COMPARISON OF VENTILATORY LIMITATION IN AVIATION AND DEEP SEA DIVING

Donald D. Joye* and John R. Clarke
Diving Medicine Department, Naval Medical Research Institute, Bethesda, Maryland, USA

INTRODUCTION

The limitations of breathing equipment have been implicated in loss of consciousness episodes (LOC) in both the undersea and aviation environment (1,2). In diving, LOC can occur whenever the human respiratory system can no longer compensate for inadequate equipment design. In air combat, G-induced LOC can occur whenever oxygen breathing systems impair a pilot's performance of the respiratory portion of anti-G straining (M-1, L-1) maneuvers.

Gas density (ρ) increases with water depth, markedly decreasing the performance of underwater breathing equipment. In aviation, gas density is low, but flow rates may be high. During the M-1 and L-1 maneuver peak flowrates may range from 360-450 l/min (3). We used a fluid dynamic comparison to demonstrate that the physical stresses imposed on the respiratory system by the diving and combat aviation environment are similar.

METHODS

We evaluated the pressure drop characteristics of a straight, corrugated hose from a U.S. Navy MK-15 closed-circuit Underwater Breathing Apparatus. The hose consisted of two sections joined together to form a 122 cm long, flexible, accordion-pleated rubber tube (inside diameter 3.48 cm) with pleats 0.6 cm high spaced 1 cm apart along the tube axis. The pressure drop along the length of hose was measured as a function of flow rate. Air at 1 ATA and 22-23 °C was moved through the tube at rates ranging from 100-600 l/min. The dimensionless friction factor (f) for the tube was calculated from the Fanning formula (4).

$$f = \Delta P \cdot D/(2\rho \cdot \upsilon^2 \cdot L) = \Delta h \cdot \pi^2 \cdot D^5 \cdot g/32L(S.G.)Q^2 \qquad (1)$$

where ΔP is the pressure drop along the hose, D is hose diameter, ρ is gas density, υ is linear gas velocity, and L is hose length, Δh is pressure drop (energy loss) in cm H_2O, S.G. is the specific gravity (gas density relative to that of water), Q is the volumetric flow rate (cm^3/sec), and g is the gravitational acceleration ($981\ cm/sec^2$). Gas densities were computed at body temperature (37°C).

Once f was determined, eqn. 1 was rearranged to yield the expected energy loss for the following conditions: 1) O_2 breathing at sea level with peak flows of 360 l/min and 2) 450 l/min, representing pilots performing anti-G straining maneuvers, 3) air breathing at 95 fsw and 4) 150 fsw, and 5) 2%O_2-98% He breathing at 1000 fsw. The diving conditions, 3-5, both assumed a minute ventilation of 60 l/min with peak flows of 188 l/min. Reynolds number (Re) was calculated as $4\rho Q/\pi\mu D$, with μ being viscosity.

---

* *present address: Dept. of Chemical Engineering, Villanova University, Villanova, PA 19085*

RESULTS

The friction factor for the diver's breathing hose was 0.094 ± 0.007 (mean ± S.D.), well outside the range of the Moody diagram (4). All experimental conditions resulted in fully developed turbulent flow (constant friction factor).

Table 1: Pressure losses for high flow/low density and low flow/high density conditions.

condition	Q (l/min)	ρ (g/l)	Re	Δh (cm H_2O)
1	360	1.26	15,200	3.2
2	450	1.26	18,000	5.3
3	188	4.4	27,700	3.2
4	188	6.30	37,800	5.5
5	188	5.60	33,600	4.9

The pressure losses for conditions 1 and 3 were similar, as were those for conditions 2, 4, and 5.

CONCLUSIONS

The pressure drops or energy losses (Δh) computed in these examples are not large, and we do not imply that they would impair the function of either diver or aviator. Actual pressures generated during exercise or anti-G maneuvers would be larger due to the additional impedance of valves and regulators. This example serves merely to show the similarities between the low flow-high density and the high flow-low density conditions, and should dispel the notion that the respiratory work required by a combat pilot is less than that of a diver.

In diving, ventilatory insufficiency due to high work demands and UBA inadequacies are not uncommon. Unconsciousness may ensue, but more frequently, breathlessness leads to a temporary suspension of work. However, neither result is desirable in real or simulated aerial combat. In the near future, the high G capabilities of new aircraft and the potential for sustained operations will undoubtedly tax a pilot physically. Therefore, new ways of reducing the pilot's respiratory work load should be considered, just as they have been for the diver.

REFERENCES

1. Buick, F., Inspiratory breathing resistance and +Gz tolerance. Aerospace Med. Ass., A22, 1990.

2. Clarke, J.R., D. Vila, A. Cabeca, E.D. Thalmann, and E.T. Flynn., The testing of physiological design criteria for underwater breathing apparatus (UBA). Proceedings of the European Undersea Biomedical Society, Elat, Israel, 1989.

3. Gordge, D., F/A-18A High-G loss of consciousness oxygen system component evaluation. Naval Air Test Center Technical Report SY-74R-87, Final Report, Patuxent River, Md., 1988.

4. De Nevers, N., <u>Fluid Mechanics</u>, Addison-Wesley, Reading, MA, 1970.