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Human CO₂ generation rates in small enclosures for different test cases

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Abstract The present study deals with experimental measurements of CO₂ generation rates, due to the human occupation of a full-scale experimental mock-up simulating the astronaut crew quarters aboard the International Space Station. The estimation of CO₂ generation rates follows different methods as described in the literature. A single test subject in four different testing cases is considered, one at rest representing the baseline case and the other three cases at varying levels of physical activity or at rest but with a fixed breathing frequency requested from the human subject. The study results indicate that imposing a fixed breathing rate even while at rest increases the generation rate unpredictably. Following literature metabolic rate estimations, the latter two cases are equivalent to the subject being engaged in light or medium physical activities. The results are used to form recommendations for studies measuring human CO₂ generation rates.

1. Introduction

This study deals with CO₂ accumulation in confined spaces. Staying in confined spaces with insufficient or ineffective ventilation, presents risks for human health due to CO₂ accumulation around the human, a fact of significant importance in the environment of the International Space Station where, in the absence of gravity and natural convective flows, pockets of CO₂ form around humans' heads [1–3].

Measuring the CO₂ accumulation around a person's head raises several questions. Firstly, at which locations is it relevant to place the measurement probes, secondly how to account for the fact that the human head is rarely stationary and finally, how to consider the variation of CO₂ generation rates across different individuals in resting cases. Given the variability of these factors and the impossibility of measuring CO₂ accumulations in every scenario, methods of estimating the CO₂ generation rate of humans have emerged. One of the frequently used estimation methods is based on the base metabolic rate (BMR) of each individual and their level of physical activity at the time of estimation [4]. Another possibility of estimating the CO₂ generation rate is based on the concept of the Tidal Volume – which is the air circulated during regular breathing [5,6] and the number of breaths each minute. Knowing that the human body strives to maintain the same level of CO₂ in the exhaled air (4% CO₂ per volume) it is possible to estimate the CO₂ generation rate. This method has been previously used in studies focusing on the ISS astronauts [7].



The author's previous work [8] has highlighted the viability of the two estimations mentioned above which, when averaged over 13 test subjects in a resting state proved to be within 5% of the experimental measurements.

The aim of this paper is to evaluate these estimation methods in cases where the subjects are either not at resting state, or are told to breathe with a specific frequency. Studies concerning the human breath often consider a fixed breathing frequency and the authors intend to evaluate if imposing such a case on a test subject impacts its CO₂ generation rate in a significant manner. To avoid the issue of the variability of CO₂ generation rates among individuals, this study was performed considering a single test subject which was measured in four different test cases accounting for scenarios of high physical exertion and imposed fixed breathing frequencies.

2. Experimental setup and testing procedures

A full-scale experimental model simulating CQ on board of the ISS was used in this study (Figure 1 a). NDIR (non-dispersive infrared) CO₂ sensors were installed at three different heights inside the experimental model, while a fourth was installed outside to monitor exterior CO₂ concentrations. The sensors have a measuring range of 0-10000 ppm accurate within ± 50 ppm, $\pm 3\%$ of the reading with signal noise levels below 10 ppm. The three sensors dubbed C1, C2 and C3 were installed in the CQ model (Figure 1 b) in the middle, top and bottom sections respectively.

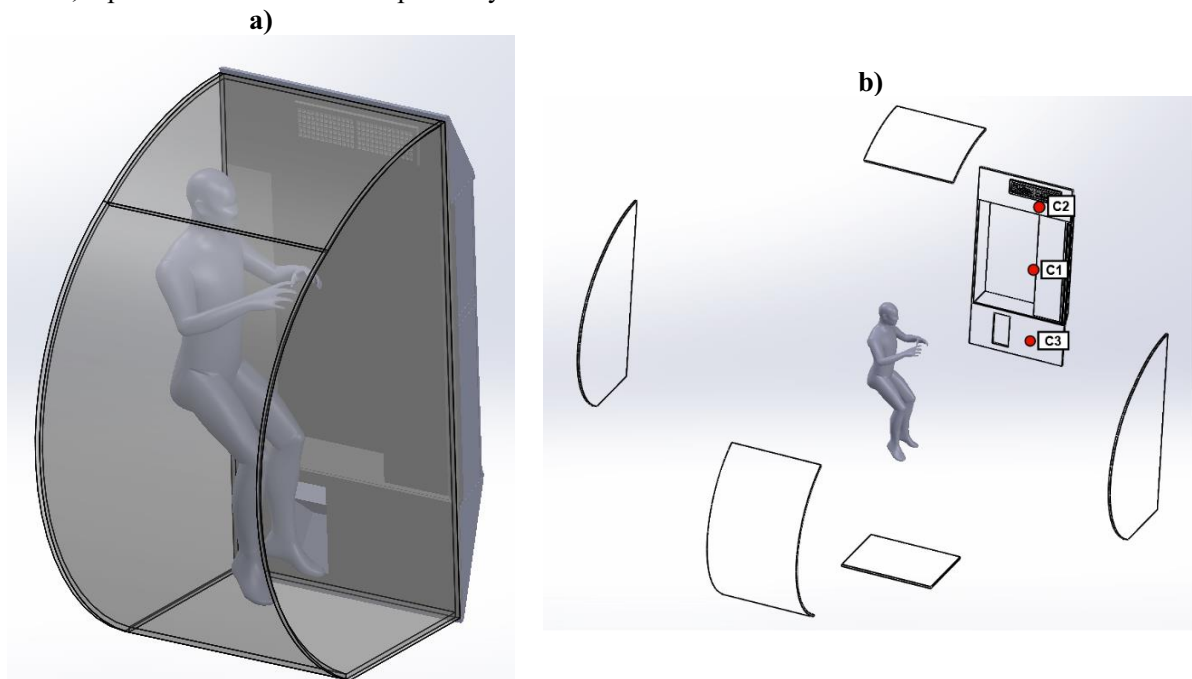


Figure 1 Full-scale CQ model, (a) the test subject's position inside and (b) the positions of the three CO₂ sensors (C1, C2 and C3).

The aim is to measure the CO₂ accumulation of a single human test subject in four different testing cases. The first case will be the baseline for comparison with the human test subject seated inside the full-scale model on a chair, at rest breathing normally for 15 minutes, with the ventilation system of the model turned off and the model intakes/exhausts sealed. The at rest test case was repeated 3 times on several days, all results being within -6 to 11% from their average and presenting similar linear increases.

The second testing case aims to reproduce a state of high physical exertion (such as during intense exercise). The confined space of the model hinders such activities taking place inside for fear of accidentally impacting the CO₂ sensors. To mimic intense physical activities the subject was instructed to engage in a 200 m sprint prior to entering the model.

The third and fourth cases, performed on different days to allow the subject to recover after each test, were aimed to directly evaluate the influence of the breathing frequency (b_f [Hz]) on the CO₂ accumulation. The subject was thus instructed to breathe with a fixed frequency of 12 and 24 breaths/min for the third and fourth test cases respectively. At any point during the measurements, a quick release system was set in place to ensure the subject could exit the model quickly for safety concerns. Once the experimental procedure began, the CO₂ concentrations were recorded for all 15 minutes at a frequency of 0.5 Hz. The subject was also instructed to count the number of breaths per minute several times during the experiment.

In the author's previous work [8] two prediction methods were shown to be in close agreement with the average experimental measurements. The first of the two was based on the human metabolic rate and the level of activity [4] and was within 1.5% of the experimental results on average. The second method was based on the Tidal Volume as described in medical literature [5,6,9], which was within 5% of the experimental average. As described in the introduction it is worth noting that these errors were obtained for the average over all measured test subjects and that individual differences can vary significantly from these values.

The first method for estimating CO₂ generation rate, based on the metabolic rate [4] is shown in Equation (1) where BMR is the basal metabolic rate and M is the level of activity calculated based on the previously cited methodology [4].

$$Q_{CO_2} = 0.000484 \cdot BMR \cdot M \text{ [l/s]} \quad (1)$$

The second method, based on the Tidal Volume (V_t) is presented in Equation (2), where $V_{t/w}$ is the Tidal Volume per weight [ml/kg], w is the weight of the human and b_f is the breathing frequency [Hz].

$$Q_{CO_2} = V_{t/w} \cdot w \cdot b_f \text{ [ml/min]} \quad (2)$$

Following the experimental measurements of the CO₂ accumulation in the four test cases will be compared to those estimated using the two methods [4,9] described above (Equations 1 and 2). Parameters for each test case as well as for each individual method are given below in Table 1. In the last row of Table 1, V_t is indirectly determined as the product of $V_{t/w}$ [ml/kg] and w [kg].

Table 1 Human subject parameters for each test case and for each estimation method.

Subject Parameters	Case 1 (resting state)	Case 2 (intense physical activity before the test)	Case 3 (resting – 12 breaths/min)	Case 4 (resting – 24 breaths/min)
w [kg]	76.5	76.5	76.5	76.5
b_f [breaths/min]	17	28	12	24
BMR [MJ/day]	7.716	7.716	7.716	7.716
M [met]	1.3	8	2.8	3.8
$V_{t/w}$ [ml/kg]	8	8	8	8
V_t [ml]	612	612	612	612

3. Results and discussion

Figure 2 shows the CO₂ accumulation at each sensor in the CQ for each of the four measured states as described in the previous section. The accumulations at sensor C1 and C2, shown in Figure 2 a and b

respectively, present very sharp increases. The curves for the High Intensity case and the 24 breaths/min case end abruptly after around 10 minutes. In both cases this was a forceful cessation of the experimental procedure. In the High intensity case due to reaching the upper limit of concentration measurable by sensor C1 (10000 ppm), and in the 24 breaths/min case the cessation was caused by health concerns expressed by the test subject.

For all three sensors, CO₂ accumulation in the case corresponding to the imposed breathing frequency of 12 breaths/min, is higher than in the Resting state despite the corresponding breathing frequency being higher (17 breaths/min). The authors assume that this phenomenon is caused by a difference in the Tidal Volume of the resting state compared to the Tidal Volume of the 12 breaths/min case. It is assumed that the test subject has difficulty breathing normally while also striving to maintain the required breathing frequency, leading to deeper inhalation/exhalations and thus a larger Tidal Volume, affecting CO₂ accumulation.

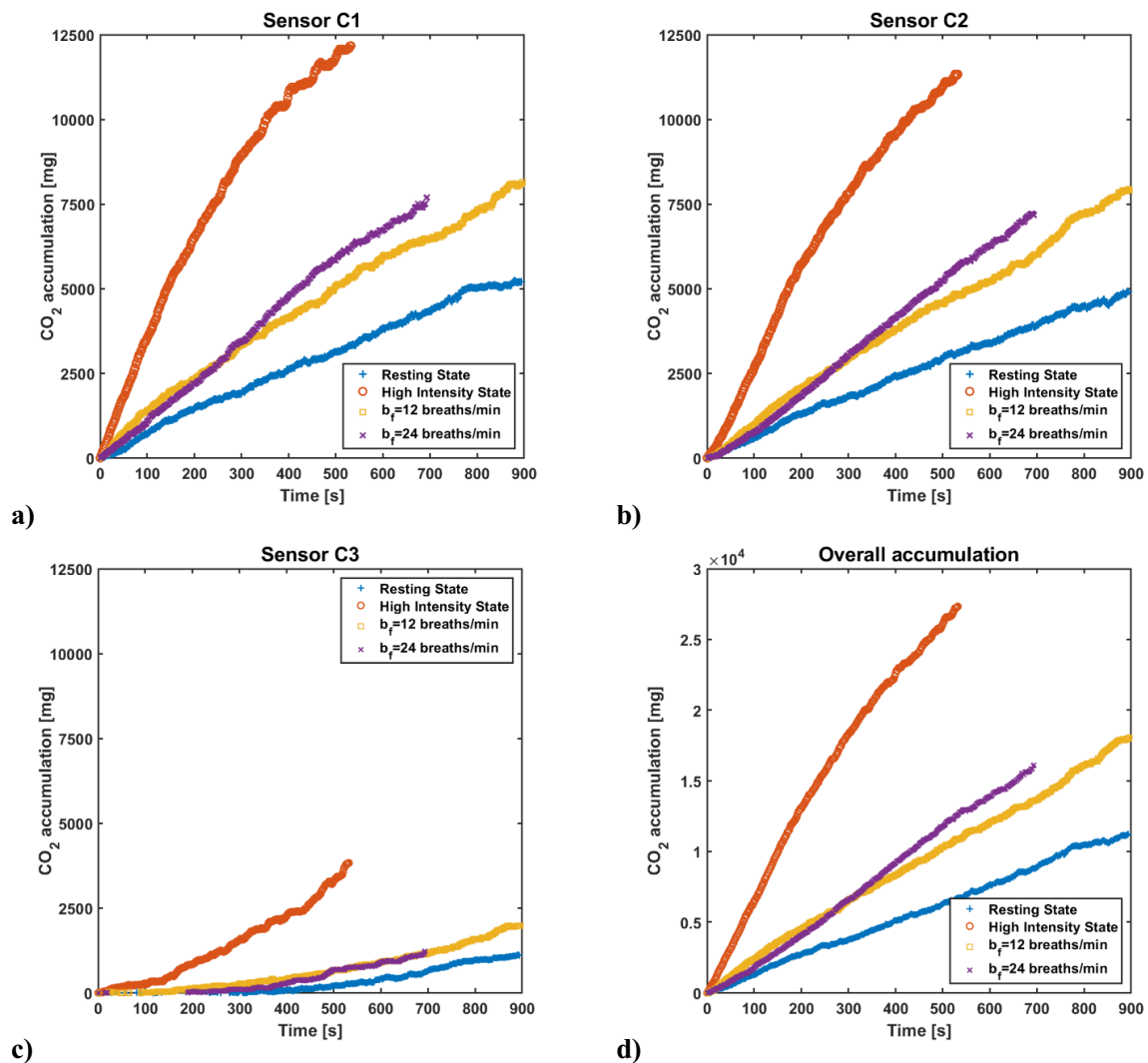


Figure 2 CO₂ accumulation at sensor C1 (a), C2 (b), C3 (c) and in the overall CQ (d) for the resting and high intensity states as well as the fixed breathing frequency measurements.

It can be observed that the difference between Cases 3 and 4 is less significant than expected despite the breathing frequency of the latter being double that of the former. At the point where the experiment was abruptly ended for Case 4, the difference between Cases 3 and 4 is around 20% at sensors C1 and C2, while no significant difference is found at sensor C3. The accumulation in Case 4 is significantly smaller than that of Case 2 (presenting the highest breathing frequency) indicating either significantly increased Tidal Volume values or higher metabolic CO₂ generation or a combination of both.

To compare CO₂ prediction methods, the overall accumulation in the CQ (Figure 2 d), obtained by summing the values at each of the three sensors, is required in order to determine the generation rate of the test subject for each of the four test cases. This generation rate was compared to those obtained from Equations (1) and (2) in Table 2.

Table 2 CO₂ generation rates determined according to the experimental, BMR and V_t methods.

	Experimental generation [g/h]	CO ₂ rate [g/h]	BMR CO ₂ generation rate [g/h] / Error from experimental values [%]	V _t CO ₂ generation rate [g/h] / Error from experimental values [%]
Case 1	46.6		31.9 / -31.5%	43.1 / -2.1%
Case 2	190.9		196.5 / +2.9%	75.1 / -60.6%
Case 3	76		68.8 / -9.5%	32.2 / -57.6%
Case 4	86.2		93.3 / +8.3%	64.4 / -25.3%

Table 2 shows that while the BMR presents significant differences in the generation rate for Case 1 (the resting case), for the other 3 cases the resulting values are within 10% of the experimental measurements, indicating that the level of activity chosen was appropriate. The V_t method on the other hand presents the opposite behavior offering good accuracy for Case 1 (2% error) while presenting errors between 25-60% for the other 3 cases. The explanation is that the assumption that V_{t/w} is between 6-8 ml/kg was made considering normal resting cases for the human body and was not designed to deal with situations with high levels of physical activity or intensive breathing.

To compensate for this fact, the authors have estimated values of V_{t/w} which would in turn modify the tidal volume to bring the generation rates more in-line with the experimental results. These estimations are presented in Table 3.

Table 3 V_{t/w} adjustment of the CO₂ estimation rate for Cases 2 through 4

	V _{t/w} [ml/kg]	Error from experimental generation rate [%]	Resulting V _t [ml]
Case 2	19 ÷ 22	-7 ÷ +8.3 %	1450 ÷ 1700
Case 3	17 ÷ 21	-10 ÷ +11 %	1300 ÷ 1600
Case 4	10 ÷ 12	-6.6 ÷ +12 %	770 ÷ 920

The intervals of V_{t/w} given in Table 3 bring the resulting CO₂ generation rates within 10% of the experimental results. The resulting V_t for each of the cases following these propositions are plausible (the inspiratory reserve volume is around 3000 ml [5]). It must also be noted that following this estimation method, V_t is closely related to the b_f. If we compare the results of Table 3 to the initial case parameters presented in Table 1 we can explain the lower values of V_t for Case 4 found in Table 3 as being compensated by the higher b_f.

The BMR estimation method was less accurate for the resting state, but accurate for Cases 2 through 4, although the only factor that changed between the cases in their BMR estimation was the level of physical activity M [met]. Another observation is that an artificial increase in the number of breaths (Cases 3 and 4) is not directly equivalent to an increase in the level of physical activity. Cases 2 and 4 are close in terms of b_f (28 breaths/min for case 2 compared to 24 breaths/min for case 4), but the resulting V_t are significantly

different. Further investigations are required along with an increase in the number of subjects and/or the number of Cases tested, in order to determine a correlation between the level of physical activity and the tidal volume required by humans during day to day activities.

4. Conclusion

The CO₂ generation rate of a human subject has been investigated in four different testing cases and compared to estimations made following two methods found in the literature, one based on the body's base metabolic rate and the other based on the tidal volume of the human lungs.

Overall, the results show that when measuring the CO₂ generation rate, even if the subject is at rest, imposing a fixed breathing frequency influences the generation rate significantly to the point that it is the equivalent of the human subject being engaged in light to medium physical activity. The tidal volume method similarly needs to be corrected in order to account for this fact. Further research for measuring CO₂ generation rates in humans should be performed with no specification of the breathing frequency, unless this specification is thoroughly accounted for when comparing experimental results to estimations.

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