IMMERSION HYPOTHERMIA IN SCUBA DIVING

Dr Michael Davis
Department of Anaesthesia, Christchurch Hospital, New Zealand

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Loss of body heat in a cold environment results not only in physical distress but also in slowing of thought processes, loss of muscle power and, if allowed to continue, eventually in coma and death. To a lesser degree it is an important, but often unrecognised cause of exhaustion and a contributing factor in many diving accidents. Since the thermal conductivity of water is more than twenty times that of air, a naked swimmer will tolerate a much narrower range of ambient temperature during immersion than a man would in an air environment. For many individuals thermal balance cannot be maintained below a water temperature of about 24°C (Beckman, 1965). The use of a diving suit somewhat modifies the response to cold immersion but it can be said that hypothermia in divers is always a real possibility at water temperature below about 18°C. This, then, defines the problem both physically and geographically. As most of New Zealand's waters rarely exceed 20°C, the majority of sports divers in this country will experience "cold water" conditions at some time. For many this is a regular occurrence. In both commercial and military diving there was until comparatively recently, a surprising lack of awareness of immersion hypothermia, cold was simply accepted as one of the rigours of life that a diver put up with. Rawlins (1972) has stated that cold stress probably constitutes the major risk factor in cold water diving operations and suggested that cold may have been a prime factor in the death of one of the Sealab III divers. A similar lack of knowledge can be assumed in sports diving. This brief review, therefore, will cover those aspects of temperature physiology relevant to cold water immersion and describe the effects of hypothermia and its implications for sports divers. Finally, first aid management will be described. For fuller reviews of various aspects the reader is referred to the excellent monograph by Keatinge (1969), and to papers by Benzinger (1969) and Golden (1972).

Physiological Responses to Cold Stress

The vital organs such as the heart and brain function well only within fairly narrowly defined limits. Many mechanisms amongst which the regulation of body temperature is particularly important exist for the maintenance and stability of this internal environment. The heat produced by metabolism is lost from the body by means of conduction, convection, radiation, and evaporation. Expressed in its simplest form the rate of heat loss (H) is proportional to the temperature gradient between the centre of the body (body "core") and the skin (dT) and to the heat conductance of the tissues (C). A functional representation of the thermoregulatory system in response to cold stress is shown in Figure 1. In addition to those mechanisms illustrated, body build and fat content play a vital role in heat conservation. Although in air, heat loss through the respiratory system amounts to 15-25% of the total, in water this contribution becomes relatively very small, except in deep oxyhelium diving, and can be largely ignored.

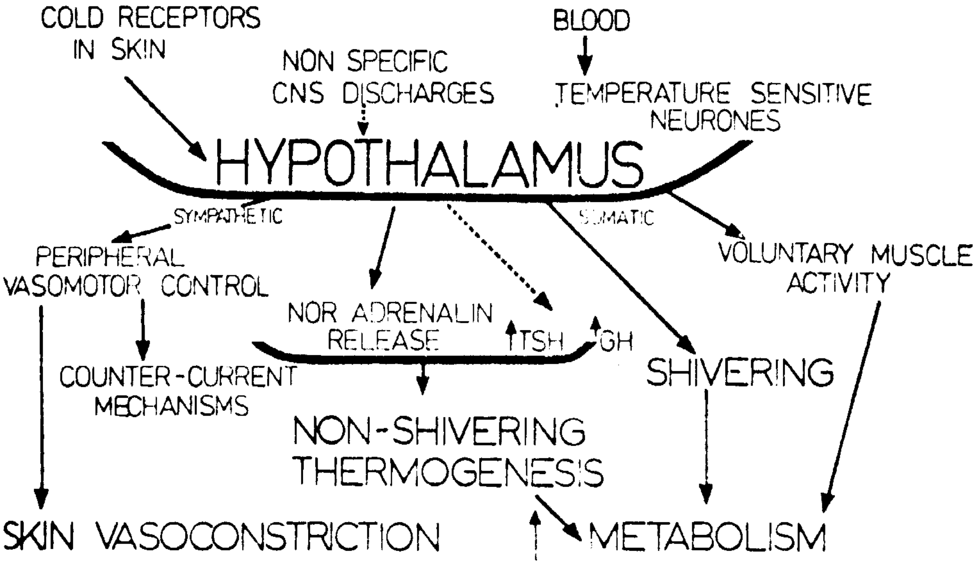

Figure 1. A schematic representation of the thermoregulatory system in response to cold stress. (Central nervous system pathways not shown). The two mechanisms for maintaining heat balance, peripheral vasoconstriction and shivering thermogenesis, important on dry land play a secondary role to subcutaneous fat insulation in determining heat loss during immersion in cold water.

Peripheral Circulation

Functionally the body, in its response to cold stress, may be divided into two parts. A periphery, consisting mainly of the limbs and skin and subcutaneous tissues of the trunk, the extent and temperature of which varies considerably with ambient conditions, and the “core” (which cannot be defined precisely) the temperature of which tends to remain constant. Temperature gradients between the “core” and peripheries always exist even in relatively warm conditions, but in acute cold stress the periphery essentially is “sacrificed” in the attempt to maintain the stability of the “core”. This is achieved by peripheral vasoconstriction, involving both skin and muscle blood vessels. The cutaneous vasculature possess a rich sympathetic innervation and is highly reactive, changes in skin circulation occurring primarily in response to the demands of temperature regulation. Peripheral vasoconstriction reduces heat loss by three mechanisms. Firstly, the total blood flow to the limbs falls dramatically (Barcroft and Edholm, 1943). Secondly, the skin possess greater insulation in the presence of vasoconstriction. Thirdly, in reduced flow states there is evidence for an effective counter-current heat exchange mechanism in the deep vessels of the limbs, and this further reduces heat flow (Hong et al., 1969).

Consequent on the peripheral vasoconstriction which occurs immediately upon immersion there is pooling of warm blood centrally. This results in a small but distinct rise in “core” temperature whether measured rectally (Skreslet and Aarlfford, 1968) or via the ear drum (Craig and Dvorak, 1966). This rise is most marked in very cold water when an extremely vigorous vasoconstrictive response occurs. Whilst in air this peripheral vasomotor response is the main effector of heat balance over a wide range of ambient temperatures, in cold water this mechanism is only of temporary benefit and is totally inadequate to maintain central body temperature for any length of time. Figure 2 demonstrates both the initial rise in rectal temperature and the subsequent progressive fall.

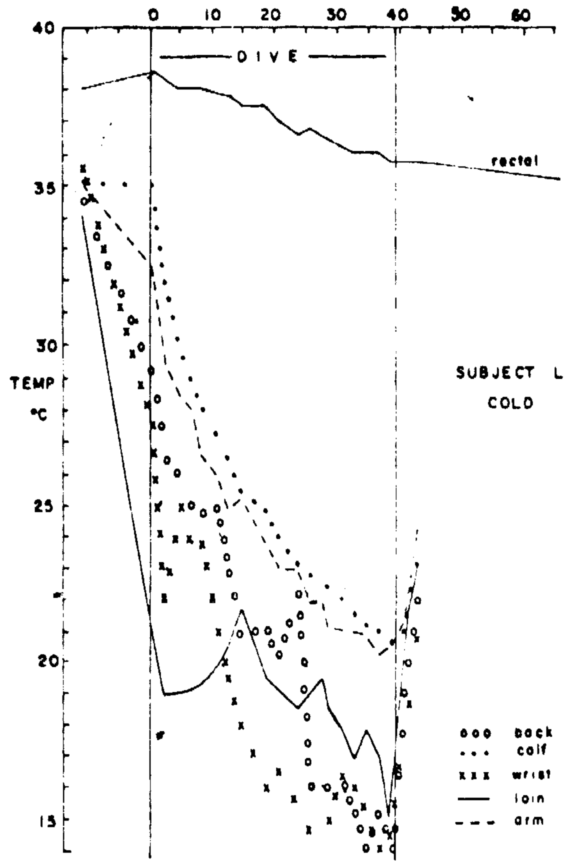

Figure 2. Skin and rectal temperature changes (° Celsius) for a wet-suited diver during a cold water (5°C) dive.

The Role of Sub-cutaneous Fat Insulation.

Most of the heat loss from the body in moderately cold water takes place from the trunk, and the rate of this loss depends upon the amount of subcutaneous fat. Studies of Channel swimmers (Pugh and Edholm, 2955; Pugh et al., 1960) demonstrated most clearly the role of subcutaneous fat in providing effective insulation during immersion. This group of sportsmen possess in general an unusual body build, being thick-set, even frankly obese, with a greater than normal subcutaneous fat layer but a lower than predicted total body fat content. When a channel swimmer and a thin individual were compared immersed at rest in 16° water, rectal temperature dropped in both but sooner and at a faster rate in the thin subject. When exercised in 16°C water, the swimmer's rectal temperature remained constant or rose slightly whereas that of the thin subject fell even more rapidly than it did at rest. Keatinge (1969) showed that the fall in rectal temperature of immersed subjects was inversely proportional to mean skin fold thickness. Upon immersion skin temperature of a naked swimmer rapidly equilibrates with the water (Craig and Dvorak, 1966) whereas in air the body at any given ambient temperature is always greater in water than in air. It is easy to see how, under these conditions, subcutaneous fat determines heat loss. In the fat swimmer heat loss across the trunk is small compared with the thin subject. The increased metabolic heat production of swimming, five to eight times resting levels, is sufficient to compensate for these losses and to maintain “core” temperature. In the thin swimmer the increased convective losses due to water turbulence around the body and the conductive losses due to increased limb muscle blood flow with exercise considerably exceed the increase in heat production and therefore he loses heat more rapidly.

Metabolic Heat Production

The mechanisms described above are concerned with reducing heat loss from the body. Contraction of skeletal muscle, whether in shivering or active exercise, constitutes the body’s only significant means of increasing heat production in response to an acute cold stress. Heat is a problem of metabolism. A highly trained athlete is able to increase metabolic rate to some fifteen times resting levels, whilst shivering will produce a maximum of five or six fold increase. (Resting metabolic heat production is approximately 30kcal per square metre per hour.) The role of non-shivering thermogenesis in man’s response and adaptation to cold is not fully understood. However, there is evidence that divers habituated to Arctic water show progressive adaptation to the cold (Skreslet and Aarlfford, 1968), whilst the Ama divers of Japan and Korea show differences in heat transfer in the limbs (an enhanced counter-current mechanism is proposed) an increased basal metabolic rate and an increased response to sympathomimetric amines when compared with non-diving women from the community (Kang et al., 1963, 1970). Within the context of acute cold immersion these mechanisms probably play little part.

Measurements of “core” temperature

It is worth considering at this stage some of the difficulties of measuring “core” temperature. The body core is a convenient concept but it is by no means uniform in its behaviour and it is only accessible for external measurement at a few sites. Most commonly rectal temperature is used as indicative of core changes, but this method has definite limitations. When the body is cooling rapidly, rectal temperature may fall more slowly than that of the brain or heart and thus be misleading. For instance, Davis (unpublished observations) measured rectal and ear drum temperatures in seven wet-suited divers before and after diving in 9°C water. Rectal temperature fell by 0.75°C whilst ear drum temperature which provides a good indication of brain temperature (Beninger, 1969) fell by 1.8°C. An eighth subject who was a long distance sea swimmer, with the characteristic build described, showed a rise in rectal temperature rose 2.4°C during the dive. As rectal temperature continues at present to be the convenient yardstick for most investigators, “core” and rectal temperature are used synonymously in this paper. A useful alternative is the temperature sensitive radio pill which the subject swallows. Transmission frequency varies with temperature and the signal can be readily picked up with an aerial strapped externally to the abdomen. Again, there are some difficulties in interpretation of gut temperature, and the use of this technique in divers is reviewed by Davis et al. (1975).

The Diving Wet Suit

It is useful to consider three questions at this stage:

1. To what extent does a wet suit modify the physiological response to cold immersion?

2. How does one type of suit compare with another?

3. What are the effects of hypothermia on the diver?

The wet suit is constructed of neoprene rubber 5 to 8 mm thick within which are trapped countless tiny bubbles of nitrogen gas to provide insulation. The suit is not designed to prevent water ingress but rather traps a thin layer between it and the diver's skin, this layer being rapidly warmed by the body. The net effect of this insulation is produce a water/skin temperature gradient and thus reduce the skin/core gradient (see Figure 2 where skin temperatures are considerably higher than the ambient water temperature of 5°C). However, the wet suit has a number of disadvantages. Beckham (1965) showed that even in a 2.5 cm thick wet suit the average diver was unable to maintain core temperature in 4°C water. Davis, et al. (1975) calculated that the mean heat loss from a resting wet suited diver in 5°C water was approximately 250 kcal per square metre per hour. Webb (1973 using a whole body calorimetry method in the laboratory), quotes 210 kcal per square metre for a forty-five minute dive at 5°C. At a water temperature of 20°C heat loss was approximately 95 kcal per square metre per hour Davis (1975). Even at this water temperature many divers are unable to maintain thermal balance and rectal temperature falls. Consisting as it does of many minute gas bubbles, the wet suit is subject to compression and expansion with changes in ambient pressure. As hydrostatic pressure increases by one atmosphere absolute (1 ATA) for every 10 metres depth of sea water then the suit becomes progressively thinner (Boyle's Law) and loses its insulative properties at depth. Thus at 30 metres its thickness is reduced about 50% and heat conductance is three times that on the surface (Rawlins, 1972).

Craig and Dvorak (in press) have recently investigated the function of the wet suit during immersion using a whole body calorimetry technique. The suit, by providing a water/skin temperature gradient prevents the initial rapid heat loss seen in the naked swimmer, but does not alter the subsequent steady rate of loss. The study also confirmed that the suit jacket contributed more to reducing heat loss than did the trousers in keeping with the view that the majority of heat loss during cold water immersion is from the trunk. Pilmanis (see next issue) using heat flow discs on wet-suited divers has provided provisional information on the areas of greatest heat loss. These appear to be from the head and neck, upper trunk and shoulder girdle, proximal parts of the arms, the calves during swimming, and the groins and antecubital fossae. This is consistent with current concepts of the mechanisms of heat loss during immersion.

The Diving Dry Suit

As its name implies this type of suit is designed to prevent ingress of water and is made of a strong rubberised material with close-fitting seals at the neck and wrists. Boots are incorporated and most current models are single-piece designs. Suitable clothing is worn beneath to trap a layer of air between suit and skin to provide insulation. To allow for the compression of this air with increasing depth, modern suits are fitted with an inflation device to maintain the gas volume within the suit more-or-less constant. Its efficiency, therefore, deteriorates little with depth. The dry dry suit (or constant volume suit) provides better cold water insulation than does a wet suit as evinced by rectal temperature measurements. Davis (unpublished observations) found that rectal temperature in eight divers fell during a thirty minute 5°C dive by 1.2°C wearing wet suits, but only by 0.5°C wearing constant volume dry suits. Despite this advantage, the lack of convenience, loss of mobility, and considerably higher price compared with a wet suit has limited the constant volume suit's popularity in sport diving but they are used widely in commercial and research diving. In addition, insulation is seriously impaired by leaks tears, and diuresis.

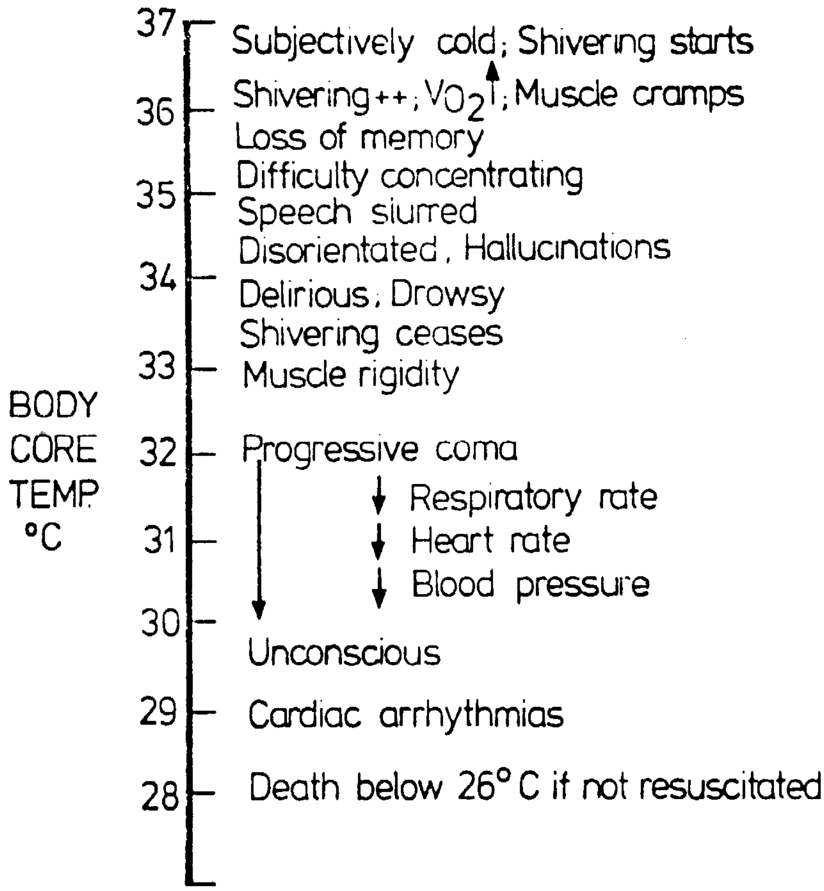

Figure 3 The general effects on man of progressive hypothermia.

<u>The Effects of Hypothermia on the Diver</u>

The general effects of hypothermia are summarised in Figure 3. These are often subtle in onset and pass unrecognised for what they are. It is, therefore, worthwhile attempting to define safe limits in diving practice, and to elaborate on the results of moderate degrees of hypothermia. It is commonsense that in diving any situation is dangerous that results in difficulties in concentration, disorientation and impaired judgment. Thus, a core temperature of 35°C can be taken as an absolute lower limit beyond which the safety of the diver and his companion will be very seriously in question. Where the rate of heat loss is rapid a diver may become prostrated by the cold long before his rectal temperature reaches 35°C. Of fifteen subjects in a cold water performance experiment (Davis, 1975) two had to be removed from the water in serious distress, before completing their 5°C dives. Both were shivering uncontrollably, breathing rapidly, exhibiting slurred speech, and exhibiting repetition of ideas and inadequate response to questioning.

In one, rectal temperature fell by 2.7°C (Figure 2) to 35.7°C and in the other by 2.2°C to 36.8°C. Several other divers exhibited much less distress with lower end-of-dive rectal temperatures, but in every case the drop in temperature was less than 2°C over approximately the same length of time (40 minutes). The more severe the cold immersion the more rapidly will brain temperature fall and the less reliably will the single measurement of rectal temperature reflect this change. Despite this, a strong case can be argued for the continuous monitoring of body temperature during extensive cold water diving programmes in the interest of safety. The Canadian Navy and the Canadian Arctic diving research programmes have both adopted just such an approach using the radio pill.

The "After-Drop" Following Cold Water Immersion

Rectal temperature continues to fall after exit from the water. This phenomenon, known as the "after-drop" (Keatinge, 1969), is characteristic of acute cold stress, and can be seen in Figure 2 in which it is about 0.5°C. Its extent depends on two factors: (1) the severity of the cold stress, and (2) the effectiveness of efforts at re-warming following immersion (see below). In extreme cases it may reach 3°C. Failure to recognise this problem has led to fatalities from exposure that could otherwise have been avoided (Pugh, 1966). A number of reports exits in which shipwreck survivors have been taken from the water conscious, only to lapse into coma and die subsequently. Even in optimal re-warming conditions such as active re-warming using a hot water circulation suit, Webb (1973) found that at least one hour was required for complete re-warming following dives to tolerance limits in 5° to 15°C water, and that core temperature continued to fall during the first fifteen minutes of the re-warming phase.

Diver Performance in Cold Water

The subtle effects of moderate hypothermia have been alluded to earlier. As these have such an important bearing on diving safety it is worthwhile to consider them in greater detail. Only a few reports on cold water performance exist in the literature (Bowen, 1968; Stang and Weiner, 1970); Vaughan and Mayor, 1972; Baddeley et al., in press; Davis et al., 1975) and the reader is referred to these for further details. Divers are less efficient at manual tasks underwater, even in optimal conditions, when compared with that on dry land. This has become known as the "immersion" effect. Superimposed on this are other factors such as nitrogen narcosis (Baddeley, 1967), anxiety (Davis et al., 1972) and cold that further impair a diver's abilities. Cold water exposure may influence performance in three ways. First, there is a peripheral effect on the extremities impairing tactile sensitivity and weakening muscle power (Bowen, 1968; Clark, 1961). Second, there is a central effect on the brain as core temperature drops slowing metabolism. Third, there is what has been called a "distraction" effect (Teichner, 1958), that is, the perceived threat of cold exposure may distract attention and interfere with the continuity of performance.

The way in which performance is altered should be different for each of these mechanisms. Peripheral effects on manual skill are dependent on the ambient temperature (Stang and Weiner, 1970) and show progressive impairment with length of exposure. There appears to be a critical temperature at about 15°C above which manual performance is unaffected (Clark 1961). Davis (1975) using a screwplate dexterity test found a slowing of 17% between 20°C and 5°C by Dusek (1957). These results are in keeping with the other reports cited. Central effects on intellectual ability should only show themselves after a variable latent period since the physiological responses outlined earlier tend to prevent core temperature from falling right from the start of exposure. There is scanty evidence for a central effect developing in cold water dives of less than one hour. Only Davis (1975) has shown any correlation between core temperature and performance. A deterioration of 11% in post-dive recognition of words from a list presented underwater occurred between 20°C and 5°C dives and this correlated with the concomitant drop in rectal temperature in each diver. The distraction effect, on the other hand, should make itself apparent from the start of cold water exposure, impairing performance at a stage when body temperatures have not yet dropped to any extent. There is rather more evidence for this hypothesis from both the studies of Baddeley et al. (in press) and Davis et al. (1975). The impairment of intellectual performance using such tests as simple arithmetic, logical reasoning, and verbal memory appears from the start of cold exposure. In at least one test - simple arithmetic - subjects appeared, in fact, to be at their worst at the beginning of a cold (5°C) dive (Davis et al., 1975).

In practice divers often have to commit to memory in-dive information which is then processed at a dive de-briefing. The resulting loss of data is considerable. Hemmings (1972) found it essential to adopt a diver-to-surface radio communication system with tapes of in-dive reports during fish behaviour studies in the North Sea. He compared tape transcripts with de-briefing reports and found the latter grossly deficient and inaccurate. This situation was mimicked in the above two studies using word lists or prose passages presented underwater for subsequent recall post-dive. In one study the overall deterioration in word recall from dry land to 5°C water was over 70% (including a 48% immersion effect) and in the other 30% from 20°C to 5°C water. This deterioration of memory in cold water is probably a state-dependent effect, that is, recall is optimal when it occurs in the same environment as the original learning process. This context-dependent hypothesis has recently been confirmed by Godden and Baddeley (in press).

First Aid Care for Acute Hypothermia

The treatment of hypothermia can be a complex problem particularly following prolonged exposure or where it is complicated by near-drowning. Only the important aspects of first aid care will be reviewed here, and the reader is referred to Golden (1972) for a thorough pathophysiological review of the subject. Fortunately, in diving one is dealing mostly with acute cases of a few hours' duration at the most, and for these simple and vigorous methods are the most effective.

(1) The first priority is to remove the victim from the water as quickly as possible.

(2) Determine the state of the respiratory and circulatory systems and perform cardio-pulmonary resuscitation (CPR) as required.

(3) Every attempt should be made to reduce further heat loss once out of the water by getting the victim under cover and especially out of the wind. This can be achieved even in small open boats by wrapping him in a tarpaulin, polythene sheet or bag, sails, etc. Remove diving suit or wet clothes and dress in dry clothing as soon as possible. These steps place the subject in a neutral environment and allow rewarming of the patient's metabolism to proceed slowly.

(4) Where facilities are available the most effective method of rewarming

is immersion of the trunk in a hot bath (40-42°C) with the limbs out of the water. This is aimed at re-warming the core as quickly as possible, while slowing down the re-opening of the peripheral circulation. Conversely warming the body surface, for example with hot water bottles, etc., should not be used as it is relatively ineffective in getting heat into the core but encourages vasodilatation. The latter results in an increased heat loss exaggerating the “after-drop” phase and also allows cold acidotic blood from the peripheries to return to the core leading to circulatory collapse, with cardiac dysrrhythmias including ventricular fibrillation.

(5) Hot sweet drinks can only be recommended if the diver is fully alert and responsive. If there are any signs of drowsiness or confusion then fluids (and food) should be withheld because of the risks of vomiting and aspiration into the lungs. Alcohol should not be used as it increases the risk of vomiting and promotes peripheral vasodilatation.

Practical Implications for Diving

(1) In cold water diving, wet suits provide inadequate thermal protection for the diver. A fall in core temperature to 35°C or by more than 2°C is dangerous and even smaller decreases will have some influence on diving safety as the cold diver is liable to panic and exhaustion.

(2) Severe cold stress results in a marked increase in metabolic rate with a raised oxygen consumption and hence more rapid use of air supplies.

(3) Manual dexterity is seriously impaired and this may make even routine procedures difficult and may limit the diver’s ability to respond rapidly to an emergency situation.

(4) There is evidence that judgment is impaired from the start of cold water exposure and that the diver’s general mental faculties are slowed.

(5) Memory for events underwater is grossly impaired in cold conditions, and this will seriously limit the value of observation and inspection work, unless in-dive records are made. The concomitant impairment in manual skills make writing difficult and therefore in-dive tape recording or diver-to-surface communications are the only effective methods available.

(6) All divers and physicians should be aware of the occurrence of the “after-drop” and must appreciate the safety implications of returning a cold diver to the water without fully rewarming in the interval.

(7) The first aid care of accidental hypothermia should be taught in all diver training courses.

Acknowledgments

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