The effect of body position on inspiratory airflow in divers.

Submitted 5/7/07; Accepted 5/22/07

M. L. KRAUZA, C. E.G. LUNDGREN

Center for Research and Education in Special Environments (CRESE) and Department of Physiology University at Buffalo, State University of New York, Buffalo, NY 14214

Krauza ML, Lundgren CEG. The effect of body position on inspiratory airflow in divers. Undersea Hyperb Med 2007; 34(6):425-430. The purpose of this study was to examine the possibility that body position influences inspiratory airflow of submerged subjects. Our previous studies have suggested that for a given (negative) inspired gas pressure, exercising divers experience more dyspnea in the prone than in the upright position. Methods: Six subjects performed maximal inspiratory efforts recorded as esophageal pressure (balloon catheter); simultaneously inspiratory flow and lung volumes were recorded. To standardize static lung load, the subjects' chest pressure centroids (representing the average water pressure on the chest) were held at a constant depth (0.33m) throughout the experiments. Results: Recordings of peak inspiratory flow (PIF) showed a decrease of 25.56 ± 4.14% (mean ± SD, P =0.01) from the submerged upright position mean flow of 6.19 ± 1.48 (l/s) to the submerged prone mean flow of 4.37 ± 0.69 (l/s). Nadiral esophageal pressure exhibited no significant differences: 5.40 ± 4.32% (mean ± SD, P = 0.512), from the upright mean pressure of (-) 51.70 ± 24.09 (cm H_2O) to the prone mean pressure of (-) 48.53 ± 25.86 (cm H_2O). Conclusions: The significant decrease in PIF when changing from the upright to the prone position, suggests a difference in the patency of the extra-thoracic airways. The higher water pressure exerted on the neck in the prone position may explain this difference. The similarity of pleural pressures in the two positions indicates that the differences in PIF were not due to differences in inspiratory effort.

INTRODUCTION

Previous experiments performed in our laboratory by Thalmann et al(1) and Hickey et al (2) have investigated respiratory function during submersion. The former study involved exercise in the prone position. In those experiments, both depth and static lung load were varied. It was observed that, at maximal exertion levels, severe work limiting dyspnea became a significant problem. At submaximal exertion levels, dyspnea would be greatly aggravated by increasing the negative static lung load (equivalent to negative pressure breathing). This dyspnea was also observed to be experienced almost exclusively on inspiration. Considerably lower dyspnea scores during exercise in the upright position were noted by Hickey and colleagues (2) Upon comparison to the earlier study (1), they hypothesized that the difference depended primarily on body position leading to differences in hydrostatic pressure exerted on the extra-thoracic airways, the airways being exposed to a greater external pressure in the prone than in the upright body position.

During inspiration, at any point in the airways downstream from the mouth, the pressure is negative. This negative pressure will be most pronounced during a maximal inspiratory effort. Since the airways are not uniformly rigid, it is possible that during submersion, when the hydrostatic pressure outside the subject's extrathoracic airways is greater than the pressure inside the airways (negative transmural pressure), compression of the airway is highly likely to occur. As the cross-sectional area of an airway decreases, flow resistance increases and the flow of air is reduced, if the pressure driving the flow remains unchanged. Increased resistance to airflow increases the work of breathing. This increased work of breathing loads the muscles of inspiration, which may cause respiratory muscle fatigue and possibly dyspnea (1, 2).

HYPOTHESIS

At a constant inspiratory effort against a negative static lung load, as commonly imposed by an underwater breathing apparatus, airflow is likely to be reduced in the prone compared to the upright body position.

METHODS

Six volunteer subjects (4 male, 2 female; age 19-26 years) were recruited from the student population of the University at Buffalo, State University of New York. Informed consent was obtained in accordance with procedures of the Institutional Review Board, which also approved the study protocol. The subjects were randomized with a coin toss into two groups at the time of enrollment. All subjects completed the experimental protocol. Group 1 was tested in the prone position first, while group 2 was tested in the upright position first. The subjects breathed room air at atmospheric pressure through a non-rebreathing bag-in-box system. Thus, there were no changes in gas density between the experimental conditions.

The location of the chest pressure centroid of each subject was determined from guidelines in the literature (2-4). A reference point was marked on the skin of the chest wall in the frontal and sagittal planes. This mark was placed on the skin at a point 14 cm below the sternal notch and 7 cm behind a frontal plane crossing through the sternal notch. The subject was then placed in a harness used for the submerged portion of the experiment. The harness consisted of a rigid back-plate, rigid padded shoulder bars and an adjustable belt. The belt was adjusted to lie across the pelvis and not infringe upon chest or abdominal movements during respiratory maneuvers. After fitting the harness, the waist belt was tightened so that the pelvis was comfortably held against the back-plate. Measurements from the externally marked representation of the subject's chest pressure centroid to fixed hard-points on the harness were made. The harness was connected to scaffolding which could be adjusted so that the subject was submerged with the pressure centroid at a constant depth (0.33 m ± 0.005 m) in both body positions.

An esophageal, balloon-tipped catheter (Nolato Inc., Torekov, Sweden) was used to measure esophageal pressure, which is a widely-used representation of pleural pressure. Before the subject was placed in the harness, the esophageal balloon was passed through a nostril and swallowed to a depth of 40 cm (measured from the nostril.) The balloon was inflated with 1.0 ml of air, and the upper end of the narrow plastic catheter tube was connected to a pressure transducer. Thereafter, the subject performed sub-maximal inspiratory expiratory and Valsalva maneuvers to confirm that the balloon was placed above the level of the diaphragm. The subject was then fitted with a full face diving mask containing valves separating inspiratory and expiratory flow as well as a port for the esophageal balloon tube. The respiratory circuit was then connected to the bag-in-box system, and the subject was strapped into the diving harness. The subject (still unsubmerged) performed maximal-effort inspiratory maneuvers with volume, esophageal pressure and time being simultaneously recorded. The subject was subsequently submerged and allowed 15 min to recover from the previous respiratory maneuvers and acclimate to the experimental situation. Water was held at thermoneutral temperature (35 ± 0.05° C.) During the recovery period, the harness was attached to the scaffolding.

After recovery, the subject was strapped into the diving harness. Once the subject was securely fastened to the diving harness/scaffolding and depth measurements had been confirmed, maximal inspiratory maneuvers were performed. The subject was allowed another recovery period between experimental conditions while the harness was recalibrated for the other body position.

The volume and pressure instruments were calibrated prior to subject immersion. Pressure measurements were made with a Validyne model # 1059 pressure transducer (Validyne Engineering Corp, Northridge CA 91324.) Volume measurements were obtained at the level of the mouth from the mask using a Hans Rudolph model # 3700 pneumotachograph (Hans Rudolph Inc, Kansas City, MO 64114.) Inspiratory flow was determined by differentiating the volume signal after the experiment had been performed. All data were sampled at 100 Hz. For the analyses, results from three repetitive maneuvers were averaged for each subject and condition. Average flow and pressure measurements were compared, upright and prone position data being expressed as percentages of the results obtained in the unsubmerged condition.

STATISTICAL ANALYSIS

Data were analyzed using Microsoft Excel Version 2003, (Microsoft Corp., Redmond, WA.). Mean percent differences in flow and pressure from control condition were compared using paired two tailed Student's t-tests.

RESULTS

The unsubmerged peak inspiratory flow (PIF) was 8.44 ± 3.54 l/s (mean ± SD.) A non-significant decrease in PIF to 6.19 ± 1.48 l/s was observed with submersion in the upright position. A further decrease in PIF to 4.37 ± 0.69 l/s (P = 0.003) was observed with submersion in the prone position. A direct comparison of the upright versus prone mean differences in flow showed a 24.52 ± 19.41 % reduction (P = 0.006,) (Fig. 1)

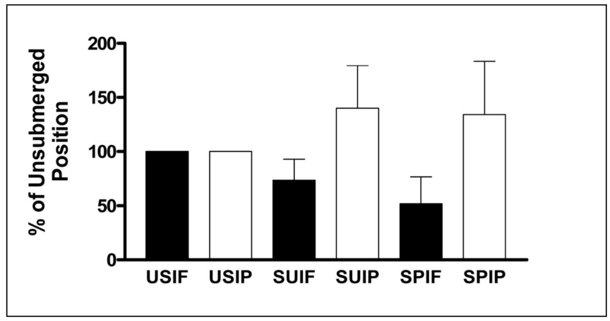

Fig. 1. Relative relationships of inspiratory (esophageal) pressure and gas flow. The values for the unsubmerged inspiratory pressure (USIP), submerged upright inspiratory pressure (SUIP), and submerged prone inspiratory pressure (SPIP) are shown in white while the unsubmerged inspiratory flow (USIF,) submerged upright inspiratory flow (SUIF) and the submerged prone inspiratory flow (SPIF) are shown in black. Values are percentages of the control condition.

During inspiration, pleural pressure is negative. The pressure measurement of interest is actually the nadir esophageal pressure measured during the inspiratory effort. For conceptual ease, this will be referred to as the maximal inspiratory pressure, understanding that this is a negative value. Maximal inspiratory esophageal pressures actually become more negative with submersion. This change indicates that the subjects generated an increased inspiratory pressure during submersion. Despite the increased inspiratory effort, PIF was reduced. A direct comparison of the upright versus prone mean differences in pressure exhibited a non-significant decrease from 51.70 ± 24.09 cm H_2O in the upright to 48.53 ± 25.86 cm H_2O in the prone position (Fig 1).

DISCUSSION

This randomized crossover experiment clearly demonstrates that, as the extra-thoracic airways are exposed to increased hydrostatic pressure, peak inspiratory flow is reduced. The significance of these experiments lies in emphasizing the physiological role of extra-thoracic airway resistance in the inspiratory flow limitations experienced by divers during submersion. The results of the present study may have implications for divers using different types of breathing gear, especially when engaging in strenuous work such as swimming for extended periods. These results are consistent with the observation that respiratory muscle fatigue limits swimming endurance in divers swimming in the prone position at 70% of maximal O_2 consumption and that their endurance is enhanced by respiratory muscle training (5).

Previous experiments have shown an increase in the dyspnea experienced by divers in the prone versus the upright body position. Hickey et al. hypothesized there were three major factors explaining this phenomenon (2). The present study was designed to isolate the role of body position on the inspiratory flow limitations experienced by divers. Since the lung pressure centroid was held at a constant depth throughout the experiment, changing the body position of the submerged subjects altered the hydrostatic forces exerted on their extra-thoracic airways alone. The prone body position showed a lower maximal inspiratory flow rate than the upright body position, with the same pleural pressures, static lung load and breathing gas density. In the prone body position, a greater hydrostatic force was put on the extra-thoracic airways. This increase in external hydrostatic pressure is likely to have resulted in greater compression of the airway (Fig. 2).

A consequent decrease in extra-thoracic airway cross-sectional area is likely to have led to increased resistance to airflow. The resulting limitation in PIF may explain the more pronounced dyspnea during exercise experienced by prone versus upright divers (1, 2).

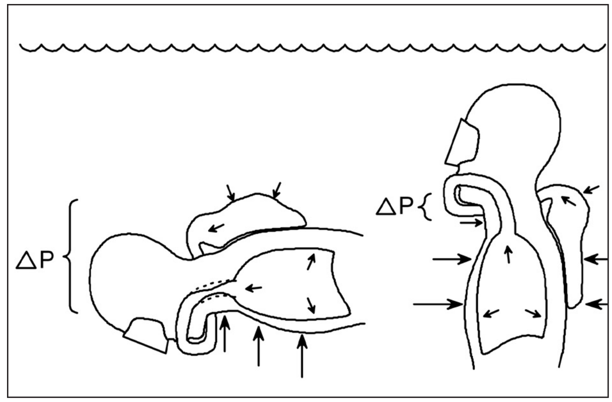

Fig. 2. Schematic of the hydrostatic and gas pressures acting on a diver's respiratory system when a generic rebreather apparatus is used in the prone or upright position. These two situations correspond to the experimental conditions of the present study. The size of the arrows symbolize the magnitude of the water pressure acting on the diver and breathing apparatus and the resulting gas pressure in the lungs and extrathoracic airway. The gas pressure is set by the water pressure on the breathing bag and is the same (same depth) in the two positions. By contrast, a higher water pressure (greater depth: greater ΔP relative to bag) is acting on the diver's neck and thus on the extra-thoracic airways (compressing them more) in the prone than in the upright position.

The subjects were able to generate greater (more negative) inspiratory pressures during the submerged phases of the experiments. This may have been due to the hydrostatic pressure on the chest, lowering its end-expiratory volume and stretching the inspiratory muscles so as to place them in a more favorable position on the length-tension curve.

A unique phenomenon of paradoxical inspiratory effort-independent flow is theoretically possible. Because there is a negative static lung load while breathing with a positive hydrostatic pressure load on the extra-thoracic airway, increases in inspiratory effort may raise the airway trans-mural pressure gradient. As this pressure gradient increases, the airway cross-sectional area can be expected to fall. This would result in an effort-dependent reduction in airway patency. As limitations in inspiratory flow are experienced, the natural compensation is to increase effort. This could conceivably result in further reductions in flow, which can augment the sensation of dyspnea. The physiology of this phenomenon is very similar to the expiratory flow limitations observed with dynamic airway compression due to loss of pulmonary elastic recoil in emphysema.

Due to resource limitations, we were unable to measure each individual subjects' chest pressure centroid. The pressure centroid locations were therefore based on historical data. As a result, some very small changes in chest volume were noted between submerged conditions. The volume differences represent a systematic error, which is not likely to have impacted the results.

This study highlights the importance of the design and use of underwater breathing devices. When so-called rebreathers are used, the position of the breathing bag relative to the diver's chest and the diver's body orientation in the water are important. While the present experimental design reproduced the effects of a common rebreather- type diving apparatus, in which the breathing bag is positioned on the divers back, similar relationships between breathing gas and airway pressures apply to other designs which, for instance, use a bag placed on the back but extending over the shoulders. In equipment with a chest-mounted bag, the most disadvantageous position of the diver is supine, for example when working under the bottom of a boat. It is of practical interest that a design has been published in which a back-mounted bag is acted upon by a weight so as to appropriately add or reduce breathing gas pressure depending on body position (6, 7). Conventional open-circuit scuba gear (popular among sport divers) delivers air equilibrated to the water pressure acting on the breathing regulator at the mouth. It follows that the maximal negative inspiratory pressure is experienced in the upright position. By contrast, practically no negative pressure will act on the divers' extrathoracic airways in the prone position.

While this study addresses a phenomenon relevant to diving, it has parallels in medicine. Obstructive sleep apnea (OSA) is a disorder of the upper airway which results in its collapse during nocturnal breathing. Neck circumference and obesity are well established risk factors for this condition (8-11). Some of the airway resistance change observed in OSA occurs through mechanisms similar to the one proposed to account for the presently-observed flow limitations. The main difference is that, in OSA, the mass of the soft tissue in the neck region is a causative factor, while in our study it is an externally imposed hydrostatic pressure.

CONCLUSION

The significant decrease in peak inspiratory flow observed when changing from the submerged upright to the submerged prone position is interpreted as a difference in the patency of the extrathoracic airways. The higher water pressure exerted on the neck in the prone position may explain why a lower inspiratory flow was achieved than in the upright position. The absence of differences in pleural pressure between the upright and prone positions indicates that the aforementioned differences in inspiratory flows were not effort-dependent.

ACKNOWLEDGMENTS

We thank Professor Brydon Grant, MD for valuable discussions of this manuscript and Messrs. Dean Marky, Andrew Barth and Bradley Panoff for skillful technical assistance.

REFERENCES

1. Thalmann ED, Sponholtz DK, Lundgren CE. Effects of immersion and static lung loading on submerged exercise at depth. *Undersea Biomed Res* 1979;6:259-90.

2. Hickey DD, Norfleet WT, Pasche AJ, Lundgren CE. Respiratory function in the upright, working diver at 6.8 ATA (190 fsw). *Undersea Biomed Res* 1987;14:241-62.
3. Jarrett AS. Effect of immersion on intrapulmonary pressure. *J Appl Physiol* 1965;20:1261-1266.
4. Taylor NA, Morrison JB. Lung centroid pressure in immersed man. *Undersea Biomed Res* 1989;16:3-19.
5. Wylegala JA, Pendergast DR, Gosselin LE, Warkander DE, Lundgren CE. Respiratory muscle training improves swimming endurance in divers. *Eur J Appl Physiol* 2007;99:393-404.
6. Arborelius M, Lundgren C. Arrangements in breathing apparatus for use under water. United States Patent Office, Patent No. 2,896,616, 1959.
7. Lundgren C. A physiologist's appoach to breathing gear design. Proceedings of the First Ocean Technology Congress. Toronto, Ontario, Canada, 1982:216-243.
8. Davies RJ, Ali NJ, Stradling JR. Neck circumference and other clinical features in the diagnosis of the obstructive sleep apnoea syndrome. *Thorax* 1992;47:101-5.
9. Kripke DF, Ancoli-Israel S, Klauber MR, Wingard DL, Mason WJ, Mullaney DJ. Prevalence of sleep-disordered breathing in ages 40-64 years: a population-based survey. *Sleep* 1997;20:65-76.
10. Netzer NC, Stoohs RA, Netzer CM, Clark K, Strohl KP. Using the Berlin Questionnaire to identify patients at risk for the sleep apnea syndrome. *Ann Intern Med* 1999;131:485-91.
11. Viner S, Szalai JP, Hoffstein V. Are history and physical examination a good screening test for sleep apnea? *Ann* Intern Med 1991;115:356-9.