Hypoventilation training – history and development of an untraditional training method

FRANTIŠEK LÖRINCZI[1]- DRAHOMÍRA LÖRINCZIOVÁ[2] - NOVODOMSKÁ ELISA[3]- MIROSLAV VAVÁK[4]

[1,3,4] *Faculty of Physical Education and Sport, Comenius University Bratislava, Bratislava, Slovakia*

[2] *University of Economics in Bratislava, Bratislava, Slovakia*

ABSTRACT

This is the first study to provide a review of the literature on the historical development of voluntary hypoventilation training (VHL). VHL is an unconventional training method that is increasingly gaining attention for its potential to improve athletic performance through controlled hypoxia and hypercapnia. Unlike traditional hypoxic training, which requires specialised equipment or high-altitude exposure, VHL relies on breathing restrictions during exercise, offering a widely accessible alternative. The purpose of this study is to provide a historical perspective on the use of VHL. The review of the literature aims to describe the historical context, physiological basis, and development of VHL, which originated in breath holding techniques used by freedivers and evolved into a training tool adopted by elite athletes like Emil Zátopek to simulate challenging race conditions. In the late twentieth century, VHL was utilised by elite swimmers and mid-distance runners, who used the technique of extension of breath-holding after inspiration. Although this technique was not proven to be effective in inducing significant hypoxia, it was still applied in sports practice and is known as hypoxic training. At the beginning of the twenty-first century, Xavier Woorons and colleagues significantly advanced awareness of VHL in the scientific community by demonstrating its effectiveness using the end-expiratory breath-hold technique. This approach was shown to be effective in altering pH, increasing cardiac output, and inducing significant hypoxia and hypercapnia during exercise. Incorporating VHL into a training cycle can enhance respiratory muscle strength, buffering capacity, and endurance abilities. Currently, VHL is applied primarily in team sports due to its proven effectiveness in improving repeated sprint ability. Future research may focus on verifying the safety of this training method and exploring its potential to improve hematopoiesis.

KEY WORDS: breathing, sport, condition, repeated sprint ability, breath-holding

DOI: https://doi.org/10.24040/sjss.2024.9.3.84-100

PROBLEM

Currently, it is still unclear what percentage of athletes have access to hypoxic training. Many athletes probably lack the equipment necessary for hypoxic training or the opportunity to participate in regular high-altitude training. Therefore, it is important to look for and promote approaches in sports practice that could be a partial substitute for hypoxic training and will be widely accessible and effective. Voluntary hypoventilation training (VHL) is an unconventional method that has gained attention due to its simplicity, accessibility, and potential to improve athletic performance. Despite its potential to improve endurance abilities, it is still rarely known and used in sport practice, probably due to a lack of awareness among coaches and athletes. Many do not realise that altering breathing patterns alone can significantly enhance conditioning. There is currently no study focussing on a literature review of the historical development of hypoventilation training. This paper seeks to address this gap by exploring the historical development of VHL, its underlying physiological principles, and the adaptations it induces.

PURPOSE

The purpose of this study is to provide the current state of literature on the history and development of VHL, its underlying physiological principles, and its impact on sports condition and performance.

The tasks of this work include a review of the available scientific literature, a detailed analysis of the information collected, and the synthesis of these findings to create a comprehensive understanding of the history, development, and fundamental physiological principles of VHL.

METHODS

The systematic literature search was carried out in the following five databases: PubMed, Scopus, Web of Science, EBSCO, and Google Scholar. For all databases, the English search terms «hypoventilation training», «hypoventilation», «voluntary hypoventilation», «reduced frequency breathing», «breath-hold training», «breath-holding» and «apnoe training», in connection with «competitive athletes», «sport» and «exercise» were used. To optimise the search process, the Boolean operators «AND», «OR», «NOT» and «*» were included uniformly in the individual databases. Additionally, reference lists of relevant studies were searched for other potential studies. There was no restriction on the period of publication of the studies. The research was completed on 7th of November 2024. The titles and available abstracts of the searched studies were reviewed and classified as potentially relevant studies. Information relevant to our work was subsequently analysed from this literature.

RESULTS

The current state of the literature on the history and development of hyperventilation training

Voluntary hypoventilation training (VHL) is an unconventional training method that has the potential to improve athletic performance beyond the scope of classical training without the use of breathing interventions (1). Hypoventilation is a state in which breathing is restricted by reducing the frequency of breathing, shallow breathing, or holding breath (apnea) (2). When external respiration is limited, there is insufficient lung ventilation, leading to reduced oxygen intake into the body (hypoxia) and increased carbon dioxide concentration in the blood (hypercapnia) (3). Hypoventilation can be an unconscious, undesirable condition, such as in certain health disorders (2), or a conscious, voluntary controlled technique used in athletic training (1). Unlike traditional hypoxic training methods, which require multiweek stays in high-altitude environments, or equipment simulating hypoxic conditions (Yu et al., 2023), VHL involves deliberately reducing breathing during exercise through breath-holds, leading to a state of controlled hypoxia and hypercapnia. This method does not require special equipment, making it accessible to a wide range of athletes. Its effectiveness in improving endurance and anaerobic capacity has been observed, especially compared to conventional training performed without breathing restriction (Holfelder & Becker, 2018).

The origins of VHL

Voluntary hypoventilation as a training method was first naturally used by freedivers and swimmers, for whom the ability to hold their breath directly limits athletic performance (5). However, the first mentions of voluntary hypoventilation are not related to sports training, but to obtaining food and other valuables hidden on the ocean floor. Ama divers in Japan, predominantly women, are traditional freedivers known for their incredible breath-holding abilities and their role in the harvesting marine resources without the use of modern diving equipment. These women have been practising their craft for more than 2,000 years. The Ama divers are particularly notable for their resilience and use of natural freediving techniques, which allowed them to descend to depths of up to 25 metres while holding their breath for extended periods, often up to two minutes or more. Historically, they did this with little to no gear, wearing only a simple loincloth, and relied on skilful breath control, body conditioning, and intimate knowledge of the ocean to sustain their dives. The practice of Ama diving, also called "sea women" diving, is an early example of breath-hold diving long before it became popularised in the modern freediving community. These women also developed specific breathing techniques that allowed them to optimise oxygen use and delay the onset of fatigue underwater (6,7).

Deep diving without equipment has a rich history, but freediving as a sport began to develop in the modern era during the twentieth century. Its popularity was significantly boosted by the impressive performances of pioneers like Enzo Maiorca and Jacques Mayol in the 1960s, who showcased 100-meter dives to the world. The introduction of organised competitions in the 1970s by organisations such as CMAS solidified the status as a legitimate sport (8).

Utilization of VHL by athletes in 20th century

The first mentions of VHL for athletic performance on land come from the training logs of eastern European runners who experimented with holding breath during rest or physical activity. This practice occurred even before freediving was established as a sport. Perhaps the most famous case is that of Emil Zátopek, who dominated the endurance running scene in the mid-20th century (9). At that time, however, these were not scientifically supported training methods, but rather empirical applications of breath holding to subjectively increase training difficulty. Many athletes sought to simulate challenging competitive conditions by adding extra respiratory strain. Most often, these involved maximal breath-holds after inhalation, performed at various running intensities.

After the XIX Olympic Games in Mexico City in 1968, the sports community began to show significant interest in hypoxic training. However, since this was not accessible to a wide range of athletes, the experimentation with reducing the breathing frequency continued. The coaches and scientists aimed to determine how to improve oxygen absorption and utilisation, particularly in high-altitude environments. American swimming coach James Counsilman hypothesised that voluntary breathing restriction during training could produce effects similar to hypoxic stress for his athletes (10). He and many other coaches believed that this type of training could also increase body acidity and ultimately improve anaerobic metabolism processes (11). In the 1970s, training with restricted breathing was commonly recognised as hypoxic training, particularly popular among swimmers due to its strong relevance to their performance, implemented by increasing the number of strokes between breaths (12).

In the 1980s, VHL transitioned from swimmers back to runners, particularly those in middle-distance events. A pioneer among coaches was Brazilian Luiz de Oliveira, who trained notable athletes such as 800m Olympic champion Joaquim Cruz and world champion in the 1500m and 3000m, Mary Decker. In practice, this involved 30 – 90m runs with breath-holding, often performed at the end of a 400- or 800-meter segment. The aim was to simulate, or even intensify, the conditions typical of the final phases of middle-distance runs. Due to the significant stress imposed, this type of training was conducted once a week. Although this was a more rational approach compared to the 1950s, it was still not scientifically substantiated (12).

Scientific research focused on the physiological response to VHL at the turn of the 20th and 21st centuries

Scientific investigation of VHL began in the 1980s, but the initial findings were not encouraging to its proponents. Although a reduced breathing frequency was shown to increase CO_2 levels, no significant drop in O_2 was observed (13,14,15). Lactate levels were often even higher with normal breathing compared to reduced breathing 16,17,18). These findings were repeatedly confirmed in the 1990s (19,20). Despite these disappointing results, VHL continued to be a common part of the training process, still referred to by athletes as hypoxic training. It remained particularly prevalent among swimmers, as coaches observed certain performance benefits despite the lack of confirmed physiological responses.

In the early 21st century, a Paris laboratory focused on cellular and functional responses to hypoxia proposed a hypothesis: “Significant reductions in blood oxygen saturation could be achieved during VHL if performed at low lung volumes” (21). Until then, breath-holding was commonly performed after inhalation; however, since a large volume of air remained in the lungs and oral cavity from which the body could draw oxygen, blood oxygen saturation did not decrease. Subsequent studies of low-lung-volume VHL (end-expiratory breath-holding technique) demonstrated significant reductions in oxygen concentration in both blood and muscle during various activities (running, cycling, swimming) (22,23,24,25, 26,27,28,12,29,30,31,32,33,34,35). The acute increases in erythropoietin, red blood cells, and hemoglobin after repeated maximum breath holds have been confirmed by several studies (36,37,38,39,40,41,42,43). However, the acute increase in the number of red blood cells and hemoglobin is probably related to contractions of the spleen, which is a reservoir of blood. This phenomenon is reversible, and increased values return to their original state after a few minutes (44,45,46). In freedivers who perform certain forms of VHL in the long term, increased values of red blood cells and hemoglobin (47,48,49), larger spleen volume

(50), increased chemoreceptor threshold for hypoxia and hypercapnia (51) and better utilisation of oxygen (52,53). However, VHL implemented in the training mesocycle of athletes did not lead to stable higher concentrations of red blood cells and hemoglobin (30). This is probably due to insufficient time volume under hypoxic conditions. Compared to classical hypoxic training, it is practically impossible to maintain the same degree of hypoxia in the same volume (54,21).

With VHL, minute ventilation is limited mainly in the form of a decrease in respiratory frequency that subsequently leads to hypercapnia (29,31). Higher levels of pCO_2 and lower levels of pO2 lead to respiratory and metabolic acidosis in which higher levels of H^+ remain in the organism and pH decreases (21). To neutralise pH and return to homeostasis, higher concentrations of hydrogen HCO3- are produced, which acts as a buffer. Therefore, VHL could increase buffering capacity, creating the potential for higher lactate tolerance and better resistance to high-intensity exercise (55).

Beyond the hypoxic and hypercapnic effect, Woorons et al. (31) demonstrated that exercising with VHL could also lead to higher lactate levels compared to regular breathing. However, later research did not confirm this statement (56).

Further research has shown that the implementation of VHL in cycling or running exercises could increase cardiac output This increase is caused by an increase in heart rate, stroke volume, or both (26,56,27,30,58).

The influence of VHL on changes in the level of conditioning abilities of athletes

Implementing VHL into the training mesocycle can lead to improved respiratory muscle strength (58,59,60,25,61).

VHL is implemented in swimming through reduced breathing frequency. This training method was shown to be more effective compared to classical training with a natural breathing frequency rate in 6 out of 7 recently published experimental studies (62,58,59, 27,28,63). Improvements are especially evident in short- and middle-distance swimming disciplines. Only one study did not confirm these statements, but has significant limitations (64), since more participants worsen their swimming performance over time during the experiment.

Regarding the impact of HYT on aerobic endurance capabilities, it is not possible to definitively confirm or refute the potential effects due to ambiguous conclusions from the study sample. Although (64, 59,30,63) did not demonstrate a significant improvement in VO2max (or significantly more pronounced compared to the control group), (32,33,43) showed more significant improvements in VO2max, VO2 and outcomes of Yo-Yo intermittent recovery test – level 1 in experimental groups using VHL compared to control groups (no breathing restrictions).

Based on the analysis of available literature, it can be assumed that VHL can significantly and more prominently improve the level of Repeated Sprint Ability (RSA) compared to traditional training without respiratory interventions. The ability to perform repeated sprints is particularly limiting for players in sports games (65,66). Improvement in RSA was observed in most cases in the number of sprints to task failure (22,23,24,25,28,32,25). Performance outcomes such as average power output, average velocity, or fatigue index during certain periods of sections were positively and more significantly influenced compared to the control group (22, 23,32,35). These results improved significantly compared to the control group, mainly in the second half of the tests. No significant improvements in the variables mentioned above control group were observed in studies of (25, 33). Trincat et al. (28) and Woorons et al. (30,33) attribute the improved anaerobic capacity to the increased buffering capacity associated with a higher tolerance to lactate.

The disparity in results may be related to the non-uniform methodology of the studies. The differences lie in various methods of applying VHL (different training means, workload volume, workload intensity) and the tests used, as well as the statistical analysis of the obtained data. In both aquatic or terrestrial, the limitations of the studies include a low number of participants, the absence of a research sample calculation, the absence of randomisation of research samples, heterogeneity of research samples, the lack of study registration, the inability to conduct blinding, and nonuniform methodology in terms of applying the experimental factor, fitness level testing, and result evaluation.

However, these studies are very valuable and address the original issue. If athletes can achieve an increase in performance above the level of gains from classical training simply by changing the breathing stereotype, these are very original and valuable findings.

Scientific studies by Woorons, but also by other sports scientists, provided valuable information for the creation of modern breathing techniques, which are known worldwide today. The most famous is Oxygen Advantage, the founder is Patrick McKeown (67).

Current and future studies investigating VHL could focus on validating the technique of end-expiratory breath-holding during intense exercise up to the breaking point (68). Breaking point is the moment when the participant is no more able to hold breath and must inhale. It would be interesting to see if a mesocycle of several weeks to several months using VHL can significantly affect haematopoiesis and thus be an effective substitute for classic hypoxic training. However, the potential risks associated with this type of training should not be forgotten either, as long-term exposure to hypoxic conditions may cause some damage to the nervous system. However, this risk is mainly associated with breath holding during deep diving, sleep apnoea, or cyclic hyperventilation (69). To date, no negative effects of rational VHL in sports training on any aspect of health have been demonstrated.

DISCUSSION

This study provides a comprehensive review of the history, development and physiological underpinnings of VHL, highlighting its progression from freediving techniques to modern sports applications. Our findings underscore the accessibility and potential to enhance endurance and repeated sprint ability, particularly in athletes without access to traditional hypoxic training.

A key strength of our work lies in its originality since this study is the first to provide current state of literature regarding the historical development of VHL. The study provides a broad historical perspective, integrating the origins of VHL in freediving with its adoption by elite athletes and scientific validation by Woorons and colleagues. By synthesising a wide range of studies, we provide a unique contextual overview of VHL's physiological mechanisms, particularly its ability to induce controlled hypoxia and hypercapnia. This review also draws attention to the diverse applications, from swimming to team sports, highlighting its practical benefits for athletes and coaches.

Although our aim was to provide an exhaustive account, the non-uniform methodologies across the included studies complicate direct comparisons. Most studies suffer from small sample sizes, lack of randomisation, and inconsistent testing protocols. Furthermore, evidence supporting long-term haematological adaptations remains inconclusive, mainly due to limited exposure to hypoxic conditions compared to traditional methods. Another limitation lies in the difficulty of accessing original historical sources, such as training diaries, so the study partially relies on secondary citations. Wider use of VHL cannot be ruled out, but the study drew information from the scientific literature, while sports practice may differ from science.

This study contributes to bridging the gap between historical practice, scientific inquiry, and practical application, underscoring VHL's relevance in modern athletic training.

SUMMARY

Voluntary hypoventilation training is an innovative and nontraditional training method that can improve athletic performance by creating controlled hypoxia and hypercapnia through breathing restrictions during physical activities. Unlike traditional hypoxic training, which requires specialised equipment or high-altitude environments, VHL offers a more accessible alternative that can improve endurance abilities. The origins of VHL can be traced back to breath-holding techniques developed by traditional freedivers. Later in the twentieth century, VHL was used by athletes from eastern Europe, like Emil Zátopek, to simulate challenging race conditions. Throughout the twentieth century, VHL techniques spread, especially among swimmers and runners, to intensify training by extending the duration during exercise (see Figure 1). Implementing VHL in training can acutely cause significant hypoxia and hypercapnia, increase cardiac output, and alter pH levels to higher acidosis. Long-term adaptation to VHL can be associated with stronger respiratory muscles and better endurance abilities, especially repeated sprint ability, probably related to higher buffering capacity and lactate tolerance. Rational VHL should be performed as an end-expiratory breath-holding during exercise. It appears safe from a health perspective since no negative effects have been confirmed to date. The potential of VHL to improve performance by altering breathing patterns holds significant promise, paving the way for modern breathing techniques such as Oxygen Advantage. There is the assumption that in the future VHL could be used in a wide range of sports, especially for the purpose of improving the endurance abilities of athletes.

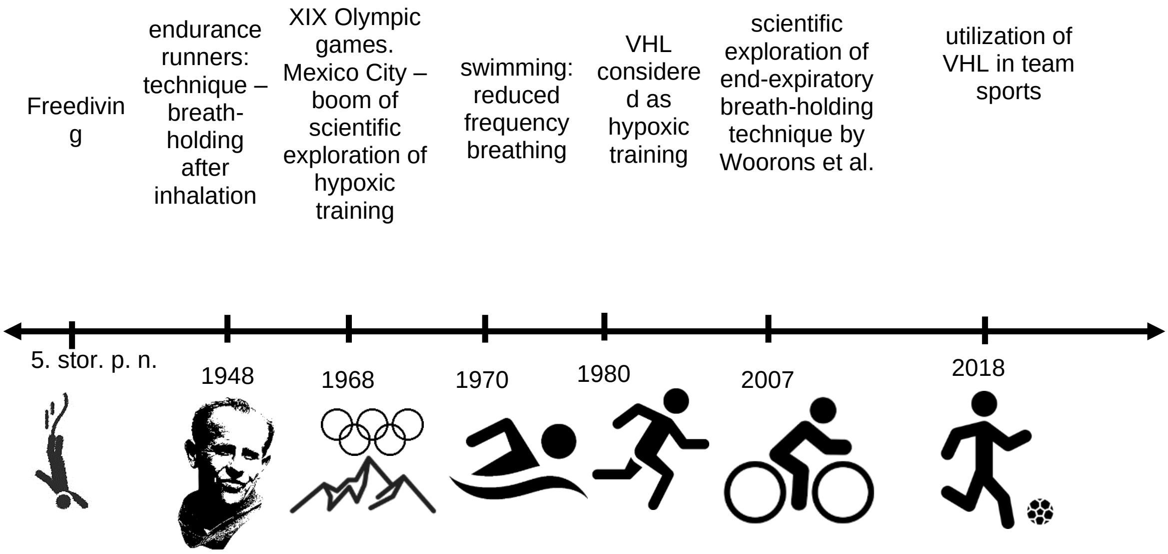

Figure 1 A brief history of hypoventilation training

REFERENCES

1. Woorons, X. (2024). *The voluntary hypoventilation at low lung volume (VHL) method in Hypoxia Conditioning in Health, Exercise and Sport*. Routledge.
2. Brown, L. K. (2010). Hypoventilation Syndromes. *Clinics in Chest Medicine*, *31*(2), 249–270. https://doi.org/10.1016/J.CCM.2010.03.002
3. Nanayakkara, B., & McNamara, S. (2024). Pathophysiology of Chronic Hypercapnic Respiratory Failure. *Sleep Medicine Clinics*, *19*(3), 379–389. https://doi.org/10.1016/J.JSMC.2024.04.001/ASSET/DDB53282-EEF8-4B27-9009-A7707DF27E2F/MAIN.ASSETS/GR2.SML
4. Yu, Q., Kong, Z., Zou, L., Chapman, R., Shi, Q., & Nie, J. (2023). Comparative efficacy of various hypoxic training paradigms on maximal oxygen consumption: A systematic review and network meta-analysis. *Journal of Exercise Science & Fitness*, *21*(4), 366–375. https://doi.org/10.1016/J.JESF.2023.09.001
5. Lahtinen, K., Kurra, S., & Nissinen, A. (2015). *Freediving*. Deep Ideas Oy.
6. Lemaître, F., Billaut, F., & Joulia, F. (2022). Editorial: Physiology and Physiopathology of Breath-Holding Activity. *Frontiers in Physiology*, *13*, 858371. https://doi.org/10.3389/FPHYS.2022.858371/BIBTEX
7. Mohri, M., Torii, R., Nagaya, K., Shiraki, K., Elsner, R., Takeuchi, H., Park, Y. S., & Hong, S. K. (1995). Diving patterns of ama divers of Hegura Island, Japan. *Undersea & Hyperbaric Medicine : Journal of the Undersea and Hyperbaric Medical Society, Inc*, *22*(2), 137–143. https://europepmc.org/article/med/7633275
8. U.S. Freediving Federation. (2024). *HISTORY OF FREEDIVING — U.S. Freediving Federation*. https://usfreedivingfederation.org/history
9. Lörinczi, F., & Vanderka, M. (2022). ROZVOJ AERÓBNEJ VYTRVALOSTI–OD ZÁTOPKA PO DNEŠOK. *Atletika 202236*, 36–47. https://fsport.uniba.sk/uploads/media/Zbornik_Atletika_2022.pdf#page=36
10. Counsilman, J. (1975). *Swimming: Science and Technique for the preparation of champions.*
11. Bonen, A. (1979). Physiological basis of training, hypoxic training. *Swimming Coaching at the Club Level. National Coaching Certification Program, Canadian Amateur Swimming Association*.

12. Woorons, X., Gamelin, F.-X., Lamberto, C., Pichon, A., & Richalet, J. P. (2014). Swimmers can train in hypoxia at sea level through voluntary hypoventilation. *Respiratory Physiology & Neurobiology*, *190*, 33–39. https://doi.org/10.1016/j.resp.2013.08.022
13. Craig, A. B. (1980). Hypoxic training: what's not in a name. *Swim. Tech*, *17*(25).
14. Dicker, S. G., Lofthus, G. K., Thornton, N. W., & Brooks, G. A. (1980). Respiratory and heart rate responses to tethered controlled frequency breathing swimming. *Medicine and Science in Sports and Exercise*, *12*(1), 20–23. https://doi.org/10.1249/00005768-198021000-00005
15. Holmer, I., & Gullstrand, L. (1980). Physiological responses to swimming with a controlled frequency of breathing. *Scand J Sports Sci*, *2*(1), 1–6.
16. Hsieh, S. S., & Hermiston, R. T. (1983). The acute effects of controlled breathing swimming on glycolytic parameters. *Canadian Journal of Applied Sport Sciences. Journal Canadien Des Sciences Appliquees Au Sport*, *8*(3), 149–154. https://europepmc.org/article/med/6640818
17. Yamamoto, Y., Mutoh, Y., Kobayashi, H., & Miyashita, M. (1987). Effects of reduced frequency breathing on arterial hypoxemia during exercise. *European Journal of Applied Physiology and Occupational Physiology*, *56*(5), 522–527. https://doi.org/10.1007/BF00635364/METRICS
18. Yamamoto, Y., Takei, Y., Mutoh, Y., & Miyashita, M. (1988). Delayed appearance of blood lactate with reduced frequency breathing during exercise. *European Journal of Applied Physiology and Occupational Physiology*, *57*(4), 462–466. https://doi.org/10.1007/BF00417994/METRICS
19. Sharp, R. L., Williams, D. J., & Bevan, L. (1991). Effects of controlled frequency breathing during exercise on blood gases and acid-base balance. *International Journal of Sports Medicine*, *12*(1), 62–65. https://doi.org/10.1055/S-2007-1024657/BIB
20. Town, G. P., & Vanness, J. M. (1990). Metabolic responses to controlled frequency breathing in competitive swimmers. *Medicine and Science in Sports and Exercise*, *22*(1), 112–116. https://doi.org/10.1249/00005768-199002000-00018
21. Woorons, X. (2014). *Hypoventilation training*. ARPEH. Lille. ISBN 978-2-9546040-1-5
22. Ali Braham, M. A., Ouchen, Y., & Woorons, X. (2024). Effects of a 6-Week Repeated-Sprint Training With Voluntary Hypoventilation at Low and High Lung Volume on

Repeated-Sprint Ability in Female Soccer Players. *International Journal of Sports Physiology and Performance*, *19*(5), 463–470. https://doi.org/10.1123/IJSPP.2023-0392

23. Brocherie, F., Cantamessi, G., Millet, G. P., & Woorons, X. (2023). Effects of repeated-sprint training in hypoxia induced by voluntary hypoventilation on performance during ice hockey off-season. *International Journal of Sports Science & Coaching*, *18*(2), 446–452. https://doi.org/10.1177/17479541221079531
24. Fornasier-Santos, C., Millet, G. P., & Woorons, X. (2018). Repeated-sprint training in hypoxia induced by voluntary hypoventilation improves running repeated-sprint ability in rugby players. *European Journal of Sport Science*, *18*(4), 504–512. https://doi.org/10.1080/17461391.2018.1431312
25. Lapointe, J., Paradis-Deschênes, P., Woorons, X., Lemaître, F., & Billaut, F. (2020). Impact of Hypoventilation Training on Muscle Oxygenation, Myoelectrical Changes, Systemic [K+], and Repeated-Sprint Ability in Basketball Players. *Frontiers in Sports and Active Living*, *2*. https://doi.org/10.3389/fspor.2020.00029
26. Lörinczi, F., Lörincziová, D., & Vavak, M. (2024). PHYSIOLOGICAL RESPONSES TO REPEATED SPRINT TRAINING WITH HYPOVENTILATION INTERVENTION. *10th INTERNATIONAL SCIENTIFIC CONFERENCE ON KINESIOLOGY*, 181–185.
27. Stavrou, V., Toubekis, A. G., & Karetsi, E. (2015). Changes in Respiratory Parameters and Fin-Swimming Performance Following a 16-Week Training Period with Intermittent Breath Holding. *Journal of Human Kinetics*, *49*(1), 89–98. https://doi.org/10.1515/hukin-2015-0111
28. Trincat, L., Woorons, X., & Millet, G. P. (2017). Repeated-Sprint Training in Hypoxia Induced by Voluntary Hypoventilation in Swimming. *International Journal of Sports Physiology and Performance*, *12*(3), 329–335. https://doi.org/10.1123/ijspp.2015-0674
29. Woorons, X., Mollard, P., Pichon, A., Duvallet, A., Richalet, J.-P., & Lamberto, C. (2007). Prolonged expiration down to residual volume leads to severe arterial hypoxemia in athletes during submaximal exercise. *Respiratory Physiology & Neurobiology*, *158*(1), 75–82. https://doi.org/10.1016/j.resp.2007.02.017
30. Woorons, X., Mollard, P., Pichon, A., Duvallet, A., Richalet, J.-P., & Lamberto, C. (2008). Effects of a 4-week training with voluntary hypoventilation carried out at low

pulmonary volumes. *Respiratory Physiology & Neurobiology*, *160*(2), 123–130. https://doi.org/10.1016/j.resp.2007.09.010

31. Woorons, X., Bourdillon, N., Vandewalle, H., Lamberto, C., Mollard, P., Richalet, J.-P., & Pichon, A. (2010). Exercise with hypoventilation induces lower muscle oxygenation and higher blood lactate concentration: role of hypoxia and hypercapnia. *European Journal of Applied Physiology*, *110*(2), 367–377. https://doi.org/10.1007/s00421-010-1512-9
32. Woorons, X., Millet, G. P., & Mucci, P. (2019). Physiological adaptations to repeated sprint training in hypoxia induced by voluntary hypoventilation at low lung volume. *European Journal of Applied Physiology*, *119*(9), 1959–1970. https://doi.org/10.1007/s00421-019-04184-9
33. Woorons, X., Billaut, F., & Vandewalle, H. (2020). Transferable Benefits of Cycle Hypoventilation Training for Run-Based Performance in Team-Sport Athletes. *International Journal of Sports Physiology and Performance*, *15*(8), 1103–1108. https://doi.org/10.1123/ijspp.2019-0583
34. Woorons, X., Billaut, F., & Lamberto, C. (2021). Running exercise with end-expiratory breath holding up to the breaking point induces large and early fall in muscle oxygenation. *European Journal of Applied Physiology*, *121*(12), 3515–3525. https://doi.org/10.1007/s00421-021-04813-2
35. Woorons, X., Daussin, F., Combes, A., & Mucci, P. (2024a). Physiological Responses to Supramaximal Running Exercise with End-Expiratory Breath Holding up to the Breaking Point. *Journal of Human Kinetics*, *90*, 111. https://doi.org/10.5114/JHK/174465
36. de Bruijn, R., Richardson, M., & Schagatay, E. (n). Increased erythropoietin concentration after repeated apneas in humans. *European Journal of Applied Physiology*, *102*(5), 609–613. https://doi.org/10.1007/s00421-007-0639-9
37. Dolscheid-Pommerich, R. C., Stoffel-Wagner, B., Alberts, J., Fimmers, R., & Eichhorn, L. (2020). Hematologic changes after short term hypoxia in non-elite apnea divers under voluntary dry apnea conditions. *PLOS ONE*, *15*(8), e0237673. https://doi.org/10.1371/journal.pone.0237673
38. Dolscheid-Pommerich, R. C., Stoffel-Wagner, B., Alberts, J., Fimmers, R., & Eichhorn, L. (2020). Hematologic changes after short term hypoxia in non-elite apnea divers under

voluntary dry apnea conditions. *PLOS ONE*, *15*(8), e0237673. https://doi.org/10.1371/journal.pone.0237673

39. Elia, A., Barlow, M. J., Deighton, K., Wilson, O. J., & O'Hara, J. P. (2019). Erythropoietic responses to a series of repeated maximal dynamic and static apnoeas in elite and non-breath-hold divers. *European Journal of Applied Physiology*, *119*(11–12), 2557–2565. https://doi.org/10.1007/s00421-019-04235-1
40. Elia, A., Gennser, M., Harlow, P. S., & Lees, M. J. (2021). Physiology, pathophysiology and (mal)adaptations to chronic apnoeic training: a state-of-the-art review. *European Journal of Applied Physiology*, *121*(6), 1543–1566. https://doi.org/10.1007/s00421-021-04664-x
41. Hurford, W. E., Hong, S. K., Park, Y. S., Ahn, D. W., Shiraki, K., Mohri, M., & Zapol, W. M. (1990). Splenic contraction during breath-hold diving in the Korean ama. *Journal of Applied Physiology*, *69*(3), 932–936. https://doi.org/10.1152/jappl.1990.69.3.932
42. Kjeld, T., Jattu, T., Nielsen, H. B., Goetze, J. P., Secher, N. H., & Olsen, N. V. (2015). Release of erythropoietin and neuron-specific enolase after breath holding in competing free divers. *Scandinavian Journal of Medicine & Science in Sports*, *25*(3). https://doi.org/10.1111/sms.12309
43. Zoretić, D., Grčić-Zubčević, N., & Zubčić, K. (2014). The effects of hypercapnic-hypoxic training program on hemoglobin concentration and maximum oxygen uptake of elite swimmers. *Kinesiology*, *46*(1), 40–45.
44. Hurford, W. E., Hong, S. K., Park, Y. S., Ahn, D. W., Shiraki, K., Mohri, M., & Zapol, W. M. (1990). Splenic contraction during breath-hold diving in the Korean ama. *Journal of Applied Physiology*, *69*(3), 932–936. https://doi.org/10.1152/jappl.1990.69.3.932
45. Richardson, M. X., de Bruijn, R., & Schagatay, E. (2009). Hypoxia augments apnea-induced increase in hemoglobin concentration and hematocrit. *European Journal of Applied Physiology*, *105*(1), 63–68. https://doi.org/10.1007/s00421-008-0873-9
46. Schagatay, E., Lunde, A., Nilsson, S., Palm, O., & Lodin-Sundström, A. (2020). Spleen contraction elevates hemoglobin concentration at high altitude during rest and exercise. *European Journal of Applied Physiology*, *120*(12), 2693–2704. https://doi.org/10.1007/s00421-020-04471-w
47. Bouten, J., Debusschere, J., Lootens, L., Declercq, L., Van Eenoo, P., Boone, J., & Bourgois, J. G. (2022). Six weeks of static apnea training does not affect Hbmass and

exercise performance. *Journal of Applied Physiology*, *132*(3), 673–681. https://doi.org/10.1152/japplphysiol.00770.2021

48. Elia, A., Barlow, M. J., Deighton, K., Wilson, O. J., & O'Hara, J. P. (2019). Erythropoietic responses to a series of repeated maximal dynamic and static apnoeas in elite and non-breath-hold divers. *European Journal of Applied Physiology*, *119*(11–12), 2557–2565. https://doi.org/10.1007/s00421-019-04235-1
49. Lindholm, P., & Lundgren, C. E. (2009). The physiology and pathophysiology of human breath-hold diving. *Journal of Applied Physiology*, *106*(1), 284–292. https://doi.org/10.1152/japplphysiol.90991.2008
50. Schagatay, E., Richardson, M. X., & Lodin-Sundström, A. (2012). Size Matters: Spleen and Lung Volumes Predict Performance in Human Apneic Divers. *Frontiers in Physiology*, *3*. https://doi.org/10.3389/fphys.2012.00173
51. Roecker, K., Metzger, J., Scholz, T., Tetzlaff, K., Sorichter, S., & Walterspacher, S. (2014). Modified Ventilatory Response Characteristics to Exercise in Breath-Hold Divers. *International Journal of Sports Physiology and Performance*, *9*(5), 757–765. https://doi.org/10.1123/ijspp.2013-0308
52. Costalat, G., Coquart, J., Castres, I., Joulia, F., Sirost, O., Clua, E., & Lemaître, F. (2017). The oxygen-conserving potential of the diving response: A kinetic-based analysis. *Journal of Sports Sciences*, *35*(7), 678–687. https://doi.org/10.1080/02640414.2016.1183809
53. Liner, M. H., & Linnarsson, D. (1994). Tissue oxygen and carbon dioxide stores and breath-hold diving in humans. *Journal of Applied Physiology*, *77*(2), 542–547. https://doi.org/10.1152/jappl.1994.77.2.542
54. Imai, A., Yamaguchi, K., & Goto, K. (2022). Comparison of systemic and peripheral responses during high-intensity interval exercise under voluntary hypoventilation vs. hypoxic conditions. *Physical Activity and Nutrition*, *26*(2), 008–016. https://doi.org/10.20463/pan.2022.0008
55. de Asís-Fernández, F., Sereno, D., Turner, A. P., González-Mohíno, F., & González-Ravé, J. M. (2022). Effects of apnoea training on aerobic and anaerobic performance: A systematic review and meta-analysis. *Frontiers in Physiology*, *13*. https://doi.org/10.3389/fphys.2022.964144

56. Rosa, C. H., Monteiro, C. P., Barata, C., Espada, M. C., Valamatos, M. J., Bento, A., Minhalma, R. J., & Reis, J. F. (2024). Cardiorespiratory and muscle oxygenation responses to voluntary hypoventilation at low lung volume in upper body repeated sprints. *European Journal of Applied Physiology*. https://doi.org/10.1007/s00421-024-05569-1
57. Woorons, X., Bourdillon, N., Lamberto, C., Vandewalle, H., Richalet, J.-P., Mollard, P., & Pichon, A. (2011). Cardiovascular Responses During Hypoventilation at Exercise. *International Journal of Sports Medicine*, *32*(06), 438–445. https://doi.org/10.1055/s-0031-1271788
58. Karaula, D., HOMOLAK, J., & LEKO, G. (2016). Effects of hypercapnic-hypoxic training on respiratory muscle strength and front crawl stroke performance among elite swimmers. *Turkish Journal of Sport and Exercise*, *18*(1), 17. https://doi.org/10.15314/tjse.83447
59. Lavin, K. M., Guenette, J. A., Smoliga, J. M., & Zavorsky, G. S. (2015). Controlled-frequency breath swimming improves swimming performance and running economy. *Scandinavian Journal of Medicine & Science in Sports*, *25*(1), 16–24. https://doi.org/10.1111/sms.12140
60. Lemaître, F., Billaut, F., & Joulia, F. (2022). Editorial: Physiology and Physiopathology of Breath-Holding Activity. *Frontiers in Physiology*, *13*, 858371. https://doi.org/10.3389/FPHYS.2022.858371/BIBTEX
61. Tetzlaff, K., Lemaitre, F., Burgstahler, C., Luetkens, J. A., & Eichhorn, L. (2021). Going to Extremes of Lung Physiology–Deep Breath-Hold Diving. *Frontiers in Physiology*, *12*, 710429. https://doi.org/10.3389/FPHYS.2021.710429/BIBTEX
62. Kapus, J., Ušaj, A., & Lomax, M. (2013). Adaptation of endurance training with a reduced breathing frequency. *Journal of Sports Science & Medicine*, *12*(4), 744–752.
63. Woorons, X., Mucci, P., Richalet, J. P., & Pichon, A. (2016). Hypoventilation training at supramaximal intensity improves swimming performance. *Medicine and Science in Sports and Exercise*, *48*(6), 1119–1128. https://doi.org/10.1249/MSS.0000000000000863
64. Burtch, A. R., Ogle, B. T., Sims, P. A., Harms, C. A., Symons, T. B., Folz, R. J., & Zavorsky, G. S. (2017). Controlled Frequency Breathing Reduces Inspiratory Muscle Fatigue.

Journal of Strength and Conditioning Research, *31*(5), 1273–1281. https://doi.org/10.1519/JSC.0000000000001589

65. Girard, O., Mendez-Villanueva, A., & Bishop, D. (2012). Repeated-Sprint Ability — Part I. *Sports Medicine 2011 41:8*, *41*(8), 673–694. https://doi.org/10.2165/11590550-000000000-00000
66. Longo, U. G., Sofi, F., Candela, V., Dinu, M., Cimmino, M., Massaroni, C., Schena, E., & Denaro, V. (2019). Performance Activities and Match Outcomes of Professional Soccer Teams during the 2016/2017 Serie A Season. *Medicina*, *55*(8), 469. https://doi.org/10.3390/medicina55080469
67. McKeown, P. (2015). *The Oxygen Advantage*. Little, Brown. ISBN 9780349406695.
68. Woorons, X., Faucher, C., Dufour, S. P., Brocherie, F., Robach, P., Connes, P., Brugniaux, J. V., Verges, S., Gaston, A. F., Millet, G., Dupuy, O., & Pichon, A. (2024b). Hypoventilation training including maximal end-expiratory breath holding improves the ability to repeat high-intensity efforts in elite judo athletes. *Frontiers in Physiology*, *15*, 1441696. https://doi.org/10.3389/FPHYS.2024.1441696/BIBTEX
69. Neubauer, J. A. (2001). Invited Review: Physiological and pathophysiological responses to intermittent hypoxia. *Journal of Applied Physiology*, *90*(4), 1593–1599. https://doi.org/10.1152/JAPPL.2001.90.4.1593