# Metabolic production of carbon dioxide in simulated sea states: relevance for hyperbaric escape systems.

M. TIPTON, P. NEWTON, T. REILLY

*Department of Sport & Exercise Science, Institute of Biomedical & Biomolecular Sciences, University of Portsmouth, St Michael's Building, White Swan Road, Portsmouth PO1 2DT*

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Tipton M, Newton P, Reilly T. Metabolic production of carbon dioxide in simulated sea states: relevance for hyperbaric escape systems. Undersea Hyperb Med 2006; 33(4):291-297. Hyperbaric Escape Systems (HES) are used when saturation diving bells have to be evacuated and divers transported to safety. The aim of the present investigation was to determine the levels of metabolic $CO_2$ production expected from the occupants of an HES in different wave states, and from this, to recommend a reasonable and safe requirement for scrubbing $CO_2$ within an HES. The $CO_2$ production and heart rate of 20 male subjects representing saturation divers were collected while they were seated in an HES seat, fixed to an inflatable rescue vessel. The vessel was tethered in a wave pool and longitudinal (L), perpendicular (P), and calm (C) sea conditions were reproduced. Heart rate did not differ between conditions (P= 0.33) the mean (SD) heart rates (b.min$^{-1}$) were: C: 71 (8.5); L: 74 (9); P: 75 (9).Carbon dioxide production was significantly higher (P=0.005) with the boat orientated perpendicular to the waves compared to the calm condition. The mean (plus 99% confidence interval) carbon dioxide production for each of the conditions was C = 319mL.min$^{-1}$ + (41mL.min$^{-1}$) = maximum of 360mL.min$^{-1}$; L= 374mL.min$^{-1}$ + (46mL.min$^{-1}$) = maximum of 420mL.min$^{-1}$; P = 409mL.min$^{-1}$ + (57mL.min$^{-1}$) = maximum of 466mL.min$^{-1}$. It is therefore recommended that a 12 person HES should be capable of scrubbing at least 8,053L of carbon dioxide in 24 hours. Thus, the current requirement for 8,415L in 24h is reasonable.

## INTRODUCTION

Hyperbaric Escape Systems (HES) are used when saturation diving bells have to be evacuated and the divers transported to safety. HES vary in size but typically hold 12 divers and should be able to support life for up to 72 hours, during which time the HES may be transported through rough water with the divers seated in padded chairs incorporating a 4-point harness.

The volume of metabolically produced carbon dioxide ($CO_2$) that has to be removed ("scrubbed") from the atmosphere of an HES will depend on the number of divers and their metabolic rate. Normally, "resting" $CO_2$ production approximates 200mL.min$^{-1}$, rising to 4L.min$^{-1}$ with heavy exercise. The current provision for scrubbing $CO_2$ assumes a metabolic rate in an HES of 200W giving 487mL.min$^{-1}$ $CO_2$ production per diver, with a respiratory exchange ratio (RER, carbon dioxide production/oxygen consumption [$VCO_2/VO_2$]) of 0.82[1], this figure remains valid for hyperbaric environments. This volume assumes that divers can remain secure and at rest in the seat of an HES, and that their metabolic rate does not increase more than two-fold from that at seated rest.

[1] Assuming 1L oxygen consumption per minute = 20.2kJ per minute = 336.7W. Thus: (200W/336.7W) x 0.82 = 487mL carbon dioxide production per minute. For 12 divers over 24h: 0.487 x 12 x 60 x 24 = 8,415L. Diver respiratory exchange ratio (RER = $VCO_2/VO_2$) taken as 0.82 (typical for mixed diet).

 

This assumption has been challenged by the suggestion that restraining against the movement caused by wave action will increase metabolic $CO_2$ production, and scrubbing capacity should therefore be raised to allow for this. The proposed theoretical figures are 3-4 times resting levels or 800-1000mL.min$^{-1}$ per diver (which results in 13,824-17,280L in 24h) and are based on a hypothetical "worst case scenario"(1). However, such a scenario has not been defined in terms of sea state and resultant motion/accelerations, and there are no data on the consequences of this motion for metabolic rate.

The aim of the present investigation was to obtain data on the $CO_2$ production of subjects in an HES seat and 4-point harness in different wave states, with a view to recommending a reasonable and safe requirement for scrubbing $CO_2$ within an HES. It was hypothesised that there would be no significant difference in the level of metabolic carbon dioxide production in rough compared to calm wave conditions if the subjects were able to remain at rest and engage in minimum levels of physical activity.

## METHODS

### Subject sample

Following ethical approval from the University of Portsmouth Ethics Committee, 20 healthy male volunteer subjects with a mean (SD) age of 36 (10) were recruited from the Royal National Lifeboat Institution (RNLI, n=16) and University (n=4). Written informed consent was obtained from each subject.

Subjects were *not* told to refrain from eating or drinking caffeinated beverages prior to attending the laboratory. Testing took place between 0900h and 1700h. The mean (SD) physical characteristics of the subjects were: Mass (kg) 91.4 (31.6) with a range of 69-115kg. Stature (m) 1.79 (0.06), range 1.66-1.90m. Percent body fat, derived from skin fold thicknesses, (2) was 23.1 (6.1), range 10.5-33%. The air temperature in the laboratory at water level was 19°C.

### Apparatus

An HES seat with harness was secured to the bow of an Atlantic 75 rigid inflatable lifeboat (RNLI, Cowes, UK. Figure 1). Subjects sat in the HES seat, the 4-point harness was secured and the subjects were instructed to rest. Although the subjects were not totally enclosed, they were unable to see oncoming waves.


**Fig 1.** A subject secured into the HES seat on the bow of the Atlantic 75 lifeboat ready to begin the experiment.

With the subject in place, the lifeboat was tethered in the centre of the RNLI sea survival wave tank with lines at the bow and stern. After 5 minutes of data collection in calm water (C), the wave-maker was started and set to a "confused" wave motion profile. This profile built up over 30-60 seconds to produce 1.5-2m waves (Figures 2 and 3). The wave profile continued for 20 minutes. The orientation of the boat to the waves was: 1) longitudinally (L) to the waves for 10 minutes or 2) orientated perpendicular (P) to the waves for 10 minutes. Ten subjects experienced longitudinal waves before perpendicular and 10 subjects experienced perpendicular waves before longitudinal.

**Figs. 2 and 3.** Experimental run Longitudinal wave orientation).

A sample of the tests was filmed in the sagittal plane; these were analysed using SIMI (reality motion systems software, Germany) two-dimensional motion analysis software. Individual points on the boat were manually digitized from the video to determine the horizontal and vertical boat movement due to wave motion. This was similar to the methods of Torner et al. (3) who examined boat motion with two-dimensional video in the sagittal plane.

During each test the oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($VCO_2$) of subjects was measured using a telemetric breath by breath analyser (Metamax 3B, Cortex, Germany [4]). According to the manufacturers, the oxygen and carbon dioxide analysers in this system have an accuracy of 0.1% and resolution of 7mL. The volume measurement has an accuracy of 2%. The Metamax system was calibrated between subjects using alpha graded gas samples. Heart rate (HR) was recorded continuously during the trials using a Polar Accurex Plus® (Finland) heart rate monitor.

### Data Analysis

A power of 0.92 - 0.99 (for the 2 active wave conditions) ($\alpha = 0.05$) required a sample size of 20. Steady state data in each condition was sampled by analysing the data collected during the last 3 minutes of the rest period and the last 7 minutes of each wave condition. The data collected were tested for normal distribution using the Kolmogorov-Smirnov test. A one-way ANOVA was employed to determine if there were any significant differences in $VCO_2$ and HR results across the 3 conditions. A Tukey post hoc analysis was determined when indicated by the ANOVA. Pearson Product Correlation Coefficients were undertaken to establish if a relationship existed between $VCO_2$ and lean body mass, mass or age. All volumes are expressed at body temperature, pressure, saturated (BTPS) to represent maximum possible exhaled volumes.

## RESULTS

### Motion Profile

The vertical motion profile monitored at the head of the subjects ranged between 0.7m and 1m when the boat was positioned longitudinally to the waves. Mean wave frequency was 0.5Hz. Over the wave cycle, subject velocities ranged between 0.2-1.7m.$s^{-1}$ and accelerations up to 5m.$s^{-2}$ were recorded.

In the perpendicular condition, an elliptical motion was observed with a frequency of 0.5Hz. This elliptical pattern had a vertical dimension of 0.73m and a horizontal dimension of 0.38m.

### Heart Rate

Heart rate data were collected from 19 subjects (one subject inadvertently switched the monitor off during the trial). The mean (SD) heart rate in the calm water was 71 (8.5) b.$min^{-1}$, 74 (9) b.$min^{-1}$for the longitudinal wave condition, and 75 (9) b.$min^{-1}$ for the perpendicular wave condition (Figure 4**).** Heart rate did not differ significantly between conditions (P= 0.33).

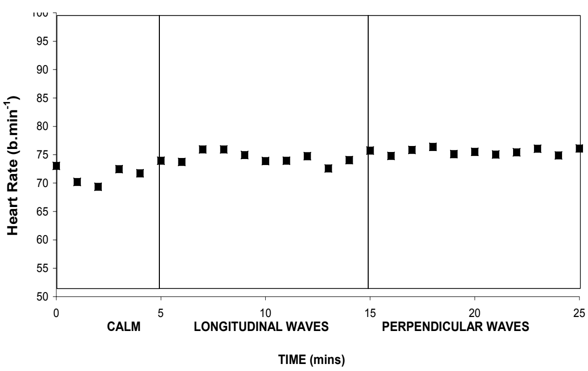


**Fig. 4.** Mean heart rate data for subjects across the three wave conditions (n=19).

### $CO_2$ production

The mean values for $CO_2$ production for each subject in each condition are shown in Figure 5. Carbon dioxide production was significantly higher *(P=0.005) in the perpendicular wave compared to the calm (no wave) condition. There was no significant difference between any of the other conditions. Figure 5 shows mean (3 SEM) for each condition.

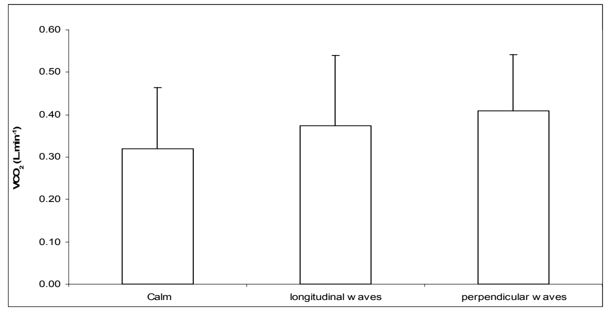


**Fig. 5.** Mean $CO_2$ production for the three wave conditions, 3SEM included (n=20, P=0.005 difference between Calm and Perpendicular Waves).

Table 1 summarizes the $VCO_2$, $\dot{V}O_2$ and RER results. The standard error of the mean (SEM), range and the 95% and 99% confidence intervals (CI) are given for $VCO_2$. Applying the 99% CI (mean data ±99% CI) provides 99% confidence that the mean $VCO_2$ of the population being studied will be within the mean of the data collected in the present study ± the 99% CI. That is 0.409±0.057 L.$min^{-1}$ for the condition giving the highest $VCO_2$ and SEM (Perpendicular waves).

| | Calm | Longitudinal Waves | Perpendicular Waves |
|---|---|---|---|
| $\dot{V}O_2$ (mean [SD]) | 0.361 (0.105) | 0.412 (0.155) | 0.47 (0.163) |
| RER | 0.87 (0.05) | 0.9 (0.08) | 0.86 (0.07) |
| $\dot{V}CO_2$ | | | |
| Mean | 0.319 | 0.374 | 0.409 |
| 2SD | 0.144 | 0.160 | 0.200 |
| Range | 0.179-0.437 | 0.213-0.537 | 0.262-0.624 |
| SEM | 0.016 | 0.018 | 0.022 |
| 95% CI on mean μ=X±Z(SEM) | ± 0.031 | ± 0.035 | ± 0.043 |
| 99% CI on mean μ=X±Z(SEM) | ± 0.041 | ± 0.046 | ± 0.057 |

**Table 1.** Summary of $VCO_2$, $\dot{V}O_2$ (L.$min^{-1}$, BTPS) and RER results in each condition (n=20).

Although the difference between $CO_2$ production in the two wave conditions was not statistically significant (P=0.42), it was apparent that when the boat was perpendicular to the waves, subjects had decreased lateral stability, this is supported by the amount of horizontal movement observed in this condition.

No significant correlation was identified between carbon dioxide production and either body mass, lean body mass or age.

## DISCUSSION

Given the significant increase in $VCO_2$ in the perpendicular compared to calm condition, we rejected our null hypothesis. However, it is clear that the increases in mean carbon dioxide production with motion in the present investigation were small (0.055-0.09 $L.min^{-1}$), and resulted in levels of carbon dioxide that were significantly lower than those estimated by others (5). The absence of larger increases in carbon dioxide production is probably because the majority of the body motion induced by the waves was passive and therefore did not increase metabolic rate. Additionally, the seat harness prevented the subjects from having to work much to resist the motion induced by the boat, again avoiding an increase in metabolic rate.

Two assumptions have to be valid before the data of the present study can be employed. The first is that our subjects were representative of the population under study (saturation divers) or, if they differed, they did so in a way that our data would over, rather than underestimate carbon dioxide production. We have no reason to believe that our subjects were not representative in this way. A survey of 100 saturation divers from ten different nations (International Marine Contractor Association [IMCA], personal communication) found an average body weight of 85.15kg. The average body weight of the subjects in the present study was 91.4kg; this higher mass could, if anything, result in higher resting carbon dioxide productions.

The second assumption is that the motion profile and other environmental conditions to which the subjects were exposed in this study resulted in $CO_2$ productions that were representative of the average profile that may be encountered over a 24h period in an HES. Little data exist about this assumption. However, we and the IMCA presume that the motions and accelerations induced in the present study probably exceeded those likely to be endured for a 24 hour period at sea. Ten minutes was a long enough period of data collection to allow steady state gas exchange to be achieved. It might be argued that other factors such as eating, sleeping and circadian variations could alter carbon dioxide production over the course of a day. Depending on the stage of sleep, $CO_2$ production can both increase and decrease, but overall tends to fall at night (6, 7). Dietary induced thermogenesis increases $CO_2$ production, this response was accommodated in the present study by allowing subjects to eat and drink before attending the laboratory; the steady state RERs in the present study were slightly higher (0.86-0.9) than those normally associated with a mixed diet (0.82).

We collected data over a 10 hour period, so part of any circadian variation in $CO_2$ production will have been accounted for in our results. In any case, the non-dietary and non-sleep related circadian variation in $CO_2$ production has been reported to be small (0.017 L.min-1), with lower values at night (7). It is unlikely that pressure per se will change $CO_2$ production levels significantly in humans in the conditions likely in an HES, and a change in breathing gas mixture to heliox or trimix should reduce the work of breathing and therefore $CO_2$ production associated with respiratory muscle activity. Although shivering would increase metabolic rate and thus $CO_2$ production, there is no evidence to suggest that the occupants of a functioning HES should become overly cold. Therefore we conclude that the data we collected during 10 minute sampling periods over the course of the day are valid and representative of that which might occur in similar conditions over a 24h period.

Accepting these assumptions permits interpretation and use of the data collected in the present study. Rather than employing an arbitrary standard based on an imaginary "worst case scenario", it would seem reasonable to use the data collected in the present study, the power and validity of which appears good, to set a standard. Our statistical analysis allows us to calculate with 99% confidence, the average $VCO_2$ for saturation divers in an HES. Employing average data means that some individuals will be producing more carbon dioxide than the average; however it is the average rate of production that will determine the scrubbing requirement within an HES.

Currently a typical HES is designed to accommodate 12 people with a metabolic rate of 200W and an average $VCO_2$ of 487mL.min$^{-1}$. This equates to 8,415L in 24h. Some protocols (8, now withdrawn) for testing HES have suggested that 430mL.min$^{-1}$ per diver be injected into the HES. For 12 divers this equates to 7,430L in 24h. A rate of $CO_2$ production of 800mL–1,000mL.min$^{-1}$ has been suggested in the IMCA's revised protocol, issued in 2004 (9, 10), after the initial work was challenged. For 12 divers this equates to 13,824-17,280L in 24h.

Calm conditions in the present study resulted in a $VCO_2$ of 319mL.min$^{-1}$ +99% CI (41mL.min$^{-1}$) = 360mL.min$^{-1}$. For 12 divers this equates to a maximum of 6,221L in 24h. The longitudinal condition in the present study resulted in a mean $VCO_2$ of 374mL.min$^{-1}$ +99% CI (46mL.min$^{-1}$) = 420mL.min$^{-1}$. For 12 divers this equates to a maximum of 7,258L in 24h.

The perpendicular position in the present study resulted in a mean $VCO_2$ of 409mL.min$^{-1}$ +99% CI (57mL.min$^{-1}$) = 466mL.min$^{-1}$. For 12 divers this equates to a maximum of 8,053L in 24h.

The difference between the $CO_2$ production in the longitudinal compared to the perpendicular conditions was considered due to the subjects' decreased lateral stability when waves were presented perpendicularly, this is supported by the amount of horizontal movement observed in this condition. Stability is likely to be improved when an HES is full, and people are sitting closely side by side. If lateral stability can be improved, the lower figure for $CO_2$ production could be used (420mL.min$^{-1}$ per diver). If it cannot be improved, the higher figure (466mL.min$^{-1}$ per diver) should be used, and a 12-person HES should be able to scrub 8,053L of carbon dioxide in 24 hours. Thus, the assumption of a 200W metabolic rate and consequent 487mL.min$^{-1}$ per diver of carbon dioxide production (8,415L in 24h) is reasonable.

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