Surprising Effects of CO_2 Exposure on Decision Making

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Abstract

Carbon dioxide (CO_2) is released from humans while they live and work in spacecraft or spacesuits. Removal of this anthropogenic pollutant requires major resources, which increase dramatically as the permissible levels of CO_2 set to protect human health and performance are reduced. The current Spacecraft Maximum Allowable Concentration (SMAC) of CO_2 aboard the ISS is 5.3 mmHg; however, according to Chits (mission action requests), NASA and its international partners have agreed to control CO_2 levels to less than 4 mmHg. In the meantime, retrospective investigations attempting to associate crew symptoms with elevated CO_2 levels over the life of the International Space Station (ISS) are underway to determine if this level is sufficient to protect against health and performance decrements. Anecdotal reports suggest that crewmembers are not able to perform complex tasks as readily in spaceflight as they were able to during ground-based training. Recently the effects of CO_2 on decision making have been investigated. Using data from this one study, we show that there are obvious adverse effects of CO_2 exposures on decision making above 1.5 mmHg. The implications and limitations of this study are paramount in determining future CO_2 SMACs for human spaceflight, both aboard the ISS and in exploration-class missions.

Nomenclature

AGARD = Advisory Group for Aerospace Research and Development
BMD = benchmark dose
cfm = cubic feet per minute
EVA = extravehicular activity
ISS = International Space Station
mmHg = millimeters of mercury
ppm = part per million
SMAC = Spacecraft Maximum Allowable Concentration
SD = standard deviation
SMS = Strategic Management Simulation

I. Introduction

This paper reviews the history of levels of carbon dioxide (CO_2) exposures that have been presumed to be safe for astronaut exposures for short and long periods of time spent in spacesuits or spacecraft. This background is used to place a newly published study into perspective and chart a way forward to resolve issues associated with the surprising findings of that study.[1] Specifically, the study by Satish et al. published in 2012 found that brief (2.5 h) exposures to CO_2 at levels slightly below 2 mmHg elicited changes in decision-making performance that the authors characterized as rendering the test subjects 'dysfunctional.' This finding, published in a highly-respected journal, could have a major impact on the levels considered necessary to preserve human health and decision-making performance during space missions. Even aboard the International Space Station (ISS), considerable resources are necessary to maintain operational levels of CO_2 near 2 mmHg with a 6 person crew.[2]

The situation within an extravehicular activity (EVA) spacesuit presents an even more challenging scenario for managing CO_2 levels near or below 2 mmHg. Furthermore, one could argue that astronauts performing an EVA are more likely to be called upon to make difficult decisions during their work outside the core habitat while in an EVA spacesuit. Current designs of EVA spacesuits may be unable to maintain CO_2 levels below 8 mmHg, in which case, under NASA flight rule B13-251, the EVA may be terminated. Major spacesuit redesigns could be necessary if effective decision-making capabilities are to be maintained during EVAs.

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Herein we will review the findings of Satish and colleagues with attention to additional experiments that are necessary to clarify how the results are to be applied to human spaceflight. We will also interpret the data using the toxicological technique of benchmark dose (BMD) modeling to set forth relationships between CO_2 levels and deficits in higher reasoning that could be expected at those levels. However, we will not apply BMD in the usual way, which is to define levels of a given compound that will elicit no appreciable effect to a certain degree of certainty, say 95% for example. Instead, we will use the data to establish an optimal dose response relationship defined by the BMD technique, and then suggest levels of control of CO_2 that would be necessary to maintain average and marginal capabilities in specific types of decision-making capability.

II. Historical Understanding of Safe CO_2 Levels

A. Spacecraft and CO_2

Earth-normal CO_2 levels are approximately 0.5 mmHg, but the levels have been rising dramatically in the past few decades.[3] Humans have evolved the capability to deal with levels near this value; however, levels in spacecraft have historically been up to 15 times this level, or more for brief periods. For example, the spacecraft maximum allowable concentration (SMAC) for CO_2 for the Apollo missions and the Space Shuttle was 7.6 mmHg.[4,5] The SMAC for 7-180 days of exposure to CO_2 aboard the ISS was set at 5.3 mmHg in 1994 to prevent hyperventilation and headaches and in 2008 a 1000-d SMAC for exploration-class missions was set at 3.8 mmHg to prevent headaches, with the 7-180 d SMAC left unchanged at 5.3 mmHg.[6,7] Anecdotal reports of headaches and behavioral problems in the crew at levels somewhat below 5 mmHg have resulted in a decision to operate the ISS at CO_2 levels below 4 mmHg. Preliminary data suggest that there is approximately a 4% risk that a headache will be reported by a crewmember during a private medical conference if the CO_2 levels have averaged about 4 mmHg during the previous day.[2] It is conceivable that CO_2 is linked to the "space stupids" phenomenon reported by astronauts.[8] On occasion crewmembers are unable to complete tasks in space that were relatively easy for them to perform on the ground.

B. Submarines and CO_2

Before 1968, US submarines were allowed to operate at CO_2 levels in the range of 0.8% to 1.2% (6.1 to 9.1 mmHg), levels that were later associated with an increased risk of respiratory diseases and ureteral calculi.[9] After 1968, improved scrubbers were able to maintain CO_2 levels at 0.5% (3.8 mmHg), which resulted in an "abrupt" decline in respiratory illness and the incidence of ureteral calculi. In 2007 a subcommittee of the National Research Council Committee on Toxicology, based on scanty evidence, recommended a continuous exposure guidance level for a 90-day patrol of 8,000 ppm (6.1 mmHg); however, to our knowledge the US Navy did not adopt this value for operations.[10] In 2003 the Institute of Naval Medicine of the UK recommended a level of 0.7% (5.3 mmHg) as a health-based ceiling limit, not to be exceeded during a 90-day patrol.[11]

C. Tight Buildings and CO_2

Efforts by building architects to improve the energy efficiency of buildings have resulted in reduced air flows and less outside make-up air in the past few decades. In 1989 the American Society of Heating, Refrigeration and Air Conditioning Engineers set a standard of 1,000 ppm (0.8 mmHg) CO_2 for office buildings, with an understanding that the intake of outside air would be 15 cfm/person. In 1999, the standard was adjusted to declare that a differential of $\leq$700 ppm CO_2 must be maintained between inside air and outside air.[12] As outdoor background levels are approaching 400 ppm these days, this implies an internal guideline of approximately 1,100 ppm. This is not considered a health limit, but rather a comfort limit that will control anthropogenic pollutants to non-odorous levels.

III. Higher Decision Making and CO_2

A. Measures of Higher Decision Making

The Strategic Management Simulation (SMS) is a computer simulation program that presents decision-making settings referred to as VUCAD (Volatile, Uncertain, Complex, Ambiguous, and Delayed). Task environments involve uncertainty and delayed feedback that challenge and stress the participant to the point where decision-making may be degraded from normal by an environmental stressor.[13] Unlike other measures of decision-making competence which focus on the "content" or "what" decision makers know, the SMS focuses on "how" that information is applied to make the "correct" decision . There are two tests types, a generic form and a profession-based form. For the purposes of this paper, we are not concerned with profession-based testing. The generic test applies across all professions and can be used universally for everyone from medical interns, to government executives, to patients with head injuries. First an individual will be briefed with a background story, then they will begin the SMS testing. A generic example may have the individual as an emergency response manager who is responsible for responding to a fire in a store. Once the briefing is complete, the test-taker will be given a variety of options on the screen to deal with their particular simulation; there are thousands of options available throughout the test, including doing nothing. The simulation utilizes twenty-five validated characteristics of human effectiveness in response to complex task settings and challenges.[13] Tests maintain universal applicability by selecting each simulation from a pool of multiple, verified simulations that all have the same basic premise, but alter the details (e.g. a fire in a grocery store versus a fire in restaurant). The test taker makes choices which affect the next stage of the test, but despite test-maker choices, there are certain constants which will occur no matter what, such as the roof caving in. The SMS uses algorithms to analyze the test taker's simple and complex cognitive functioning; the results are expressed as a numerical score indexed against average scores from a large population of ordinary individuals.

B. Recent Data on the Effects of CO_2 on Decision Making

In this section we will summarize the data gathered by Satish et al.[1] with an eye to how their data may be applied to astronauts living and working in a relatively high CO_2 environment. Of the 25 available measures of performance, Satish and her colleagues selected 9 measures and applied them to 22 test subjects, using blinded exposures of 2 ½ hours to CO_2 at 600 ppm, 1000 ppm (0.8 mmHg) or 2500 ppm (1.9 mmHg). The results for four of the performance measures – applied activity, focused activity, task orientation, and information orientation – remained in the "average" or better performance range even at the highest exposure of 2500 ppm. None of the 9 performance measures were in the "marginal" or "dysfunctional" category when subjects were exposed to 1000 ppm. Our concern is with the 5 measures that fell into the "marginal" or "dysfunctional" range when test subjects were exposed to 2500 ppm (1.9 mmHg), a level commonly exceeded within the ISS.

It is important to characterize what the performance terms mean. "Average" is indexed to the average performance of the large population of ordinary test subjects available before any of the CO_2 testing was performed. For example, this might be the average performance a professor might expect from his class based on historical data from years of teaching. The average for an individual class could be substantially different from the population average. "Marginal" means significantly degraded performance relative to the index population. "Dysfunctional" means that the performance was so poor that the required decisions were not made at a level exhibiting any competence. This level is characteristic of individuals impaired by drugs, alcohol, or brain injuries.

C. Benchmark Dose Modeling of the Data as a Predictor of Deficits in Decision Making

In this section, we will use the data developed by Satish et al.[1] to predict the magnitude of deficit in the 5 decision-making measures that she and her collegues demonstrated were most affected by exposure to CO_2. We use BMD modeling to identify the best fit to the data and then use threshold levels provided by Satish to demark the boundries between average and marginal and between marginal and dysfunctional to roughly predict the CO_2 exposures that could be expected to elicit these deficits. This assumes that the population of persons studied by Satish and her colleagues is representative of the astronaut population and that spaceflight does not alter the decision-making response to slightly elevated levels of CO_2. Our estimates are shown graphically in figures 1 through 5 as follows: basic activity (Fig. 1), initiative (Fig. 2), information utilization (Fig. 3), breadth of approach (Fig. 4), and basic strategy (Fig. 5).

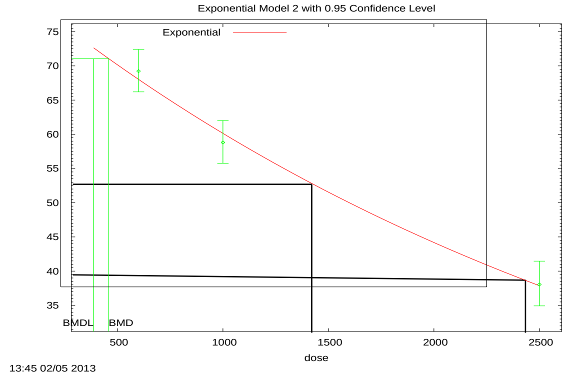

Figure 1. BMD modeling of the reduction of scores (mean response) on basic activity with increasing CO_2 levels (dose in ppm) from Satish et al.[1] The error bars represent one standard deviation (SD) and the horizontal black lines represent the transitions from average to marginal and marginal to dysfunctional performance. The corresponding black vertical lines that intersect the horizontal lines at the dose response curve show the CO_2 level at these transition levels. For measurement of basic activity, the marginal zone is above 1400 ppm CO_2 and the dysfunctional zone begins above 2400 ppm.

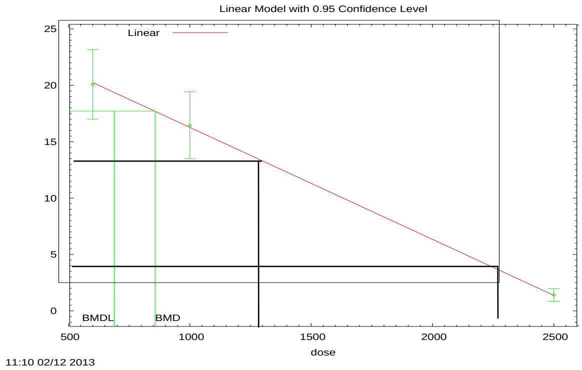

Figure 2. BMD modeling of the reduction of scores (mean response) on initiative with increasing CO_2 levels (dose in ppm) from Satish et al.[1] The error bars represent one SD and the horizontal black lines represent transitions from average to marginal performance and from marginal to dysfunctional performance. Corresponding black vertical lines show the CO_2 levels at those transition levels. For measurement of initiative, the marginal zone is above 1300 ppm CO_2 and the dysfunctional zone begins at about 2300 ppm.

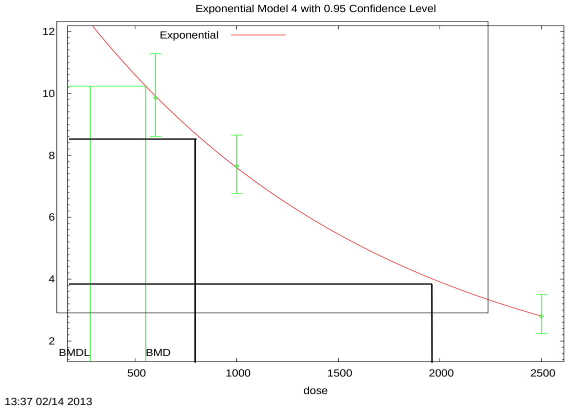

Figure 3. BMD modeling of the reduction of scores (mean response) on information utilization with increasing CO_2 levels (dose in ppm) from Satish et al.[1] The error bars represent one SD and the black horizontal lines represent transitions from average to marginal performance and from marginal to dysfunctional performance. Corresponding black vertical lines show the CO_2 levels at those transition levels. For measurement of information utilization, the marginal zone is above 800 ppm and the dysfunctional zone begins about 1900 ppm.

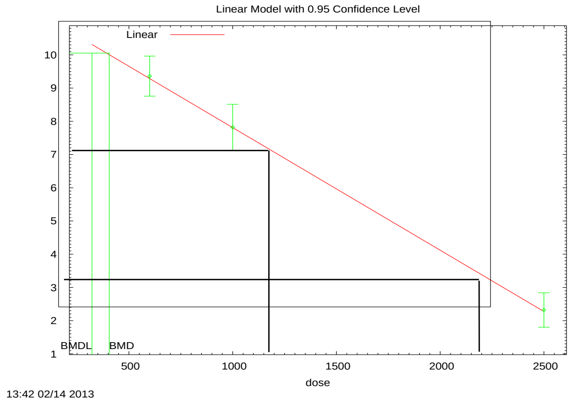

Figure 4. BMD modeling of the reduction of scores (mean response) on breadth of approach with increasing CO_2 levels (dose in ppm) from Satish et al.[1] The error bars represent one SD and the horizontal black lines represent transitions from average to marginal performance and from marginal to dysfunctional performance. Corresponding black vertical lines show the CO_2 levels at those transition levels. For measurement of the breadth of approach, the marginal zone is above 1200 ppm CO_2 and the dysfunctional zone begins at about 2200 ppm.

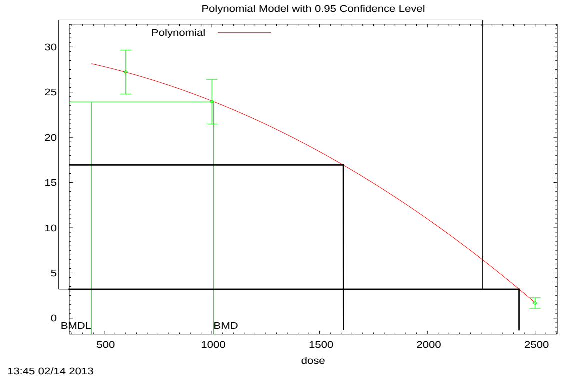

Figure 5. BMD modeling of the reduction of scores (mean response) on basic strategy with increasing CO_2 levels (dose in ppm) from Satish et al.[1] The error bars represent one SD and the horizontal black lines represent transitions from average to marginal performance and from marginal to dysfunctional performance. Corresponding black vertical lines show the CO_2 levels at those transition levels. For measurement of basic strategy, marginal zone is above 1600 ppm CO_2 and the dysfunctional zone begins at 2400 ppm.

The levels of CO_2 that elicit marginal or dysfunctional decision making performances are troubling in terms of our current permissible operating levels aboard the ISS, and especially during EVAs. The authors of the original paper were surprised by their findings and recommend that a study much like the one they performed is needed to confirm their findings. Assuming that their findings can be repeated, one might ask if there are other factors that could mitigate our concerns about the effect of CO_2 on decision making in astronauts.

IV. Possible Mitigating or Enhancing Factors for the Effects of CO_2

A. Transient Effects of CO_2 to which Humans Can Adapt

Many of the physiological effects of CO_2 are transient after concentrations are elevated to much higher levels than have been considered here. For example, cerebral blood flow increases at 0.7% (5.3 mmHg) and 1.2 % (9.1 mm Hg) CO_2 in 4 subjects exposed for 23 days occurred only in the first 1-3 days of exposure.[14] The transient changes, amounting to about 35% increase in flows, were not dose dependent; that is, the increases at 1.2% were no higher than at 0.7%. Headaches were also reported only during the initial phases of the study. Likewise, in exposures of 5 or 11 days to 21 mmHg or 30 mmHg CO_2 test subjects (n=4 at each condition) reported mild headaches and awareness of increased ventilation only during the first 24 hours of the exposures.[15]

B. Spaceflight Effects that Could Interact With Response to High CO_2

In setting limits for air pollutants, NASA considers any evidence that the toxic effects of a compound may be exacerbated by physiological adaptations to spaceflight. Due to the absence of significant gravity in orbiting space vehicles (the centrifugal force vector cancels the gravity vector), bodily fluids shift toward the head in space. This causes an increase in intracranial pressure and may be associated with ocular changes that can remain even after a mission has ended.[16] Due to the increased blood flow in cerebral arteries caused by CO_2, one can speculate that the combination of fluid shifts and elevated CO_2 in the air could exacerbate adverse effects on the crew compared to CO_2 alone; however, this combined effect has not been proven.

C. Testing for Recovery of Higher Reasoning During CO_2 Exposures

We agree with the original investigating team that the results of Satish et al.[1] must be independently confirmed. Once that has been done, research must address the question of whether test subjects would recover their decision making capability in an environment where CO_2 levels remain substantially elevated for a few days, perhaps up to a week. If this is the case, then operational strategies can be developed to deal with the expectation that those newly arrived into a high CO_2 environment must be given only simple tasks until they have adapted to the new, higher CO_2 levels. Our understanding needs to be developed in light of the reports from crewmembers that they experience an apparently episodic phenomenon called “space stupids,” which is sometimes called “mental viscosity” or “space fog.”[8] Abrupt, modest increases in CO_2 concentration may elicit this effect.

There is some evidence that “mental performance” as measured in a different way than with the SMS is potentially degraded by sustained, exposure to high CO_2. Manzy and Lorentz[17] selected 4 performance measures from the Advisory Group for Aerospace Research and Development (AGARD) battery of standardized tests to evaluate a group of 4 men exposed in a diving chamber to 0.7% (5.3 mmHg) or 1.2% (9.1 mmHg) CO_2 for 26 days continuously. Another group of 4 men were subjected to the same testing, but were not confined or given any additional CO_2 exposure above ambient concentrations. The 4 performance measures were as follows: grammatical reasoning (compare the truth value of 2 statements), memory search task (short-term memory of small sets of letters), unstable tracking (using a joy stick to keep a cursor in a target zone), and dual-task (ability to perform 2 of the memory tasks at once). Subjective mood scores reported by the crew included alertness, contentedness, and relaxation.

Manzy and Lorentz found that the 0.7% CO_2 group had "disturbed" tracking ability when compared to the controls; however, they attributed this to chamber adaptation. During exposures to 1.2% CO_2, tracking performance was also disturbed, but, according to the investigators, the time course of the differences from controls over the course of exposures suggested that this was an effect of CO_2 exposure. Interestingly, this change seemed to covary with the subjective measure of alertness, which appeared to be lower throughout the 26-day exposure. The small number of subjects (n=4) used in these experiments limits what can be deduced from them; however, it is tempting to suggest that the reported loss of alertness could be related to some of the SMS deficits, albeit at much higher and longer exposure concentrations than were used for the SMS testing.

V. Conclusions

The United States and other spacefaring nations must ensure that the data of Satish et al.[1] are either confirmed or refuted. If the data are confirmed, then investigators must determine whether test subjects can adapt to moderate CO_2 levels at some time point after their exposure begins. If adaptation occurs, we will have to know how quickly it occurs at various CO_2 concentrations and if there are individual differences in the adaptation rate. For example, adaptation might occur more quickly at low CO_2 values and never occur at higher levels in some individuals. As the new data now stand, NASA must plan to maintain far lower CO_2 levels in spacecraft and EVA suits than it has before, unless it considers potentially transient deficits in decision making acceptable. Marginal decision-making capability should be expected above 1000 ppm (0.8 mmHg) and dysfunctional capability in some measures above 2000 ppm (1.5 mmHg). Exposures to CO_2 may be behind the "space stupids" often reported by crewmembers.

Acknowledgments

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