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Heat loss and tolerance time during cold exposure in heliox atmosphere at 16 ATA

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Brubakk AO, Tønjum S, Holand B, Peterson RE, Hamilton RW, Morild E, Onarheim J. Heat loss and tolerance time during cold exposure in heliox atmosphere at 16 ATA. Undersea Biomed Res 1982; 9(2):81–90.—Four different types of protective clothing and three different methods of heat conservation protection were evaluated during an exposure to 4°C cold in a heliox atmosphere at 150 msw. The divers using protective systems with little insulation had to quit the test after 1–2 h due to uncontrollable shivering and an extreme feeling of cold, whereas the divers using the heavily insulated clothing were able to stay in the chamber for 8–10 h. However, even with adequate protection against convective heat loss from the skin, respiratory convective heat loss will be high unless inspired gas is heated. This can be adequately done by using a combined heat-exchanger and scrubber where the heat produced by CO_2 absorption is used to warm the inspired gas.

protective clothing
convective heat loss
respiratory heat loss
lost bell

During deep sea diving the problem of thermal stability of the diver is of major importance. The human being will experience a larger heat loss in a hyperbaric heliox (helium/oxygen) atmosphere than in a comparable environment at sea level (1).

Two major problems can be identified. One is the gradual hypothermia that can occur during long exposure to cold water and, according to Keatinge et al. (2), this is more common than was previously assumed. The other problem is the one encountered when all supply of heating is cut off, as would happen during an accident involving cable breakage. In such a situation the problem will be one of survival for a sufficiently long time until the diver can be rescued. Furthermore, it is important to estimate the length of time the diver will be able to do something active to assist in the rescue operation.

Heat is lost through respiration and by radiation, convection, and evaporation from the skin. Skin convection is by far the most important avenue of heat loss, but heat loss due to respiration will increase and heat loss due to radiation will decrease as the diver is exposed to higher pressures (see Table 1 and DISCUSSION).

The present study was initiated in order to study the effect of passive thermal protection on heat loss during exposure to 4°C in a heliox atmosphere at 16 ATA. The divers were protected

TABLE 1
APPROXIMATE PERCENTAGE OF HEAT LOSS THROUGH DIFFERENT MODES IN HELIOX ATMOSPHERE AT 100% HUMIDITY

Depth	Respiration	Convection	Skin Radiation	Evaporation
Sea level	5	60	30	5
150 msw	8	66	23	3
350 msw	15	67	15	3
500 msw	17	68	13	2

Adapted from Flynn et al. (4).

by different types of protective clothing and breathing equipment. Body and skin temperatures, as well as diver behavior, were monitored. The objective was to simulate as closely as possible a real "lost bell" situation.

MATERIAL AND METHODS

The experiments were performed at the chamber facilities of the Norwegian Underwater Institute. One of the chambers was used as a living chamber. Another chamber was chilled to approximately 4°C–6°C. Three male volunteers aged 32–38 years were studied. All three were members of the research team and were highly motivated. The physical characteristics of the three divers can be seen in Table 2.

The divers were compressed to 150 m (492 ft) on heliox containing approximately 90% helium, 6% nitrogen, and 4% oxygen. Temperatures in the living chamber were maintained at a level considered comfortable to the divers (28°C–32°C).

Four different types of protective clothing and three different types of breathing equipment were tested. Apart from one of the breathing regenerators, all equipment was commercially available. The different survival systems are described in Table 3. The breathing equipment described in System 3 is an experimental prototype. As can be seen, the survival sytems are of two different kinds. Systems 1 and 4 consist of considerable insulating material that would be expected to give protection against heat loss due to convection. Systems 2 and 3 are similar to the survival system used on surface, and this system has in fact been installed in diving bells; they can be expected to give little protection against heat loss due to skin convection.

TABLE 2
PHYSICAL CHARACTERISTICS OF EXPERIMENTAL DIVERS

					Skinfold Thickness		
	Age, yr	Weight, kg	Height, cm	BSA, m^2	Upper arm, mm	Upper chest, mm	Abdomen, mm
Diver 1	33	75	190	2.015	11	9	9
Diver 2	38	73	185	1.954	10	9	9
Diver 3	32	74	178	1.911	12	15	17

BSA, body surface area.

TABLE 3
SURVIVAL SYSTEMS

Survival System	Description
System 1	Vest-hood combination inside a suspended bag, both made of 5–13 mm polyester monofilament wool (Polagar R*). Thermal boots (monofilament polyester). Mask connected to a thermal regenerator and a CO_2 scrubber canister (Kinergetics**). The canister is placed inside the vest.
System 2	Heat-reflective suit made of 3-mm open-celled foam material with an inner aluminized lining. Wool socks and thermal boots, wool gloves and mittens, wool knitted hood. Mask connected to a thermal regenerator and connected by a 50-cm-long hose to the CO_2-absorbing canister (Comex†).
System 3	Water survival suit made of 1-mm polymer-coated fabric, insulated with 5-mm polyester, and having a reflective inner layer. Woolen underwear with socks and hood; thermal boots and mittens. Mask with directly attached polyethylene canister containing 320 g of Sodasorb.‡ A tube (diam 1.5 cm) made of plastic screen surrounded by polyester wool was directly connected to the mask without valves and was extended down the inside of the canister. The diver breathed in and out through the canister (Hamilton Prototype).
System 4	Sleeping bag made of two layers of polyester hollow filament (Holofill R§) separated by a reflective layer. "Wooly bear" suit with hood and socks; thermal boots and mittens. Breathing equipment as in System 3.

*Polagar R: Reliance Products, Oakland, CA. **Kinergetics: Kinergetics, Inc., Los Angeles, CA. †Comex: Comex, Marseilles, France. ‡Sodasorb: W.R. Grace & Co., Lexington, MA. §Holofil R: DuPont, Wilmington, DE.

To make the test as realistic as possible, the divers were put into the cold chamber wearing only a 3-mm wet suit, which they put on immediately before entering the chamber. They started dressing in the different survival systems after a cold exposure of 4–5 min.

The divers were monitored using an ECG from which heart rate could be continuously recorded. Thermistors [Yellow Springs 700 series (Yellow Springs Instrument Co., Yellow Springs, OH), accuracy ± 0.1°C] were taped to the back of the hand and at the instep of the foot, and a thermistor was inserted 3–4 cm into the rectum. Esophageal temperatures were monitored using a thermocouple (copper constantan). Inside each breathing mask a glass bead thermistor for monitoring respiratory gas temperature was installed; these thermistors were calibrated and found to give a linear response from 45°C to 25°C, and they had a response time of 2–3 s.

In one diver an experimental deep-body temperature probe was used. The principle of this probe is to create a zero temperature gradient between the core of the body and the skin where the probe is placed. A circular aluminum block is placed on the skin, and the block is alternately heated and cooled until there is no temperature gradient between the skin and the block. Then heat flow between the inner parts of the body and the skin will be zero, and temperature of the skin will equal deep-body temperature. This method has been compared with rectal temperature measurements, and close agreement has been found (3).

Chamber temperature was measured at the level of the deck plate, 1 m above the deck, and at the top of the chamber. The data were recorded on magnetic tape and on a paper recorder outside the chamber. All temperatures were read every 15 min during the experiment.

Every 15 min during the experiment each diver was interrogated about his subjective sensations. The exposure was stopped either at the wish of the diver himself or when rectal temperature had reached 35.5°C.

RESULTS

In Fig. 1 the output from the thermistors in the three different breathing systems can be seen. The temperature difference between expired and inspired gas was about 1°C in Survival System 1 (Table 1), about 5°C in System 2, and about 2°C in System 3. From these results we can conclude that System 1 was the most effective conserver of heat of the three.

In Figs. 2 and 3 the diver temperatures are shown plotted against time during exposure using Survival Systems 2 and 3. It can be seen that the temperatures of the extremities are very rapidly reduced, and after 75 and 110 min, respectively, the divers had to leave the chamber. Diver 2 was then so cold that he had to be helped out of the chamber. Both divers experienced a further drop in rectal temperature during rewarming. Respiratory rate increased from 15 to 22 breaths/min in Diver 2 and from 20 to 26 breaths/min in Diver 3, while heart rate increased from 70 to 85 beats/min and from 70 to 90 beats/min in Divers 2 and 3, respectively, during exposure.

Figures 4 and 5 show temperature plots in two divers using Survival Systems 1 and 4. Using these systems, the divers were capable of staying in the chamber 10 and 8 h, respectively. Several times during this period the divers removed their breathing protection, something that can be clearly seen in the esophageal temperature registration in Diver 1. Again the divers experienced very little change in core temperature but a steady decline in the temperature of the extremities. Diver 1 removed his breathing equipment for the last 1.5 h, and during this period his rectal temperature dropped from 36.5°C to 36.2°C.

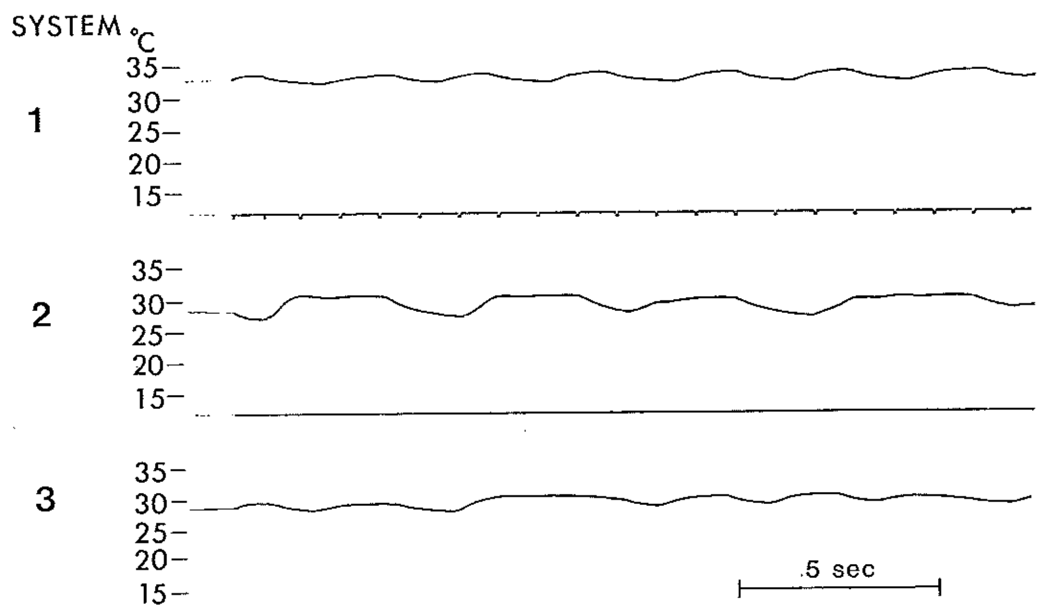

Fig. 1 Temperature difference between expired and inspired air for the three respiratory systems tested.

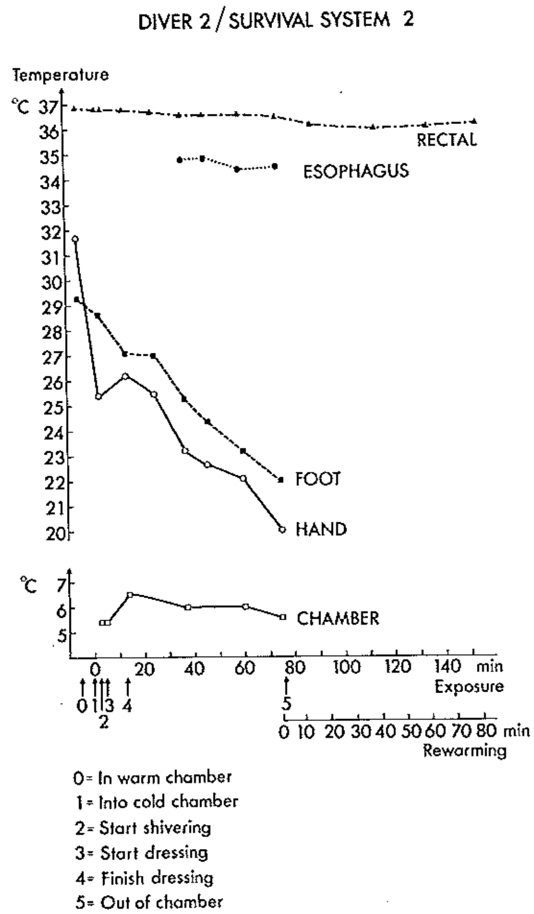

Fig 2. Temperatures monitored on Diver 2 during exposure to cold.

The temperature difference between the extremities and the core, giving a measure of the degree of vasoconstriction, was plotted in Fig. 6. It is of interest to note that all divers gave up when the temperature difference was between 17°C and 20°C, regardless of the length of time the exposure had been maintained. Diver 3, experiencing the largest temperature difference, was the one with the thickest layer of subcutaneous fat and also was the one diver who had worked as a commercial diver.

DISCUSSION

As on the surface, the most important avenue of heat loss during exposure is convection (See Table 1). As depth increases, however, heat loss due to radiation decreases and heat loss due to respiration increases. Thus, to protect the diver from excessive heat loss in a pressurized heliox atmosphere, proper insulation of the skin as well as reduction of heat loss through inspiration of cold gas is necessary.

The validity of these simple theoretical considerations was adequately shown in our experiment. Even with adequate conservation of respiratory heat, the divers using Systems 2 and 3 (Table 3), which offered no significant insulation, were incapable of staying long in the cold

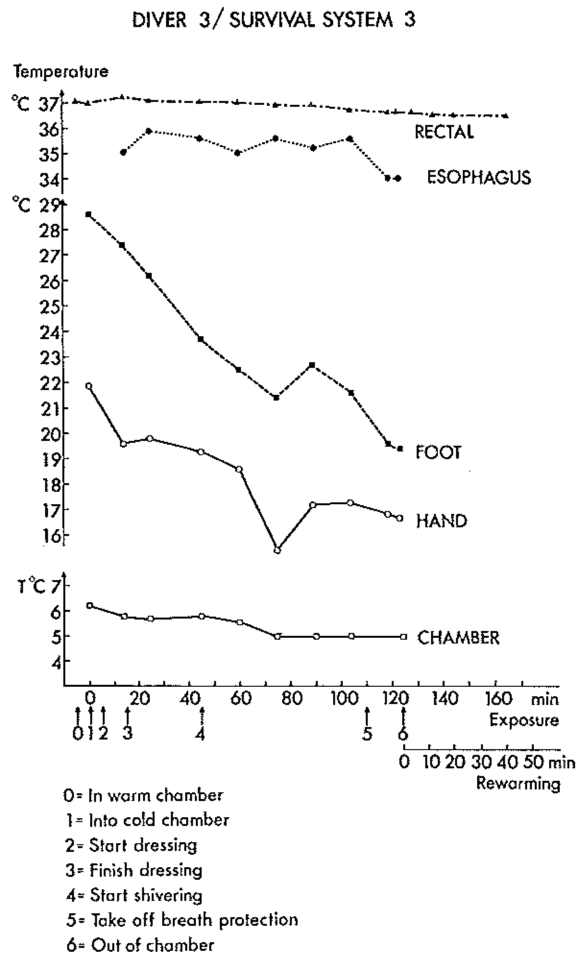

Fig 3. Temperature monitored on Diver 3 during exposure to cold.

chamber. At the termination of exposure, they were quite incapable of helping themselves and would probably have experienced hypothermia in a short period of time. On the other hand, the divers using Systems 1 and 4 were capable of staying in the chamber for an extended period of time. System 1 in particular offered good protection. This diver took off his breathing gear several times during the exposure because it became uncomfortably hot, and this could probably explain the steady decline in peripheral temperatures. When this diver had been without his breathing gear for 1.5 h, he had to give up the experiment.

Respiratory heat loss can be calculated from the formula

$$H_{RESP} = V \cdot e \cdot C_p(T_e - T_i) + V \cdot 0.58(W_e - W_i) \text{ kcal/min}$$

in which V = respiratory minute volume (liter/min), e = density of gas (g/liter), C_p = specific heat of gas (kcal $\cdot$ g^{-1} $\cdot$ $°C^{-1}$), T_e = temperature of expired air (°C), T_i = temperature of inspired air (°C), 0.58 = latent heat of vaporization of water (kcal/liter), W_e = water content of expired air (%), W_i = water content of inspired air (%).

Assuming that respiratory minute volume is constant at 10 liters/min and using the values for density and specific heat found in Flynn et al. (4), it can be calculated that thermal loss

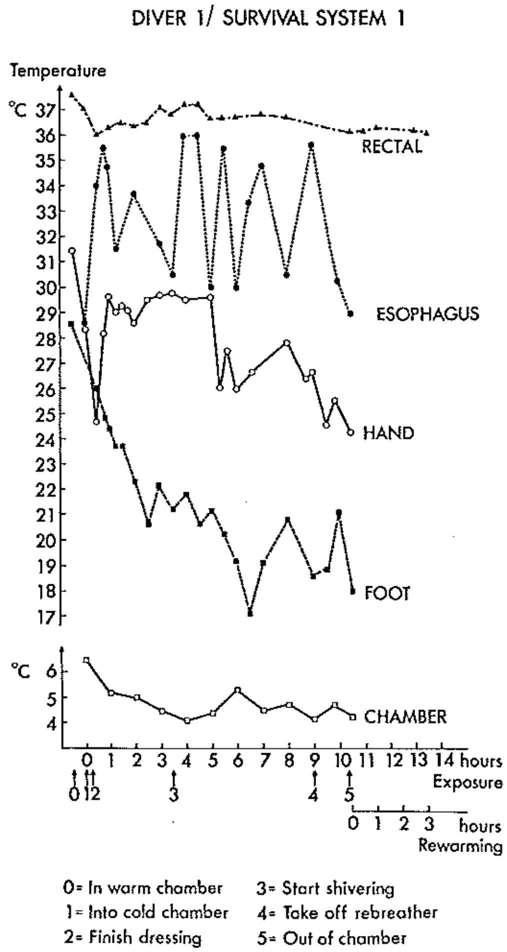

Fig 4. Temperature monitored on Diver 1 during cold exposure.

from respiration will be approximately 2 W using System 1 and approximately 14 W using System 2. Without any breathing protection the diver will lose about 65 W. This last value is in close agreement with the values presented by Webb (5), who gives the value of 50 W heat loss through respiration from a diver breathing heliox of 4°C at 150 msw. As a resting man produces about 100 W of heat (6), it is clear from these data that an unacceptably high proportion of heat production is lost through the respiratory tract. Even with sufficient protection of the skin and normal skin temperatures, core temperature will fall if no protection for respiratory heat loss is given during an increase in ventilation (7).

One practical problem in judging the reaction to cold is deciding what temperatures should be measured. Our study has shown that rectal temperature shows little change even when the diver is quite incapable of helping himself. In this study esophageal temperature showed considerable change, which could probably be caused by placing the thermocouple too high in the esophagus. Measurement of mean skin temperature might be a good way to establish tolerance limits to thermal environments. Iampietro (8) found that final skin temperature and tolerance time to cold were related. A final skin temperature under 21.1°C seemed to be linearly related to tolerance time. Extrapolation of the published curve gives tolerance time of zero once skin temperatures have reached 15.6°C.

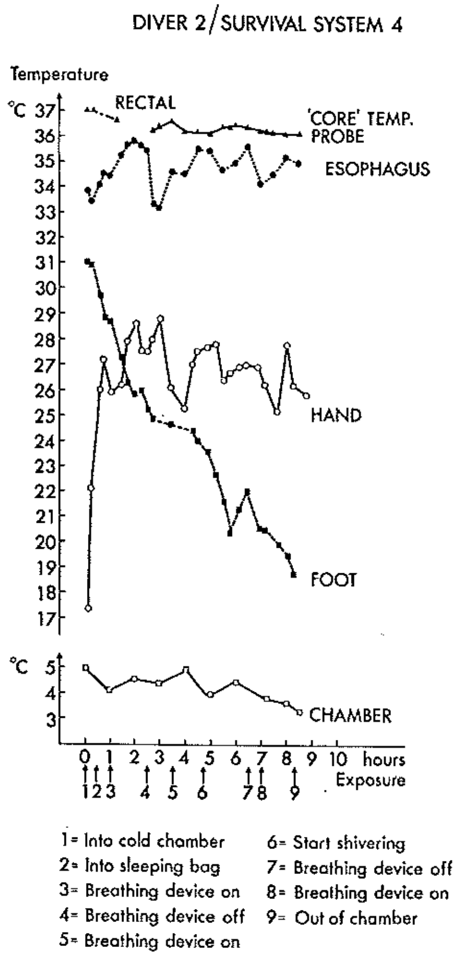

Fig 5. Temperature monitored on Diver 2 using System 4 during cold exposure. Instead of rectal temperature, the output from the core temperature probe is depicted.

Calculation of mean skin temperature requires measurements of the temperatures at several body sites. In this study skin temperature was examined to determine whether the temperature difference between the coldest part of the skin and the core had any relation to tolerance time. The rationale for doing this was our consideration that this value would steadily decrease until vasodilation led to a drop in central temperature. This occurs at a skin temperature of approximately 10°C–12°C, when paralysis of vascular muscle occurs (9). Our results indicate that this value indeed has a relation to tolerance time. The same relationship has also been found in cold exposures at sea level (A. J. Påsche and A. O. Brubakk, unpublished observation). Further work is needed in order to study the value of this observation, but it seems that our results are in agreement with the results of Iampietro (8).

One additional point can be considered regarding the skin temperature. It has been shown that the increase in metabolic rate during cold exposure is controlled both peripherally and centrally. Thus, the higher the skin temperature, the lower the core temperature will have to fall in order to increase metabolic rate (10). Thus, keeping the skin temperature high with warm water or insulation can perhaps reduce the ability of the body to increase metabolism to a necessary degree and thus can increase net heat loss.

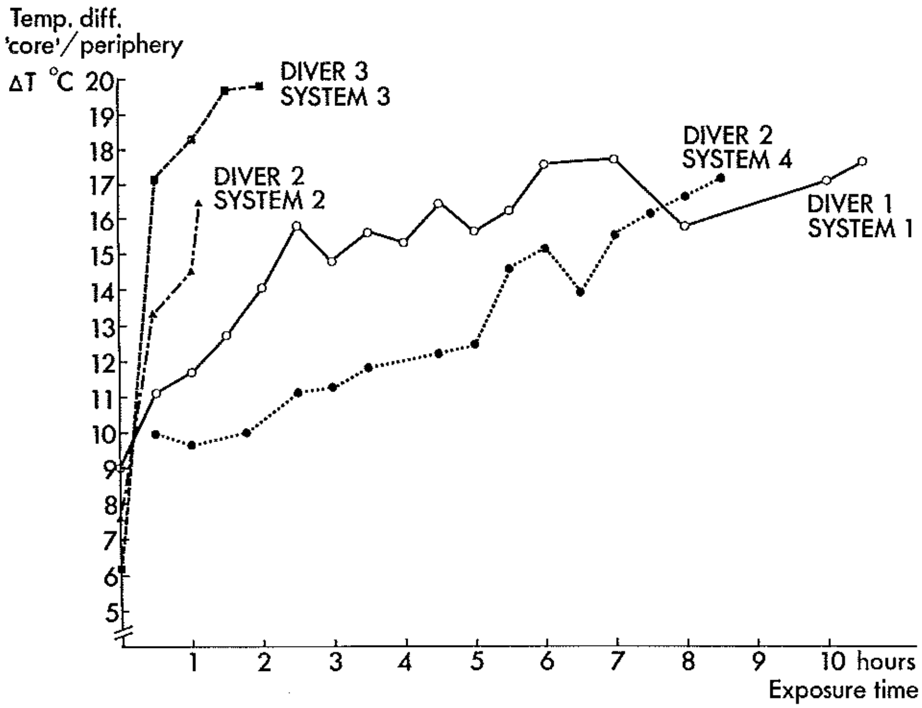

Fig. 6. Temperature difference between the rectal probe and the coldest extremity is shown as related to time of tolerance to cold.

Kuehn et al. (11) indicate that an unprotected resting diver will need approximately 1000 W to compensate for heat loss at 150 msw in heliox atmosphere. This would indicate that a survival system must conserve nearly 90% of body heat in order to keep the diver in a steady thermal state. No passive system can achieve this, but it is apparent from this study that passive systems can keep the divers in reasonable comfort for 10 h and probably can ensure survival for 24 h.

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Brubakk AO, Tønjum S, Holand B, Peterson RE, Hamilton RW, Morild E, Onarheim J. Déperdition calorique et tolérance en durée au cours de l'exposition au froid en atmosphère héliox à 16 ATA. Undersea Biomed Res 1982; 9(2):81–90.—Quatre types de vêtements protecteurs différents et 3 sortes de protections respiratoires ont été essayés au cours d'une exposition au froid à 4°C, dans une atmosphère héliox à 150 m. Les plongeurs munis de systèmes protecteurs à faible isolation devaient abandonner l'épreuve après 1–2 heures à cause d'un grelottement incontrôlable et d'une sensation de froid extrême, tandis que les plongeurs munis d'un vêtement à forte isolation pouvaient rester 8–10 heures dans le caisson. Cependant, même avec une protection adéquate contre les déperditions caloriques par convection cutanée, les déperditions caloriques par convection respiratoire seront importantes sauf si le gaz inspiré est chauffé. Ceci peut être fait de façon adéquate en utilisant un échangeur de chaleur et un épurateur combiné dans lequel la chaleur produite par l'absorption de CO_2 est utilisée pour chauffer le gaz inspiré.

vêtement protecteur
déperdition calorique respiratoire
déperdition calorique parconvection
tourelle perdue

REFERENCES

1. Timbal JH, Viellefond H, Guenard H, Varene P. Metabolism and heat losses of resting man in a hyperbaric helium atmosphere. J Appl Physiol 1974; 36:444–448.
2. Keatinge WR, Hayward MG, McIver NK. Hypothermia during saturation diving in the North Sea. Br Med J 1980; 280:291.
3. Togawa T, Nemoto T, Yamasaki T, Kobayashi T. A modified internal temperature measurement device. Med Biol Eng 1976; 14:361–364.
4. Flynn ET, Vorosmarti J Jr, Modell HI. Temperature requirements for the maintenance of thermal balance in high pressure helium oxygen environments. Research Report 21–73, Navy Experimental Diving Unit, 1974.
5. Webb P. Thermal stress in undersea activity. In: Lambertsen CJ, ed. Underwater physiology V. Proceedings of the fifth symposium on underwater physiology, Bethesda:Federation of American Societies for Experimental Biology, 1976:705–724.
6. Webb P. Cold exposure. In: Bennett PB, Elliott DH, eds. The physiology and medicine of diving and compressed air work. London:Ballière Tindall, 1975:285–306.
7. Hoke B, Jackson DL, Alexander JM, Flynn ET. Respiratory heat loss and pulmonary function during cold gas breathing at high pressures. In: Lambertsen CJ, ed. Underwater physiology V. Proceedings of the fifth symposium on underwater physiology, Bethesda:Federation of American Societies for Experimental Biology, 1976:725–740.
8. Iampietro PF. Use of skin temperature to predict tolerance to thermal environments. Aerosp Med 1971; 42:396–399.
9. Keatinge WR. Survival in cold water. Oxford: Blackwell Scientific Publications, 1969.
10. Benzinger TH. Heat regulation: homeostasis of central temperature in man. Physiol Rev 1969; 49:671–759.
11. Kuehn LA, Smith TJ, Bell DG. Thermal requirements of divers and submersibles in arctic waters. In: Amaria PJ, Brunean AA, Lapp PA, eds. Arctic Systems, New York: Plenum Press, 1977:801–831.