Respiratory Medicine (2014) **108**, 758—765

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/rmed

Divers revisited: The ventilatory response to carbon dioxide in experienced scuba divers

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Received 9 December 2013; accepted 12 February 2014
Available online 20 February 2014

KEYWORDS
Diving;
Hypercapnia;
Hypoxia;
Chemosensitivity;
Exercise

Summary
Purpose: To investigate the ventilatory response to CO_2 in hyperoxia, hypoxia, and during exercise amongst experienced scuba divers and matched controls.
Methods: Two studies were performed. The first investigated the CO_2 sensitivity in rest and exercise using CO_2 rebreathing in hyperoxia at a workload typical for diving with divers ($n = 11$) and controls ($n = 11$). The second study examined the respiratory drive of divers ($n = 10$) and controls ($n = 10$) whilst breathing four different gas mixtures balanced with N_2 (ambient air; 25% O_2/6% CO_2; 13% O_2; 13% O_2/6% CO_2) to assess the combined response to hypercapnia and moderate hypoxia.
Results: Exercise at a load typical for diving was found to have no effect on the ventilatory sensitivity to CO_2 in divers (rest: 1.49 ± 0.33; exercise: 1.22 ± 0.55 [l/min $\times$ mmHg^{-1}]) and controls (rest: 2.08 ± 0.71; exercise: 2.05 ± 0.98 [l/min $\times$ mmHg^{-1}]) while differences in sensitivity remained between the groups. Inhalation of the four gas mixtures revealed the tested oxygen pressures caused no significant alteration in the ventilatory sensitivity to CO_2 in divers and controls.
Conclusions: Experienced divers possess a lower ventilatory response to CO_2 which was not affected by exercise or the tested oxygen pressures suggesting a dominant adaptation of central CO_2 sensitivity.

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http://dx.doi.org/10.1016/j.rmed.2014.02.010

Introduction

Hypercapnia related symptoms ranging from increased depth and rate of breathing, breathlessness (air hunger), headache, dizziness, mental disorientation to complete unconsciousness are risks associated with diving whilst breath holding or using underwater breathing apparatus [1,2]. Elevated PCO_2 is reported in both diving groups however breath hold diving is associated with prolonged apneusis [3]. Elevation of PCO_2 during a scuba (self-contained underwater breathing apparatus) dive can be the result of a combination of factors including intentional 'skip breathing', unintentional hypoventilation and the use of a semi-closed or closed circuit rebreather [2]. Exposure to even mild levels of hypercapnia has been shown to substantially increase the risks of developing central nervous system oxygen toxicity [4,5]. Earlier studies have compared the ventilatory patterns, lung volume and chemosensitivity of non-divers with either breath hold or scuba divers with varying results [3]. Florio, Morrison and Butt [3] found Royal Naval Clearance Divers possessed a lower mean ventilatory response to hypercapnia compared to non-divers of similar age and build.

There remains an ongoing debate as to whether exercise has an influence on the ventilatory response to PCO_2. Cummin et al. [6] found an increase in the ventilatory response when cycling above 75 Watts whereas Clark and Godfrey [7] found a decrease. Furthermore, Kelley, Owen and Fishman [7,8] and Martin et al. [9] found no change in the ventilatory response to CO_2 with exercise, whilst McConnell and Semple [10] found endurance athletes had a lower ventilatory response to PCO_2 during rest compared to sprint trained athletes. However during exercise their ventilatory response to CO_2 was the same as sprint trained athletes and control subjects. To our knowledge Froeb's [11] research is the only study which has assessed the effects of exercise on the ventilatory response to CO_2 amongst scuba divers. Froeb [11] tentatively concluded a tendency existed for scuba divers to display a diminished ventilatory response to CO_2 during rest however this was not present whilst performing light exercise of 3 km·h on a flat treadmill (≈70 Watts). It is a concerning prospect that few studies have investigated the effects of exercise on the ventilatory response to CO_2 amongst scuba divers as diving is an active activity involving primarily the lower body to propel the diver through the water at an estimated workload of 7 METS [12] If as Clark and Godfrey [7] found exercise lowers the ventilatory response to CO_2 then the risks of CO_2 retention during a scuba dive may be greater than previously thought.

If the divers are found to process a lowered ventilatory response to PCO_2 as we hypothesise, questions still remain as to whether this can be attributed solely to central adaptation of chemosensitivity or whether there is a contribution by the peripheral chemoreflex. As of yet, research with scuba divers has only tested the ventilatory response to CO_2 with hyperoxic conditions. It is regarded in most individuals that hyperoxia (PO_2 = 150 mmHg) effectively silences the peripheral chemoreflex response to CO_2 [13,14]. In order to investigate the influence of the peripheral chemoreflex on the ventilatory response to CO_2, tests need to be performed in hypoxic conditions. Hypoxic stimulation of the peripheral chemoreflex response has been shown to increase the peripheral chemoreflex sensitivity to CO_2 via changes in [H+] at the carotid body [13,15,16]. In this current study we hypothesised that the ventilatory response to hypoxia would not be significantly different between scuba divers and controls as divers are often exposed to hyperoxia. Melamed and Kerem [17] found no impairment in the hypoxic ventilatory response amongst active O_2 divers, ex-O_2 divers and non-diving controls. In order to assess whether the peripheral chemoreflex to CO_2 is altered through scuba diving the ventilatory response to CO_2 with and without the presence of hypoxia was compared. In this study we used a hypoxic mixture of 13% O_2 obtaining an average end-tidal pO_2 of 56.5 ± 3.99 mmHg. This mixture fits closely with Duffin's [13] recommendation of a hypoxic pO_2 of 50 mmHg being used to add the peripheral response.

Methods

Participants

This study comprises of two experiments which were both approved by the Ethics Committee of Bangor University (Gwynedd, Wales) and carried out in accordance with the Declaration of Helsinki for research on human subjects. Written informed consent was obtained from all subjects prior to testing. Male experienced scuba divers and non-divers were recruited. To be eligible for the scuba diving group, subjects were required to have performed at least 100 dives (Table 1). For inclusion in the control group, participants were required not to had any experience in scuba or breath hold diving. The participants' level of physical activity was collected and assessed through the use of a physical activity questionnaire and the groups matched for age; body mass, height and physical activity (see Table 2).

Table 1 Diving experience of the scuba diving group measured with a diving questionnaire in all studies. All divers used open-circuit breathing apparatus and regularly used enriched air nitrox gas mixtures. Values represented mean ± SD.

Parameter:	Experiment 1: rest vs. exercise	Experiment 2: hypercapnia and/or hypoxia
N	11	10
Years diving	15.5 ± 9.0	15.0 ± 9.2
Number of dives	1045 ± 1083	1621 ± 1250
Max depth dived (m)	52.6 ± 11.7	45.8 ± 21.11
Common diving depth (m)	26.4 ± 6.4	28.0 ± 10.3