Thermal Balance of Man in Water: Prediction of Deep Body Temperature Change

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Abstract. Changes in rectal temperature and metabolic rate were continuously monitored in men immersed in water at 15, 20, 25, 30, and 35°C. The subjects (12 healthy male students) wore swimming suits while either resting or doing leg exercise (AM= 60 kcal·h⁻¹·m⁻²·s⁻¹=70 W·m⁻²) for 1 h. At all water temperatures below 30°C, the metabolic rate increased but the rectal temperature fell continuously, resulting in hypothermia. The rate of fall in rectal temperature (cooling rate, CR, °C·h⁻¹) was inversely proportional to water temperature (Tw, °C) according to the equation CR=3.818 – 0.109 Tw in resting subjects and CR=3.434 – 0.110 Tw in exercising subjects. At a given Tw the cooling rate was greater in resting than in exercising subjects and in lean than in obese subjects. From the relationships between the cooling rate and water temperature the duration of useful activity and the survival time were predicted for resting and exercising subjects of various fatness.


Keywords: body temperature, immersion, exercise, subcutaneous fat, hypothermia

Introduction

Maintenance of normal body temperature is a critical problem for subjects immersed in cold water. Because of the high thermal conductivity and heat capacity of water, body heat is rapidly lost from the skin to the adjacent layer of water (Nadel et al., 1974). This drain of body heat and eventual hypothermia is the principal problem of unprotected individuals exposed to cold water (Beckman, 1963; Keatinge, 1969; Bullard and Rapp, 1970).

Numerous previous studies have shown that heat loss during immersion changes with water temperature (Cannon and Keatinge, 1960; Hayward et al., 1975), work load (Keatinge, 1961; Craig and Dvorak, 1968; McArdle et al., 1984; Toner et al., 1985) and subcutaneous fat thickness (Pugh and Edholm, 1955; Keatinge, 1960; Sloan and Keatinge, 1973; Hayward and Keatinge, 1981). However, few studies have established quantitative relationship between the degree of hypothermia and water temperature in subjects with various fat thickness at rest and during exercise. Hayward et al. (1975) have reported a prediction equation for deep body temperature change for subjects with clothing and kapok life jacket immersed in cold water. The present study provides similar equations for unprotected subjects of various fatness at rest and during exercise in water.

Methods

Twelve healthy male medical students were recruited as subjects with a range of subcutaneous fat thickness from 2.4 to 8.0 mm. All of them were born and grown up in South Korea. They were divided into three groups, Lean, Normal, and Obese, according to subcutaneous fat thickness. None of them were in a rigorous physical training. Their anthropometric characteristics are summarized in Table 1. Skin fold thickness was measured with a Lange caliper (Cambridge Scientific Inc., Cambridge, MD) at each of 10 positions (chin, cheek, back, chest, mid-lateral thorax, umbilicus, lateral waist, triceps, knee, and calf), and the weighted mean subcutaneous thickness (SFT) was estimated after correction for 4-mm double-skin thickness for each position as described by Allen et al. (1956).

$$SFT = \frac{\text{Sum of 10 skin fold thickness} - 10 \times \text{double-skin thickness}}{2 \times \text{number of sites}}$$

$$= \frac{\text{Sum of 10 skin fold thickness} - 40}{20}$$

Subjects were clad in swim suits and immersed up to the neck in a constant temperature water bath, vigorously circulated. The water temperature was adjusted to 15, 20, 25, 30 or 35°C. The subjects were either rested in a seated position or performed leg exercise at a constant intensity using a bicycle ergometer submerged in water bath for 1 h. An external work load that could increase the metabolic rate by about 60 kcal·h⁻¹·m⁻² (~ 70 W·m⁻²)
Table 1  Physical characteristics of subjects

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<th>BSA (m²)</th>
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BSA: Du Bois body surface area.
SFT: mean subcutaneous fat thickness.

was established empirically for each subject by modifying the frequency of pedaling.

The rectal temperature (Tre) was measured at 10 min-intervals using a copper-constantan thermocouple inserted ~ 15 cm beyond the anal sphincter and connected to a digital thermometer (Bailey Instrument, Model BAT 8). The oxygen consumption (\(\dot{V}O_2\)) was measured by collecting expired gas in a Douglas bag for 5 - 10 min at 30-min intervals. \(\dot{V}O_2\) content of collected gas was analyzed by a blood gas analyzer (Radiometer, model ABL-30, Copenhagen), and its volume was measured immediately by passing it through a dry gas meter (Harvard, Cat. No. 50-6162). The metabolic rate was calculated as 4.83 \(\dot{V}O_2\) (STPD) and expressed in kcal-h\(^{-1}\)-m\(^{-2}\) (1 kcal-h\(^{-1}\)-m\(^{-2}\) is 1.16 W-m\(^{-2}\)).

In each group, half of the subjects were tested in summer and the other half in winter.

Results

General patterns of metabolic rate and rectal temperature changes during immersion

Figure 1 depicts average changes in oxygen consumption (\(\Delta\dot{V}O_2\), upper panel) and rectal temperature (\(\Delta\)Tre, lower panel) of 12 subjects resting in water at 20, 25, 30 and 35°C. As expected, both the \(\dot{V}O_2\) and Tre did not undergo significant variations at 35°C, the thermoneutral water temperature (Craig and Dvorak, 1968). At lower temperatures, however, \(\dot{V}O_2\) increased (reflecting shivering), but Tre decreased, indicating that subjects were in a negative thermal balance. The Tre fell linearly with time after an initial delay of ~ 20 min, the rate of fall being greater with lower temperatures.

Figure 2 illustrates the time course of changes in \(\dot{V}O_2\) (upper panel) and Tre (lower panel) in subjects exercising on bicycle ergometer. The frequency of pedaling (hence the external work load) was maintained constant, however the \(\Delta\dot{V}O_2\) appeared to be greater with lower temperatures probably due to increased shivering. The Tre remained unchanged during the initial 15 min, but thereafter it declined steadily, with the rate of fall increasing as the water temperature decreased.

Figure 3 (upper panel) depicts the average rate of Tre fall (cooling rate, CR, °C·h\(^{-1}\)) as a function of water temperature (Tw, °C). Both in resting and exercising subjects, the CR increased linearly as the Tw declined showing the following relationships:

Rest: \[ CR = 3.818 - 0.109 \text{ Tw} \]  \[ (1) \]

Exercise: \[ CR = 3.434 - 0.110 \text{ Tw} \]  \[ (2) \]

Covariance analysis indicated that the two regression lines are significantly (p<0.01) different in elevation (the intercept with ordinate); thus at any given Tw the deep body cooling rate was significantly lower in exercising than in resting subjects.

Also plotted in Figure 3 (lower panel) is the average

<Fig. 1> Time course of changes in oxygen consumption (upper panel) and rectal temperature (lower panel) of subjects resting in water. Data represent the mean of 12 subjects.
metabolic heat production (M, kcal-h⁻¹-m⁻²) during 1 h immersion. In both resting and exercising subjects the M changed inversely with Tw. The relationship between the two variables is described by the equations:

Rest: \[ M = 173 - 3.8 \times Tw \]  
Exercise: \[ M = 245 - 4.1 \times Tw \]

It can be noticed that at all Tw the M of exercising subjects was approximately 60 kcal-h⁻¹-m⁻² (~70 W-m⁻²) higher than that of resting subjects, indicating that the external work load was maintained constant.

**Effect of subcutaneous fat thickness on deep body cooling**

Although general pattern of the Tre or M responses to immersion was similar, the quantitative change varied considerably depending upon the fatness of an individual. We therefore analyzed data after dividing the subjects into 3 different groups, Lean, Normal and Obese, according to their subcutaneous fat thickness (SFT) (Table 1).

The number of subjects in each group was 4 and the average SFT was 2.8 ± 0.2 (SE), 4.5 ± 0.2, and 7.7 ± 0.3 mm for the Lean, Normal and Obese group, respectively (Table 1).

Figure 4 shows the relationship between the cooling rate and the water temperature for each group. Both at rest and during exercise, the CR is linearly regressed with the Tw. The equations of regression lines are:

Rest, Lean: \[ CR = 5.33 - 0.148 \times Tw \]  
Rest, Normal: \[ CR = 3.97 - 0.115 \times Tw \]  
Rest, Obese: \[ CR = 1.93 - 0.066 \times Tw \]  
Exercise, Lean: \[ CR = 4.91 - 0.150 \times Tw \]  
Exercise, Normal: \[ CR = 3.26 - 0.106 \times Tw \]  
Exercise, Obese: \[ CR = 2.33 - 0.082 \times Tw \]

In covariance analysis the regression lines for each groups appeared to be significantly (p<0.01) different (in the intercept) between each other (except between Eqs. 5 and 6) both in resting and exercising conditions.

**Fig. 2.** Time course of changes in oxygen consumption (upper panel) and rectal temperature (lower panel) of subjects performing leg exercise in water. The external work load for each subject was adjusted to increase the metabolic rate by about 60 kcal-h⁻¹-m⁻². Data represent the mean of 12 subjects.

**Fig. 3** Deep body cooling rate (upper panel) and metabolic rate (lower panel) as a function of water temperature in resting and exercising subjects. Data represent the mean ± SE of 12 subjects. All the values for exercising subjects are significantly (p<0.05) different from the corresponding control values.
Discussion

Deep body temperature change during immersion.

In most subjects of the present study, the Tre declined in water below 30°C, regardless of whether they were resting or exercising (Figs. 1 and 2). This emphasizes that an exposure to sea water in most part of the world will eventually lead to hypothermia. The annual average Tw is below 25°C in 67% of the total global ocean surface and below 20°C in 47% (Beckman et al., 1966). It has been reported that during the World War II more than 30,000 British naval personnel, two-thirds of all fatal naval casualties, died of immersion hypothermia (Keatinge, 1969). It is therefore important to realize that one of the most critical physiological problems during sea water exposure is hypothermia.

In the present study the overall average cooling rate of the resting subjects changed linearly with the water temperature according to the equation 1. Calculation of cooling rate using this equation gives 1.08°C·h⁻¹ at 25°C, 1.64°C·h⁻¹ at 20°C, and 2.18°C·h⁻¹ at 15°C. These values are somewhat higher than those (0.39, 0.63, and 1.65°C·h⁻¹ at 25, 20 and 15°C, respectively) calculated by the equation of Hayward et al. (1975) (CR = 0.0785 - 0.0034 Tw, °C·min⁻¹). This discrepancy is probably attributed to the difference in subjects’ attire in the two studies. While the present subjects wore only swimming trunks, those in the above study wore standardized clothing (consisting of long sleeved, cotton shirts, long cotton pants, ankle socks, undershirts (male) or two-piece bathing suits (female), and running shoes) and kapok life jackets. Although the thermal insulation of clothing will disappear almost immediately upon wetted (Hall and Polte, 1956), as the insulation of clothing is primarily determined by the layer of stagnant air contained in it (Beckman, 1963), the convective heat loss, which constitutes the major avenue of heat drain from the body surface of the immersed person (Nadel et al., 1974), could be greatly reduced by wearing clothing. In fact, Keatinge (1961) has observed in subjects immersed in well circulated water at 15°C that during naked immersion the skin temperature was maintained at 2°C above the Tw and the Tre fell at a rate 0.33°C·20 min⁻¹, whereas during immersion with business suits the skin temperature could be maintained at 5.1°C above the Tw and the rate of Tre fall was reduced to 0.16°C·20 min⁻¹. Furthermore, the life jacket could provide an additional protection against heat loss. Since the physical insulation of life jacket itself may be quite big, and more importantly it covers the trunk in which the convective heat flux from the deep tissue to the surface can not be effectively controlled (Ferretti et al., 1988), the overall skin heat loss could be greatly reduced by wearing a life jacket.

In the present study the cooling rate in water appeared to be considerably smaller in exercising than in resting subjects (Fig. 3). Previous reports on the exercise effect are controversial. While in some studies (Cannon and Keatinge, 1960; Keatinge, 1961; Hayward and Keatinge, 1981) exercise accelerated body cooling, in other studies (Craig and Dvorak, 1968; Moore et al., 1970; McArdle et al., 1984; Toner et al., 1985; Golden and Tipton, 1987) it retarded cooling. Such a discrepancy among studies might be attributed to the difference in the type of exercise. Keatinge (1961) has observed that standardized swimming movement (whole body exercise) of moderate intensity (AM =100 kcal·h⁻¹·m⁻²) increased Tre fall in 5 and 15°C water but it had no effect on the Tre in 25°C water and converted a fall to a rise in 35°C water. More recently, Toner et al. (1985) and Golden and Tipton (1987) have observed in subjects immersed in water at 18-30°C and 15°C, respectively, that the Tre fall was significantly retarded by performing moderate leg exercise, as observed in the present study. Toner et al. (1984) have also noticed that the Tre fall was much smaller in leg exercise than in arm or combined arm-leg exercises. A high

**Fig. 4** Deep body cooling rate as a function of water temperature in lean, normal and obese subjects at rest (upper panel) and during exercise (lower panel). Data represent the mean ± SE of 4 subjects in each group.
heat loss in arm exercise compared with leg exercise was attributed to 1) a relatively high convective heat transfer from body core to the arm by exercise-induced hyperemia in a small muscle mass, 2) a relatively short thermal conduction distance between the tissue core and the surface in the arm, and 3) a relatively large surface area-to-mass ratio in the arm (Burton, 1985; Toner et al., 1984). Evidently, exercises involving arm movements have an adverse effect, while those involving primarily leg movements have a beneficial effect on the thermal economy of a subject immersed in cold water.

The present study clearly showed that the deep body cooling rate decreases with an increase in subcutaneous fat thickness (Fig. 4). The protective effect of subcutaneous fat in cold water immersion has been documented in numerous previous studies (Pugh and Edholm, 1955; Carlson et al., 1958; Cannon and Keatinge, 1960; Keatinge, 1960; Sloan and Keatinge, 1973; Holmer and Bergh, 1974; Kollias et al., 1974; McArdle et al., 1984). The present study, however, provides equations (Eq. 5 - 10) for quantitative analysis of such protective effect.

Prediction of deep body temperature change

The results of the present study could be used for predicting the degree of hypothermia during cold water immersion.

Studies on Korean women divers have indicated that the Tre of 35°C was the maximal degree of hypothermia that they voluntarily tolerated, regardless of the season (Kang et al., 1965; Kang et al., 1983). If the Tre falls below 35°C, mental and physical abilities to perform a task become impaired (Golden, 1973; Maclean and Emslie-Smith, 1977). Thus, a deep body temperature of 35°C can be chosen as the lower limit for maintenance of “useful activity”. The duration of underwater exercise for which the Tre would decline to 35°C (t_{limit}) can be estimated by the equation:

\[ t_{limit} (h) = \frac{(\text{initial Tre} - 35)}{\text{cooling rate}} + t_i \quad (11) \]

in which \( t_i \) is the initial delay (h) in Tre change (~ 15 min during exercise, Fig. 2). Such estimations for subject groups Lean, Normal, and Obese for a wide range of Tw (assuming that cooling proceeds linearly with time at all Tw) are illustrated in Figure 5. The initial Tre was assumed to be 37°C and the cooling rates at each Tw were estimated by Eqs. 8, 9, and 10 (the values of \( t_{limit} \) would be increased by ~ 20% if the initial Tre was assumed to be 37.5°C). The \( t_{limit} \) increases exponentially as the Tw increases in all groups. Figure 6 depicts that the \( t_{limit} \) increases as the subcutaneous fat thickness increases, the effect being greater at a higher Tw. Using Figures 5 and 6 one may predict how long an unprotected individual could sustain an useful underwater activity (such as skin or SCUBA diving). Thus, a man of average build with a 4 - 5 mm subcutaneous fat thickness, for instance, may engage in unprotected skin or SCUBA diving for ~ 1 h in 10

Fig. 5 Prediction of the time for useful activity as a function of water temperature in lean, normal, and obese subjects. The time for useful activity was defined as the duration of underwater leg exercise for which the Tre would decline from 37°C to 35 °C (\( t_{limit} \)) and was calculated using the following equation: \( t_{limit} (h) = (37 - 35)/\text{cooling rate} + t_i \).

Fig. 6 Prediction of the time for useful activity as a function of subcutaneous fat thickness at 4 different water temperatures.
°C water, ~ 2 h in 20°C water, and ~ 3.5 h in 25°C water without any problem, but will gradually fall into a danger if the diving is further prolonged.

The cooling rate data of the present study may also be used to predict a hypothetical survival time in an accidental immersion, as in a study by Hayward et al. (1975). Taking the Tre of 30°C as a criterion of hypothermic death (Hayward et al., 1975), the equation for survival time ($t_{\text{survival}}$, i.e., the duration of immersion for which Tre would decline to 30°C) is:

$$t_{\text{survival}} (h) = (37 - 30)/\text{cooling rate} + t_i \quad \text{(12)}$$

Figure 7 illustrates the average $t_{\text{survival}}$ estimated for all 12 subjects in the present study at various Tw. The cooling rates for resting and exercising conditions were calculated using the Eqs. 1 and 2, respectively, and $t_i$ was assumed to be 20 min at rest and 15 min during exercise (see Figs. 1 and 2). In general, the $t_{\text{survival}}$ increases exponentially with the Tw, and at the same Tw it is longer in exercising than in resting subjects, although the difference getting smaller in very cold water (the absolute values of $t_{\text{survival}}$ would be increased by ~ 6% in resting and ~ 7% in exercising subjects if the initial Tre was assumed to be 37.5°C, rather than 37°C). Also depicted in Figure 7 are $t_{\text{survival}}$ estimated by Hayward et al. (1975) for subjects wearing clothing and kapok life jacket (dashed curve) and by Molnar (1946) for Dachau prisoners (dashed lines). The present data appear to be comparable to the Molnar’s estimates of 50% survival, but somewhat lower than the estimates by Hayward et al. (1975), which may be due to a protective effect of clothing and life jacket in the latter study.

Figure 8 presents estimated $t_{\text{survival}}$ as a function of subcutaneous fat thickness. Cooling rates were calculated using Eqs. 5, 6 and 7 for resting subjects, and Eqs. 8, 9 and 10 for exercising subjects; the $t_i$ was assumed to be 20 and 15 min for resting and exercising subjects, respectively. The $t_{\text{survival}}$ increases with the fat thickness, and for a subject of a given fat thickness the $t_{\text{survival}}$ increases by doing leg exercise, the effect being greater at a higher Tw. During a prolonged accidental immersion the subject may not be able to sustain exercise, but will alternate exercise and rest, thus the actual $t_{\text{survival}}$ is predicted to be located somewhere between the values for resting and exercising conditions. Accordingly, a man with a 5 mm subcutaneous fat thickness, for instance, may survive for ~ 3 h in 10°C, ~ 6 h in 20°C, and ~ 10 h in 25°C water. The $t_{\text{survival}}$ may be slightly shorter than these for a lean subject, but much longer for an obese person (see Fig. 8). This emphasizes that the subcutaneous fat plays a very important role in protecting deep body temperature. It is therefore not surprising to find that most of the successful channel swimmers who swim across the English channel (34.5 km, average Tw in August and September is 15 - 16°C) are very obese (Pugh and Edholm, 1965).

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