Heat loss and hypothermia in free diving: Estimation of survival time under water

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The heat exchange between a diver and the colder surrounding water is analyzed on the basis of the fundamental equations of thermal transport. To estimate the decrease in the diver's body temperature as a function of time, we discuss the complex interplay of several factors including the body heat production rate, the role of the diver's wet suit, and the way different heat exchange mechanisms (conduction, convection, and radiation) contribute to thermal transport. This knowledge could be useful to prevent physiological disorders that occur when the human body temperature drops below 35 °C.
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I. INTRODUCTION

Starting a physics lecture with an example related to everyday life (for example, sports, hobbies, and recreational activities) is a well-known pedagogical resource for increasing the attention of students. Furthermore, it constitutes an excellent way to promote active learning through discussion with peers and/or teachers.[1] In particular, sport-related examples are common in elementary physics textbooks,[2] and several interesting monographs devoted to the physics involved in golf, baseball, and basketball are available.[3–5]

We discuss one particular aspect of diving: the thermal interaction between the diver and the surrounding water. The underwater world has a deep fascination for many people. So, it is not surprising that diving has become increasingly popular, including scuba and apnea diving. Recent reports estimate about 1.7–2 million divers in the U.S. and cumulative worldwide certifications are between 8 and 8.5 million. A better knowledge of human physiology and the response of the human body to extreme environmental conditions has made it possible for free divers to stay longer and go deeper. For instance, the depth limit of 150 m for a free diver was surpassed last year.[6] On the other hand, technology has also helped to make diving more enjoyable by the development of incredibly warm and comfortable titanium "water gliding" neoprene suits.

The safe and comfortable practice of diving, either free diving or scuba diving, requires the use of suitable material including masks, isothermal suit, fins, and gloves. Part of this equipment aims to keep the body temperature nearly constant. Because seawater is usually at a lower temperature than the human body and water conducts body heat up to 26 times faster than air at the same temperature, heat loss cannot be avoided, and becomes more important the longer the duration of the dive. Here lies the importance of isothermal suits to minimize this heat transfer (in addition to providing protection of the skin against any diving hazards).

The heat loss of a diver submerged in the water depends not only on the water conditions (its temperature and thermal conductivity), but also on the diver, including the thickness of the isothermal suit, the temperature of the skin, the surface area to mass ratio, and exercise intensity. Under certain conditions, this thermal transfer leads to a severe decrease in body temperature, known as hypothermia, when the internal temperature drops below 35 °C (95 °F). The human body is better designed to face high-temperature environments rather than low-temperature ones, because skin nerves provide the connection of high temperature to the feeling of pain. The corresponding reflex behavior is to increase blood circulation (vasodilatation) and favor thermal transfer via the evaporation of sweat. These mechanisms are effective and nondamaging, while body protection against a cold environment is usually ineffective (shivering and getting goosebumps) or can involve irreversible damage (decrease of blood circulation).[7]

In this paper we use the basic equations of thermal transport to describe the cooling of the diver's body when immersed in water. This simple approach gives an estimate of the critical time period in which it is safe to practice diving, and also provides a physical picture beyond some of the data reported in the literature. This aspect of the energy exchange between the diver and the water is seldom discussed when talking about the physics of scuba diving, because immersions usually last less than 1 h because of the limited capacity of the air tanks. However, it is relevant in breath-hold diving where divers often remain in water more than 3 h.

The motivation to predict human endurance in aquatic environments also is related to the development of clothing that provides suitable insulation. The kind of suit that has made diving sports so popular is the wet suit made of neoprene. Gas bubbles (usually nitrogen) are permanently trapped inside the cells of the neoprene foam of the suit forming an insulating barrier between the body and the surrounding water. A thin layer of water fills the space between the skin and the wet suit and is quickly warmed to body temperature. The suit must fit snugly to the body if it is to be an effective insulator. There are also dry suits that provide a small insulating air layer just at the skin surface. However, these suits become too easily depressed in water and lose their insulating properties. Among polar animals we can find outstanding examples of natural wet and dry suits. For instance, the fur of arctic seals and bears is an effective wet suit. It adds exterior insulation to their thick fat layer by trapping a 2- to 10-mm water layer near their skin. The feather pelt of penguins, on the other hand, works like a dry suit, maintaining an insulating layer of air.[8–10]

It is important to discuss the complexity of the problem under study. An accurate description of the system should

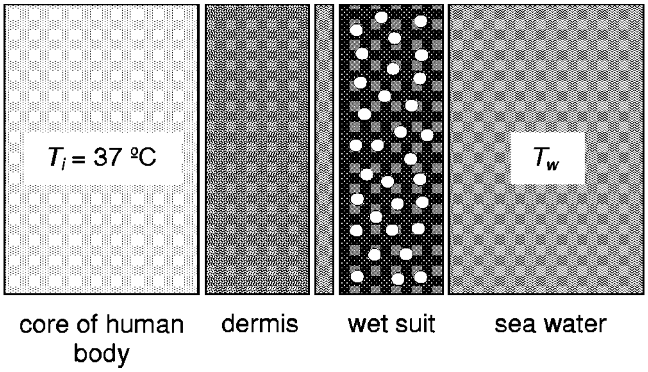

Fig. 1. Simplified model of heat transfer between the diver's body and the water. The internal temperature of the human body remains approximately constant at approximately 37 °C. The temperature gradient spans the central three layers. The thickness of these three layers is not shown on the same scale for the sake of clarity.

consider not only the biophysics of human heat exchange, but also the physiological adaptative responses to heat exchange common to all homeotherms. However, the physiology of the human body depends on many not easily quantifiable factors and hence it is usually described in terms of phenomenological equations. That is, the current understanding of the relevant physicochemical phenomena is incomplete and a detailed physical model is not yet possible. Our approach is simple and consistent with present knowledge about human physiology and is useful in illuminating the main physical features of free diving.

II. THERMAL EXCHANGE

The body loses heat by respiration, evaporation, conduction, radiation, and convection. Both respiration and evaporation are effective biophysical mechanisms that oppose hyperthermia (high temperature), but can be neglected for a diver immersed in a cooler medium.[7,10] We first investigate which mechanisms are responsible for the heat transfer at each step of the entire process: from the diver's body to the water, across the skin layer (dermis) and through the diving suit (see Fig. 1).

The major mechanism of thermal transfer inside the body is the blood flow that "picks up" the heat excess of high temperature organs like the heart and the liver and loses it when passing near the skin, which is usually colder (about 34 °C).[10] This mechanism can be regarded as convective, because it is accomplished by a moving medium; its magnitude depends on such complex factors as metabolic effort, heart rate, and oxygen uptake rate.

On the other hand, energy is transferred across the skin and the diving suit by conduction, which is determined by peripheral factors like the average fat content of the skin tissues, the thickness of the water layer between the skin and the wet suit, and the properties of the neoprene itself.

At the outer surface of the diver exposed to the water, we need to consider convection again, which is now related to the motion of the water surrounding the diver. Heat loss by this mechanism is many times higher than in air because of the higher thermal capacity of water. Although this qualitative trend is clear, little or no quantitative data exist in the literature. The problem is how to separate this contribution from sweat and evaporation, because all of them take place simultaneously in the boundary layer. In addition, all theoretical estimations of heat loss by convection are critically dependent on assumptions about body shape and type of water motion. Thus, the description of convection will be expressed in terms of empirical equations that offer only rough estimations.[10]

It is also important not to forget the possible contribution of radiation. Radiation is the most important heat transfer mechanism at ordinary room temperatures for an unclothed person at rest, but becomes comparable to convection for a clothed person in motion.[7]

Fourier's law for solids describes conductive heat transfer, and states that the heat flow q is proportional to the gradient of temperature

$$q = kA\frac{\Delta T}{\Delta x}, \tag{1}$$

where k is the thermal conductivity of the medium and Δx the thickness of a slab of cross-sectional area A. The temperature difference is ΔT. Convective transfer can be described in a simple way starting from Eq. (1), which is not generally valid in a fluid, but is valid near a solid surface (the skin or the diving suit) where the fluid is stagnant. Then, we obtain the so-called Newton's law of cooling:

$$q = hA\Delta T, \tag{2}$$

where h is the heat transport coefficient or convective heat transfer coefficient. Equations (1) and (2) can be treated using the formal analogy with Ohm's law for the electric current. In each case, the constant term that relates the heat flow to the difference of temperature is called the thermal resistance of the medium:

$$q = kA\frac{\Delta T}{\Delta x} = \frac{\Delta T}{R_{\mathrm{cond}}}, \tag{3a}$$

where

$$R_{\mathrm{cond}} = \frac{\Delta x}{Ak} \tag{3b}$$

and

$$q = hA\Delta T = \frac{\Delta T}{R_{\mathrm{conv}}}, \tag{4a}$$

with

$$R_{\mathrm{conv}} = \frac{1}{hA}. \tag{4b}$$

The next step is to estimate the radiative transfer. The net rate at which an object at temperature T_{in} emits thermal radiation to an environment at temperature T_{out} can be estimated by using the Stefan–Boltzmann law:

$$q = A\varepsilon\sigma(T_{\mathrm{in}}^4 - T_{\mathrm{out}}^4), \tag{5}$$

where σ is the Stefan–Boltzmann constant and ε is the emissivity of the surface with area A. The usual range of water temperatures allows for a Taylor expansion of Stefan–Boltzmann law.[7] By keeping only the first-order term in $\Delta T/T$, we obtain

$$q = 4A\varepsilon\sigma T_{\mathrm{out}}^3(T_{\mathrm{in}} - T_{\mathrm{out}}). \tag{6}$$

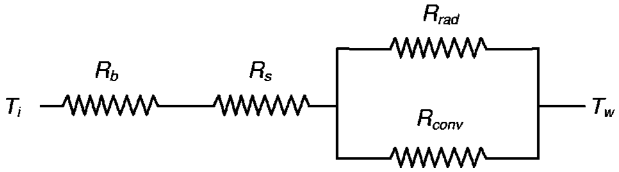

Fig. 2. Simplified model of heat transfer between the diver body and the water. The model is based on an electrical analogy in which heat flux is associated with electric current, temperature difference with potential difference, and electrical resistance with thermal resistance. Except for very low water temperatures, the contribution of body radiation is very small compared to heat loss by external convection.

This linear relationship between q and ΔT enables us to define the thermal resistance associated with the radiation process:

$$R_{\mathrm{rad}}=\frac{1}{4A\varepsilon\sigma T_{\mathrm{out}}^3}. \tag{7}$$

The advantage of using thermal resistances is clear for a diver immersed in water where we are dealing with a nonhomogeneous medium formed by layers of different materials and heat transfer is driven by different mechanisms. The total resistance is then calculated as the equivalent resistance of each one of the homogeneous layers composing the system: human tissue, diver's suit, and water. To calculate the equivalent resistance we need to know how all these layers contribute to the overall resistance. We propose the physical picture shown in Fig. 2.

Note that heat transfer inside the body and across the diving suit is controlled only by one mechanism in each case (convection and conduction, respectively). These contributions are described by means of two resistors placed in series, R_b (body) and R_s (diving suit). On the other hand, the thermal transport from the outer surface of the body to the water can take place by two independent mechanisms, radiation and convection, which can be depicted as two resistors placed in parallel, R_{rad} and R_{conv}.[11]

The thermal resistance of the human body R_b is not easy to estimate because of several complex factors. The first problem is the quantification of the blood flow on the skin tissues which depends on the activity level, which in turn depends on the heart rate, oxygen uptake rate, etc. The second factor is the physiological reaction to a cold environment, for example, the superficial muscular contraction and vascular changes.[10] It is possible to find in the literature completely different approaches that lead to very similar results. Thus, an indirect estimation based on the average metabolic rate power produced by the human body (120 W) leads to $R_b=0.03$ K/W,[12] and an alternative calculation that considers the conductivity of human tissues and blood, as well as their proportion in the body gives a similar value.[13]

The thermal resistance of the diving suit can be calculated by taking into account that most of them are made of fluffy neoprene with injected gas bubbles. Thus, we obtain $R_s=x/kA$, where A is the surface of the suit and x its thickness. The thermal conductivity is calculated as a weighted average of the values for the neoprene rubber ($k=0.190$ W/m K) and gas bubbles (usually nitrogen) giving for the neoprene foam $k=0.044$ W/m K, in agreement with the data provided by manufacturers. The gas volume percentage is obtained from the density values of neoprene rubber, nitrogen, and the suit itself.

The contribution of radiation R_{rad} to the total resistance can be calculated using Eq. (7) if we consider that the human body is an almost ideal radiator in the infrared region, and that human skin emissivity is 0.97 regardless of its color. The resistance due to the convection of water R_{conv} is calculated by means of Eq. (2), giving $R_{\mathrm{conv}}=0.08$ W/m K.[14] We stress that there is no general agreement on the suitable values of the convective heat transfer coefficient h. In fact, many authors point out that the major obstacle to an adequate description of thermal exchange in water immersion is the determination of the convective heat loss.[10,15,16] We have used the value $h=10\ \mathrm{W/m^2\,t}$ reported in Ref. 12. Nevertheless, values of one or even two orders of magnitude higher are used in other studies, both theoretical and experimental.[15,16] In theoretical models, the assumptions about the shape of the body and the relative motion between the diver and the water are crucial, changing completely the estimation of h. Experimental measurements show how diving stimulates evaporation and transpiration, so that all contributions are mixed within the boundary layer flow, thus making an accurate determination of h difficult.

Finally, the equivalent resistance R_e of the whole process is obtained as:

$$R_e=R_b+R_s+\frac{R_{\mathrm{rad}}R_{\mathrm{conv}}}{R_{\mathrm{rad}}+R_{\mathrm{conv}}}, \tag{8}$$

and, consequently, the total heat transferred from the diver's body (at internal temperature T_i) to the water (at temperature T_w) is

$$q_{\mathrm{trans}}=\frac{T_i-T_w}{R_e}. \tag{9}$$

This approach based on the use of equivalent thermal resistances might appear rather simplistic but presents at least three advantages: (a) it is consistent with the use of empirical relations that are common in human physiology studies; (b) it avoids the use of many unknown parameters in the estimation of intermediate temperatures nonaccessible experimentally; and (c) it is intuitively simple. However, students should be warned that, unlike electricity, heat is not the flow of particles that is impeded by resistance, but the flow of energy that is conducted by the material. The electrical analogy refers to the formal structure of equations.

III. THE DIVER'S COOLING AND HYPOTHERMIA

On the basis of the ideas we have introduced, we can study the evolution of the diver's temperature and estimate how long the diver can remain safely under water.

The energy balance between the heat production of the human body q and the heat transferred to the water (see Eq. (9)) dictates the cooling rate of the diver:

$$q-\frac{T_i(t)-T_w}{R_e}=C_eM\frac{dT_i}{dt}, \tag{10}$$

where C_e is the heat coefficient of the human body and M its mass. The metabolic energy term q is related to the free energy produced by the transformation of chemical energy during aerobic and anaerobic metabolic activities within the

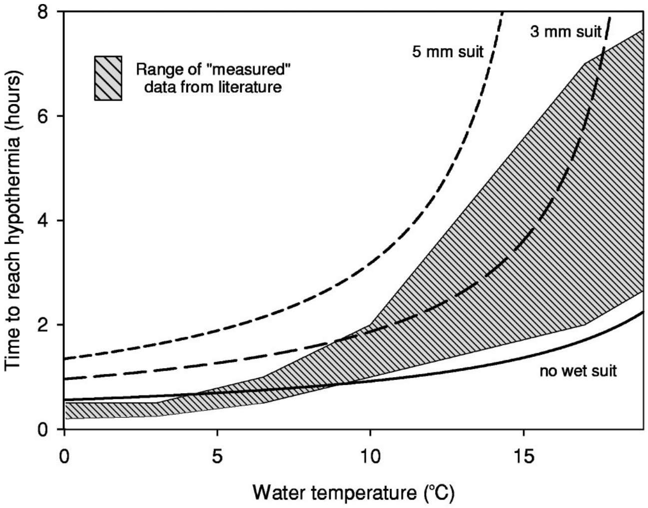

Fig. 3. Time needed for the diver's body temperature to reach hypothermia (35 °C), as a function of water temperature and thickness of the diver's suit. The solid line corresponds to a nude diver. The cross-hatched region represents the wide range of reported data for an average diver without special thermal protection, taken from a survey in Ref. 17. See the main text for the parameter values used in Eq. (12).

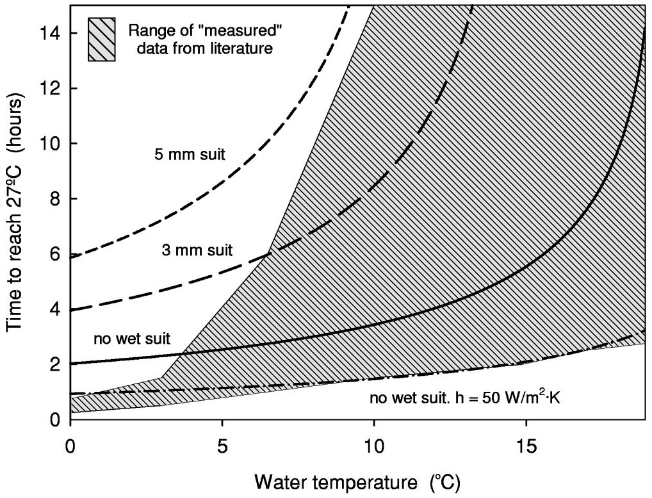

Fig. 4. Time needed to reach an internal temperature of 27 °C for several thicknesses of the diving suit. Solid lines correspond to a nude diver for different values of convective coefficient h. The cross-hatched region represents the wide range of reported data for an average diver without thermal protection. (Ref. 17) See the main text for the parameter values used in Eq. (12).

body. Its value increases with metabolic effort from $q = 70\ \mathrm{W}$ at rest up to 10 times higher at high intensity exercise.[10] We take $q = 120\ \mathrm{W}$, $C_e = 3469.4\ \mathrm{J/kg\,K^2}$, and $M = 75\ \mathrm{kg}$ as typical values. Equation (10) is a first-order differential equation, so we need to know the initial temperature of the human body, $T_{io} = 37\,°\mathrm{C}$. Then, we find the following solution:

$$T_i(t) = qR_e + T_w - (qR_e + T_w - T_{io})\exp\left[-\frac{t}{C_e M R_e}\right]. \tag{11}$$

According to Eq. (11), the diver's body temperature decays exponentially when immersed in cooler water. The time necessary to reach the temperature T_i is given by

$$t(T_i) = C_e M R_e \ln\left(\frac{qR_e + T_w - T_{io}}{qR_e + T_w - T_i}\right). \tag{12}$$

As noted above, we are interested in the maximum time period that is safe to remain under water. It is widely admitted that hypothermia appears when body temperature drops below 35 °C. Hypothermia is extremely dangerous because the diver may be unaware of it. Some physiological mechanisms start to undergo minor disorders that can turn into loss of consciousness, collapse, and even death when body temperature reaches 27 °C.

Figure 3 shows the time necessary to reach a body temperature of 35 °C as a function of the water temperature. The same curve is presented for neoprene wet suits of several thicknesses. The cross-hatched region represents existing data in the literature for divers without special thermal protection.[17] (Note that these values are reported in the literature with wide ranges.) The curves show the relevance of the insulation provided by the diving suit. For a reasonable value of water temperature, $T_w = 15\,°\mathrm{C}$, the time to reach hypothermia increases from 1 h when no suit is used to about 4 h for a 3-mm-thick suit.

Figure 4 shows the time necessary to reach a body temperature of 27 °C as a function of the water temperature. Sometimes, authors refer to this time as the survival time. As in Fig. 3, several plots are shown corresponding to neoprene wet suits of several thicknesses. The cross-hatched region represents survival time data in the literature for divers without special thermal protection.[17] The calculated values of the survival time at low water temperatures are higher than the reported values, showing the limitations of the present model. Under such conditions ($T_w < 4\,°\mathrm{C}$), we can argue that the Taylor expansion that linearizes the Stefan–Boltzmann law is no longer valid, and the radiative contribution is underestimated. Although this argument is correct, it can be easily shown by numerical calculations that the discrepancy for the survival time cannot by explained only by the failure of the Taylor approximation. For instance, when the water temperature is 0 °C, the difference between the full Stefan–Boltzmann equation and the linearized one is only about 4%, which is far from the values required to fit the experimental data. Therefore, we conclude that the convective contribution is not properly estimated and the value used for the coefficient h at low temperatures is not appropriate.

In Fig. 4 we have also shown the estimated survival time under water for a value of $h = 50\ \mathrm{W/m^2\,t}$, similar to that found in Ref. 15 for cold water. It seems that a higher value of h could explain the observed behavior at low temperatures. The physical picture behind this change of h is not clear to us. One could say that the increasing value of h includes in some way the physiological response under such severe environment, and that the response is far more complex than the simple picture assumed here of constant metabolic heat production rate. But it is also true that such colder temperatures could be beyond the scope of our simple model, which describes free diving as a sport rather than a survival activity.

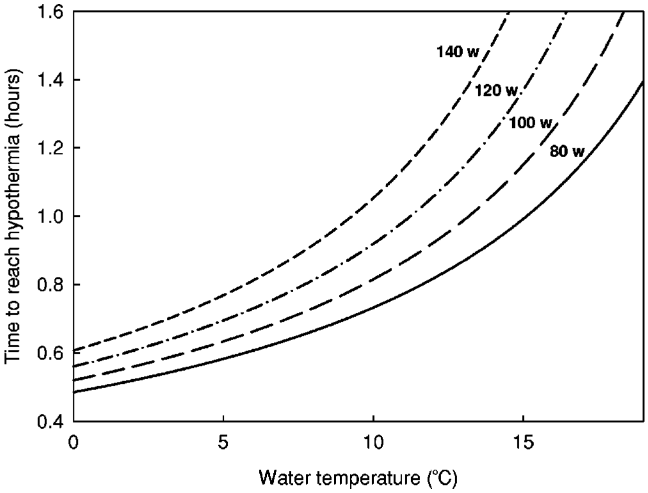

Fig. 5. Time needed for the diver's body temperature to reach hypothermia (35 °C), as a function of the diver's metabolic heat production rate.

Figure 5 illustrates the adaptive thermal response of the human body: it can face changes in the environment by modifying the level of activity and the subsequent metabolic heat production. For a fixed water temperature (for instance, $T_w = 15\,°\mathrm{C}$), we can see how the calculated time to reach hypothermia increases with heat production (from 55 min for $q = 80$ W up to nearly 2 h for $q = 140$ W). Very frequent immersions during that period could produce muscular fatigue contributing in the opposite direction via the increase of oxygen uptake.[10] Nevertheless, it is important to remember that the human body can face changes of temperature not only by changing the internal production of heat but also by modifying the effective resistance of the external tissues, an effect not shown here.

Finally, it is necessary to keep in mind that the present approach is based on average values that depend crucially on the metabolism of a particular diver (including the rate of energy production, oxygen uptake rate, mass, age, and physical condition). Furthermore, we have not included in this simple model detailed parameters describing how human physiology changes with time in an attempt to adapt to the environment. All these factors indicate that survival time could be longer than previously calculated. Although this can be true, the loss of consciousness previous to irreversible damages can also lead to death by drowning.

IV. CONCLUSIONS

The thermal exchange between a diver and the surrounding water has been analyzed in terms of a simple model for the biophysics of human heat exchange in a cooler medium. Key factors are the thermal resistance of the diving suit, the metabolic heat production of the human body, and the temperature of the water. Although the lack of data for physiological responses does not justify a more detailed description, the model provides reasonable values that agree with the qualitative and quantitative estimates of those who practice this sport.

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