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EXPERIMENTAL DIVING UNIT
WASHINGTON NAVY YARD
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NAVXDIVINGU REPORT 22-74

OPERATIONAL MONITORING OF OXYGEN CONSUMPTION IN SEMI-CLOSED CIRCUIT UNDERWATER BREATHING APPARATUS

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ABSTRACT

An equation is developed which permits calculation of a diver's oxygen consumption in a semi-closed circuit UBA if the inspired partial pressure of oxygen, the depth, the mixed gas injection rate, and the supply gas oxygen percentage are known. The approximate nature of this calculation and its limitations are discussed.

INTRODUCTION

The semi-closed circuit underwater breathing apparatus, Mark 11, is equipped to measure the partial pressure of oxygen in the diver's inspired gas. If certain parameters of the dive are known, and others are assumed, it is possible to transform this reading directly into the diver's oxygen consumption. Although this method is too approximate to be useful in an experimental setting, it can provide a reasonable estimate of the severity of the work being performed by a diver in the open sea. When coupled with other physiological information, such as heart rate and respiratory rate, it allows topside supervisory personnel to obtain a more complete picture of the physical status of the diver. The details of this method follow.

METHOD

According to the laws of mass balance, the mass of oxygen entering the underwater breathing apparatus per minute must be equal to the mass of oxygen taken up by the diver plus the mass of oxygen leaving the apparatus per minute. Algebraically:

$$\dot{V}_i \cdot F_{O_2} = \dot{V}_{O_2} + \dot{V}_e \cdot F_{B_{O_2}} \quad (1)$$

where:

$\dot{V}_i$ = volume of supply gas injected into rig per minute (L/min STPD)

F_{O_2} = fractional concentration of oxygen in the supply gas mixture

$\dot{V}_{O_2}$ = diver's oxygen consumption (L/min STPD)

$\dot{V}_e$ = volume of gas being exhausted from rig per minute (L/min STPD)

$F_{B_{O_2}}$ = fractional concentration of oxygen in gas leaving apparatus.

If the concentrations of oxygen and carbon dioxide in the exhausted gas are assumed to be equal to those in mixed expired gas, Equation (1) may be transformed into:

$$\dot{V}_i \cdot F_{O_2} = \dot{V}_{O_2} + \dot{V}_e \cdot F_{E_{O_2}} \quad (2)$$

where:

$F_{E_{O_2}}$ = fractional concentration of oxygen in mixed expired gas.

It can be shown mathematically for the steady state that the volume of gas leaving the rig is given by:

$$\dot{V}_e = \frac{\dot{V}_i - \dot{V}_{O_2} \pm \dot{V}_{inert}}{1 - F_{E_{CO_2}}} \quad (3)$$

where:

$\dot{V}_{inert}$ = the volume of inert gas either entering or leaving the blood per minute (negative sign when blood absorbing inert gas).

$F_{E_{CO_2}}$ = fractional concentration of carbon dioxide in mixed expired gas.

combining Equations (2) and (3):

$$\dot{V}_I \cdot F_{O_2} = \dot{V}_{O_2} + \left(\frac{\dot{V}_I - \dot{V}_{O_2} \pm V_{inert}}{1 - F_{E_{CO_2}}} \right) \cdot F_{E_{O_2}} \tag{4}$$

The diver's oxygen consumption is equal to:

$$\dot{V}_{O_2} = \dot{V}_I \cdot F_{I_{O_2}} - \dot{V}_E \cdot F_{E_{O_2}} \tag{5}$$

where:

$\dot{V}_I$ = volume of gas inspired (L/min STPD)

$F_{I_{O_2}}$ = fractional concentration of oxygen in the inspired gas

$\dot{V}_E$ = volume of gas expired (L/min STPD)

The volume of gas inspired ($\dot{V}_I$) can be given by:

$$\dot{V}_I = \dot{V}_E + \dot{V}_{O_2} - \dot{V}_{CO_2} \pm \dot{V}_{inert} \tag{6}$$

where:

$\dot{V}_{inert}$ = positive when the blood is absorbing inert gas.

$\dot{V}_{CO_2}$ = volume of CO_2 produced per minute (L/min STPD).

The respiratory gas exchange ratio (R) is defined as:

$$R = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} \tag{7}$$

substituting Equation (7) in Equation (6) and rearranging:

$$\dot{V}_I = \dot{V}_E + \dot{V}_{O_2} \cdot (1 - R) \pm \dot{V}_{inert} \tag{8}$$

combining Equations (8) and (5):

$$\dot{V}_{O_2} = \left(\dot{V}_E + \dot{V}_{O_2} \cdot (1 - R) \pm \dot{V}_{inert} \right) \cdot F_{I_{O_2}} - \dot{V}_E \cdot F_{E_{O_2}} \tag{9}$$

similarly, the CO_2 production may be expressed as:

$$\dot{V}_{CO_2} = - \left(\dot{V}_E + \dot{V}_{O_2} \cdot (1 - R) \pm \dot{V}_{inert} \right) \cdot F_{I_{CO_2}} + \dot{V}_E \cdot F_{E_{CO_2}} \tag{10}$$

where:

FI_{CO_2} = fractional concentration of CO_2 in the inspired gas.

converting $\dot{V}_{CO_2}$ to $\dot{V}_{O_2}$:

$$R \cdot \dot{V}_{O_2} = - \left(\dot{V}_E + \dot{V}_{O_2} (1 - R) \pm \dot{V}_{inert} \right) \cdot FI_{CO_2} + V_E \cdot FE_{CO_2} \quad (11)$$

solving Equation (10) for FE_{O_2} and Equation (11) for FE_{CO_2}:

$$FE_{O_2} = \frac{\left(\dot{V}_E + \dot{V}_{O_2} \cdot (1 - R) \pm \dot{V}_{inert} \right) \cdot FI_{O_2} - \dot{V}_{O_2}}{\dot{V}_E} \quad (12)$$

$$FE_{CO_2} = \frac{\left(\dot{V}_E + \dot{V}_{O_2} (1 - R) \pm \dot{V}_{inert} \right) \cdot FI_{CO_2} + R \cdot \dot{V}_{O_2}}{\dot{V}_E} \quad (13)$$

substituting Equation (12) and Equation (13) in (4):

$$\dot{V}_i \cdot F_{O_2} = \dot{V}_{O_2} + \left\{ \frac{\dot{V}_i - \dot{V}_{O_2} \pm \dot{V}_{inert}}{1 - \left[\frac{\left(\dot{V}_E + \dot{V}_{O_2} \cdot (1 - R) \pm \dot{V}_{inert} \right) \cdot FI_{CO_2} + R \cdot \dot{V}_{O_2}}{\dot{V}_E} \right]} \right\} \cdot \left[\frac{\left(\dot{V}_E + \dot{V}_{O_2} \cdot (1 - R) \pm \dot{V}_{inert} \right) \cdot FI_{O_2} - \dot{V}_{O_2}}{\dot{V}_E} \right] \quad (14)$$

The respiratory minute ventilation ($\dot{V}_E$) expressed in L/min BTPS is linearly related to the diver's oxygen consumption as follows:

$$\dot{V}_E = S \cdot \dot{V}_{O_2} \quad (15)$$

where:

S = the increment in minute ventillation per unit increase in oxygen consumption ($\Delta \dot{V}_{E\,BTPS} / \Delta \dot{V}_{O_2\,STPD}$).

$\dot{V}_E$ = minute ventilation (L/min BTPS)

$\dot{V}_{O_2}$ = oxygen consumption (L/min STPD)

To be used in Equation (14), however, $\dot{V}_E$ must be expressed in L/min STPD. This conversion can be done as follows:

$$\dot{V}_E = S \cdot \dot{V}_{O_2} \cdot \left(\frac{P_B - .0618}{1} \right) \cdot 273/310 \quad (16)$$

where:

P_B = diver's depth (ata)

.0618 = water vapor pressure (atm) at 37°C

rearranging:

$$\dot{V}_E = S \cdot V_{O_2} \cdot (.88\,P_B - .054) \tag{17}$$

substituting Equation (17) in Equation (14) and converting $F_{I_{CO_2}}$ and $F_{I_{O_2}}$ to $P_{I_{CO_2}}$ and $P_{I_{O_2}}$:

$$\dot{V}_i \cdot F_{O_2} = \dot{V}_{O_2} + \left\{ \frac{\dot{V}_i - \dot{V}_{O_2} \pm \dot{V}_{inert}}{1 - \left[\dfrac{\left(\dot{V}_{O_2} \cdot S \cdot (.88P_B - .054) + \dot{V}_{O_2}(1 - R) \pm \dot{V}_{inert}\right) \cdot \dfrac{P_{I_{CO_2}}}{P_B - P_{H_2O}} + R \cdot \dot{V}_{O_2}}{S \cdot (.88P_B - .054) \cdot \dot{V}_{O_2}} \right]} \right\} \cdot \left(\frac{S \cdot (.88P_B - .054)\,\dot{V}_{O_2} + \dot{V}_{O_2}(1 - R) \pm \dot{V}_{inert}) \cdot \dfrac{P_{I_{O_2}}}{P_B = P_{H_2O}} - \dot{V}_{O_2}}{S \cdot (.88\,P_B - .054) \cdot \dot{V}_{O_2}} \right) \tag{18}$$

where:

P_{H_2O} = water vapor pressure in the inspired mixture.

This complex equation describes the exact relationship between oxygen consumption ($\dot{V}_{O_2}$) and the inspired oxygen partial pressure ($P_{I_{O_2}}$), but requires knowledge of several factors which cannot be ascertained in an operational situation. In addition, it is too cumbersome to be practical use. If the following assumptions are made, however, the equation can be made more manageable. Assume:

(1) That the exchange of inert gas in the lung ($\pm\dot{V}_{inert}$) is negligible.

(2) That there is no CO_2 in the inspired gas ($F_{I_{CO_2}} = 0$).

(3) That the respiratory gas exchange ratio (R) equals 1.

(4) That the corrections for water vapor (.054 and P_{H_2O}) are negligible factors compared with the magnitude of the absolute pressure (P_B).

(5) That the slope of the ventilatory response (S) = 26. Equation (18) then reduces and rearranges to:

$$\dot{V}_i \cdot F_{O_2} = \dot{V}_{O_2} + \left(\frac{\dot{V}_i - \dot{V}_{O_2}}{1 - \dfrac{1}{22.9P_B}} \right) \cdot \left(\frac{P_{I_{O_2}}}{P_B} - \frac{1}{22.9P_B} \right) \tag{19}$$

Since the term $1 - \frac{1}{22.9P_B}$ rapidly approaches a value of 1 at depth, it can be set equal to 1 for practical purposes. Therefore:

$$\dot{V}_i \cdot F_{O_2} = \dot{V}_{O_2} + (\dot{V}_i - \dot{V}_{O_2}) \cdot \left(\frac{P_{I_{O_2}}}{P_B} - \frac{1}{22.9P_B} \right) \quad (20)$$

rearranging:

$$\dot{V}_{O_2} = \frac{\dot{V}_i \left(F_{O_2} - \frac{P_{I_{O_2}}}{P_B} + \frac{1}{22.9P_B} \right)}{1 - \frac{P_{I_{O_2}}}{P_B} + \frac{1}{22.9P_B}} \quad (21)$$

where:

$\dot{V}_{O_2}$ = diver's oxygen consumption (L/min STPD)

$\dot{V}_i$ = mixed gas injection rate (L/min STPD)

F_{O_2} = supply gas oxygen fraction

$P_{I_{O_2}}$ = inspired partial pressure of oxygen (atm)

P_B = ambient pressure (atm)

For example:

For a dive to 600 feet (19.2 Ata), a supply gas oxygen percentage of 6% (F_{O_2} = 06), an injection rate of 60 L/min STPD, and a $P_{I_{O_2}}$ of 0.5 atm.

$$\dot{V}_{O_2} = \frac{60 \left(.06 - \frac{0.5}{19.2} + \frac{1}{(22.9)(19.2)} \right)}{1 - \frac{.5}{19.2} + \frac{1}{(22.9)(19.2)}} = 2.23 \text{ L/min}$$

If the $P_{I_{O_2}}$ increases to 1.0 atm,

$$\dot{V}_{O_2} = \frac{60 \left(.06 - \frac{1.0}{19.2} + \frac{1}{(22.9)(19.2)} \right)}{1 - \frac{1.0}{19.2} + \frac{1}{(22.9)(19.2)}} = .64 \text{ L/min}$$

PROCEDURE

To apply this method in an operational setting, the following steps should be taken.

(1) Determine the following three factors:

(a) depth of the dive (Ata)
(b) supply gas mixture oxygen fraction
(c) supply gas injection rate (L/min STPD)

The latter may be computed from the following formula:

$$\dot{V}_I = \dot{V} \cdot C \cdot P_B \cdot \frac{273}{273 + T_A} \tag{22}$$

where:

$\dot{V}_I$ = supply gas injection rate (L/min STPD)

$\dot{V}$ = measured gas injection rate at depth (L/min ATPD)

C = dry gasometer correction factor

P_B = chamber depth at which measurement made (Ata)

T_A = ambient chamber temperature (°C)

(2) Compute $\dot{V}_{O_2}$ at a $P_{I_{O_2}}$ of 0.5 and 1.0 atm using Equation (21)

(3) Plot the computed $\dot{V}_{O_2}$'s as a function of $P_{I_{O_2}}$ on rectilinear coordinates and connect two points by a straight line as in Figure 1.

(4) The $\dot{V}_{O_2}$ corresponding to any $P_{I_{O_2}}$ in the diver's inspired gas may be read from this line.

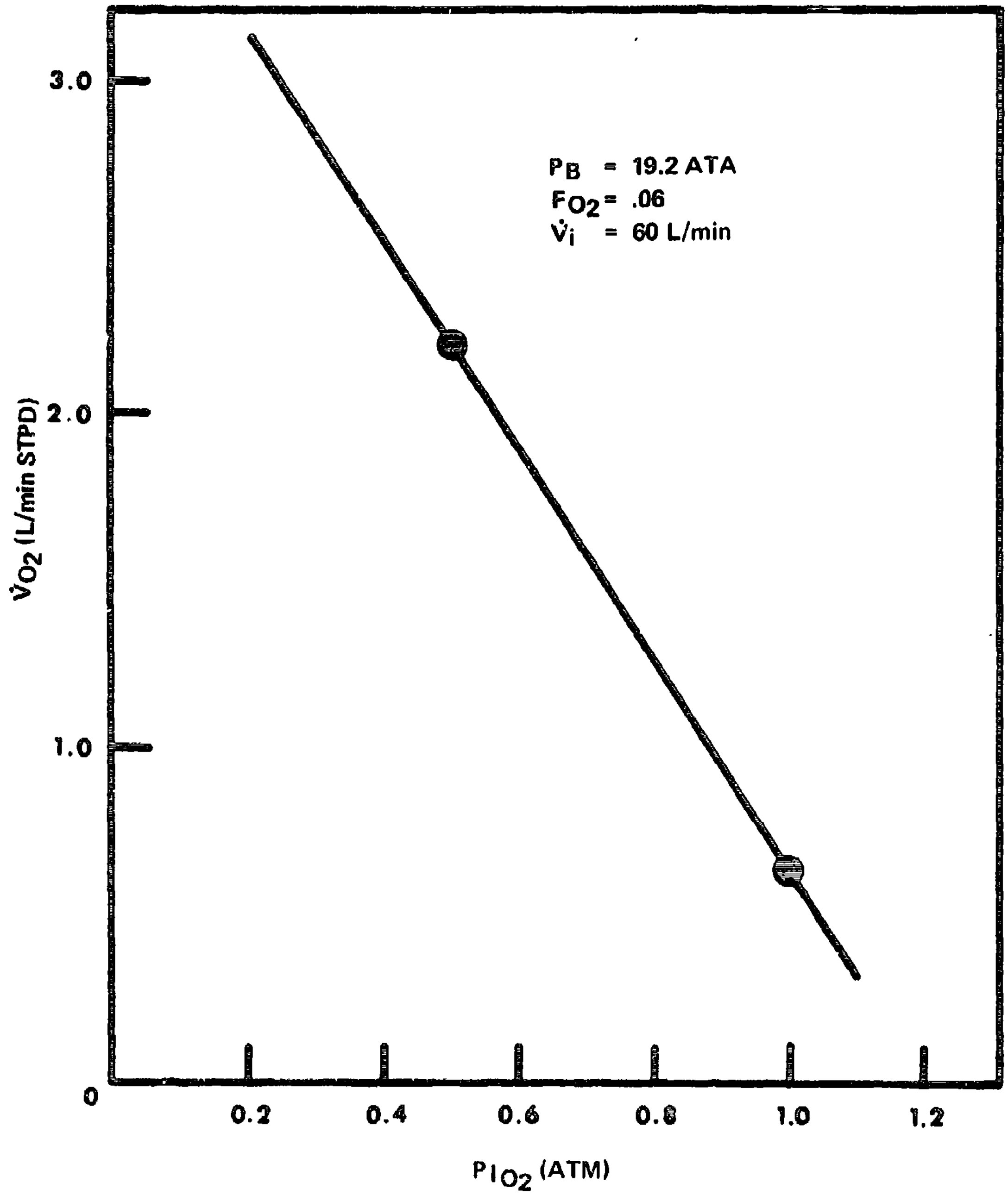

FIGURE 1

Relationship between diver's oxygen uptake and the inspired oxygen pressure. This linear relationship is derived using the procedure outlined in the text for a dive to 600 feet (P_B = 19.2 atm), a supply F_{O_2} of .06 and a supply injection rate of 60 L/min STPD.

DISCUSSION

It is clear from the foregoing that numerous assumptions and approximations underlie Equation (21). These assumptions make it impractical to use the equations for research purposes. However, it is easily possible to obtain an approximate oxygen consumption. Under field conditions, this is all that is necessary.

The error that one makes using Equation (21) will depend on the extent to which the actual conditions deviate from the assumptions outlined above. From a physiological standpoint, the most important sources of error are the uptake and elimination of inert gases in the lung during changes in ambient pressure, and significant deviations of the slope of the ventilatory response from an average value of 26. In general, the inspired P_{CO_2} may be expected to remain close to 0 during exercise in the absence of canister failure and the respiratory exchange ratio (R) approaches the assumed value of 1 in most subjects with exercise.

An additional source of error arises from use of the procedure suggested above since Equation (21) is not a straight line. At the depths of normal operation for the Mark 11, however, the deviations from linearity are quite small, and unimportant from a practical standpoint.

The greatest single limitation to the application of this method is the existence of non-steady-state conditions in the UBA. Thus, with changes in depth, exercise level, or following actuation of the by-pass mechanism, a finite time is required before a steady state P_{O_2} is reached. These transients are often frequent in occurrence and lead to errors which are far greater than those due to the mathematical or physiological assumptions. Two other major sources of error in practice are: (1) inaccurate measurement of the mixed gas injection rate at depth, and (2) drift in the calibration of the oxygen electrode. These, however, can be reduced by careful technique.