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Control of metabolic gases in hyperbaric chambers

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Abstract: Respiratory effort in hyperbaric conditions is increased, leading to an increase in the diver's respiratory flow, increased oxygen consumption, and consistent carbon dioxide production. The knowledge of these physical and physiological phenomena involved during the hyperbaric respiration was studied theoretically in collaboration with the "Ovidius" University of Constanta, Faculty of Medicine. They were verified by experimental determinations on groups of divers in the Diving Center hyperbaric complex.

1. Introduction

Changes in the volumetric proportions of the gaseous components of the respiratory mixture greatly influence the ability of the diver's respiratory function. Therefore, it is necessary to know the evolution of oxygen consumption and carbon dioxide production for each tested subject, under resting conditions and sustained effort, at the surface and during diving.
The human respiratory system is affected by hydrostatic pressure, its function adapting to the new conditions. Increasing density leads to increased gas flow resistance both through the anatomical airways and through the breathing apparatus paths. The risk factors presented in this paper are:

- Hypoxia
- Hyperoxia
- Hypercapnia

Breathing **oxygen** at a high partial pressure has a toxic effect on the human body. Oxygen toxicity is manifested in the central nervous system. The range of partial oxygen pressures between 0.21 bar and 0.42 bar is considered to be a normal-oxygen range. It is considered hyperoxia a mixture at which the partial pressure of oxygen is $Pp_{O2} > 0.42 bar$.
Hyperoxia can be chronic or acute. *Chronic hyperoxia* occurs when the partial pressure of oxygen in the respiratory mixture is between $0.42 \div 1.7 bar$. Acute hyperoxia manifested by a hyperoxic crisis may occur when the partial pressure of oxygen in the respiratory mixture is $Pp_{O2} > 1.7 bar$. If chronic hyperoxia is well tolerated by divers during short-term diving, acute hyperoxia (hyperoxic crisis) should be avoided as it may have serious consequences.
The moment of triggering the hyperoxic crisis is variable from individual to individual and depends both on partial oxygen pressure and on exposure time to that pressure.
To prevent the occurrence of the hyperoxic crisis, diving with compressed air should be limited to a depth of 70 m, the depth at which the partial pressure of oxygen in the breathing air is $Pp_{O2} = 1.7 bar$.
Reducing the level of oxygen in the respiratory mixture induces hypoxia. It is said about a respiratory mixture that it is hypoxic if the partial pressure of the oxygen in this mixture, is $Pp_{O2} < 0.17 bar$. Symptoms of hypoxia come from defective equipment adjustment, or from inadequate breathing.[1]
Excessive **carbon dioxide** in blood or hypercapnia characterizes a set of physiological effects and might be due to increased partial pressure of carbon dioxide in the respiratory tract. Hypercapnia may be chronic if the partial pressure of carbon dioxide is $0.1 mbar < Pp_{CO2} < 5 mbar$ and acute when the partial pressure of carbon dioxide is $Pp_{CO2} > 15 mbar$.

Chronic hypercapnia, which occurs quite often in autonomous breathing divers, is rather an adaptation of the body to the conditions of respiration of a gaseous mixture with a high proportion of carbon dioxide, whereas acute hypercapnia is a serious accident, with important effects on respiration, on blood circulation and on nervous system [1].
Respiratory flow resistance is due to the density of the gas flow passing through the tubing, the holes and hoses of the diving equipment. When the density of the gas increases, a higher pressure must be provided to keep the gas flow at the same value. The diver must exert a greater inhale differential pressure and greater exhaust pressure. If the ventilation increases with increasing physical exercise levels, a larger gradient of pressure must be provided to keep the gas flow at the same value. Since the respiratory muscles can only exert the necessary effort to inspire and expire, it is reached the point where these values of inhale and expiration pressures can no longer be increased. At this point, the carbon dioxide produced by the metabolism is not properly removed and its value in the blood increases, causing symptoms of hypercapnia [2].
The evolution of the concentration of the two gases, oxygen and carbon dioxide during diving is vital, to various types of effort.

2. Oxygen consumption and carbon dioxide production in hyperbaric chambers

2.1. Loss of oxygen in the hyperbaric chamber

The procedure for calculating the average oxygen consumption of a hyperbaric chamber, during diving, is based on an average value 0,7$m^3 O_2/day/$diver [3]. This value corresponds to the recommended average metabolic consumption of oxygen,*0.5l/min/diver*, under stationary conditions. At the same time, the body of the diver produces carbon dioxide.
At atmospheric pressure, the maximum volumetric concentration of oxygen in the air is $r_{O2max} =$ 0.21. The level of minimum volumetric concentration of oxygen in the respiratory diving air is $r_{O2min} =$ 0.19 at atmospheric pressure.
The permissible oxygen loss $\boldsymbol{V_{O2}(l)}$ for a hyperbaric chamber with volume $\mathbf{V_b}$***(l)*** is:

$$V_{O2} = (r_{O2max} - r_{O2min}) \cdot V_b = (0.21 - 0.19) \cdot V_b = 0.02 \cdot V_b \tag{1}$$

To maintain the minimum amount of oxygen required it has to be done the fill of the losses and calculate the time after which supplementation of oxygen is required.
For n divers the oxygen consumption rate $RC_{O2}(l/min)$ is:

$$RC_{O2} = \mathrm{n} \cdot 0.5 \tag{2}$$

The maximum allowed time $\tau_{ox}\,(min)$ after which oxygen is to be filled in the hyperbaric chamber is:

$$\tau_{O2} = \frac{V_{O2}}{RC_{O2}} \tag{3}$$

2.2. Increasing the carbon dioxide level in the hyperbaric chamber

The metabolic production of carbon dioxide is *0.5l/min/diver*. The maximum allowed level of carbon dioxide Pp_{CO2max} is 10 *mbar*. The minimum allowed level of carbon dioxide Pp_{CO2min} is 1 *mbar*. Maximum permitted carbon dioxide production $\boldsymbol{V_{CO2}(l)}$ in a hyperbaric chamber with the volume $\mathbf{V_b}$***(m³)*** is:

$$V_{CO2max} = (Pp_{CO2max} - Pp_{CO2min}) \cdot V_b = (10 - 1) \cdot V_b = 9 \cdot V_b \tag{4}$$

Normally admitted carbon dioxide level Pp_{CO2n} is 5 *mbar*. The production of normal carbon dioxide V_{CO2n}(l) in a hyperbaric chamber with the volume V_b*(m^3)is*:

$$V_{CO2n} = (Pp_{CO2max} - Pp_{CO2n}) \cdot V_b = (10 - 5) \cdot V_b = 5 \cdot V_b \tag{5}$$

For n divers, the production rate of carbon dioxide RP_{CO2}*(l/min)* is:

$$RP_{CO2} = n \cdot 0.5 \tag{6}$$

The maximum permissible time $\tau_{CO2max}\,(min)$, after which carbon dioxide is removed from the hyperbaric chamber, is:

$$\tau_{CO2max} = \frac{V_{CO2max}}{RP_{CO2}} \tag{7}$$

The normal time allowed $\tau_{CO2n}(min)$ after which carbon dioxide is removed from the hyperbaric chamber is:

$$\tau_{CO2n} = \frac{V_{CO2n}}{RP_{CO2}} \quad (8)$$

For the time interval $\tau_{CO2n} \div \tau_{CO2max}$ diving can proceed without ventilation.
The metabolic oxygen consumed during decompression must be completed with the amount of oxygen added to maintain the Pp_{O2} level to the required level according to the decompression dive plan!

3. Experimental procedures for determining oxygen consumption and carbon dioxide production

Experimental air diving were conducted at 50 msw in the Diving Center hyperbaric complex with 12 subjects.
Subjects participated in professional training courses for underwater workers divers and experienced divers.

3.1. Measuring devices and materials used for testing
The „Spiro Thor" digital spirometer of Figure 1 was used to measure breathing rates.

Figure 1 The „Spiro Thor" digital spirometer

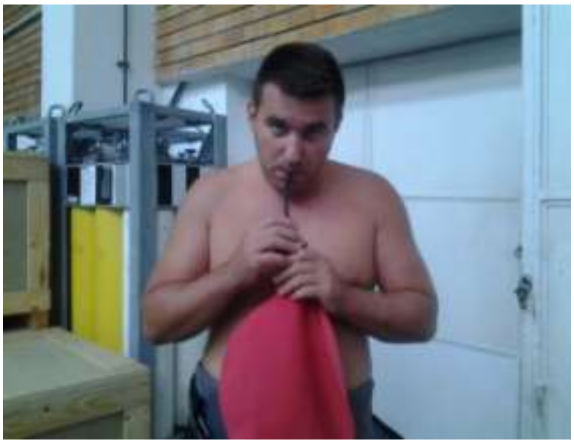

Figure 2 The gas collection flask

Technical details of the spirometer:

- VC, FVC, **PEF (**Peack expiratory flow), FEV, FEV1, FEF 25-75%, FEV, FIVC, PIF, FIV1, FIV1/FVC..
- Temperature sensor: semiconductor 0-45^{0}C;
- Flow sensor: bidirectional turbine;
- Volume accuracy: ±3% or 50 [ml];
- Flow accuracy: ±5% or 200 [ml/s];
- Dynamic resistance at 12 l/s: < 0,5 [cmsw/l/s]
- USB communication port;
- Direct power to PC via USB;
- Spirometry Software works connected to a PC or independently;
- Measuring principle: ultrasonic.

Figure 3 The Gas Analysis Rack

For the collection of respiratory gas samples the gas collecting flask from Figure 2 was used.
The gases were analyzed at the Analysis Rack from the Diving Center of the Hyperbaric Laboratory to determine the concentrations of oxygen and carbon dioxide. The rack is equipped with complex pressure, temperature and atmosphere components monitoring instruments (oxygen and carbon dioxide analyzers) from the hyperbaric chamber.

3.2. Tests and results

The diver's anthropometric parameters and age are important and their influence on respiratory capacity is measured just like any performance sportsman, with the HIRTZ index. The HIRTZ index represents the difference in chest circumference measured at forced breath and circumference after forced expiration. By modifying it, the individual's lung capacities also change [4]. The HIRTZ index was measured before and after diving. Professional experience and smoking habits are important factors that matter in assessing the respiratory function of divers. The personal data of the subjects and the evolution of the HIRTZ index can be found in Table 1.

Table 1
Personal data of the test subjects

Subject	Age (years)	Weight (kg)	Height (cm)	Initial Index Hirtz (cm)	Finale Index Hirtz (cm)	The history of diving (hours)	Smoking
1	41	96	191	8	7	4000	No
2	30	71	165	6	4	800	No
3	32	79	173	8	6	1600	No
4	27	76	174	8	7	400	No
5	29	104	182	10	8	250	No
6	34	75	180	4	4	150	No
7	29	90	175	6	5	500	Yes
8	26	75	170	5	3	350	No
9	29	65	173	4	3	200	No
10	46	89	181	8	4	5000	No
11	30	86	178	6	4	1000	Yes
12	47	88	185	8	5	3000	No

For the calculation of volumetric flow rates of oxygen consumption, the PEF ventilation air flow rate with 3 expires per subject was recorded before each gas sample at the surface (see Figure 4 and Figure 5). The divers gave a sample of gas in the gas collecting flask, gas analysis was performed on oxygen and carbon dioxide analyzers from the rack of the hyperbaric laboratory (Figure 3) and the two gases concentrations were recorded for each subject. Surface results are recorded in Table 2.

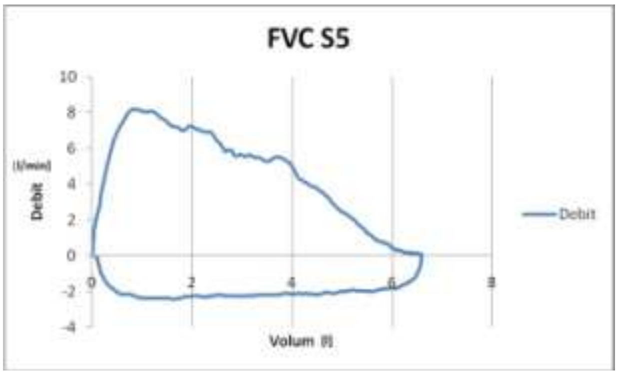

Figure 4 Spirometry of subject 5

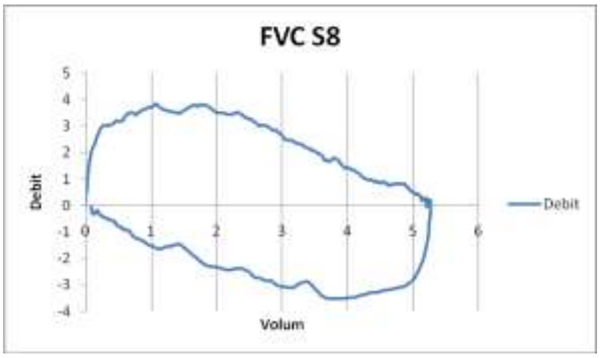

Figure 5 Spirometry of subject 6

Table 2
Test results for S1-S12 subjects at surface and after diving effort

Subject	PEF_1 [l_N/min]	PEF_2 [l_N/min]	PEF_3 [l_N/min]	% O_2 * 0m	%CO_2 * 0m	% O_2 ** 50(m)	%CO_2 ** 50(m)
1	102	90	66	18.1	3.4	17.7	4
2	120	126	108	17.9	3.1	17.5	3.5
3	120	66	48	18.2	2.8	18	3
4	96	84	66	18.1	2.9	17.6	3.4
5	78	66	72	18	3	17	4
6	48	54	60	17.5	3.5	16.5	4.5
7	102	66	108	16	5	16	5.1
8	84	90	96	17.5	3.5	17	4
9	60	66	72	17	4	16.5	4.5
10	78	84	72	17.6	3.4	17	4
11	120	132	138	16.6	3.4	16.3	3.7
12	90	96	108	17	4	16.4	4.6

* recording before the effort at the surface
** recording after the effort of diving
Simulated dives took place on different days, with 4 subjects each time.
The divers entered the dry hyperbaric chamber and, after compressing at 50msw, exercised for 5 minutes and expired in the discharge mask. From the outside of the hyperbaric chamber, from the discharge circuit, for each subject, the exhaled gas was drawn into the flask and was taken to the two gas analyzers in the analysis rack. Gas analysis was performed and oxygen and carbon dioxide concentrations recorded.
Subjects 1 ÷ 4 instead of physical exercises descended into the wet simulator at 60msw, and did a simple mechanical workout. After leaving the water, they gave samples of gas for analysis.
The results are in Table 2: PEF ventilated air flows with the three expires, oxygen and carbon dioxide concentrations for each subject, at the surface and after the physical effort deposited during diving.
Oxygen consumption rates, based on air ventilation rate, with formulas (9), (10) and (11), have been calculated.
The results are in Table 3.

$$C_{O2}\% = \%\, O_2^{*} - \%O_2^{**} \quad (9)$$

$$RC_{O2} = rC_{O2} \cdot PEF \quad (10)$$

$$rC_{O2} = \frac{C_{O2}}{100} \quad (11)$$

rC_{O2} - the volumetric participation of oxygen consumed
RC_{O2} (ml_N/min) – rate of oxygen consumption
PEF_1(ml_N/min) – ventilated air flow
$C_{O2}\%$ – oxygen consumption

Table 3
Oxygen consumption rates RCO_2, based on air ventilation rate in hyperbaric atmosphere

Subject	PEF_1 [ml_N/min]	$C_{O2}\%$	R_1C_{O2} [ml_N/min]	PEF_2 [ml_N/min]	R_2C_{O2} [ml_N/min]	PEF_3 [ml_N/min]	R_3C_{O2} [ml_N/min]
1	$102*10^3$	0.4	408	$90*10^3$	360	$66*10^3$	264
2	$120*10^3$	0.4	480	$126*10^3$	504	$108*10^3$	432
3	$120*10^3$	0.2	240	$66*10^3$	132	$48*10^3$	96
4	$96*10^3$	0.5	480	$84*10^3$	420	$66*10^3$	330
5	$78*10^3$	1	780	$66*10^3$	660	$72*10^3$	720
6	$48*10^3$	1	480	$54*10^3$	540	$60*10^3$	600
7	$102*10^3$	0.5	510	$66*10^3$	330	$108*10^3$	540
8	$84*10^3$	0.5	420	$90*10^3$	450	$96*10^3$	480
9	$60*10^3$	0.5	300	$66*10^3$	330	$72*10^3$	360
10	$78*10^3$	0.6	468	$84*10^3$	504	$72*10^3$	432
11	$120*10^3$	0.3	360	$132*10^3$	396	$138*10^3$	414
12	$90*10^3$	0.6	540	$96*10^3$	576	$108*10^3$	648

The carbon dioxide production rates of formulas (12), (13) and (14).
rP_{CO2} - the volumetric participation of carbon dioxide produced
RP_{CO2} (ml_N/min) – rate of carbon dioxide production
P_{CO2} % – carbon dioxide production

$$P_{CO2}\,\% = \%CO_2^{**} - CO_2^{*} \quad (12)$$

$$RP_{CO2} = rP_{CO2} \cdot PEF \quad (13)$$

$$rP_{CO2} = \frac{P_{CO2}}{100} \quad (14)$$

The results are in Table 4.

Table 4
Carbon dioxide production rate, based on air ventilation rate in hyperbaric atmosphere

Subject	PEF_1 [ml_N/min]	P_{CO2} %	R_1P_{CO2} [ml_N/min]	PEF_2 [ml_N/min]	R_2P_{CO2} [ml_N/min]	PEF_3 [ml_N/min]	R_3P_{CO2} [ml_N/min]
1	$102*10^3$	0.6	612	$90*10^3$	540	$66*10^3$	396
2	$120*10^3$	0.4	480	$126*10^3$	504	$108*10^3$	432
3	$120*10^3$	0.2	240	$66*10^3$	132	$48*10^3$	96
4	$96*10^3$	0.5	480	$84*10^3$	420	$66*10^3$	330
5	$78*10^3$	1	780	$66*10^3$	660	$72*10^3$	720
6	$48*10^3$	1	480	$54*10^3$	540	$60*10^3$	600
7	$102*10^3$	0.1	102	$66*10^3$	66	$108*10^3$	108

8	$84*10^3$	0.5	420	$90*10^3$	450	$96*10^3$	480
9	$60*10^3$	0.5	300	$66*10^3$	330	$72*10^3$	360
10	$78*10^3$	0.6	468	$84*10^3$	504	$72*10^3$	432
11	$120*10^3$	0.3	360	$132*10^3$	396	$138*10^3$	414
12	$90*10^3$	0.6	540	$96*10^3$	576	$108*10^3$	648

Figure 6 Sample collection before diving

Figure 7 Diving in wet hyperbaric chamber

4. Conclusions

The evolution of the respiratory function of the diver in the hyperbaric environment depends on the intensity and type of effort, as well as on the degree of training, so the adaptation to the individual's effort. It is determined by the increased energy demand during the effort, which induces acceleration of the tissue burns, thus increasing the external breathing and gaseous changes in the body.

Divers are well-trained athletes, with the majority of individuals, the Hirtz index values, reduced after sinking, returned to baseline in about 30 minutes after diving, when their body returned from tiredness. The tested divers have a lower respiration frequency compared to the measures made at the surface, so at their effort they have been better suited and the oxygen consumption rate has reached values of 500-600 [ml / min].

From the diagram in Figure 8 for the subjects S5, S7, S8 and S9, the influence of the physical characteristics of the divers, namely the HIRTZ index (the difference between the chest circumference at the inspiration and at the expiration), on the rate of oxygen consumption is well observed.

At the same ventilated air flow rate of 80 [l / min], the subject S5, with the HIRTZ index of 10 [cm], has an oxygen consumption approximately twice the size of the subject S9, with the HIRTZ index of 4 [cm].

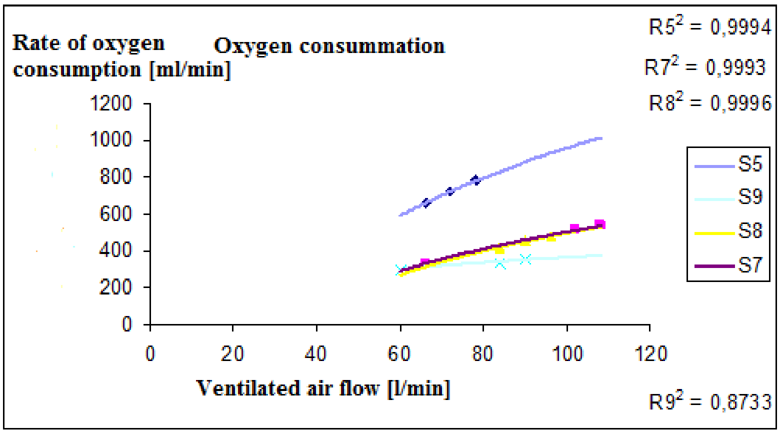

Figure 8 Oxygen consummation related to ventilated air flow for subjects S5, S7, S8 and S9

The subject S7, smoker, has a HIRTZ index of 5.5 [cm]. Its physical properties (body weight, height) are close to that of the subject S5 with a Hz of 8 [cm]. It can be assumed that smoking affects the adaptability of divers to sustained efforts in diving.
The average oxygen consumption rate, based on ventilated air flow and type of activity performed by divers, is classified by US Navy in Table 5.
The activity of the divers was moderate, they had to mount and dismantle a metallic construction, under water, at 50 msw deep. This exercise is part of the course's training. The average oxygen consumption rate for the 12 tested divers was 433 [ml / min], which is half that of US Navy values under similar effort and ventilation conditions. It follows that the test subjects are well trained, the metabolism is gradually accelerated and the increase in oxygen consumption is metered according to the effort.
Following Tables 1 and 3, it is noted that the subject S4, which has the lowest dive experience (400 hours), has the highest oxygen consumption compared to the other subjects with a professional experience that is 10 times higher.
The S3 subject, with medium age (32 years) and average experience (1600 hours) was the best.
Average carbon dioxide production is 439 [ml / min], lower but close to the standard value of 500 [ml/ min].

Table 5
Oxygen rate consumed and ventilated air flow during diving [5]

The type of activity	Average oxygen consumption [ml / min]	Ventilated air flow [l/min]
Seated	240	10
Standing peacefully under water	400	12
He walked quietly under the water	580	15
Easy activity in the hyperbaric chamber	700	18
He went mildly through the mud	800	20
Moderated walking in the simulator	1100	28
He walked fast through the mud	1200	32
Moderate swimming	1400	38
Swim fast	2500	60

Increased metabolic demand, showed by measuring the oxygen consumption of divers during testing, causes a respiratory mechanical dysfunction which is not noticed in resting conditions, It allows for the prevention of specific occupational diseases and knowledge of adaptation boundaries.
Test results will be used by diving specialists (doctors, engineers) to improve human respiratory function in the hyperbaric environment by optimizing respiratory techniques that lead to:

- increased oxygenation in relation to effort;
- reducing internal resistance to respiratory flow;
- avoiding specific occupational diseases in the long run.

The results presented will help to improve the human respiratory function in the hyperbaric environment by an individual training, adapting better the divers and increasing their physical performance.

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