Exercise intensity inferred from air consumption during recreational scuba diving

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Abstract

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Introduction: Episodic exercise is a risk factor for acute cardiac events and cardiac complications are increasingly recognized in fatalities during recreational scuba diving. What is not known is the exercise intensity involved in typical recreational diving.

Methods: This study used pre- to post-dive gas cylinder pressure drop to estimate air consumption and, from that, exercise intensity during recreational dives. Dive profiles were captured electronically and divers self-reported cylinder pressure changes, perceived workload, thermal status and any problems during dives. Mean surface air consumption (SAC) rate per kg body weight and mean exercise intensity (reported in metabolic equivalents, MET, multiples of assumed resting metabolic rate of 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$) were then estimated. Data are reported as mean ± standard deviation.

Results: A total of 959 recreational air dives (20 ± 9 metres' sea water maximum depth; 50 ± 12 min underwater time) by 139 divers (42 ± 10 y age; 11 ± 10 y of diving; 12% smokers; 73% male) were monitored. Problems were reported with 129/959 dives: buoyancy (45%), equalization (38%), rapid ascent (10%), vertigo (5%) and other (2%). Assuming a 10% overestimate due to cylinder cooling and uncontrolled gas loss, the estimated exercise intensity associated with monitored dives was 5 ± 1 MET. Mean ± 2SD, or 7 MET, captures the effort associated with the vast majority of dives monitored.

Conclusion: Our estimates suggest that uncomplicated recreational dives require moderate-intensity energy expenditure to complete, with a 7-MET capacity generally adequate. Higher levels of aerobic fitness are still strongly recommended to ensure ample reserves. Further research is needed to quantify energetic demands of recreational diving during both typical and emergent events in both experienced and less experienced divers.

Key words

Aerobic capacity, oxygen consumption, physiology, exercise, fitness to dive, diving research

Introduction

Episodic exercise is a risk factor for acute cardiac events and cardiac complications are increasingly being recognized as a common contributing factor in fatalities occurring during recreational scuba diving activity.[1,2] A recent review of the medical assessment records of 200 professional divers found that 81% had at least one cardiovascular risk factor and 66% had an alterable risk factor.[3] While the presence of such risk factors may promote discussion of physical fitness for diving, such efforts are limited by the fact that the exercise intensity involved in a typical range of recreational diving is not well known.

Aerobic capacity ($\dot{V}O_{2\,max}$) is defined as the maximum amount of oxygen that can be consumed per unit time. Describing $\dot{V}O_{2\,max}$ per kilogram body mass ($mL \cdot kg^{-1} \cdot min^{-1}$) eliminates total body size as a confounder. The complicated units associated with $\dot{V}O_{2\,max}$ can be eliminated by converting weight-indexed $\dot{V}O_{2\,max}$ measures into dimensionless metabolic equivalents (MET), multiples of assumed resting metabolic rate (3.5 $mL \cdot kg^{-1} \cdot min^{-1}$). For example, a $\dot{V}O_{2\,max}$ of 35 $mL \cdot kg^{-1} \cdot min^{-1}$ would be divided by 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ to yield a dimensionless 10 MET capacity (10 MET_{max}).[4] A review of studies actually measuring aerobic capacity in divers found the mean in 14 varied groups of mainly male and mainly experienced divers ranged from 37–57 $mL \cdot kg^{-1} \cdot min^{-1}$ (10.6–16.3 MET).[4] Aerobic fitness was not known to be a problem in these groups, but it is also not known what fraction of their fitness level was required for routine or exceptional diving conditions. Another point to appreciate is that land-based aerobic capacity may not translate directly to in-water capability. A comparison of maximal performance achieved during a treadmill test and during tethered finning on scuba found significantly lower $\dot{V}O_{2\,max}$ and ventilation volume while on scuba (32 vs 42 $mL \cdot kg^{-1} \cdot min^{-1}$ and 72 vs. 104 $L \cdot min^{-1}$, respectively).[5]

Recommendations for aerobic capacity to be maintained for recreational diving are typically based on expert opinion or consensus in the absence of comprehensive data. The proceedings of the 2010 Divers Alert Network Fatality Workshop concluded, "*It was generally agreed that the metabolic requirement for normal swimming in modest to benign diving conditions was around 4 MET, and a safety margin is gained by having the capacity to sustain a 6-MET exercise intensity.*"[6] This is similar to both the 5.7 mean MET (SEM ± 0.2) estimated from heart rate during exercising dives, and a 7-MET capacity posited by other authors to represent a desirable minimum capacity.[5,7,8]

Efforts to develop field assessment of metabolic demand have been limited, in no small part because of the potential confounders of experience, capability, equipment performance, psychological comfort and an array of environmental conditions. Dwyer investigated the relationship between heart rate and oxygen uptake ($\dot{V}O_2$) and minute ventilation ($\dot{V}_E$) among male divers while performing three levels of exercise intensity in relatively controlled ocean dives at 203, 304 and 406 kPa.[9] The dives were conducted in temperate waters with the divers wearing wetsuits, weight belts, buoyancy compensators, dual-hose regulators, single 71.2 ft^3 cylinders and a single model of relatively-high-torque fins. The subject-divers finned along marked circuits. Heart rate, ventilatory frequency, minute ventilation ($\dot{V}_E$) and oxygen consumption ($\dot{V}O_2$) were determined for the final minute of individual four minute exercise periods at different depths with multiple resistive loads. $\dot{V}_E$ was calculated from the cylinder pressure drop over a test period, effectively similar to how divers describe their air consumption operationally. Our goal was to see if we could use Dwyer's regression formulae with cylinder pressure drop information from recreational dives to estimate mean workloads.

Methods

Adult certified divers making recreational, open-water dives were recruited as previously described.[10,11] Briefly, dive businesses and dive clubs in Western Australia (WA) were invited to participate. A researcher met groups of recreational divers at popular dive sites around the WA coast. The study was approved by the Human Research Ethics Committee of the University of Western Australia (approval # RA/4/1/1664). Written informed consent was obtained.

Dive and diver information was collected using a modified Divers Alert Network (DAN) Project Dive Exploration (PDE) questionnaire and Sensus Ultra data-loggers (ReefNet, Mississauga, Ontario) were attached to the front of each diver's buoyancy compensator to capture pressure-time profiles. Depth to ± 0.01 metres' sea water (msw) resolution (0.3 msw accuracy) and water temperature (± 0.01°C and 0.8°C accuracy) were estimated every 10 seconds.[12] Diver data collected included sex, age, height, mass, certification level, current smoking status, number of years of diving and dive counts within the most recent year. Dive-specific data included dress, thermal comfort ('cold', 'pleasant' or 'warm'), perceived workload ('resting/light', 'moderate' or 'severe/exhausting'), starting and ending cylinder pressures and any problems occurring during dives. Any dives lacking one or more of the required variables (cylinder capacity, start and end pressures, or body mass) were excluded from analysis.

Mean depth was calculated by dividing the total of recorded depths (depth >1 msw) for each dive by the number of samples recorded. This then would include time for divers swimming back to the boat underwater but exclude time spent swimming at the surface. It was assumed that divers at the surface would have temporarily discontinued using scuba and breathed air from the atmosphere, but this could not be confirmed. Surface air consumption was calculated by dividing the gas volume used by the number of minutes spent underwater and the ambient pressure in bar at the mean depth.

Dwyer produced regression equations based on the correlation between $\dot{V}O_2$ and $\dot{V}_E$ at different test pressures. The formula for the 203 kPa trials (r = 0.79, standard deviation 0.411) was $\dot{V}O_2 = 0.0256\dot{V}_E + 1.070$. This formula was used in the current study to estimate $\dot{V}O_2$ since it was computed for a depth closest to the mean depth for the current dive series. Dwyer also calculated regression equations for 304 and 406 kPa exposures, but these were not applicable in the present study.

Data were imported into the Statistical Analysis System (SAS) version 9.3 (Cary, North Carolina) for analysis. The analysis was conducted in two phases. Firstly, to investigate the gas consumption rate (SAC) per kg body weight, likely associated variables were fitted to a linear regression model (PROC GLM). These included sex (SEX), age in years (AGE), body mass index (BMI) calculated by dividing each diver's weight by the square of their height ($kg \cdot m^{-2}$), certification status (CERT), current smoking status (SMK), number of dives within the previous year (NUM), time since first diving, in years (TIME) and perceived workload (WORK). Certification was classed as 'basic' for levels requiring fewer than 10 training dives, 'intermediate' for certification requiring 10–20 total training dives and 'leadership' for certifications requiring more than 20 total training dives. Data were stratified by organized group dive and the effect of this was accounted for by retaining a stratification variable (ORG) throughout the backwards elimination of non-significant variables. The initial model built was:

$$SAC_{ij} = \beta_0 + \beta_1 SEX_i + \beta_2 AGE_i + \beta_3 BMI_i + \beta_4 CERT_i + \beta_5 CERT2_i + \beta_6 SMK_i + \beta_7 NUM_i + \beta_8 TIME_i + \beta_9 WORK_{ij} + \beta_{10} WORK_{ij} + \beta_{11} ORG_j \quad (1)$$

where β_0 = the intercept of the regression. Variables were associated with the diver (subscript i) and/or the group dive on which data were collected (subscript j). The regression equation correlation coefficient of the final model (r) was derived from the square-root of the coefficient of determination (R^2). In the second phase, $\dot{V}O_2$ and mean inferred exercise intensity were estimated using Dwyer's formula, as described previously. Descriptive anthropometric and dive data are reported as mean ± standard deviation (SD), dive certification is reported as percentage within each level and dive experience is reported as median and range, because of the non-normal distribution of years of experience and dives within the previous year. Significance for all statistical tests was accepted at $P < 0.05$.

Results

A total of 1,032 recreational dive profiles were collected from 163 individual divers. SAC was estimated for 959 dives (93% of the 1,032 dives) made by 139 divers (85% of the 163 divers). A total of 73 dive records were excluded due to missing information. All dives were made with compressed air. Minimum water temperature during dives followed

Table 1

Diver demography and dive characteristics; mean (SD) or percent, as appropriate, with median and range for dive experience; BMI – body mass index; Certification = 'basic' if required training dives < 10, 'intermediate' if 10–20 and 'leadership' if > 20

Demography	Males (n = 102, 73%)		Females (n = 37, 27%)		Pooled (n = 139)	
Age (y)	43	(10)	39	(9)	42	(10)
Weight (kg)	88	(15)	67	(13)	82	(17)
Height (cm)	179	(7)	166	(8)	175	(9)
BMI (kg m^{-2})	27	(4)	24	(4)	27	(4)
Smokers (%)	11	(11)	5	(14)	16	(12)
Years of diving	10	(0–40)	6	(0–37)	9	(0–40)
Dives in previous year	25	(0–250)	42	(0–200)	39	(0–250)
Certification (% basic/ intermediate/leadership)	27/33/40		24/35/41		26/34/40	
Dive characteristics						
Maximum depth (msw)	20.7	(9.0)	20.3	(9.4)	20.5	(9.1)
Mean depth (msw)	10.7	(4.3)	10.9	(4.3)	10.8	(4.3)
Total dive time (min)	49	(12)	55	(12)	50	(12)

Table 2

Gas consumption and inferred exercise intensity by perceived workload; mean (SD); BMI – Body mass index; SAC – Surface-equivalent air consumption; $\dot{V}O_2$ – oxygen uptake

	Resting/Light (n = 683)		Moderate (n = 247)		Severe/exhausting (n = 9)		Pooled (n = 939)	
Age (y)	41	(9)	40	(8)	44	(10)	41	(8)
Weight (kg)	84	(16)	78	(17)	78	(16)	83	(17)
Height (cm)	176	(9)	172	(9)	174	(7)	175	(9)
BMI ($kg{\cdot}m^{-2}$)	27	(4)	26	(5)	26	(5)	27	(5)
Mean depth (msw)	10.6	(4.3)	11.0	(4.4)	10.4	(3.4)	10.7	(4.3)
SAC (VE) ($L{\cdot}min^{-1}$)	17.4	(5.4)	17 .9	(5.5)	22.3	(6.2)	17.6	(5.5)
$\dot{V}O2$ ($L{\cdot}min^{-1}$)	1.52	(0.14)	1.53	(0.14)	1.64	(0.16)	1.52	(0.14)
SAC ($L{\cdot}kg^{-1}{\cdot}min^{-1}$)	0.21	(0.07)	0.23	(0.07)	0.29	(0.06)	0.22	(0.07)
$\dot{V}O2$ ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) estimate	18.6	(3.6)	20.4	(4.4)	21.5	(3.1)	19.1	(3.9)
Exercise intensity (MET) estimate	5.3	(1.0)	5.8	(1.3)	6.2	(0.9)	5.5	(1.1)

geographic lines, from 15°C in the south of the state to 29°C in the north. Problems were reported with 129 of the 959 dives; buoyancy (45%), equalization (38%) rapid ascent (10%), vertigo (5%) and other (2%). Diver demography and characteristics of the dives are presented in Table 1.

There were 887 data (86%) that were complete for all nine variables in the regression model. A higher SAC was not significantly associated with either sex (P = 0.25) or smoking status (P = 0.08) but was significantly associated with older age (P < 0.01), lower BMI (P < 0.01), lower dive certification (P < 0.01), higher number of dives in the previous year (P < 0.01), fewer years of diving (P < 0.01) and higher perceived workload (P = 0.01). The final model is shown with the respective coefficients in equation 2 (r = 0.52). The dive stratification variable was retained but is not shown because it was not significant (P = 0.46) and had low estimated effect (β = -0.00004):

$$SAC_{ij} = -2.73 + 0.002AGE_i - 0.006BMI_i + 0.054CERT_i + 0.015CERT2_i + 0.0002NUM_i - 0.001TIME_i - 0.052WORK1_{ij} - 0.047WORK2_{ij} \quad (2)$$

Air consumption, inferred oxygen consumption and inferred exercise intensity categorized by subject-perceived workload are presented in Table 2. A trend was apparent for mean exercise intensity to increase with increasing perceived workload (Table 2). Overall (n = 939), mean inferred exercise intensity was 5.5 MET, approximately midway between the perceived workloads 'Resting/Light' (5.3 MET) and 'Moderate' (5.8 MET).

To explore the potential influence of thermal status, Table 3 presents air consumption, inferred oxygen consumption and inferred exercise intensity categorized by subject-perceived thermal comfort. Regardless of perceived thermal status, mean inferred exercise intensity for 'Cold', 'Pleasant' and 'Warm' were all also between 5 and 6 MET (Table 3).

Table 3
Gas consumption and inferred exercise intensity by perceived thermal comfort; mean (SD); BMI – body mass index; SAC – Surface-equivalent air consumption; $\dot{V}O_2$ – oxygen uptake

	Cold (n = 105)		Pleasant (n = 527)		Warm (n = 324)		Pooled (n = 956)	
Age (y)	39	(9)	42	(9)	40	(7)	41	(8)
Mass (kg)	74	(16)	85	(16)	82	(17)	83	(16)
Height (cm)	170	(9)	175	(10)	176	(9)	175	(9)
BMI ($kg \cdot m^{-2}$)	25	(4)	28	(5)	26	(4)	27	(4)
Time (min)	51	(11)	50	(12)	51	(13)	50	(12)
Mean depth (msw)	11.4	(4.5)	11.0	(4.4)	10.3	(3.9)	10.8	(4.3)
Max depth (msw)	21.1	(8.8)	21.0	(9.0)	20.1	(9.2)	20.6	(9.1)
SAC ($\dot{V}_E$) ($L \cdot min^{-1}$) estimate	16.0	(5.0)	17.5	(5.2)	18.5	(5.6)	17.7	(5.4)
$\dot{V}O_2$ ($L \cdot min^{-1}$) estimate	1.48	(0.13)	1.52	(0.13)	1.54	(0.15)	1.52	(0.14)
SAC ($L \cdot kg^{-1} \cdot min^{-1}$) estimate	0.22	(0.07)	0.21	(0.07)	0.23	(0.07)	0.22	(0.07)
$\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$) estimate	20.8	(4.2)	18.5	(3.7)	19.4	(3.9)	19.0	(3.9)
Exercise intensity (MET) estimate	5.9	(1.2)	5.3	(1.1)	5.5	(1.2)	5.4	(1.1)

Discussion

We estimated oxygen consumption from gas cylinder pressure drop in 959 recreational dives conducted in temperate to tropical open water. Higher SAC was significantly associated with older age, lower BMI, lower dive certification, higher number of dives in the previous year, fewer years since first diving and greater perceived workload. That lower certification level was associated with higher gas consumption is in keeping with the assumption that additional training and experience improves diving skills and, thus, lowers gas consumption. It was also not surprising that a higher SAC was associated with newer divers (fewer years of experience). It was not expected that divers who had made more dives in the previous year would have a higher SAC. It is possible that this reflects a higher degree of difficulty associated with the dives conducted, but this cannot be confirmed by the current data.

The BMI data are most difficult to interpret. As a simple ratio of body mass to height, BMI establishes neither body composition nor physical fitness, but nevertheless, it is reasonable to accept that BMI is positively correlated with body fat. This does not help much for interpretation since the use of external weighting and thermal protection may confound commentary on potential differences in buoyancy and/or thermal protection that might be postulated based on BMI. Further research is required to determine the precise role BMI plays in the energetics of recreational diving.

Applying Dwyer's regression formula to this sample of recreational dives provided an estimate of aerobic effort. The accuracy is unconfirmed, but the fundamental pattern is as expected with the mean MET levels increasing across self-reported levels of perceived effort. Still, the validity and practical utility of the results are open to question given the relatively small absolute difference between dives with varying degrees of effort.

Several factors are most likely to lead to an overestimate for any computation based on tank pressure. First, the cooling of a cylinder upon immersion will reduce initial readings. It is common for cylinder pressures to drop 10–20 bar when cooled by immersion, equating to a 5–10% overestimation if the pre-immersion pressure is used as the reference. Second, gas may be lost during surface swimming prior to descent or at the end of the dive. For example, at a SAC of 20 $L \cdot min^{-1}$, a diver breathing from his cylinder during a 10-minute surface swim would consume 200 litres, raising the exercise intensity estimate by 10%. Third, free flow from a regulator, or additional exhalation to clear a leaking mask could further contribute to non-respiratory losses. Fourth, hyperventilation, driven by anxiety or cold stress below the level of reportability by a diver, could also increase ventilation over the course of a dive. The cumulative effect of such factors could result in a significant overestimation of mean exercise intensity. Differences in self-reported thermal status in the current study did not correlate with differences in $\dot{V}O_2$ or MET estimates (Table 3), with mean inferred exercise intensity narrowly ranged between 5 and 6 MET for all three perceived thermal categories.

Given the uncertainty in our measures, it is prudent to assume a 10% overestimate in gas consumption in this study, reducing the overall mean estimated exercise intensity of 5.4 MET to about 5 MET. With a standard deviation of 1.1 MET, 7 MET (mean plus two standard deviations) would meet the demands of the vast majority of dives we monitored. To consider this as a threshold target for aerobic fitness necessary to meet the demands of uncomplicated recreational dives is consistent with previous recommendations.[4,6,8] Describing a 7-MET capacity as a possible lower-end aerobic fitness target, one review specified that this might be acceptable for divers with strong watermanship skills and comfort.[4] A 10-MET capacity has been recommended for less experienced divers, although balancing temporal with quantitative experience has yet to be defined satisfactorily.[4]

While we have focused on minimum capability targets, it should be remembered that higher levels of aerobic fitness should be encouraged to ensure that exceptional demands arising during any dive can be met.

There are several limitations to this study. Foremost is the rough estimate of tank pressure drop. The divers were not cautioned on the importance of reporting starting cylinder pressures after cooling was complete or to avoid breathing from the cylinder at the surface. Dwyer's methods included swimming at a fixed depth for four minutes while pushing a board and his gas collection took place during only the last minute of steady-rate exercise, whereas our study involved free-swimming recreational divers and our data were averaged over much longer and more variable periods.[9]

Conclusions

Based on estimated breathing gas consumption, a moderate energy expenditure of 7 MET is required to meet the normal demands of almost all uncomplicated recreational dives. Higher aerobic fitness levels are strongly encouraged to meet any emergent demands with ample aerobic reserves. Research into the aerobic demands of a range of recreational diving and for both experienced and inexperienced divers is currently absent and deserving of attention.

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