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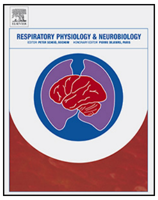

Swimmers can train in hypoxia at sea level through voluntary hypoventilation

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ABSTRACT

This study used an innovative technique of pulse oximetry to investigate whether swimmers can train under hypoxic conditions through voluntary hypoventilation (VH). Ten trained subjects performed a front crawl swimming series with normal breathing (NB), VH at high (VH_{high}) and low pulmonary volume (VH_{low}). Arterial oxygen saturation was continuously measured via pulse oximetry (SpO_2) with a waterproofed forehead sensor. Gas exchanges were recorded continuously and lactate concentration ([La]) was assessed at the end of each test. In VH_{low}, SpO_2 fell down to 87% at the end of the series whereas it remained above 94% in VH_{high} during most part of the series. Ventilation, oxygen uptake and end-tidal O_2 pressure were lower in both VH_{high} and VH_{low} than in NB. Compared to NB, [La] significantly increased in VH_{low} and decreased in VH_{high}. This study demonstrated that swimmers can train under hypoxic conditions at sea level and can accentuate the glycolytic stimulus of their training if they perform VH at low but not high pulmonary volume.

1. Introduction

In the early seventies, a new training method appeared in competitive swimming. This method, still widely used, consists in reducing breathing frequency with fewer breaths relative to arm strokes (i.e. inhale every 5, 7, or 9 strokes instead of 2–3 single arm strokes). At the beginning, it was thought that holding one's breath during exercise would decrease the oxygen (O_2) availability to the muscles and could therefore simulate the effects of altitude training (Counsilman, 1975). For this reason, this method was called "hypoxic training". It was also expected that, because of the lower O_2 supply, this kind of training would improve the anaerobic metabolism (Counsilman, 1975; Bonen, 1979). However, in the following years, some studies showed that a decrease in breathing frequency during exercise provoked only a hypercapnic effect (Dicker et al., 1980; Holmer and Gullstrand, 1980). Furthermore, other studies failed to find any increase in anaerobic metabolism since blood lactate concentration ([La]) was not different (Hsieh and Hermiston, 1983; Yamamoto et al., 1987; Town and Vanness, 1990), or even lower (Holmer and Gullstrand, 1980) when compared with normal breathing. Despite these findings, breath holding has become a classical training method in swimming which continues to be called erroneously "hypoxic training" by many coaches or swimmers.

In the mid 2000s, a new approach of exercising with voluntary hypoventilation (VH) was proposed by our laboratory. We postulated that when VH is performed in the classical way, which is at high pulmonary volume like in swimming, the alveolar O_2 stores are enhanced and gas exchanges are facilitated which therefore prevents obtaining a hypoxemic effect (Woorons et al., 2007). On the contrary, we hypothesized that VH at low pulmonary volume, that is at or below functional residual capacity (FRC), should lower the alveolar O_2 partial pressure ($P_{A_{O_2}}$) and induce a greater heterogeneity of the ventilation to perfusion ratio ($\dot{V}/\dot{Q}$), thus increasing the alveolar to arterial difference for O_2 ($D(A\text{-}a)O_2$). This hypothesis was verified in cycling and running where the arterial O_2 saturation (SaO_2) fell down to 87% on average (Woorons et al., 2007, 2008, 2010, 2011). The severe hypoxemia induced by VH at FRC also led to a greater muscle deoxygenation and therefore likely to tissue hypoxia (Woorons et al., 2010). This phenomenon was probably responsible for the higher [La] we reported for the first time in the same study and which reflects a greater solicitation of anaerobic glycolysis. In all the above mentioned studies, the changes were systematically accompanied by respiratory acidosis

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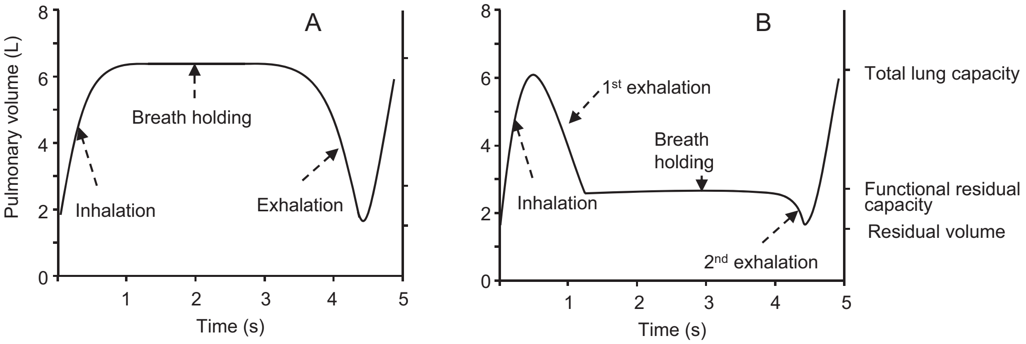

Fig. 1. Description of the voluntary hypoventilation technique at high (A) and low (B) pulmonary volume.

under the effect of the elevated carbon dioxide (CO_2) pressures. Thus it appears that in terrestrial sports, the main feature of exercise with VH at low lung volume is to provoke a combined lactic and respiratory acidosis as the result of both hypoxic and hypercapnic effect.

So far, it is not known whether a swimming exercise performed with VH at low pulmonary volume could induce a hypoxic effect. First, in front crawl swimming in particular, gas exchange may be better than in cycling or running because $\dot{V}/\dot{Q}$ matching is improved in prone position (Mure and Lindahl, 2001). Therefore, both arterial O_2 pressure and SaO_2 might not decrease as much as in terrestrial sports. Second, the measure of SaO_2 used to be technically problematic in an aquatic environment. However for the first time, thanks to an innovative equipment based on a waterproofed forehead sensor, it becomes possible to continuously measure arterial O_2 saturation by pulse oximetry (SpO_2) in swimmers and then precisely assess the effects of VH.

Training under hypoxic conditions thanks to VH and without leaving sea level could be interesting for swimmers. It has been shown that VH training reduces blood and probably muscle acidosis (Woorons et al., 2008) which could delay the onset of fatigue. Therefore, the goal of the present study was to determine and compare the effects of VH at low and high pulmonary volume on SpO_2 in swimmers through the validation of a novel technique of measurement using a waterproof forehead sensor. We expected a significant drop in SpO_2 only with VH at low lung volume but hypothesized that the degree of hypoxemia would not be severe (i.e. $SpO_2 < 88\%$ [Dempsey and Wagner, 1999]).

2. Methods

2.1. Subjects

Ten subjects including six competitive swimmers (1 woman, 5 men) and 4 male triathletes were recruited to participate in this study. Two of the swimmers were involved in national competitions and trained 6–10 times a week. The four remaining swimmers had a regional level and trained 3–5 times a week. The triathletes carried out 2–4 swimming sessions a week and had also a regional level in this discipline. The characteristics (mean ± SD) of the subjects were age 29.2 ± 8.4 years, height 180.6 ± 5.0 cm and weight 75.1 ± 8.7 kg. All the subjects were informed about the nature, the conditions and the risks of the experiment and gave their written informed consent. All the procedures were approved by the ethical committee Ile de France II, Paris, France.

2.2. Protocol

The whole experiment was conducted in the city of La Madeleine (59110) in the northern France (altitude = 29 m). The tests took place in a 25-m swimming pool with a water temperature of 27 °C.

Pre-experiment session: Before beginning the experiment, the subjects came once or twice to the pool to familiarize with the equipment as well as VH technique. For some of them, it was necessary to train breathing through a snorkel so that they could feel more relaxed afterwards. Furthermore, since a standard flip turn could not be carried out, the subjects had to learn making an open turn with the equipment to keep it safe and in place. All the subjects had already performed VH at high pulmonary volume (VH_{high}) during their training since it is the classical method used for decades in swimming. This breathing technique consists, just after inhaling, to hold one's breath for a few seconds and then to rapidly exhale the air before the next inhalation (Fig. 1a). On the other hand, VH at low pulmonary volume (VH_{low}) requires to hold one's breath after exhaling down to about FRC and then exhaling the remaining air just before the inhalation (Fig. 1b). Prior to the experiment, the subjects had never carried out VH_{low} during their training so it was necessary to familiarize them to what could be called the "exhale-hold" technique. We especially aimed to determine the number of arm strokes over which the subjects had to exhale before the breath holding. Even though the pulmonary volumes were not controlled, it was possible, thanks to several learning exercises, to get close to FRC given the fact that at this pulmonary volume it remains about 1 l to reach the residual volume. Depending on the subjects, the exhalation was made over 2 or 3 arm strokes.

When the subjects were accustomed to both the equipment and the VH technique, they first carried out a 400-m front crawl swimming at maximal speed. Then, in three other sessions separated by 48–72 h, they completed one series of ten 50-m front crawl swimming at 95% of their 400 m speed under the following randomized conditions: normal breathing (NB), VH_{high} and VH_{low}. During each 50 m, the speed was verified with an auditory signal at 12.5 m intervals. A visual mark was placed at the bottom and in the middle of the pool so that the swimmers could adjust their velocity when hearing the auditory signal. Between each 50 m, they rested motionlessly for 12 s along the wall, breathing normally. The characteristics of the series were determined in collaboration with a confirmed swimming coach. For VH_{high} and VH_{low}, we asked the swimmers to hold their breath as long as possible but to take care not to go to asphyxia in order to successfully complete the whole series. Subjects were instructed to refrain from strenuous exercise 24 h prior each testing session.

2.3. Measurements

2.3.1. SpO_2 and heart rate

SpO_2 and heart rate (HR) were measured via the pulse oximeter Nellcor N-595 (Pleasanton, CA, USA) with the adhesive forehead sensor Max-Fast (Nellcor, Pleasanton, CA, USA). To enable the utilization of the equipment in an aquatic environment, we waterproofed the sensor by wrapping it in an adhesive plastic film. The sensor was connected to the oximeter that was kept out of the