

## Energy exchanges in water

E. R. NADEL

John B. Pierce Foundation Laboratory and Departments of Epidemiology and Public Health and Physiology,  
Yale University School of Medicine, New Haven, CT 06519

Nadel ER. Energy exchanges in water. Undersea Biomed Res 1984; 11(2):149-158.—The thermal physical properties of water make water a medium of high heat transfer relative to air. This paper describes the body temperature pattern during immersion in still and moving water, the avenues for energy exchange, the energy transfer characteristics of humans, and the physiological means by which the body attempts to compensate for the excess heat loss in water. Fat is the major defense against cooling in water when exercising or shivering. Skeletal muscle is a significant additional factor during quiet rest.

immersion  
temperature

heat loss  
energy

At the beginning of his excellent treatise *Survival in Cold Water*, Keatinge noted that recognition of the lethal effects of cold during accidental immersion is a relatively recent one (1). He recounted the press reports of the sinking of the *Titanic* in April 1912; there was hardly a mention of the possibility that any of the deaths were due to anything other than drowning, despite the fact that the *Carpathia* reached the scene of the disaster in less than 2 h and there were more than a sufficient number of flotation devices available. Keatinge claimed that there was abundant evidence that the effect of the cold water was the predominant factor in causing the vast majority of the deaths in this as well as other shipwrecks, yet drowning is nearly always the documented cause of death. The lack of information concerning the power of water as a medium of heat transfer no doubt contributed to the lack of appreciation of the consequences of prolonged immersion. In the following paragraphs I review the advances that have been made in this area in recent years, discussing first the body temperature pattern during immersion in still and moving water at different temperatures, then the avenues for energy exchange, and finally the energy transfer characteristics of humans, which are related to both the physics of energy exchange and the physiological means by which the body attempts to compensate for excess flux.

Water has a specific heat around 4000 times that of air and a thermal conductivity about 25 times greater. For these reasons it is not surprising that the heat transfer characteristics of water are much greater than those of air. Thus, even when the body's energy production is elevated above basal levels by 10- to 15-fold, as is the case during intense swimming, if the

water temperature is sufficiently low and the insulation is inadequate the internal body temperature can be gradually reduced to the point at which confusion and disorientation occur and normal muscular activity is impossible to maintain.

The importance of an evaluation of the characteristics of the energy exchanges in water has a practical as well as an academic side. Besides providing a better understanding of the means by which shipwreck victims might avoid hypothermia during prolonged immersion, the characterization of heat transfers in water should aid productivity in the various diving industries over the world.

## BODY TEMPERATURE IN WATER

The classic paper of Pugh and Edholm (2) provides the reader with a detailed and entertaining description of scientific method as well as the value of insulation during immersion in water. Their primary insights were developed from the study of two subjects: one was an experienced channel swimmer who measured 164 cm in height and 96 kg in weight, and the other was tall and lean. The channel swimmer could reportedly withstand extended (12–15 h) exposures in 16°C water without undergoing a decrease in body core temperature. Following such swims, his "... forearms and legs were intensely pale; his brachial pulse was felt with difficulty, and his radial pulse was impalpable until 50 minutes later." Such observations as this suggested that there was a functional shutdown of blood flow, and thus heat flow, to the periphery, providing a great resistance to heat loss. In contrast the lean subject underwent a drop in rectal temperature from 37°C to less than 34°C following 50 min of swimming in 16°C water, and he was incapable of standing or walking afterward. They concluded from their studies of a number of channel swimmers and control subjects that the amount of body fat rather than the amount of movement was the primary determinant of the rate of body heat loss in the water.

In the years following the Pugh and Edholm report (2) other investigators confirmed and quantified the finding that the decrease in body core temperature during water immersion was inversely related to the thickness of the subcutaneous fat layer. The many studies of Keatinge in particular produced relations such as the one in Fig. 1 (3). One of the most thorough investigations of the changes in internal temperature in the water was that of Holmér and Bergh (4). They recorded esophageal temperatures continuously during swimming in water at different temperatures. Four of their five subjects underwent decreases in esophageal temperature during 20 min of swimming in 18°C water, with the amount of decrease inversely proportional to the skinfold thickness. The maximal decrease in body core temperature was 1.6°C in 20 min in a subject with a 5-mm skinfold thickness. The subject with a 14-mm skinfold thickness barely decreased his internal temperature at all in the 20-min swim at 18°C. It should be remembered that during swimming the insulative capacity of muscle is considerably lower than during rest in water because of the increased muscle blood flow; hence, one would expect the resistance to heat flow to be more closely correlated with the fat thickness during swimming.

## AVENUES OF ENERGY EXCHANGE

In air, heat transfer from the skin to the environment is primarily by radiation, convection, and evaporation. In water, heat exchange by radiation and by evaporation are insignificant, and convection is practically the only avenue for exchange (a small and constant transfer of heat by conduction (5) occurs in water; this component is usually lumped with the term

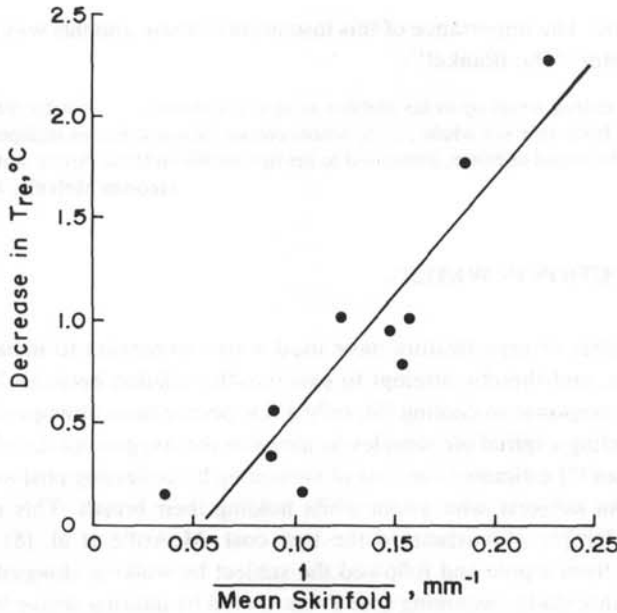


Fig. 1. Relation between fall in rectal temperature after 30 min immersion in 15°C water and mean skinfold thickness. [Adapted from Keatinge (3).]

*convection*). Also in water, unlike in air, the effective skin surface area for exchange is nearly 1.0. The heat flux, then, can be described simply as follows:

$$HF = h_c (T_{sk} - T_w)$$

where: HF = rate of energy transfer in  $W \cdot m^{-2}$ ,  $h_c$  = the convective transfer coefficient in  $W \cdot m^{-2} \cdot ^\circ C^{-1}$ , and  $T_{sk} - T_w$  = the skin to water temperature gradient in  $^\circ C$ . For any ambient medium the convective transfer coefficient is related to the heat transfer characteristics—the kinematic viscosity and thermal conductivity, and the velocity of the medium with respect to the source. Thus the value of  $h_c$  varies both between environments and within a given environment.

Water, because of its thermal physical properties, has a much greater value of  $h_c$  than does air and offers practically no insulation at the interface of skin and water. As a result heat reaching the skin surface is rapidly transferred to the water and therefore the skin temperature becomes relatively close to the water temperature. Since the heat flux is affected by both the value of  $h_c$  and the temperature gradient from skin to water, the heat flux can be minimized if the resistance to heat flow from core to skin is great. The resistance to heat flow from core to skin is composed of a variable resistance, offered by the adjustable conductance of heat in the circulation of blood from core to skin, and a fixed resistance, which is a function of the thickness of the layer of subcutaneous body fat. Maximal constriction of peripheral vascular beds maximizes the variable resistance in any individual. Therefore, in conditions of maximal peripheral vascular constriction, the resistance to heat flow from core to skin is greater in people with a thick layer of subcutaneous fat; this phenomenon has been recognized by the marine mammals, which have evolved to meet the requirements for survival in the water environment by developing an insulating layer of fat between the body core and skin. Fat is a relatively underperfused tissue whose thermal conductivity is around half that of muscle and

a third that of blood. The importance of this insulation to these animals was noted by Melville in 1850 in his chapter "The Blanket":

For the whale is indeed wrapt up in his blubber as in a real blanket . . . It is by reason of this cosy blanketing of his body that the whale . . . to whom corporeal warmth is as indispensable as it is to man . . . should be found at home, immersed to his lips for life in those Arctic waters.

Herman Melville, *Moby Dick*, 1850

## ENERGY PRODUCTION IN WATER

Although a number of investigators have used water immersion to induce an increase in energy production, and thereby attempt to examine the relation between body temperature and the metabolic response to cooling (6), only a few people have attempted to overcome the obstacles of collecting expired air samples to measure the oxygen uptake of swimmers. Karpovich and Millman (7) estimated the cost of swimming by collecting post-swimming samples of expired air from subjects who swam while holding their breath. This method produced values that considerably overestimated the true cost. McArdle et al. (8) suspended a gas collection system from a pole and followed the subject by walking alongside the pool as the subject swam. In this study swimming speed was altered by altering stroke frequency, not the technique used by competitive swimmers, which nonetheless yielded an appropriate increment in metabolism per unit of increase in swimming speed, at least at submaximal speeds. Di Prampero et al. (9) suspended a gas collection system above swimmers who swam around a circular pool. They found that the energy production at a given speed was directly proportional to the body drag that the swimmer had to overcome. They further reported that drag increases with the swimming velocity, and therefore the energy cost of swimming should increase exponentially with swimming speed. This was indeed the finding of Holmér (10). His experiments were made feasible by use of a specially designed swimming flume that enabled a subject to swim at any preset speed and water temperature without changing position with respect to the apparatus (11). Thus, probes could be easily attached and many simultaneous measurements made without the inconvenience of the subject's moving in space. He found that oxygen uptake tended to be linearly related to swimming speed at low speeds but tended to increase disproportionately at high speeds. Recently Pendergast et al. (12) published similar results from unskilled, skilled, and elite swimmers, emphasizing that although the cost of swimming at a given speed is greater in unskilled than in skilled or elite, the exponential relation between energy cost and swimming speed at the higher speeds exists in all three groups. My associates and I (13) found essentially similar results to those of Holmér using 33°C and 26°C water (the latter temperature being that used by Holmér), but swimmers in 18°C water had a generally elevated metabolic rate throughout the range of swimming speeds (Fig. 2). The elevation in oxygen uptake at any swimming speed in the cold water was about 400 to 500 ml · min<sup>-1</sup> and was the consequence of the shivering cost that was superimposed upon the cost of exercise. It is also possible that a part of the elevation in metabolic rate was the result of a decrease in the ratio of efficiency to drag associated with the extraneous movement accompanying the shivering contractions.

The shivering activity in the 18°C water was in response to the lowered skin and body core temperatures and is an appropriate thermoregulatory response to body cooling. Holmér and Bergh (4), in studying the excess metabolic rate above that required for swimming, were able to relate it to the decrease in internal temperature. Figure 3 illustrates their observation. During submaximal swimming at a given speed 4 of their 5 subjects showed the same linear relation

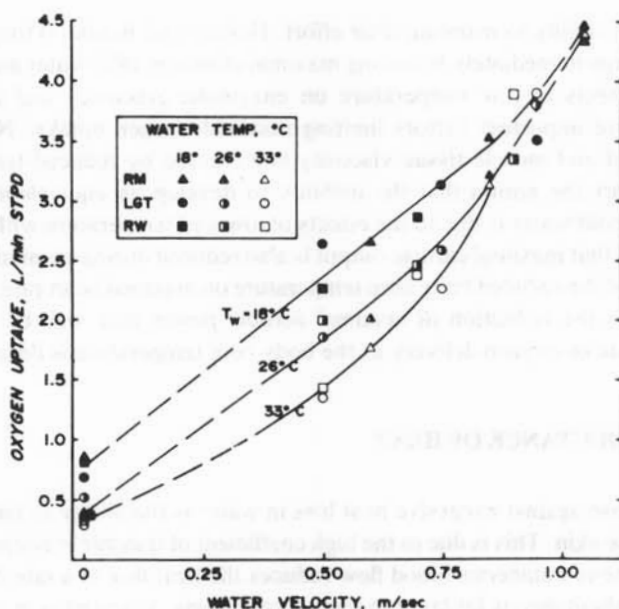


Fig. 2. Oxygen uptake as a function of swimming speed at 3 water temperatures. [From Nadel et al. (13).]

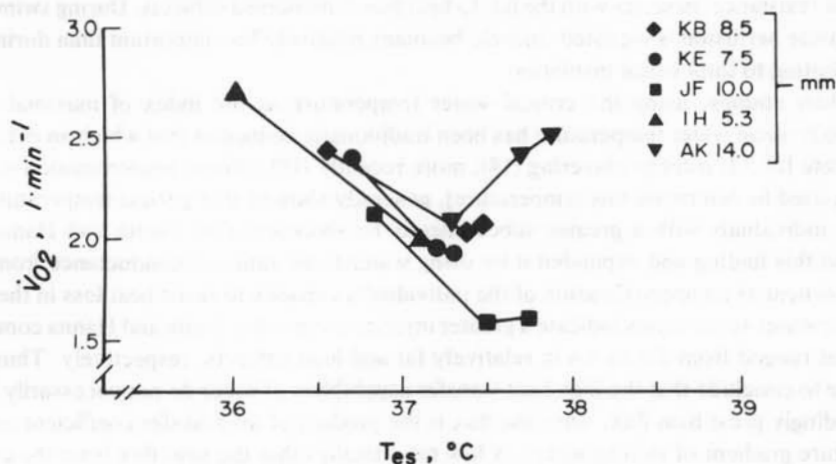


Fig. 3. Oxygen uptake as a function of internal temperature during submaximal swimming in 18°C water. [Adapted from Holmér and Bergh (4).]

between increased oxygen uptake and decreased esophageal temperature below an esophageal temperature threshold around 37.2°C. This relation is similar to that described for the control of shivering metabolism in air (14).

Swimmers cannot achieve the same maximal aerobic power in colder water that is possible in warmer water (13, 15). Our group found that in water temperatures of 18°C and 26°C lean subjects were only able to reach 85% and 92% of their maximal aerobic power in 33°C water. These subjects complained of muscle fatigue rather than cardiorespiratory fatigue when asked

the cause of their inability to maintain their effort. Holmér and Bergh (4) found relatively low muscle temperatures immediately following maximal efforts in 18°C water and concluded that the deleterious effects of low temperature on enzymatic efficiency and cellular diffusion characteristics were important factors limiting maximal oxygen uptake. Nerve conduction velocity is reduced and muscle tissue viscosity is increased by reduced temperatures, both factors that support the notion that the inability to develop an equivalently high maximal oxygen uptake in cold water is due to the effects of lowered temperature within the muscle. It is likely, however, that maximal cardiac output is also reduced during swimming in cold water, due to the effects of the reduced body core temperature on maximal heart rate and the viscosity of blood (15); thus the reduction of maximal aerobic power may well be due in part to a reduction in the rate of oxygen delivery as the body core temperature is decreased.

### INTERNAL CONDUCTANCE OF HEAT

The major defense against excessive heat loss in water is the ability to limit heat flow rate from the core to the skin. This is due to the high coefficient of transfer between skin and water. Minimizing the rate of cutaneous blood flow reduces the heat flux to a rate dependent on the thickness of the subcutaneous fat layer in resting conditions. Veicsteinas et al. (16) as well as Park et al. (17) have recently pointed out that the true maximal resistance to heat flux, or maximal tissue insulation, is a more complex function than just a consideration of the fat thickness. Their data confirmed the hypothesis that vasoconstricted muscle also provides an important resistance, in series with the fat, to heat flux in immersed subjects. During swimming, when muscle perfusion is elevated, muscle becomes relatively less important than during rest in contributing to total tissue insulation.

The older studies, using the critical water temperature as the index of maximal tissue insulation [critical water temperature has been traditionally defined as that which an individual can tolerate for 3 h without shivering (18); more recently (19) a linear approximation method has been used to determine this temperature], generally showed that critical temperature was lower in individuals with a greater subcutaneous fat thickness (20). Smith and Hanna (19) confirmed this finding and expanded it by using water-to-air ratios of conductance from core to environment as an approximation of the individual's capacity to resist heat loss in the cold. The lower water-to-air ratios indicate a greater insulative capacity. Smith and Hanna computed ratios that ranged from 2.3 to 4.4 in relatively fat and lean subjects, respectively. Thus they were able to conclude that the high heat transfer capabilities of water do not necessarily cause an accordingly great heat flux, since the flux is the product of the transfer coefficient and the temperature gradient of skin to water. A low ratio implies that the heat flux from the core to the skin is relatively low and the temperature gradient from skin to water may be likewise small.

Bullard and Rapp (21) computed the requirements to attain minimal skin conductances as low as  $6 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$ ; either a subcutaneous fat thickness of 3 cm or an unperfused muscle 6 cm thick is necessary. Veicsteinas et al. (16) pointed out that muscle and fat are both important. Rennie et al. (22) showed years ago that fat accounts for not more than half of the total insulative capacity, and recently Rennie et al. (20) stated that the overall insulation of resting subjects in water is made up primarily (75%) of underperfused muscle and less so (25%) of nonperfused subcutaneous fat and skin. This provides an explanation for Hong's (18) observation that the ama divers have a consistently higher insulative capacity than nondivers at any skinfold thickness; one of the adaptations used by the ama was an ability to maintain a



lower muscle perfusion than nondivers when exposed to cold water. This adaptation contributed to their increased ability to retard heat loss during immersion.

While swimming (or shivering at rest) the oxygen demands of the contracting muscles require an elevated muscle blood flow, thereby reducing the insulative capacity of the muscle. We have reported conductance values during swimming in cold water of around  $14 \text{ to } 22 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$ , 3 to 5 times the minimal values that occur during rest (13). The greater the swimming speed, the higher the conductance. Further, conductance values were quite high in swimmers swimming in warmer water, implying that cutaneous vasodilation occurs if the body temperatures become sufficiently elevated. Rennie et al. (20) stated that the insulative component of muscle is abolished at exercise intensities of 3 met or more. Thus, a lean individual should be at a considerable disadvantage during immersion at rest or while swimming in resisting heat flux to the skin, from where the heat would be rapidly dissipated to the water.

### ENERGY LOSSES TO WATER

To evaluate the driving force for heat loss to the water one must determine the value of the convective transfer coefficient in individuals at rest in still water and while swimming at different velocities. Direct measurement of  $h_c$  in humans in the water has been difficult because of the requirement of making continuous measurements of the heat flux and temperature gradient during swimming. Based on theoretical analyses using heat transfer theory, measurements of convective transfers in air, and differences in thermal physical properties between water and air, Rapp (5) predicted values of  $h_c$  of  $94 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$  in still water and  $400 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$  while swimming at  $0.5 \text{ m} \cdot \text{s}^{-1}$ . These values should be adjusted upward due to Rapp's underestimating the metabolic rate in  $22^\circ\text{C}$  water (13); revised values are 172 and  $459 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$ , respectively. Witherspoon et al. (23) used a heated copper manikin and monitored the energy input to maintain the manikin's temperature in the different conditions. They obtained  $h_c$  values of  $137 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$  in still water and  $570 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$  in water moving at  $0.5 \text{ m} \cdot \text{s}^{-1}$ . These values, predicted by an entirely different method from that used by Rapp, are remarkably similar.

Some years ago my colleagues and I made direct measurements of  $h_c$  on human subjects during rest in still and moving water and while swimming at different speeds (13). Our experiments were made feasible by use of the specially designed swimming flume described earlier in this paper. We used copper-tellurium disks to estimate heat flux across the skin on 4 sites and measured skin temperature (also on 4 sites adjacent to the disks) and water temperature to obtain the thermal gradient. To determine the value of  $h_c$  we plotted the mean weighted heat flux against the temperature gradient from skin to water in different water temperatures and at different water velocities. Figure 4 illustrates these relations for subjects resting in still and moving water and while swimming; the slope of each relation is the value of  $h_c$  for that condition. We found values of  $h_c$  of  $230 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$  during rest in still water and  $580 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$  during swimming at any speed. These values were very like those predicted by Rapp (5) and obtained from the copper manikin by Witherspoon et al. (23). Of interest in our data was the fact that  $h_c$  was independent of water velocity, because the value of  $h_c$  in air is dependent to a large extent on the air movement (24). Our interpretation of the independence of  $h_c$  from velocity in water is that, due to the turbulence around the subject associated with swimming, the effective water velocity around the body does not differ at different swimming speeds.

The above-described determinations of  $h_c$  have been the only ones accomplished on human subjects to this date. The difficulty in making such estimations from humans is not only the

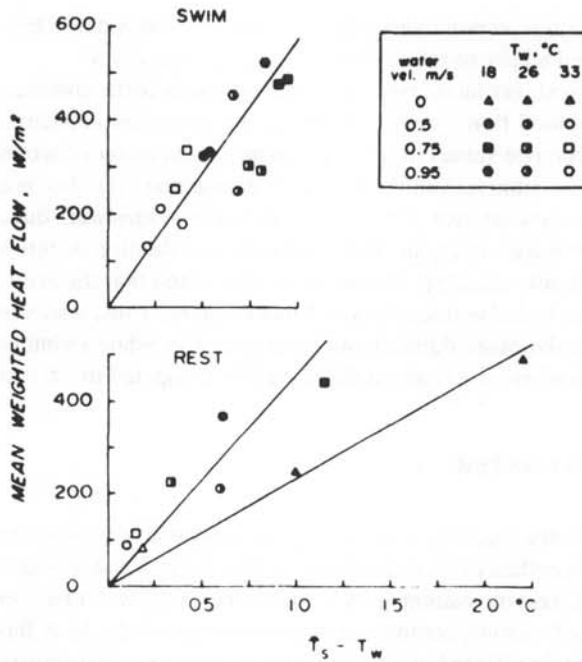


Fig. 4. Mean weighted heat flow as a function of the temperature gradient from skin to water ( $n = 3$ ). Slope of each relation is convective heat transfer coefficient for the particular condition. [From Nadel et al. (13).]

result of the difficulty in making measurements in water in general, but also that it is very difficult to obtain adequate indirect calorimetric data in the water. The estimation of the heat storage term is problematic during swimming because it is not known how the redistribution of body heat occurs between the body core and subcutaneous tissue during immersion.

The values of  $h_c$  in water are at least 100 times greater than in air. Thus, the interface of skin to water offers practically no resistance to heat flow, and nearly all the heat reaching the skin is rapidly transferred to the water. It is noteworthy that the heat transfer coefficient during swimming is not much greater than that during rest in moving water. The total heat flux in the two conditions, however, can only be evaluated with a knowledge of the relative rates of heat production and the relative rates of peripheral blood flow, which influence the rate of heat transfer from core to skin and therefore skin temperature.

## CONCLUSION

In conclusion the thermal physical properties of water are such as to promote energy transfer away from the skin to the environment. The heat transfer coefficient is between 100 and 200 times that of air; thus all the heat that reaches the skin surface is rapidly transferred to the water. Insulation between the core and skin is provided by relatively underperfused muscle and fat. Generally, the thicker the layer of subcutaneous fat, the greater the resistance to heat flux from the body during immersion. During swimming the increase in energy production is counterbalanced by the increase in muscle blood flow and the convective heat transfer coefficient; the former phenomenon promotes transfer of heat to the periphery and the latter



promotes heat loss to the water. Thus, the major defense against excessive body cooling in cold water is to be fat. The thermoregulatory system is relatively inadequate in water because of the overwhelming heat transfer characteristics of water.

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Nadel ER. Echanges d'énergie dans l'eau. Undersea Biomed Res 1984; 11(2):149-158.—Les propriétés physiques thermiques de l'eau en font un milieu de transfert de chaleur élevée relativement à l'air. Ce texte décrit l'évolution de la température corporelle durant l'immersion dans l'eau dormante et courante, les avenues pour l'échange d'énergie, les caractéristiques du transfert d'énergie des humains et les moyens physiologiques dont le corps dispose pour compenser la perte excessive de chaleur dans l'eau. Le tissu adipeux est le mécanisme principal de défense contre le refroidissement dans l'eau lors de l'exercice ou du frisson. Le muscle squelettique est un autre facteur significatif au repos.

immersion  
température

perte de chaleur  
énergie

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