EFFECTS OF SUBMERSION AND DEPTH ON RESPIRATORY MECHANICS

Held HE, Pendergast DR, Lundgren CEG

Center for Research and Education in Special Environments and Department of Physiology and Biophysics, University at Buffalo, Buffalo, NY

Abstract

The energy cost of ventilation (V_{O2}/V_E) is increased in water, due to increased static lung load, and as a function of depth i.e. gas density. This study examined these effects on some aspects of respiratory mechanics.

Experienced divers (n=4) completed dry and submersed experiments at 1ATA, 2.7ATA, and 4.6ATA. Subjects rested, cycled an ergometer (10min at 100W), rested, and rested while voluntarily matching their ventilation to a ventilation tracing recorded during exercise (ISEV). V_E, V_{O2}, maximal static mouth pressures (P_{mouth}, as a function of lung volume) and alveolar pressure (P_A, interruption method) were measured.

During submersion V_E was higher (~9%). V_E decreased with pressure (9% to 13%) for all conditions. V_E during ISEV was not different from exercise (36.25 ± 5.26 L/min and 37.29 ± 5.61 L/min, respectively). V_{O2} at the surface was 0.30 ± 0.06 L/min during rest, 1.71 ± 0.17 L/min during exercise, and 0.42 ± 0.09 L/min during ISEV. VO2 did not change with depth. P_A at rest in the dry was -2.45 ± 1.12 cmH_2O (inspiration) and 2.10 ± 1.61 cm H_2O (expiration) and was 29-46% greater wet. P_A increased 221% (inspiration) and 155% (expiration) during exercise and 208% and 271%, respectively, during ISEV. P_{mouth} increased as a function of lung volume (%VC); however, the increase was greater dry than wet (0.22 vs. 0.14 cmH_2O/%VC) and greater at depth (18% more at 2.7ATA and 36% more at 4.6ATA).

This study's protocol allowed the effects of submersion and depth to be evaluated. V_E was increased by submersion, but decreased as a function of pressure. V_{O2} did not change with depth or submersion. Maximal P_{mouth} did not change with depth or submersion. The increase in Pmouth per increase in lung volume was diminished by submersion but slightly enhanced by depth. P_A increased with submersion. For confirmation of these preliminary results, a larger subject pool is currently being studied.

Note: This abstract has been updated to reflect the most current data

Introduction

Scuba diving presents physiological challenges.
- Submersion redistributes blood from the extremities to the chest, which decreases vital capacity (VC) and lung compliance.
- Static lung loading is imposed if the source of breathing gas is located at a different depth than the chest centroid.
- Gas density increases with depth, which may increase resistance in the airways.

Purpose: The purpose of this study is to determine how the effects of submersion and depth alter respiratory mechanics.

Methods and Protocol

Protocol: Subjects were seated on a cycle ergometer behind the Buffalo barrier in a hyperbaric chamber. Each experiment consisted of four periods of varying effort.
- *Rest* (10 min)
- *Exercise* (10 min)
  - –Spirometer volume recorded continuously for playback
- *Rest* (20 min)
- *Isocapnic Simulated Exercise Ventilation (ISEV)*
  - –Ventilation paced to match the previously recording exercise VE
  - –Subjects breathed air with CO added$_2$ to prevent hypocapnia

The protocol was repeated on separate days, both dry and fully submersed, at 1ATA, 2.7ATA (55fsw), and 4.6ATA (120fsw). The order of the trials was randomized.

Subjects: Five healthy adult male subjects (32.20 ± 3.68yrs, 179.89 ± 0.97cm, 86.00 ± 6.23kg) were recruited from the local diving community.

Measurements: During each of the four periods, the following data were recorded:
- VE, VT, and f_b using a rolling seal spirometer or a dry gas meter
- F_{O2}, F_{CO2} from a mass spectrometer
- P_A was taken from interruptions of airway flow using a guillotine style interrupter at the mouth
  - –Interruptions were triggered ~100ms after the start of inhalation or exhalation and lasted ~100ms
  - –Interruptions were triggered randomly to prevent anticipation
  - –P_A was the intercept of an extrapolated best-fit line at the time of occlusion

After the four periods, maximal P_{mouth} was recorded at different lung volumes (20, 40, 60, 80, and 100% of VC)

Figure 1. Ventilation During Exercise and ISEV

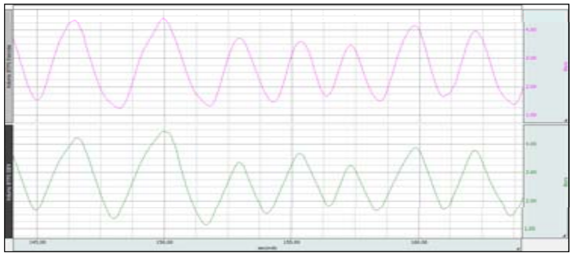


Fig. 1. Sample spirometer tracings of breathing during exercise (upper waveform) and ISEV (lower waveform)

Figure 2. Experimental Setup

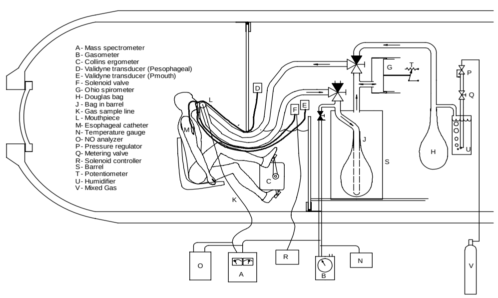
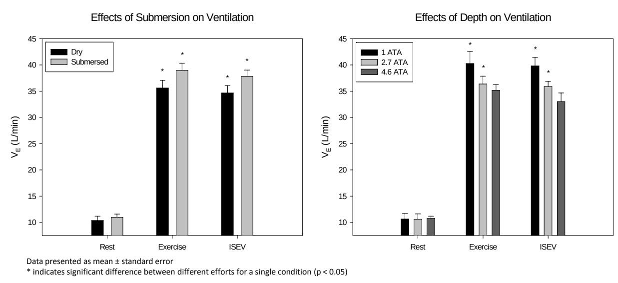


Fig 2. Schematic of a subject seated on a cycle ergometer behind the Buffalo barrier
- During submersion, the water level imposed a 15cmH_2O static lung load

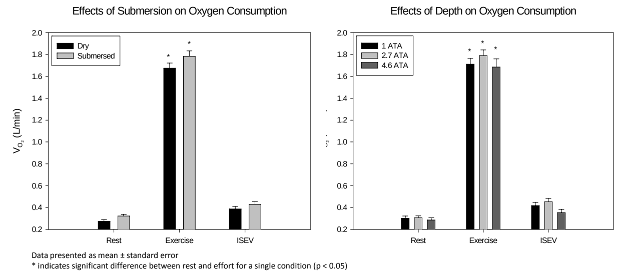
Results

Figures 3 A and B. Effects of Submersion and Depth on Ventilation



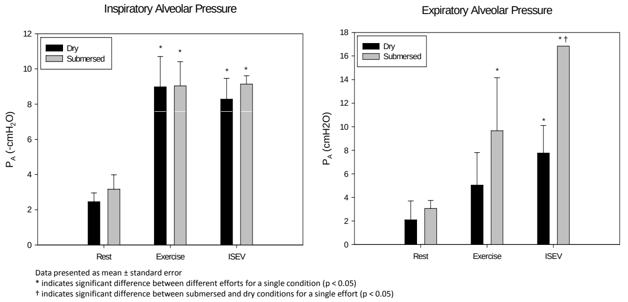
Figs. 3 A and B.
- V_E tended to increase with submersion (Fig. A)
- V_E tended to decrease as a function of depth (Fig. B)
- Changes in VE were largely due to changes in f_b, while V_T was defended

Figures 4 A and B. Effects of Submersion and Depth on Oxygen Consumption



Figs. 4 A and B.
- V_{O2} tended to increase with submersion (Fig. A)
- V_{O2} did not change significantly with depth (Fig. B)
- V_{O2} tended to increase from rest to ISEV (Figs. A and B)
- V_{O2} increased significantly from rest to exercise (Figs. A and B)

Figures 5 A and B. Effects of Submersion on Alveolar Pressure



Figs. 5 A and B
- Inspiratory P_A increased significantly from rest to exercise and ISEV
- There were no significant differences in inspiratory P_A between dry and submersed conditions
- Expiratory P_A tended to increase from rest to exercise and ISEV
- Expiratory P_A increased slightly from dry to submersed conditions at all efforts
- Expiratory P_A increased significantly from dry to submersed conditions during ISEV

Figure 6. Effects of Depth and Submersion on Maximal Expiratory Mouth Pressure

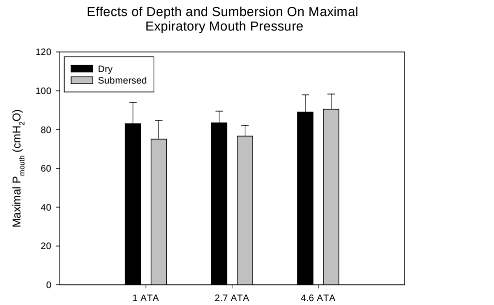


Fig. 6.
- There were no significant changes in maximal Pmouth with submersion or depth

Figure 7. Effects of Depth and Submersion on Pmouth as a Function of Lung Volume

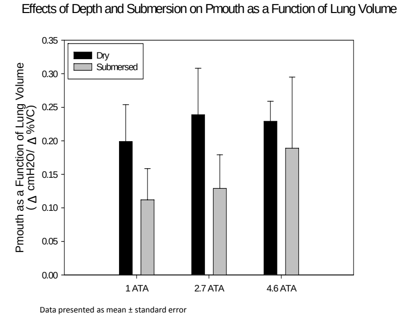


Fig. 7.
- There were no significant differences with submersion or increasing depth
- When data from all depths were combined, there was a significant decrease from dry to submersed conditions

Summary

- Depth depressed ventilation, but submersion tended to enhance it. These changes were predominantly due to changes in f_b and not V_T.
- Inspiratory P_A increased significantly from rest to exercise and ISEV.
- Submersion did not affect inspiratory P_A.
- Expiratory P_A tended to increase from rest to exercise and ISEV
- Expiratory P_A increased slightly from dry to submersed conditions at all efforts
- Expiratory P_A increased significantly from dry to submersed conditions during ISEV
- Maximal expiratory P_{mouth} did not change with submersion or depth

Conclusions

- The decrease in V_E at depth may reflect compensation for the increased gas density by a reduction in frequency of breathing
- The increase in V_{O2} from rest to ISEV likely reflects the increased work of breathing associated with exercise hyperpnea
- The reduction, from dry to submersed conditions, of maximal P_{mouth} as a function of lung volume might be due to the effects of added hydrostatic pressure on the chest wall, changed lung compliance due to vascular engorgement, or lung compression during submersion.

Future

- We are continuing to test this protocol with more subjects.
- We have begun to examine changes in respiratory mechanics after resistive respiratory muscle training (RMT), which is known to enhance exercise endurance.
  - – RMT consists of one full vital capacity effort against a spring-loaded mouthpiece every 30 seconds for 30 minutes, five days a week. The springs are initially set at 60% of the subjects' maximal inspiratory and expiratory pressures and are increased by 10cm H_2O each week.

Funding

This research is sponsored by the Office of Naval Research, Grant# N00014-08-1-0255