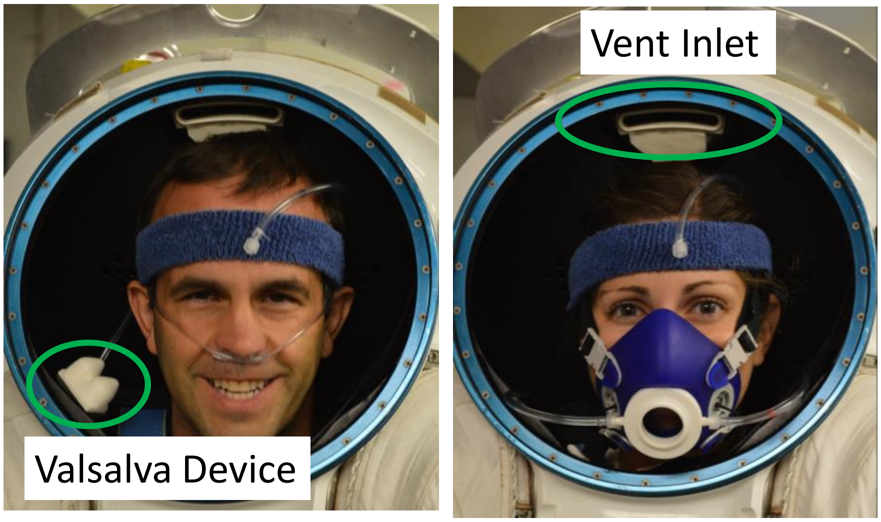
III. Test Hardware

C. Nasal Cannula

The nasal cannula, shown in Figure 2(a), is a Bound Tree Medical[6] 355-302-EEA. The cannula was unaltered for this test. The cannula was placed inside the nasal cavity, and the sample tubes from the left and right nasal prongs were merged with a Y-adapter. The sample was analyzed as a single stream.

D. Oronasal Mask

The oronasal mask, shown in Figure 2(b), is a Hans Rudolph[7] 7450 series mask. The mask is held against the test subject’s face with a head net. This seals the mask against the face and restricts all flow to and from the nose and mouth through a single orifice at the front of the mask. Air sampling ports are located at the left and right sides of the orifice.



a) b)

Figure 2. Nasal cannula (a) and oronasal mask (b).

E. Valsalva Device

A Valsalva device is a urethane foam block that a test subject uses to block their nasal passages so that they can perform the Valsalva maneuver. The device is mounted on the inside of the suit, near the test subject’s face (typically on the helmet or neck ring). The Valsalva device that was used in this test was manufactured by Carwild P/N SDD13100436-003. This device is commonly used by extra-vehicular mobility unit (EMU) crew members, and it will be used with the Z-2 space suit during sub-ambient pressure tests. The Valsalva device is shown in Figure 2(a).

F. Mark III Space Suit

All test points were completed in the Mark III space suit (Figure 3), which is a rear-entry, prototype planetary walking suit. The suit is comprised of hard elements, including a hard upper torso and a hard brief, and soft elements, including softgood arms and legs. The suit has a rear hatch for rear donning/doffing. The suit has bearings at the shoulder, upper arm, wrist, waist, hip, and ankle. A neck ring provides an interface for a removable 13-inch circular helmet. Breathing gas enters at the rear of the helmet through a vent inlet (circled in Figure 2). The gas then flows over the top of the head, in front of the face, and then out into the body of the suit. Gas is removed from the suit via an outlet vent near the lower back that feeds the gas to the suit's exhaust port on the hatch. The suit nominally operates at 4.3 psig with a gas flow rate of 6 ACFM. Mark III test subjects are cooled by a liquid cooling garment (LCG).

Figure 3. Mark III space suit.

IV. Data Analysis Techniques

Past studies have shown that several variables determine the measured inspired CO_2 value[1,2]. The primary variables are air flow rate and metabolic rate. While these variables were controlled in this study, slight fluctuations in the variables over the course of the tests precluded the use of standard statistical tests like a repeated measures analysis of variance. To allow for direct comparison between the data sets, data in this test were analyzed using mixed-effects regression-based modeling. The controlled variables were air flow rate, metabolic rate and breathing style. The respiratory rate was a potential covariate and accounted for in the analysis and several interaction terms such metabolic rate x air flow rate were also considered. The model used random intercepts to accommodate the repeated-observations within subjects, and fixed-effects parameters to account for breathing style, metabolic rate, and flow rate. Individual breath-by-breath data were included in the model for every observation (peak or trough value). This allows the evaluation of breathing type (nose-only or unrestricted (mouth + nose)), metabolic rate, and air flow rate to be evaluated while accounting account for inter-subject differences in breathing rate during data acquisition.

The regression model was used to determine the expected mean inspired, and peak expired CO_2, at a 95% confidence interval[9].

Inspired CO_2 was monitored in real-time to prevent the inspired CO_2 from exceeding pre-defined safety limits. A test subject could exceed a consistent inspired CO_2 level of greater than 23 mmHg for up to two minutes and they could not exceed 30 mmHg for any period of time. Some test points, particularly at low flow rates, were not completed because of these test termination limits. To account for these differences in sample size, the statistical analysis treats each breath as a single sample and no gross averaging across subjects of all collected peak or trough CO_2 measurements was used.

V. Results and Discussion

G. Breathing Style Analysis

To determine the consistency of the CO_2 measurements across test subjects, the 95% confidence intervals were calculated for the modeled means of inspired and expired CO_2 values. The confidence intervals for unrestricted breathing and nose-only breathing are shown in Table 3. The intervals were relatively constant across all flow rates and metabolic rates, so only a single value is provided for each breathing style. Data shows that nose-only breathing provides lower breath-to-breath variability than normal breathing for both the inspired CO_2 and expired CO_2.

Table 3. 95% confidence intervals for different breathing styles with nasal cannula.

	Inspired CO_2
Unrestricted	2.7 mmHg
Nose-Only	1.0 mmHg
	Expired CO_2
Unrestricted	7.7 mmHg
Nose-Only	5.2 mmHg

In addition to smaller confidence intervals for nose-only breathing, this breathing style also resulted in lower troughs and higher peaks for all flow rates and metabolic rates. This is shown in Figure 4 and Figure 5. The troughs could be lower because nose-only breathing directs the exhaled CO_2 down the helmet, whereas unrestriced breathing generally directs expired breath towards the front of the helmet. The troughs could also be lower because when test subjects switched to nose-only breathing, their respiratory rates (RR) noticeably decreased. Figure 6 shows a respiratory trace taken from a single subject as an example of these RR changes. Because metabolic rate did not change during the breathing style transition, it can be assumed that the subjects decreased their RR because they increased their tidal volume: the test subjects took longer, deeper breaths when they breathed only through their nose. After switching to nose-only breathing, the RR decreases, inspired CO_2 decreases, and expired CO_2 increases. An increase in tidal volume would lead towards more productive gas exchange by decreasing the impact of dead space ventilation and delivering gas deeper into the lungs where they are most perfused. This leads to higher expired CO_2 values. Also, by having longer expired breaths and more time between breaths, it would allow the expired CO_2 to be more effectively washed away from the oronasal area. This leads to lower CO_2 troughs.

When all of these factors are considered, nose-only breathing provides more consistent CO_2 washout data, but it may not necessarily be representative of how a test subject would breathe in the suit, especially at high metabolic rates.

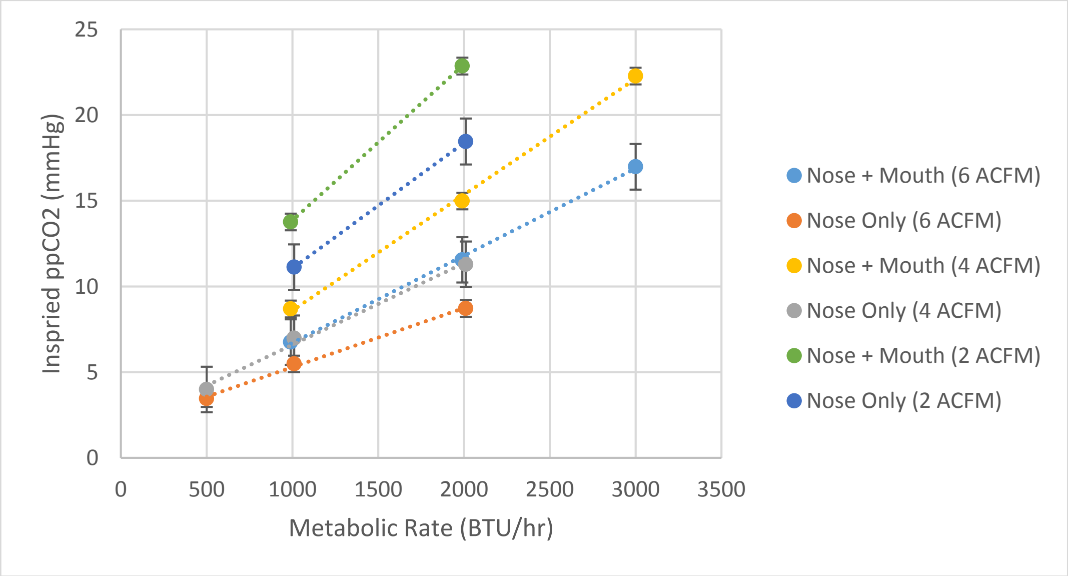


Figure 4. Modeled means and 95% confidence intervals for trough CO_2 partial pressures using nasal cannula

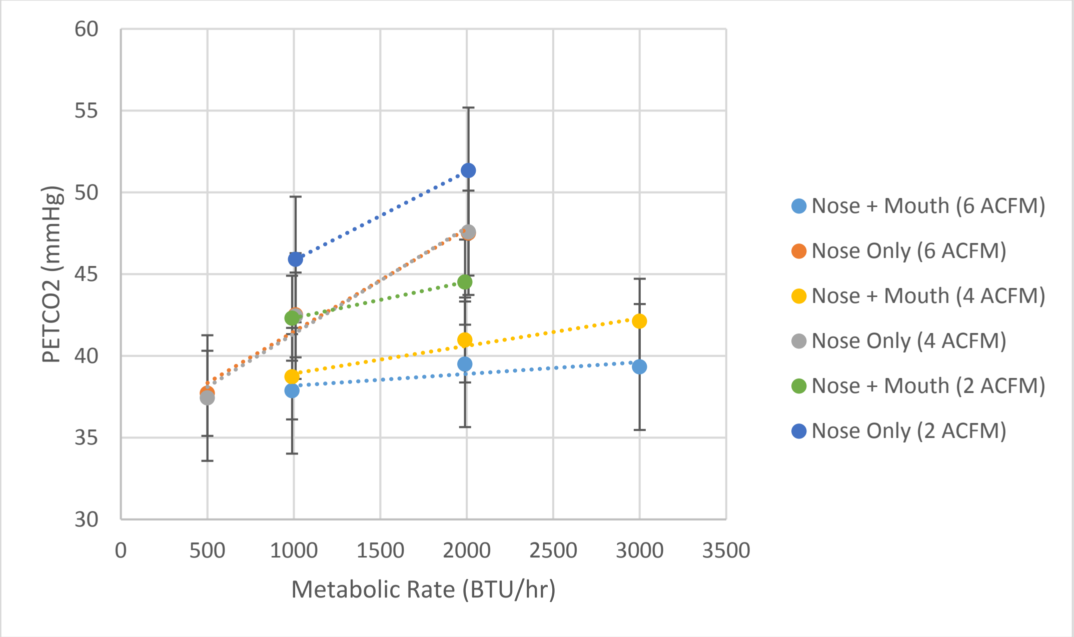


Figure 5. Modeled means and 95% confidence intervals for end tidal CO_2 partial pressures using nasal cannula

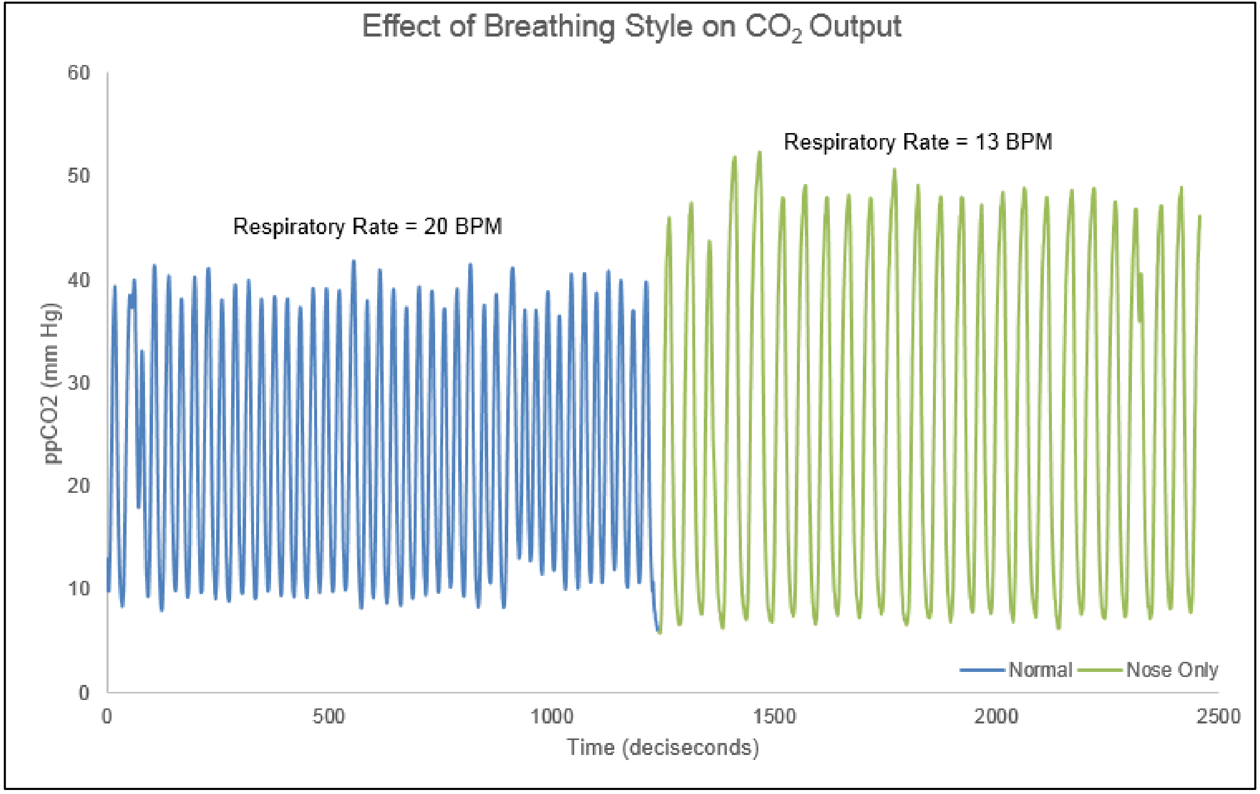


Figure 6. Example respiratory profile change from unrestricted (nose + mouth) to nose only breathing style.

B. Comparison of Nasal Cannula Data to Historical Oronasal Mask Data

In addition to the nasal cannula, one test subject in this study also completed the test matrix in Table 1 with the oronasal mask. Three test subjects from this study also participated in an evaluation of the oronasal mask in July-August 2014. The purpose of the latter study was to compare the performance of the Hans Rudolph oronasal mask to several other oronasal mask concepts in the Mark III suit. Data from the four test subjects has been analyzed for comparison to the nasal cannula data. All data was collected at an air flow rate of 6 ACFM and at metabolic rates from 1000 to 3000 BTU/hr.

Table 4 shows the modeled inspired and expired CO_2 at different metabolic rates based on data from the four test subjects using the oronasal mask. Comparing **Error! Reference source not found.Error! Reference source not found.** to Table 4, the inter-subject variability for inspired and expired CO2 is much lower for the nasal cannula for normal breathing. Nose-only breathing was not tested with the oronasal mask.

Table 4. Inspired and expired CO_2 (mmHg) modeled mean ± 95% confidence intervals for unrestricted breathing with oronasal mask at 6 ACFM.

Metabolic Rate, BTU/hr	Inspired ppCO2, mmHg	PETCO2, mmHg
1000	6.5 ± 4.2	36.0 ± 8.1
2000	12.8 ± 4.2	35.5 ± 8.1
3000	19.0 ± 4.2	36.6 ± 8.1

The testing conducted with the nasal cannula also identified that breathing style effects on measured CO_2 values was highly subject dependent. In cases evaluated at 6 ACFM, the cannula troughs for nose + mouth breathing sometimes resulted in similar inspired $ppCO_2$ values (Figure 7, Subject B and D) to those measured with the oronasal mask. For two other subjects, $ppCO_2$ values were markedly different between the nasal cannula and oronasal mask (Figure 7, Subject A and C).

Inspired ppCO2 data collected using the cannula was either consistent with the oronasal mask data or closer to what would be physiologically expected[8] and expected based on engineering concerns that the oronasal mask might impede flow to and from the face. Table 5 presents data available in literature for $P_{ET}CO_2$ measurements. Measurements taken with the oronasal mask were often lower than what would be typically expected.

Table 5. Normal Values for end tidal CO2 (PETCO2)

Resting $P_{ET}CO_2$	Exercise $P_{ET}CO_2$	Comments	Reference
33.8 ± 3.4 mmHg	40.1 ± 2.3 mmHg	2351 BTU/hr was mean calculated metabolic rate for exercise $P_{ET}CO_2$	[1]
35.6 ± 2.4 mmHg	43.9 ± 1.9	2632 BTU/hr was mean calculated metabolic rate for exercise $P_{ET}CO_2$	
37.6 ± 3.1 mmHg	49.6 ± 3.8	2839 BTU/hr was mean calculated metabolic rate for exercise $P_{ET}CO_2$	
36-42 mmHg	Increases 3-8 mmHg during moderate exercise	Exercise increase in $P_{ET}CO_2$ depends on breathing pattern	[2]
	Decreases with heavy exercise	No definition is given for heavy exercise	

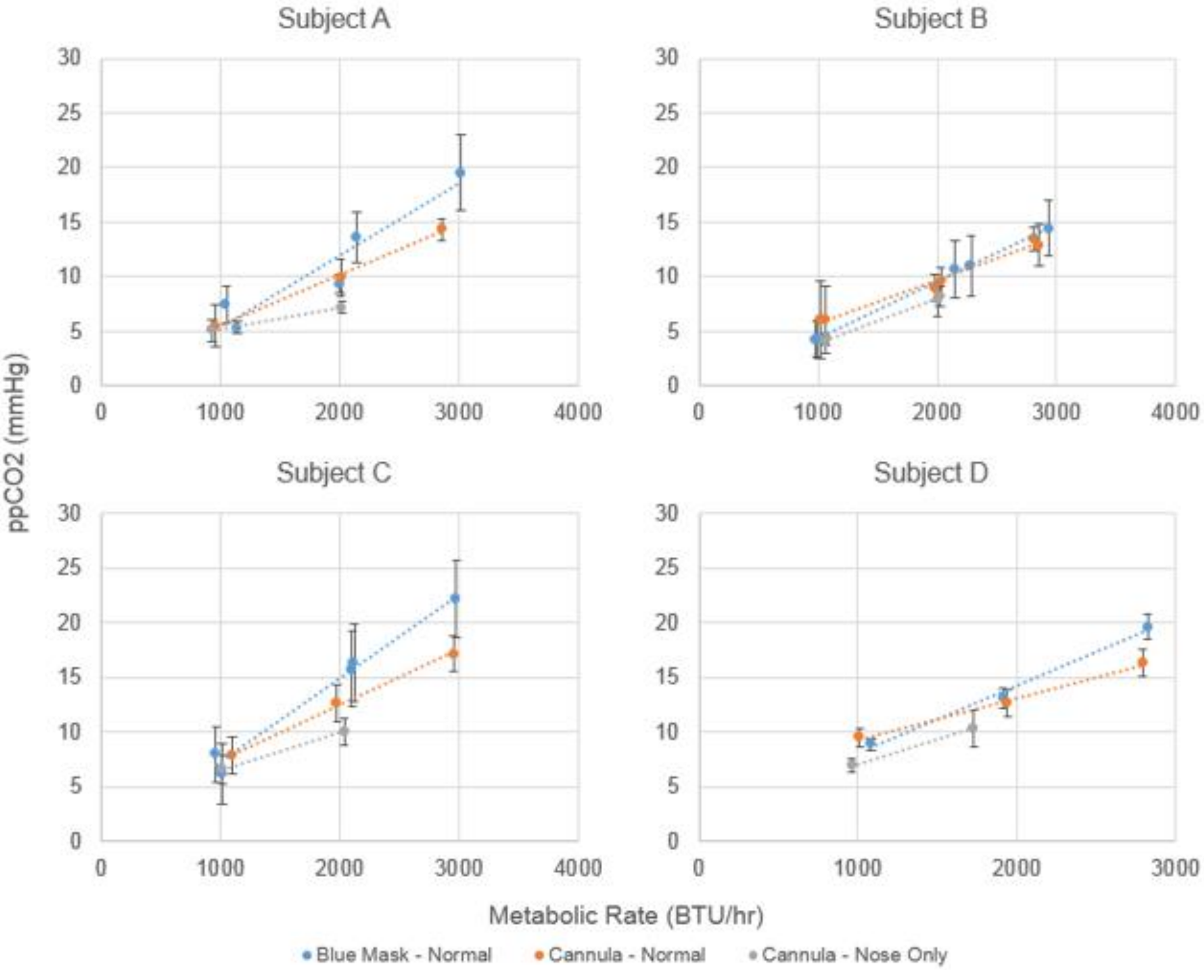


Figure 7. Inspired ppCO$_2$ data from four subjects using different sampling techniques and breathing styles at 6 ACFM.

In cases evaluated at 6 ACFM, breathing through both nose and mouth resulted in similar (Figure 8, Subjects A, C and D) or greater (Figure 8, Subject B) end tidal CO$_2$ values than measured with the oronasal mask. In most cases, the cannula nose only data generated the least variability as indicated by the standard deviation and the highest end tidal CO$_2$ likely due to a lower respiratory rate and increased tidal volume. Again, the data collected using the cannula was either consistent with the oronasal mask data or closer to what would be physiologically expected and expected based on engineering concerns that the oronasal mask might impede flow to and from the face.

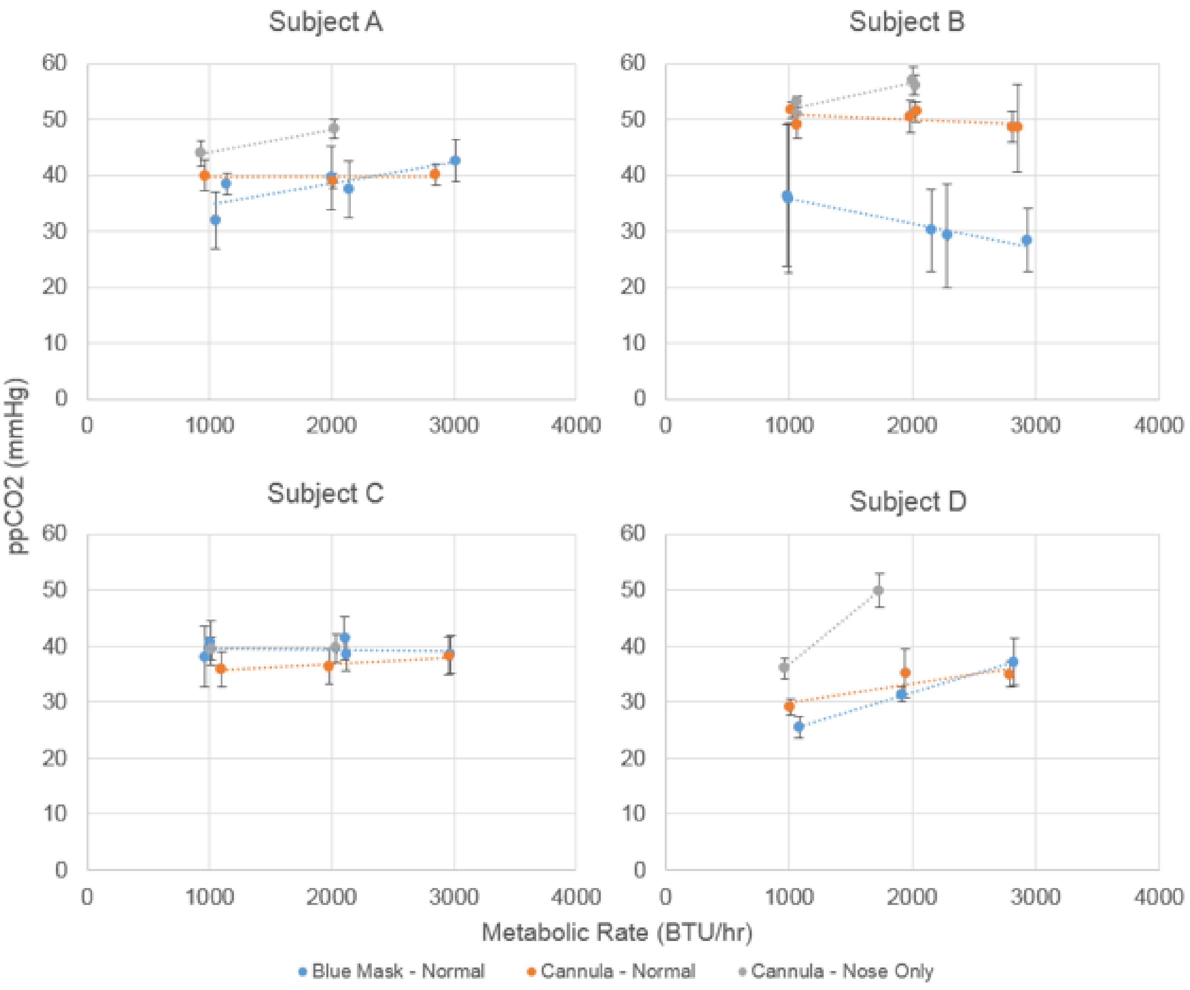


Figure 8. Expired peak ppCO$_2$ data from four subjects using different sampling techniques and breathing styles at 6 ACFM.

One test subject also participated in a past CO$_2$ washout test with the Mark III and oronasal mask. The latter study evaluated the CO$_2$ washout characteristics of various vent inlet configurations. While the means of the CO$_2$ troughs/peaks cannot be compared to the current study because the vent configurations were different, this test subject's respiratory profiles can be compared. From the past study, this subject repeatedly had total displacement (peak – trough) of approximately 10-15 mmHg at 2000 BTU/hr at 6 ACFM with a peak CO2 value of approximately 23mmHg, which was notably different than the other two subjects in that study who at the same conditions usually had a total displacement of 25-30 mmHg with inspired ppCO$_2$ of 10-15 mmHg and expired peaks of 35-40 mmHg. Additionally, the end tidal CO$_2$ value was much lower than what would be physiologically expected at that workload [8].When using the nasal cannula in this study, this same subject had a total displacement of approximately 30 mmHg with mouth/nose breathing and 40-45 mmHg with nose only. In this example, the data collected with the cannula similar to other subjects tested and also looks more like expected physiological results for end tidal CO$_2$ and respiratory rate [2]. Figure 9 demonstrates an example of data for one minute for this subject using the oronasal mask (both left and right samples are shown) and from the cannula breathing with nose only and both nose and mouth.

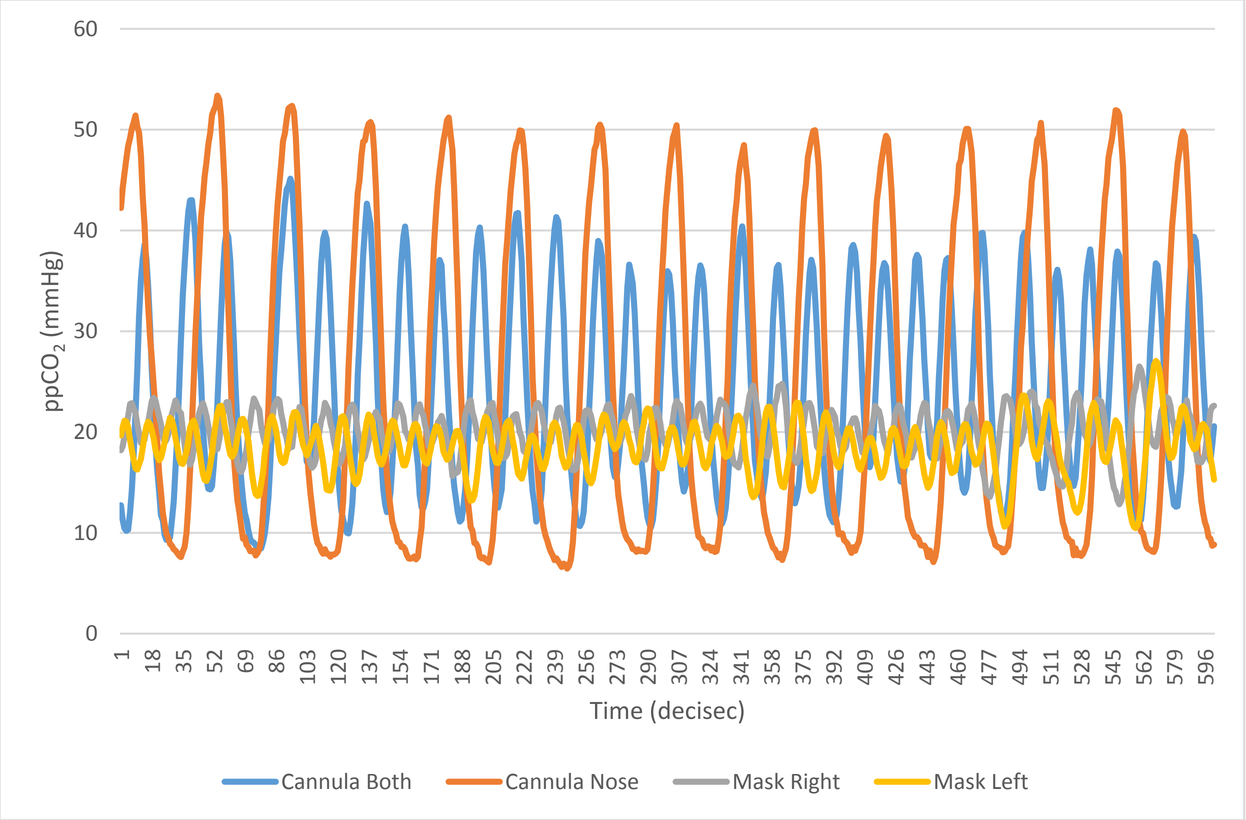


Figure 9. Example of single subject's oronasal ppCO$_2$ at 2000 BTU/hr and 6 ACFM in the Mark III breathing with the oronasal mask and nasal cannula with normal breathing.

C. Subjective Data

All test subjects rated the comfort and security of the nasal cannula as "acceptable". All test subjects were able to use the Valsalva device to clear their ears, but it was not easy to do so. The nasal cannula prevents the Valsalva device from completely sealing against the nose, so test subjects had to blow hard to clear their ears. The nasal cannula has a small flap that helps position the nasal in the nasal passages. All test subjects commented that it was easier to clear their ears when the flap was pointed up.

VI. Conclusions and Future Work

Objective and subjective data from this test series shows that the nasal cannula is an acceptable replacement for the oronasal mask for sub-ambient pressure space suit tests. Specifically, data shows that the nasal cannula provides more statistically consistent data across test subjects, with a lower intrasubject variance than the oronasal mask that has been used in previous tests. For normal breathing, the 95% confidence interval of inspired CO2 measurements for the nasal cannula and oronasal mask are approximately 2 mmHg and 4 mmHg, respectively. These modeled data provide estimates that are applicable to comparison of means for the population. Test data also shows that the breathing style affects the consistency and the magnitude of CO$_2$ washout measurements. Nose-only breathing provides more consistent data than unrestricted breathing across test subjects, but both breathing styles provide data that is more consistent than oronasal mask data. Although the data is more consistent for nose-only breathing, this method provides lower inspired CO$_2$ measurements and higher expired CO$_2$ measurements. This data is likely may not be representative of nominal CO$_2$ washout because this breathing style might not characterize a test subject's actual breathing pattern, especially at higher metabolic loads (>1000 BTU/hr).

Because this test series showed that there are differences between nose-only and unrestricted (normal) breathing styles, future CO$_2$ washout studies should further quantify the differences in CO$_2$ washout data when test subjects are instructed to breathe only through their nose or through their mouth and nose. This data would help determine if breathing style restrictions should be used for future space suit CO$_2$ washout tests.

Forward work will aim to characterize the CO$_2$ washout of the extravehicular mobility unit (EMU). This will provide information on the inspired CO$_2$ levels that astronauts have typically experienced during EVAs. In addition to knowing what astronauts have experienced during EVAs, it is also important to determine the functional consequences of CO_2 exposure during EVA. Severe CO_2 symptoms resulting from high partial pressures during acute exposures should clearly be avoided, but cognitive symptoms and performance decline can also be experienced with exposure to slightly elevated CO_2 [4-5, 8,10]. None of these exposures mirrors the actual CO_2 exposure during EVA, and it remains unknown what impact elevated CO_2 has on nominal EVA performance. This forward work will help develop CO_2 washout requirements for future space suits.

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