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ABSORBED CARBON DIOXIDE AS CONTROL OF THE QUALITY OF SODA LIME AND OF CLOSED-CIRCUIT ISOLATING BREATHING APPARATUS

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The amount of absorbed CO_2 on soda lime in closed-circuit isolating apparatus is an important physiological and technical parameter. For its determination we used the classical method modified and improved in our laboratory.

Soda limes of different quality were tested in standard self-rescuing isolating breathing apparatus and in oxygen SCUBA. The results show that the CO_2 content absorbed during CO_2 autonomy can give useful information about construction characteristics of the apparatus when soda lime of known quality is used. This parameter also enables the evaluation of soda lime quality when used in closed-circuit isolating breathing apparatus of well-known characteristics.

From the total CO_2 quantity in the soda lime used in closed-circuit isolating apparatus the user's average energy expenditure can be estimated and accidents with oxygen SCUBA can be reconstructed.

Isolating breathing apparatus are widely used in conditions necessitating prolonged exposure in unbreathable atmosphere, where either toxic gases or lack of oxygen may occur. They are used, in particular, in some sorts of military diving. Generally, they are divided in two groups: open and closed-circuit self-contained isolating breathing apparatus. In the first group the exhaled air is eliminated into the outer atmosphere; in the second, the exhaled oxygen, after carbon dioxide is absorbed on soda lime, is rebreathed together with the oxygen supplied from the oxygen bottle.

The initial enthusiasm for self-contained open-circuit isolating breathing apparatus has been brought to more realistic limits today. These devices cannot replace closed-circuit isolating apparatus in military divings, and in some self-rescuing operations. The small size and long autonomy make them irreplaceable for some categories of military divers and for conditions where a device should always be carried along, or be within reach, as for example in mines.

Autonomy for carbon dioxide is one of the most important factors for evaluating the protective characteristics of closed-circuit isolating apparatus. This autonomy may be defined as a time interval in which the level of carbon dioxide in the breathing bag does not reach the threshold

limit value. It depends on the soda lime quality, on the construction characteristics of the apparatus, on physical load and environmental temperature. The autonomy for carbon dioxide of closed-circuit isolating apparatus is determined by continuous or periodical analyses of carbon dioxide in the inhaling hose. It is considered that the apparatus has exhausted its autonomy for carbon dioxide when the partial pressure of carbon dioxide in the sample has reached 5.06 or 10.13 mbars (1, 2). This method for testing this type of isolating apparatus, though irreplaceable, provides only partly the information necessary for evaluating the quality of the device. To improve technical control of closed-circuit isolating breathing apparatus, we have considered the possibility of using the absorbed carbon dioxide content in soda lime. So far this method has been used only for routine control of soda lime quality. During the past few years it has been used also for testing closed-circuit breathing apparatus in our laboratory.

In a pilot study we tested the accuracy of the modified method of measuring the bound carbon dioxide in soda lime. In addition we checked the stability of the carbonate compound of bound carbon dioxide in soda lime after prolonged exposure of the soda lime in normal atmosphere and in water environment.

MATERIAL AND METHOD

Two groups of self-contained closed-circuit breathing apparatus were tested. One consisted of standard self-rescuing isolating apparatus for prolonged use in unbreathable atmosphere. In the other oxygen SCUBA (Self-Contained Underwater Breathing Apparatus) was checked.

Two types of isolating breathing apparatus for self-rescuing in mines, coded X_1 and X_2, and five more types of diving apparatus coded Y_1 to Y_5 were tested by experienced divers. Relevant details of all experiments are given in Tables 1 and 2.

The apparatus were prepared according to the standard procedure. The canisters were filled with previously analysed soda lime. During analysis, special care was taken to determine the initial carbon dioxide content in soda lime. The subjects were switched on apparatus and continuously exercised breathing in it, until carbon dioxide in the inhaling hose reached a level of 10.13 mbars. After the experiment, canisters were carefully disconnected from the apparatus. Representative samples of soda lime from the canisters were taken in two ways: by layers and segments, and from the homogenised rest of soda lime.

Standard self-rescuing isolating apparatus

Standard self-rescuing isolating apparatus were tested with subjects walking on treadmill at average speeds of 3584 m/h and 6683 m/h, corresponding to moderate and heavy work (5).

Table 1

Standard self-rescuing isolating apparatus

Experiment	Apparatus	Absorbent	Breathing time (min)	Room temperature (°C)	Absorbent quantity (kg)	CO_2 autonomy (min)	Total absorbed CO_2 (L)	CO_2 production (L/min)	Absorbed CO_2 during autonomy for CO_2 (L/kg)
E_4	X_1	Z_1	60	21.5	0.442	60	56.0	0.93	126.7
E_{16}	X_1	Z_1	45	22.5	0.461	45	37.3	0.83	80.9
E_{19}	X_2	Z_1	14	24.5	0.335	0	12.1	0.86	0
E_9	X_1	Z_2	30	25.5	0.414	19	51.8	1.73	79.3
E_{14}	X_1	Z_2	15.5	25.0	0.463	4	26.1	1.68	14.5
E_{15}	X_2	Z_2	9.5	22.0	0.293	0	16.7	1.76	0
E_{18}	X_1	Z_2	25	25.5	0.468	13	31.9	1.28	35.4

Table 2
Oxygen SCUBA

Experiment	Apparatus	Absorbent	Breathing time (min)	Room temperature (°C)	Absorbent quantity (kg)	CO_2 autonomy (min)	Total absorbed CO_2 (L)	CO_2 production (L/min)	Absorbed CO_2 during autonomy for CO_2 (L/kg)
E_5*	Y_1	Z_1	413	14.0	3.77	413	682	1.65	181
E_4	Y_2	Z_1	246	14.0	2.35	227	282	1.15	111
E_3	Y_3	Z_1	150	14.0	1.60	140	197	1.31	115
E_9	Y_4	Z_1	153	13.6	2.18	121	236	1.54	86
E_5	Y_5	Z_1	150	13.5	1.65	106	170	1.13	73
E_7	Y_2	Z_3	210	13.9	2.21	164	239	1.14	84
E_1	Y_2	Z_4	170	14.2	2.12	149	177	1.04	73

At moderate work the eliminated carbon dioxide varied from 0.83 L/min to 0.93 L/min, and at heavy work from 1.67 L/min to 1.76 L/min.

Oxygen in the inhaling hose was continuously analysed with Biomarine OM-300 apparatus. Samples for carbon dioxide analysis were taken periodically, and were analysed on Lloyd-Gallenkamp apparatus.

Oxygen SCUBA

Samples of carbon dioxide and oxygen from the inhaling hose were taken periodically and measured during underwater swimming in recompression chamber's wet pot at a depth of 7 meters. The carbon dioxide analysis was done on Lloyd-Gallenkamp apparatus. During underwater swimming the eliminated carbon dioxide varied from 1.04 L/min to 1.65 L/min.

RESULTS

The data obtained by examining the standard self-rescuing isolating apparatus are shown in Table 1. They are grouped by experiments for the sake of comparison.

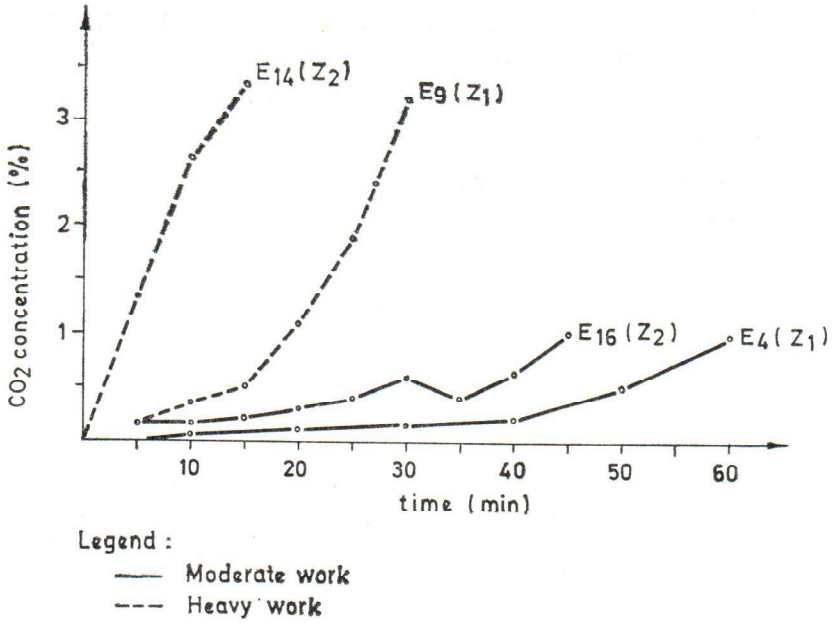

Fig. 1 — *Comparison of the absorbents' quality in standard self-rescuing isolating apparatus*

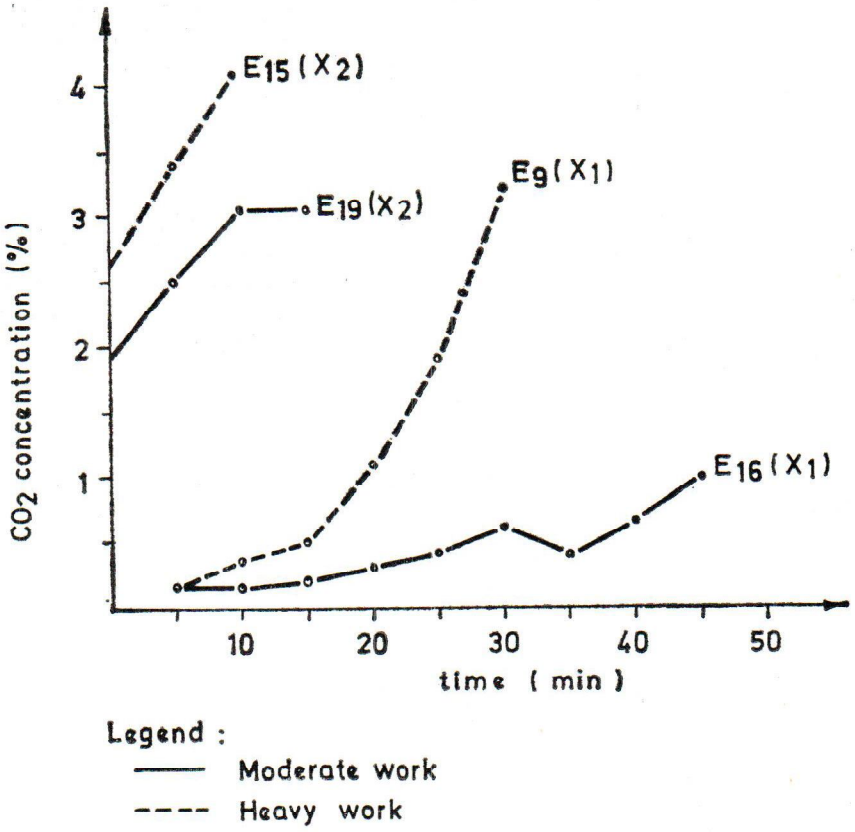

Fig. 2 — *Comparison of carbon dioxide autonomies of standard self-rescuing isolating apparatus*

Figure 1 shows the autonomy for carbon dioxide of apparatus X_1 with two different absorbents Z_1 and Z_2 at moderate and heavy work. The construction characteristics of apparatus X_1 and X_2 with the same absorbent Z_2 at moderate and heavy work are compared in Figure 2. Figure 3 clearly illustrates the dependence of autonomy for carbon dioxide of apparatus X_1 on the intensity of physical work.

Table 2 and Figures 4 and 5 show the results of testing oxygen SCUBA Y_1, Y_2, Y_3, Y_4 and Y_5. The real autonomy for carbon dioxide of oxygen SCUBA Y_1, Y_2, Y_3, Y_4 and Y_5, tested in the recompression chamber's wet

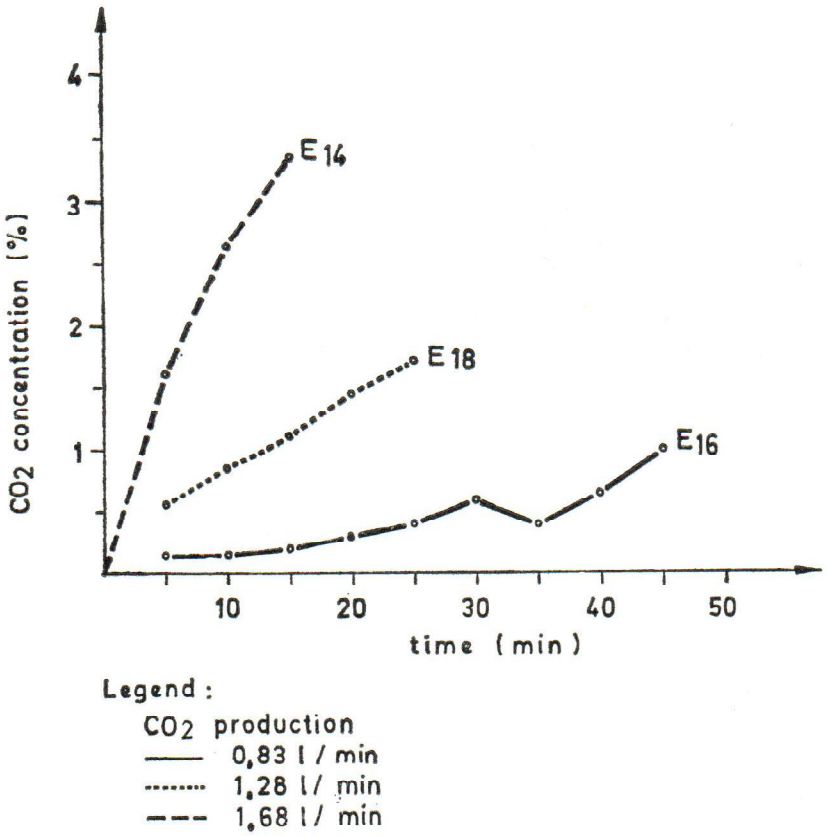

Fig. 3 — *Dependence of carbon dioxide autonomy on the intensity of physical activity*

pot with absorbent Z_1, is shown in Figure 4. A comparative review of the autonomy for carbon dioxide of apparatus Y_2 with absorbents Z_1, Z_3 and Z_4 is given in Figure 5.

DISCUSSION

Continuous or periodical measuring of carbon dioxide in the inhaling hose or in the breathing bag of the closed-circuit isolating apparatus is a classical method for examining the autonomy of these apparatus for

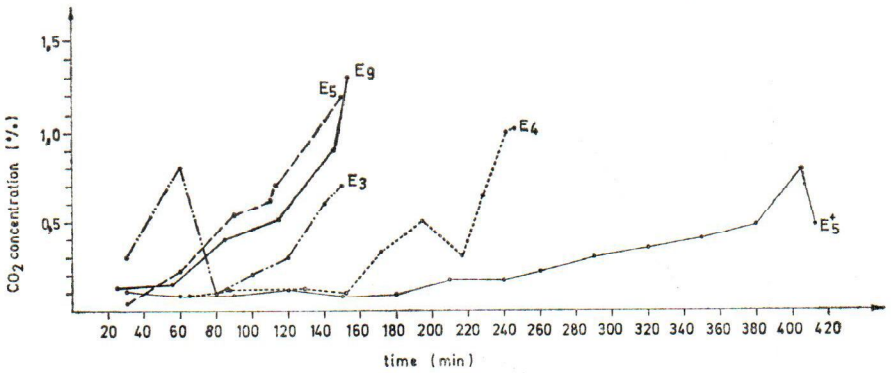

Fig. 4 — *Parallel review of oxygen SCUBA's autonomy for carbon dioxide*

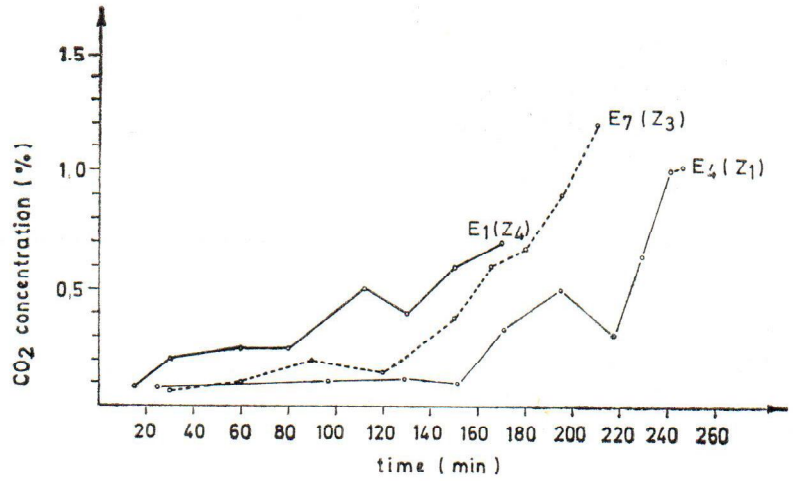

Fig. 5 — *Comparison of absorbent' quality in the same oxygen SCUBA*

carbon dioxide. This method offers information about the length and quality of the autonomy, but not about the factors influencing these parameters.

The content of bound carbon dioxide in non-used soda lime is determined by the method of the Soviet authors with a calcimeter (3). With this method the carbon dioxide volume is measured during its liberation from soda lime by chloral-hydrate acid. By increasing the amount of sample, introducing a special apparatus for this purpose and developing a reaction in controlled temperature conditions, *Radić and co-workers* (4) significantly increased the accuracy of the method. The accuracy of the method was ± 2.4%.

Our experience shows that by measuring the absorbed carbon dioxide in used soda lime useful information can be obtained about soda lime quality and construction characteristics of closed-circuit isolating apparatus. The method enables a very precise measurement of the quantity of carbon dioxide eliminated by the person wearing the apparatus. The energy consumption of this person can be determined precisely, too.

The estimation of carbon dioxide autonomy of apparatus X_1 using Z_1 and Z_2 soda limes, is an example of the possibility of testing the soda lime quality in the isolating apparatus with checked construction characteristics. The carbon dioxide autonomies of apparatus X_1 with Z_1 and Z_2 absorbents were 60 and 45 minutes respectively at moderate work rate. During that time, the quantity of absorbed carbon dioxide per kilogram of used soda lime was 126.7 and 80.9 litres respectively. It is obvious that the quantity of carbon dioxide per kilogram of absorbent correlates with the autonomy period for carbon dioxide. The shorter carbon dioxide autonomy in the second case is a direct consequence of inferior soda lime quality. The same tendency was established for the same apparatus and absorbents (E_9 and E_{14}) during a physical activity corresponding to heavy work rate (2).

If the same absorbent of checked quality is used in a different apparatus, construction characteristics of the latter can be evaluated. The fact that the tested apparatus X_2 with absorbent Z_2 of middling quality has no protective characteristics at moderate work, and that apparatus X_1 with the same absorbent has the autonomy of 45 minutes and 80.9 L/kg of absorbed carbon dioxide, points at extremely poor construction characteristics of apparatus X_2. At heavy physical work in E_9 and E_{15} and with a better quality absorbent Z_1, apparatus X_1 retained a 19-minute autonomy, while carbon dioxide in the inhaling hose of apparatus X_2 at first breathing was markedly higher than with absorbent Z_2 at moderate work.

With this method the autonomy of the apparatus can also be defined from the dependence on the intensity of physical activity. For example, by comparative analysis of experiments E_{16}, E_{18} and E_{14} using the same

apparatus and absorbent at different work loads, the energy expenditure of the person breathing in the apparatus can be estimated. In E_{16} at a carbon dioxide autonomy of 45 minutes, average carbon dioxide elimination was 0.83 L/min corresponding to moderate physical work. In E_{18} at a 13-minute autonomy, carbon dioxide production was 1.28 L/min, and in E_{14} 1.68 L/min corresponding to heavy physical work. These results plainly show that autonomy for carbon dioxide is inversely proportional to physical activity.

Owing to the particularity of the water environment, measuring absorbed carbon dioxide in closed-circuit diving apparatus is far more important than in standard isolating apparatus. Since in E_5*, E_4, E_3, E_9 and E_5 the same absorbent of checked quality and dissimilar apparatus Y_1, Y_2, Y_3, Y_4 and Y_5 were used from the content of absorbed carbon dioxide in used soda lime construction characteristics of apparatus could be assessed. The fact that in E_5* the autonomy of carbon dioxide was 413 minutes, and that the adsorbed carbon dioxide content in that autonomy period at heavy work, was 181 L/kg, points out remarkable protective characteristics of apparatus Y_1. Carbon dioxide autonomies of diving apparatus Y_2 and Y_3 (E_4 and E_3) of 227 minutes and 140 minutes at comparable quantities of absorbed carbon dioxide (111 L/kg and 115 L/kg), point out that the difference in autonomies is caused only by different volumes of soda lime canisters. The quantities of 111 L/kg and 115 L/kg of absorbed carbon dioxide during the autonomy period indicate in both cases that it is a question of diving apparatus of rather inferior construction characteristics. The protective ability of apparatus Y_2 in experiments E_7 and E_1, using absorbents Z_3 and Z_4, is in general satisfactory. However, by comparing absorbed carbon dioxide contents in the same Y_2 apparatus with absorbents Z_3, Z_4 and Z_1 (84 L/kg, 73 L/kg and 181 L/kg), it can be concluded that the soda lime quality of absorbents Z_3 and Z_4 is much lower than of absorbent Z_1.

The results of experiments E_9 and E_5, where only 86 L/kg and 73 L/kg of carbon dioxide was absorbed in very good quality soda lime Z_1 point at apparatus with unsatisfactory construction characteristics.

Measurement of absorbed carbon dioxide in used soda lime can also give other useful information. By dividing the volume of carbon dioxide absorbed in soda lime by the breathing time, average elimination rate of carbon dioxide is obtained. This parameter, though indirectly, enables precise determination of the energy expenditure of the person breathing in the apparatus. This is especially interesting in diving activities, because under water it is practically impossible to determine energy expenditure by a classical method because of the inconstant temperature of the environment and uncontrolled oxygen loss. The simplicity of the discussed method and the fact that it measures energy expenditure over the whole period of breathing in the apparatus, makes it the method of choice.

In our laboratory, the quantity of absorbed carbon dioxide is also used for expertises on accidents with closed-circuit diving apparatus. This information makes judgement about the time, place and the circumstances of an accident more accurate.

CONCLUSION

The quantity of absorbed carbon dioxide in used soda lime from a closed-circuit isolating apparatus provides useful information on the construction characteristics of the apparatus when soda lime of trustworthy quality is used. The measurement of CO_2 quantity is also useful for assessing soda lime quality in closed-circuit isolating apparatus of well-known construction characteristics. The method serves to estimate user's average energy expenditure during the breathing in the apparatus, and gives valuable information when expert opinions about SCUBA accidents are requested.

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Sažetak

APSORPCIJA UGLJIKOVOG DIOKSIDA KAO KONTROLA KVALITETE NATRONSKOG VAPNA I APARATA ZA DISANJE SA ZATVORENIM KRUGOM

Apsorbirani CO_2 iz natronskog vapna korištenog u izolirajućem aparatu zatvorenog kruga značajan je fiziološki i tehnički parametar. Da bismo ga mogli precizno odrediti koristili smo se klasičnom metodom koja je modificirana i poboljšana u našem laboratoriju.

Ispitivanja su provedena s različitim natronskim vapnima u standardnim izolirajućim aparatima za samospašavanje i u autonomnim ronilačkim apa-

ratima s kisikom. Rezultati ovih ispitivanja pokazuju da sadržaj CO_2 apsorbiran u periodu trajanja autonomije za CO_2, može dati korisne informacije o konstruktivnim karakteristikama ispitivanih aparata kada se u njima upotrebljava natronsko vapno poznate kvalitete. Ovaj parametar također omogućava ocjenu kvalitete natronskog vapna kada se upotrebljava u aparatu dobro poznatih karakteristika.

Ukupna količina CO_2 iz natronskog vapna upotrijebljenog u izolirajućem aparatu zatvorenog kruga omogućava određivanje prosječne energetske potrošnje a također i rekonstrukciju nesreće s autonomnim ronilačkim aparatima s kisikom.

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