Thermal problems in diving.

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Thermal problems in diving are almost always looked upon as being linked to excessive heat loss and risk for hypothermia. The reason being that water usually is cold in relation to the human body and has a higher specific heat and thermal conductive capacity than air, the medium humans normally are dressed for. This does not mean that the other side of the coin, hyperthermia, is never seen. Diving in warm water such as cooling water reservoirs and waiting in sunshine, while dressed for a dive in cold water, may overheat divers.

Thermal balance

We can look at the body as a machine: Fuel is burned to produce work. In the process there are losses in the form of heat. The over all mechanical efficiency is said to be in average 20 – 30%. Which means, that about three quarters of all energy produced in the body is lost as heat. The sum equation for this process can be written

The body heat balance
S = (M) – (C) – (K) – (R) – (E) – (W)

Where:
S is body heat storage
M is metabolic heat production
C is heat exchange by convection
K is heat exchange by conduction
R is heat exchange by radiation
E is heat exchange by evaporation
W is work

Work in this context is the output in the form of muscular contractions, chemical processes in the kidney, mental work in the brain etc. Since the body is homothermal at 37°C (the enzymes taking care of the metabolism has optimum working conditions at this temperature) the body has a thermoregulatory system that balances energy production and energy loss, mainly through the vascular system in the skin. If the energy balance is negative (we lose heat), despite maximum vasoconstriction, the body can increase the metabolism to maintain the temperature of the body. This happens, in the short perspective, as muscular contraction (shivering), or as for the Amas, an elevation of the basal metabolism described by Kang and Hong 1963. They showed a 30% higher basal metabolism during the winter. Similarly, individuals living in cold climate have a different metabolism compared to individuals living close to the equator.

The water has a specific heat that is 1000 times higher than air, which means that much more energy is lost from the body when heating a layer of water in immediate contact with the skin than heating a layer of air. If this heated water flows away, and new water has to be heated, we talk of convection. Convection is a mechanism that can be triggered by the density difference between cold and warm water and does not need any motion or current, but of course it is easy to understand that a moving body in cold water will lose energy at a higher rate.

Even if the water is not moving, heat can be conducted through the water as it can be in metal and other solids. Conduction of heat is about 27 times faster in water compared to air.

The third way of energy transport, radiation, is of less importance because the temperature differences are small.

The differences in the thermal properties between the two media explain why thermo-neutral temperature for a resting nude individual is 28°C in air and 35°C in water, which is very close to the body temperature 37°C. If the individual increases the metabolism these temperatures will be experienced as too high for comfort.

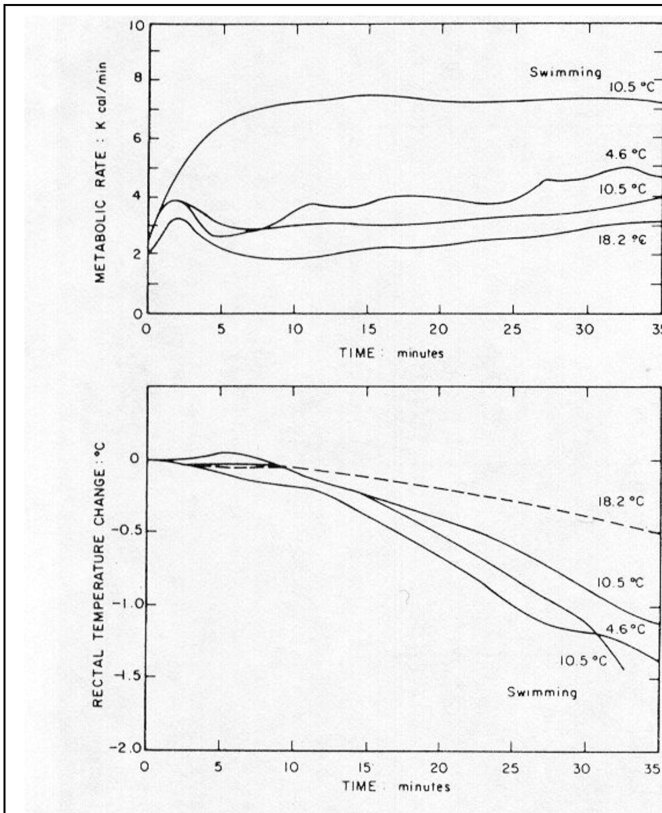

Figure 1. Deep body temperature and metabolism in 12 men dressed in shirt and trousers, immersed in water at different temperature. From Hayward. Can J Physiol Pharmacol 1975.

The time course for lightly dressed men immersed in water is illustrated by Fig 1. from, Hayworth 1975. The dramatic difference of being still or moving is clearly illustrated. For the first 15 minutes the increased metabolism can compensate for the increase in convection caused by the swimming, but then energy losses become higher than production and the body chills faster during swimming than during rest. This is further illustrated by Ketinge 1969. (See Fig 2) Ketinge has also stressed the importance of insulation in the form of subcutaneous fat. Webb 1980, has brought this further and made a mathematical model that predicts body temperature in different water temperature as a factor of body fat content. Fig 3.

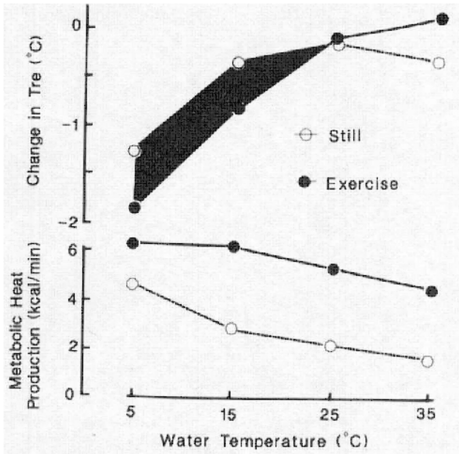

Fig 2 Change of rectal temperature and metabolic heat production during immersion in water at different temperatures while still and exercising. After Keatinge 1969.

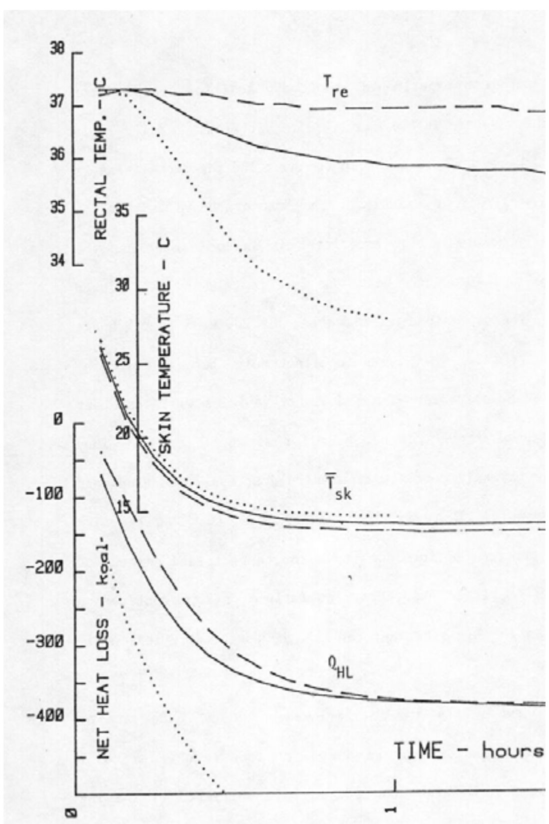

Fig 3. Predicted rectal and skin temperature together with energy loss during immersion in 12 degree C water of nude men at three different body fat contents, 7%, 15% and 30%
(Webb, Thermal constraints in diving UHMS 1980)

The insulating property of the skin and underlying tissues depend largely on the circulation. Vasoconstriction increases the insulating properties and it has been shown by Johnston 1996 that hypercapnea (higher than normal CO2 in the body) reduces the defence against hypothermia, which leads to 25% faster cooling of the body. This effect is not only caused by a less effective vasoconstriction, but an increased ventilation and reduced shivering also contribute.

Effects of cold breathing gas.

To maintain the blood temperature and the elasticity of the lungs the air entering the lungs need to be close to 37° and saturated with humidity when it enters the alveoli. Energy is spent to heat the gas on its way to the lungs both in heating the gas, but also in the evaporation of water to humidify the gas. On exhalation some of the heat and humidity is reclaimed in the trachea and nose. When the gas density is increased and the breathing media comes from a bottle of compressed gas with almost no humidity the energy loss is markedly increased. If the increase in gas density due to compression at depth is pronounced, and the diver uses mouth breathing to minimize the work of breathing, the losses of heat are even worse.
The cold air causes contraction of the smooth muscles of the airways and the increase in airway resistance has been observed up to one hour after single dives with air to 50 m depth by Tetzlaff et al 2001. During saturation dives at greater depth, when an ambient temperature of 30 - 33°C is needed for thermal comfort, inspired gas temperatures of +7 to +18°C resulted in increased airway resistance in experiments described by Burnet et al

1990. At low pressure these effects are usually not seen even if the air temperature is below 0°C. However, persons with reactive airways (asthmatics) may develop extreme sensitivity to cold air.

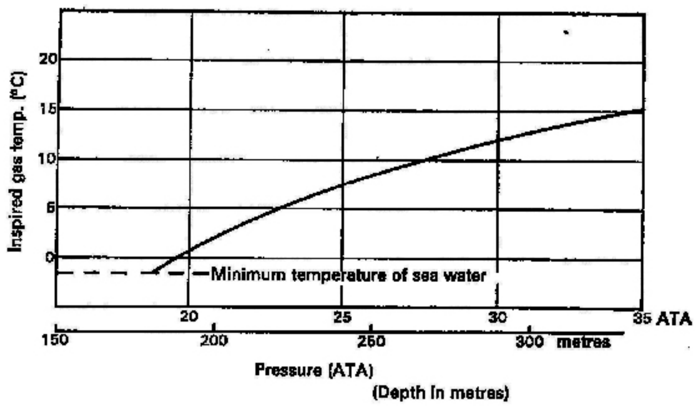

Figure 4. Minimum recommended breathing gas temperature for different diving depths.

Pronounced cooling of the airway mucosa can lead to excessive production of mucous and oedema of the lungs.

To counteract these effects minimum gas temperatures for the breathing gas has been defined. See Fig 4.

<u>Signs and symptoms of hypothermia</u>

Table 1.

Effects of Reduced Body Temperature on Body Function[a]

T_r, °C	Impairment of function
36–37	Cold sensations, cutaneous vasoconstriction; increase in oxygen consumption and in muscle tension by electromyogram
35–36	Sporadic shivering, suppressed by voluntary movements; bouts of shivering give way to uncontrollable shivering; oxygen consumption rises to 200–500% of resting value; *decreasing will to struggle increases risk of drowning*
34–35	Amnesia and poor articulation; sensory and motor dysfunction
33–34	Clouding of consciousness, hallucinations, and delusions
32–33	Cardiac abnormalities
30–32	Motor performance grossly impaired; no response to pain; familiar persons not recognized

[a] Adapted from Webb (*in press*).

In Table 1 are the gradual development of signs and symptoms listed. Hypothermia starts, according to the definition at a deep body temperature of 35°C. Please note that long before this the individual has been "frozen" and the body has started to cope with the thermal stress.

The loss of muscular power and control in hypothermia is important to know for people who may get involved in the rescue and care of victims of hypothermia.

Interesting to note is that hypothermia has a marked effect on the mind and there is a loss of awareness of the danger in the situation. Individuals might even lose interest in getting rescued.

Non freezing cold injury
Necessary to know for divers and doctors is, that it does not take subfreezing temperatures to create a cold injury. The condition seen after longer periods of wet and cold feet coined the term "trench foot" during the First World War.

Non Freezing Cold Injury, NFCI

- Can be seen at 8 – 10° C skin temperature
- Most common in feet and hands
- Risk is decreased if you allow a maximum of 30 minutes "numbness"

The solutions, The diving suit
The first used suits did not offer much thermal protection and although people were tougher and adapted to life in less good heated homes and dressed in simpler cloths the divers of yesterday must have suffered. Figure 5. The simple cotton dress of the Ama and the canvas suit of the early divers with open helmets, did not offer any insulation.

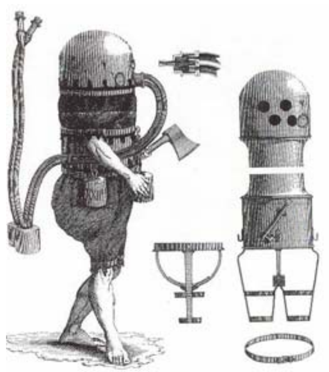
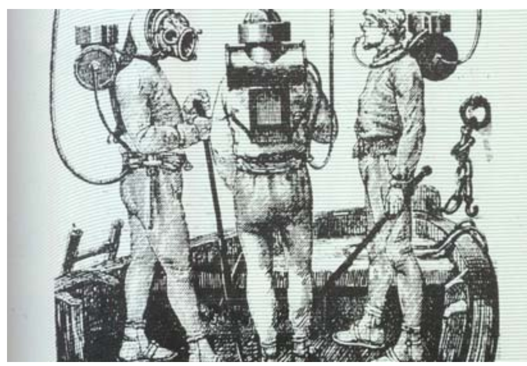

Figure 5. To the left Klingert´s diving gear from 1797, and to the right, Rouquayrol and Denayrouze semi-selfcontained UBA and suit 1865. Scans from: Bachrach. A pictorial history of diving, 1988.

When the suit was integrated with the helmet and the fabric was rubberized, there was a theoretical possibility to get insulation through air in dry underwear. This was not until the mid 19th century with the invention of the Siebe Gorman helmet diving system. Interestingly this design is still in use in many shallow dive operations.

The dry suit for scuba divers 1930 gave a similar possibility to insulation, but only for shallow dives until the "constant volume suit" with air bottle to prevent squeeze came on the market.

In the 50-ties the foamed neoprene wet suit was introduced and it became rapidly the golden standard for all scuba divers. With better fit and more stretchable material it is today sold as "semi-dry", which means there is only little water to heat for the skin at the beginning of the dive. The fact that the pressure increase, when going deep, made the suit loose the insulation was a factor that prevented this type of suit from getting popular among professional divers.

Among Amas the suit meant a dramatic improvement of comfort and they could double their breath hold diving time. The accumulated diving time over the day increased 100 % in summer water and more than tenfold during winter conditions, when wet suits were introduced (Park et al, 1983).

With the combination of the sealed neoprene suit, and volume compensation with compressed air at compression, the Unisuit was invented. See Fig 6. The first order was placed by the Swedish navy in 1968, but later it became popular among both professional and amateur divers. The water and gas tight zipper made it possible to design these suits for easy donning and doffing. Today most suits are of the shell and insulation type, which allows the user to vary the insulation in form of a cover all of different material to the actual diving conditions.

Figure 6. To the left a Healthways Coronado neoprene wet suit from 1950. To the right a Poseidon Unisuit from 1968.
The combination of nylon lined foam neoprene, a water tight zipper and air in- and out-let, are the signs of a modern diving suit for scuba diving.
Scans from: Bachrach. A pictorial history of diving, 1988.

There has been discussions whether the addition of a gas with lower thermal conduction should mean better insulation of dry suits and argon has been used by many so called “tech divers” when scuba diving to depths beyond 50 m. In a study performed by Risberg and Hope, 2001, it was shown that there was no advantage with argon in comparison to air as a suit insulator. See Fig 7.

If it does not make any dramatic difference what kind of gas is in the dry suit, it is, however, essential that it is dry. Even a small amount of water can seriously affect the insulation properties. Note that it does not make any difference from where the water comes. A leak into an arm could be irritating, but sweat condensing all over in the underwear during the early phase of a dive, could be a risk factor for hypothermia during periods of low activity during a long in-water decompression period.

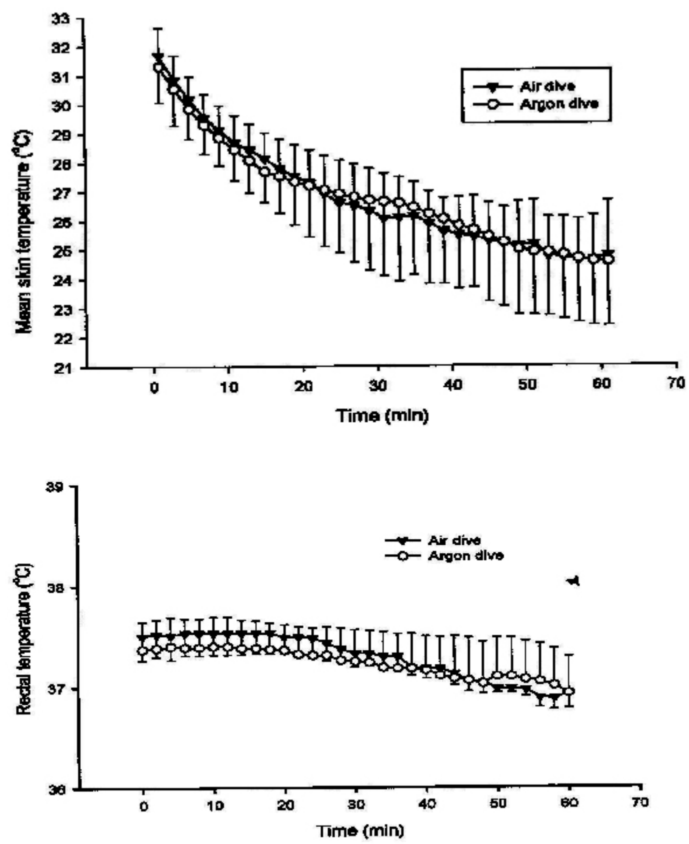

Figure 7. Skin (upper panel) and rectal temperatures for men diving at 9 m withe either air or argon filled suits. From: Risberg & Hope, UBR 2001.

Heated suits

The most widely used solution to heat divers is the hot water suit. In these suits, usually made of foamed neoprene, 40°C water is pumped down to the diver in a hose in the umbilical. The diver can regulate the flow to the suit with a valve. The distribution of the water to the different parts of the suit and the gloves and boots is through a tubing system. The outflow goes to the surrounding water. For a schematic illustration see Fig 8. The energy need to comfortably heat a diver can be as high as 3500W according to Hayes, 1991. In large, the today existing diver heating systems offer an acceptable and comfortable situation to divers according to Mekjavic and co-workers, 2001. Attempts have been made to reduce the energy spending and increase the comfort trough the use of dry suits and water circulating in an internal closed hose system and a heat exchanger.

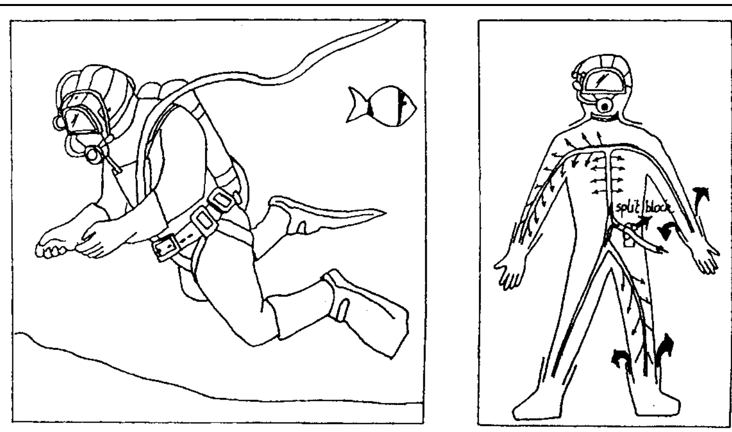

Figure 8. Schematic illustration of a hot water suit.
From: Ornhagen, 1998.

Electrically heated suits have been around for many years, but never found any wide spread commercial use. Over the last years electric suits using battery power have been introduced for untethered diving.

Gas heaters and re-breathers

When diving deep the human metabolism is not enough to compensate for all energy losses if the diver is using an open breathing system. With high specific heat of the compressed gas, and insufficient energy reclaim in the airways and nose on exhalation, the diver will get a negative energy balance. Since increased metabolism means higher ventilation, there is no way the diver can compensate for the energy loss.

The only solution to prevent the traumatic effects of low gas temperature is to either heat the gas in heat exchangers, normally using the hot water from the suit heating. Recommended minimum temperatures at different depths are seen in Fig 4.

For un-tethered scuba diving catalytic combustion of small amounts of hydrogen (0.5%) added to the breathing gas has been tried, but not found any practical operative use.

When using re-breathers (breathing apparatus in which the exhaled gas is reused after CO_2 removal) the thermal stress on the airways will decrease through both conservation of heat in the circulated gas, but also since the gas is fully saturated with water, and the evaporative heat loss will be reduced.

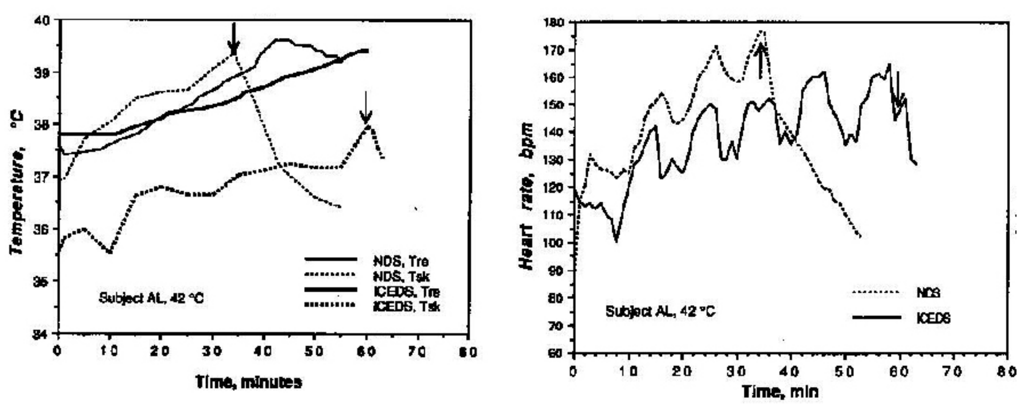

Figure 9. Rectal and skin temperature (left panel) and HR (right panel) for men diving in 42° C water without (NDS), and with (ICEDS) ice vest. From Holmér UBR 1989.

Hyperthermia

Situations of hyperthermia are less frequent than hypothermia. However diving in hot water is performed sometimes and during such operations the diver need to be chilled not to lose performance and to avoid the risks of hyperthermia. The only defence mechanism the body can use in situations when the body surface is warmer than 37 °C is sweating and chilling through evaporation. In water or in a dry suit this does not work since in the water the sweat does nor evaporate and in the dry suit the gas is rapidly saturated which automatically stops the evaporation. The solution is cooling of the torso, and ice vests have been designed and tested with good results as seen in Fig 9. Holmér 1989.

Conclusions

- For diving in the air-diving range (surface to 50 m) a good dry suit and insulation is enough.
- Argon does not provide any advantages compared to air as suit inflation gas in dry suits.
- Non freezing injury can happen at skin temperatures below 8° C.
- For longer exposures at depths > 50 m as in saturation diving, hot water suits and heated breathing gas is necessary.
- If water temperature is above 30° C cooling might be necessary.

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