Carbon Dioxide Physiological Training at NASA

Jennifer Law; Millennia Young; David Alexander; Sara S. Mason; Mary L. Wear; Claudia M. Méndez; David Stanley; Valerie Meyers Ryder; Mary Van Baalen

INTRODUCTION: Astronauts undergo CO_2 exposure training to recognize their symptoms that can arise acutely both on the ground and in spaceflight. This article describes acute CO_2 exposure training at NASA and examines the symptoms reported by astronauts during training.

METHODS: In a controlled training environment, astronauts are exposed to up to 8% CO_2 (60 mmHg) by a rebreathing apparatus. Symptoms are reported using a standard form.

RESULTS: Symptom documentation forms between April 1994 and February 2012 were obtained for 130 astronauts. The number of symptoms reported per session out of the possible 24 was related to age and sex, with those older slightly more likely to report symptoms. Women reported more symptoms on average than men (men: 3.7, women: 4.7). Respiratory symptoms (90%), flushing sensation/sweating (56%), and dizziness/feeling faint/lightheadedness (43%) were the top symptoms. Only headache reached statistical significance in differences between men (13%) and women (37%) after adjustment for multiple testing. Among those with multiple training sessions, respiratory symptoms were the most consistently reported.

DISCUSSION: CO_2 exposure training is an important tool to educate astronauts about their potential acute CO_2 symptoms. Wide interindividual and temporal variations were observed in symptoms reported during astronaut CO_2 exposure training. Headache could not be relied on as a marker of acute exposure during testing since fewer than half the subjects reported it. Our results support periodic refresher training since symptoms may change over time. Further study is needed to determine the optimal interval of training to maximize symptom recognition and inform operational decisions.

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KEYWORDS: acute hypercapnia awareness, CO_2 training, astronaut health.

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CO_2 training for astronauts was implemented at NASA following an incident at the Johnson Space Center (JSC) in 1992. During a spacesuit familiarization session, a crewmember experienced a rapid buildup of CO_2 when air flow to the spacesuit via the umbilical was disrupted, resulting in lower than nominal flow rates. The individual subsequently hyperventilated and lost consciousness (Fox M, Martinez F, Lopez R; JSC, Houston, TX. Personal communications; 2014). Per recommendation by the mishap investigation board, the Medical Operations Crew Training Flow began to include CO_2 training in 1994 to teach astronauts to detect early symptoms of CO_2 intoxication to prevent critical incidents in the suits.[1,10,11] Today, astronauts generally receive CO_2 exposure training as part of their astronaut candidate training flow and refresher training within the first 6 mo of their long-duration mission training flow in order to become familiar with their own symptoms.

Astronauts can be exposed to acute elevations in CO_2 levels in a number of settings both on the ground and in spaceflight. Preflight, operations are conducted routinely in the Extravehicular Mobility Unit (EMU) for extravehicular activity (EVA) training at the Neutral Buoyancy Laboratory and in the Sokol suit during Soyuz simulator training. If ventilation to the EMU or Sokol is interrupted, CO_2 can build up rapidly in the suit. On orbit, acute elevations of CO_2 can occur when local pockets

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of CO_2 form around poorly ventilated areas (e.g., behind an equipment rack), when a large number of crewmembers gather in a small volume (e.g., for public outreach events), or when the CO_2 scrubber inside the EMU becomes saturated or fails. In a recent hardware-only test using a CO_2 generator, it was demonstrated that the rate of rise in the EMU for a simulated metabolic rate of 1200 BTU/hr could reach 19.4 mmHg/min if the metal oxide CO_2 scrubber failed.[9]

Symptoms of acute CO_2 exposure include headache, dyspnea, intercostal pain, and visual disturbance.[12] In addition to adverse effects on crew health and performance, crew symptoms can drive operational decisions. For example, flight rule calls for EVA termination if there are symptoms of CO_2 toxicity.[6] Thus, it is important to understand how astronauts are trained to recognize CO_2 symptoms. This article will describe acute CO_2 exposure training at NASA and examine the symptoms reported by astronauts during their training.

METHODS

Subjects

The Electronic Medical Record (EMR) at JSC was queried for all available CO_2 symptom documentation forms. Only U.S. astronauts were included in the analysis. The forms were collected and tallied by members of the CO_2 Working Group credentialed to work with personally identifiable information (PII), with approval by the Lifetime Surveillance of Astronaut Health (LSAH) Advisory Board. The JSC Institutional Review Board (IRB) certified that this work was exempt from further IRB review because the activity involved no risk to the subjects. To maintain astronaut privacy, PII was accessed only on password-protected computers and stored on a special-access server.

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Equipment and Materials

During the practical portion of a class, each trainee donned a nose clip and breathed through a mouthpiece attached to a 15-L anesthesia bag filled with 100% O_2. A pulse oximeter was applied to the finger. Inspired and expired CO_2 levels were monitored by a capnograph, displayed in percent.

Procedure

Each 30-min CO_2 training class was conducted in a classroom at JSC. The trainees first received didactic instruction on typical CO_2 levels on the International Space Station (ISS) and symptoms related to CO_2. They were subsequently introduced to the symptom documentation form, which listed 24 symptoms, including air hunger, dizziness, increased respiratory or heart rate, headache, visual disturbance, and confusion (see **Fig. 1**).

During the practical portion, the trainee exhaled CO_2 into the anesthesia bag, with each breath increasing the CO_2 level in the bag. When the trainee experienced a symptom, he or she pointed to that symptom on the symptom documentation form and it was recorded by the instructor. The trainee could terminate the exposure at any time, or when 8% CO_2 (60 mmHg) was reached. A flight surgeon was physically present during the entire exposure to monitor the trainee. The exposure generally lasted 6-10 min.

Upon cessation of the exposure, the trainee resumed breathing room air normally. The mouthpiece, microbial filter, and anesthesia bag were replaced for the next trainee, and the process was repeated. After all the trainees completed the experience, the instructor and students debriefed the symptoms. Following the session, the trainees' symptom documentation forms were scanned into their EMR.

Statistical Analysis

Because many of the symptom documentation forms did not record the specific CO_2 level at which a symptom was experienced, only the symptom's presence or absence was tallied. Similar symptoms were grouped together in the following way to simplify the analysis and interpretation:

1. Air hunger, breathing difficulty, increased breathing rate, and shortness of breath (henceforth referred to as respiratory symptoms)
2. Anxiety, excitation, giddiness, and restlessness
3. Confusion, difficulty concentrating, and drowsiness
4. Dizziness, feeling faint, and lightheadedness
5. Flushing sensation, and sweating

Statistical analyses were performed using SAS 9.3 (SAS Institute Inc., Cary, NC). Because some of the individuals in this group were tested more than once, logistic regression with generalized estimating equations was used to adjust for these repeated measures. The number of symptoms reported out of the 24 listed on the form was modeled using logistic regression to assess any association between total number of symptoms reported with age and sex.

For each of the grouped symptoms that had been reported during at least one training session, logistic regression was used to analyze the binary report (0 or 1). Age and sex were used as covariates to look for possible associations. If the covariate effect was not found to be significant or suggestive, then it was dropped from the model and an overall incidence proportion was estimated. The Bonferroni method of alpha correction was used to adjust for the multiple testing of the 12 grouped symptoms with at least one report, making the significance cutoff $P = 0.05/12$ (0.0042). One symptom of the possible 13, chest wall pain, was never reported in any training session so it was dropped from the analysis.

RESULTS

The EMR query yielded 243 CO_2 symptom documentation forms during the period from April 1994 to February 2012. Of these, 19 duplicate forms were deleted, and 32 forms for Russian cosmonauts and non-NASA astronauts were excluded from the analysis. In the end, 192 forms were available for 130 individual NASA astronauts (110 men, 20 women). Most had one symptom documentation form; 42 astronauts (37 men,

Carbon Dioxide Exposure Training
Symptom Documentation Form

Name: ____________________ Date: ____________

From the list below, indicate the symptoms you notice while breathing elevated levels of carbon dioxide, as well as, the level of CO2 in which it is experienced.

_______ %CO2 AIR HUNGER	_______ %CO2 HEADACHE
_______ %CO2 ANXIETY	_______ %CO2 INCREASED BREATHING RATE
_______ %CO2 BREATHING DIFFICULTY	_______ %CO2 INCREASED HEART RATE
_______ %CO2 CHEST WALL PAIN	_______ %CO2 LIGHTHEADEDNESS
_______ %CO2 CONFUSION	_______ %CO2 NAUSEA
_______ %CO2 DIFFICULTY CONCENTRATING	_______ %CO2 RESTLESSNESS
_______ %CO2 DIZZINESS	_______ %CO2 SHORT OF BREATH
_______ %CO2 DROWSINESS	_______ %CO2 SWEATING
_______ %CO2 EXCITATION	_______ %CO2 TINGLING SENSATION
_______ %CO2 FEELING FAINT	_______ %CO2 TREMORS
_______ %CO2 FLUSHING SENSATION	_______ %CO2 VISUAL DISTURBANCES
_______ %CO2 GIDDINESS	_______ %CO2 HEAVYHEADEDNESS

Other Symptoms:

Comments/Suggestions:

Fig. 1. Sample symptom documentation form.

5 women) had two forms, and 10 astronauts (9 men, 1 woman) had three forms.

The mean age (SD) at each training session was 43.3 (5.2) yr for men and 41.3 (7.5) yr for women. On average, women reported more symptoms (men: 3.7, women: 4.7, $P = 0.01$). Age ($P = 0.01$) and sex ($P = 0.01$) were significantly associated with the number of symptoms reported per session out of the possible 24. For every year of increase in age, the odds of the astronaut reporting a symptom increased by 2% (OR: 1.02, 95% CI: 1.00, 1.04). The odds of a man reporting a symptom were 28% less compared to a woman (OR: 0.72; 95% CI: 0.56, 0.92). Overall, the astronauts reported 0 to 9 symptoms (mean 3.9; 95% CI: 3.6, 4.2). Male astronauts reported 0 to 9 symptoms (mean 3.7; 95% CI: 3.4, 4.0) and female astronauts reported 2 to 9 symptoms (mean 4.7, 95% CI: 4.0, 5.5) ($P = 0.01$). All astronauts reported symptoms during their first session; however, there was one male astronaut who reported no symptoms during his second training. **Fig. 2** shows a histogram of the frequency of symptoms reported by astronauts.

Among the 13 symptom groups, respiratory symptoms (90.1%), flushing sensation/sweating (56.3%), dizziness/feeling faint/lightheadedness (43.1%), headache (men: 13.3%; women: 37.0%), and increased heart rate (16.4%) were the top 5 symptoms reported (see **Fig. 3**). Visual disturbance was reported by 6.3%. Only headache ($P = 0.003$) showed statistically significant differences between the sexes (see **Table I**). Age was found to be a significant covariate for respiratory symptoms ($P = 0.006$), with an estimated 10% increase in the odds of reporting a respiratory symptom with each year older (OR: 1.10, 95% CI: 1.03, 1.18) and heavyheadedness with an estimated 20% increase in the odds of reporting for each year older ($P < 0.0001$, OR: 1.20, 95% CI: 1.10, 1.31).

The 52 astronauts with multiple training sessions consistently did not report chest wall pain, tremors, nausea, and confusion/difficulty concentrating/drowsiness. Respiratory symptoms were most consistently reported, with 80.8% of astronauts reporting at least one symptom across all sessions. **Table II** summarizes the consistency of symptoms across multiple sessions.

DISCUSSION

CO_2 exposure training at NASA is designed to educate astronauts on their own symptoms in response to acute exposure to CO_2. Analysis of the symptom documentation forms demonstrated wide interindividual and temporal variations in the 24 CO_2-related symptoms reported during this training. Respiratory symptoms were most commonly and consistently reported, corresponding well to the known effects of acute CO_2 exposure.

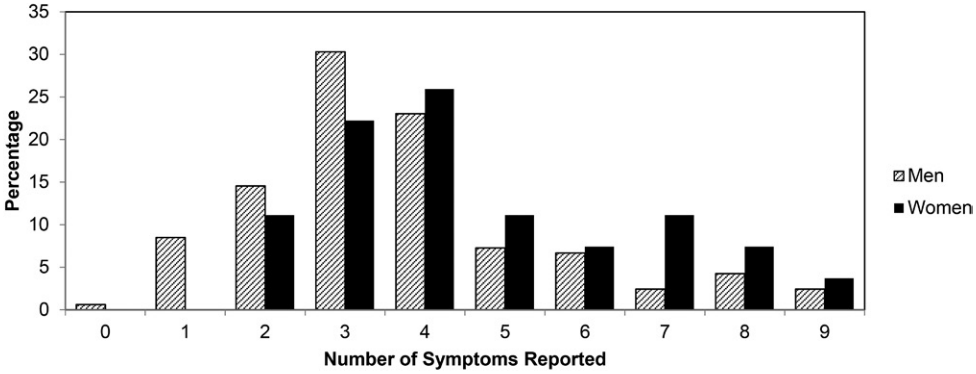

Fig. 2. Frequency of number of symptoms reported by U.S. astronauts per training session.

headaches go unreported on the documentation form since the headaches often do not occur until 20 min or more after class completion; more work would be needed to assess the prevalence of these postexposure headaches. Our results suggest that headache cannot be relied upon as a timely response to acute CO_2 exposures. Furthermore, the acute symptoms elicited in our CO_2 exposure training cannot be extrapolated to chronic CO_2 exposure on orbit.

Few astronauts reported cognitive symptoms, and none reported chest wall pain.

Notably, headache, which has been associated with chronic exposure to elevated CO_2 on the ISS,[4] was reported in less than half of the study cohort, suggesting high variability among individuals, or more likely, the method of eliciting CO_2-related symptoms acutely during the training was not representative of the conditions inside the ISS: whereas exposure on the ISS occurs in microgravity over months, astronauts are exposed to several minutes of CO_2 after breathing 100% O_2 during the ground training. The instructors have also noted that many

We observed that female astronauts were statistically more likely to report symptoms during training than male astronauts. However, only headache (odds ratio 3.9, 95% CI: 1.6, 9.4) had a statistically significant difference between the sexes, with women being more likely to report. The observed difference between the sexes is biologically plausible, given that vascular compliance is generally higher in premenopausal women than in men due to estrogen's direct effects on the vascular system.[5,7] Indeed, Kastrup et al. found that premenopausal women had higher cerebrovascular reactivity to CO_2 than their male counterparts or than postmenopausal women.[2] In another study, Kastrup et al. showed that women had a significantly stronger vasodilatory response to changes in CO_2 than men as measured by blood flow velocity in the middle cerebral artery, and theorized this difference could be due to an increased frequency of subclinical atherosclerosis in men.[3]

We also observed that age was associated with respiratory symptoms and heavyheadedness. Literature on age differences in response to CO_2 in healthy individuals is limited. Cerebrovascular reactivity to CO_2 appears to be unchanged in men with age, and only significantly higher when comparing women 20–40 yr of age vs. 40–70 yr, again due to hormonal effects.[2] In subjects less than 30 yr of age vs. over 60 yr of age, ventilation responses to increasing CO_2 have been noted to be lower in the older group, though the difference was not significant.[8] The discrepancy between our observations and these published studies could be explained by the effect of increasing awareness of CO_2 symptoms

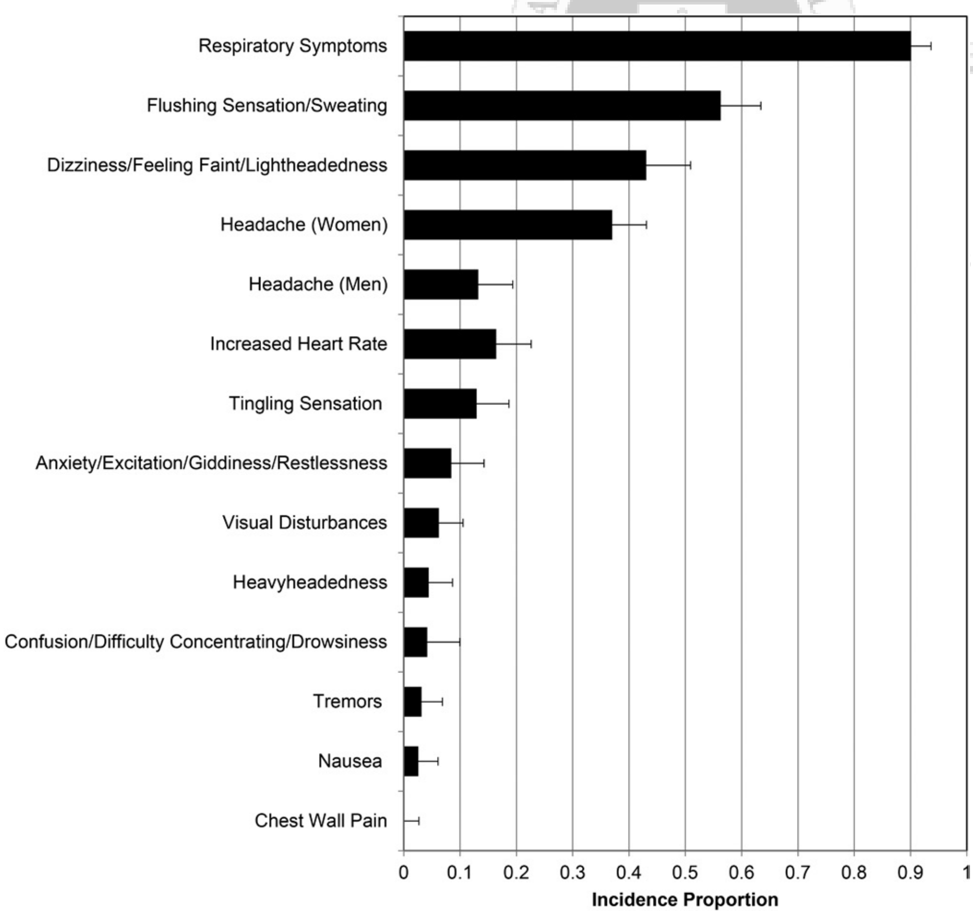

Fig. 3. Incidence of symptoms reported during CO_2 exposure training, adjusted for repeated measures; error bars denote width of the 95% confidence interval.

Table I. Reported CO_2 Symptoms By Sex, Adjusted for Repeated Measures.

SYMPTOM	MEN	WOMEN	*P*-VALUE
Respiratory Symptoms	89.1%	96.4%	0.23
Anxiety / Excitation / Giddiness / Restlessness	8.8%	6.7%	0.77
Chest Wall Pain	0.0%	0.0%	NA
Confusion / Difficulty Concentrating / Drowsiness	4.2%	3.7%	0.90
Dizziness / Feeling Faint / Lightheadedness	41.6%	51.7%	0.39
Flushing Sensation / Sweating	54.0%	70.4%	0.078
Headache	13.3%	37.0%	**0.0032**
Heavyheadedness	5.2%	0.0%	NA
Increased Heart Rate	14.1%	29.6%	0.057
Nausea	2.4%	3.7%	0.69
Tingling Sensation	13.9%	7.4%	0.36
Tremors	3.1%	3.7%	0.85
Visual Disturbances	6.0%	7.7%	0.73

in our cohort over time: rather than age-related physiological differences, it is possible that older, more experienced astronauts were more willing to report symptoms during their training.

As a retrospective observational series, this study had several major limitations. We evaluated a sample of convenience and only forms extracted from the EMR were tallied. It was possible that some forms were not entered into the EMR or extracted by the query. Secondly, the symptoms recorded in the forms could have been over-reported because of the topic of the class, or under-reported because the instructors could only mark down the symptoms the trainees noted. Objective measures such as increased tidal volumes and increased respiratory rates were not recorded. Furthermore, the CO_2 level at which each symptom was experienced was not universally documented, so we could not analyze the CO_2 level at which each symptom occurred, only its presence or absence.

While the form captured the major symptoms that would be expected based on our current understanding of the physiology of CO_2 exposure, the design of the form, with an alphabetical listing of the symptoms (see Fig. 1), might have confounded the data, since the first symptom on the list—air hunger—was also the most commonly reported symptom. On the other hand, air hunger is known to be one of the first noticeable effects of CO_2. A simpler form that groups symptoms by system (e.g., respiratory, cardiovascular, neurological) and combines similar symptoms would be less confusing. To be as informative as possible, the form should be revised, with mandatory documentation of the inhaled CO_2 level at which each symptom is experienced. In the debrief portion of the class, the trainees should be asked to compare their symptoms with the symptoms they experienced previously, and whether they have other symptoms not listed in the form. The instructors should also document any postexposure symptoms that the trainees report. However, it is important to recognize that the primary purpose of this form is to train individuals to recognize their CO_2 symptoms, not to gather research data or control for confounders.

It has been suggested that some astronauts could be resistant to the effects of elevated CO_2. We found that all astronauts reported symptoms during their first training session. It is likely that the one individual who reported no symptoms in his second session 5 yr later still could have had signs of CO_2 exposure observable by the instructor—for example, increased breathing rate or sweating. However, the form was designed for self-reporting of symptoms and not instructor observations of signs, and given the nature of our data, we are unable to get more details about his experience. Adding continuous monitoring of objective measures in the future, including tidal volume, respiratory rate, and heart rate, would be instructive in demonstrating more subtle responses to CO_2, such as hyperventilation and tachycardia, and rely less on subjective reporting.

Noting that symptoms may change over time and training was often waived for experienced astronauts historically due to scheduling constraints and the belief that CO_2 symptoms remained static, we support recent efforts at JSC to mandate CO_2 exposure training every 5 yr, an interval chosen to match hypoxia training requirements. It should be noted that this study was not designed to determine the optimal interval of

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Table II. Consistency of Symptoms in the 52 Astronauts With Multiple Training Sessions.

SYMPTOM	ASTRONAUTS WHO REPORTED SYMPTOM IN ALL SESSIONS	ASTRONAUTS WHO DID NOT REPORT SYMPTOM IN ANY SESSION	% OF ASTRONAUTS WHOSE SYMPTOMS WERE CONSISTENT ACROSS ALL SESSIONS
Flushing Sensation / Sweating	15	12	51.9%
Dizziness / Feeling Faint / Lightheadedness	10	25	67.3%
Headache	1	35	69.2%
Tingling Sensation	1	38	75.0%
Increased Heart Rate	1	40	78.8%
Respiratory Symptoms	41	1	80.8%
Visual Disturbances	0	45	86.5%
Heavyheadedness	0	46	88.5%
Anxiety / Excitation / Giddiness / Restlessness	4	44	92.3%
Confusion / Difficulty Concentrating / Drowsiness	0	49	94.2%
Nausea	0	50	96.2%
Tremors	0	51	98.1%
Chest Wall Pain	0	52	100.0%

training nor the effectiveness of the training in preventing adverse events. However, anecdotally, this training improves awareness among astronauts and promotes discussion about CO_2 between the crew and ground teams. As such, we support providing CO_2 exposure training also to ground personnel who are involved in CO_2 management on orbit—including flight directors, flight surgeons, Environmental and Thermal Operating Systems specialists, and EVA officers—to help them better understand symptoms that crewmembers may report and facilitate discussions about CO_2 control onboard the ISS and during EVA.

In conclusion, CO_2 exposure training is an important tool to educate astronauts and ground personnel about CO_2 symptoms, which can adversely affect crew health and performance and inform operational decisions. Currently NASA requires refresher training every 5 yr and we support this approach, although further study is needed to determine the optimal interval of training to maximize symptom recognition.

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