Physiology of cold-water diving as exemplified by Korean women divers

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The specific heat of water is 1000 times and thermoconductivity 25 times greater than those of air. Consequently, the human body cools considerably faster in water than in air of the same temperature. This direct loss of body heat to the water is one of the most dominant problems of the diver even in tropical water, the temperature of which is still considerably lower than the thermoneutral level (34°–35°C). Since 1960, we have been studying thermal physiology of Korean and Japanese professional breath-hold divers (both sexes) who engage in stressful diving work in cold water (22°–25°C in summer and 10°C in mid-winter). Originally, we conducted extensive studies dealing with the assessment of the degree of cold stress and the pattern of cold acclimatization in traditional Korean women divers. More recently, these divers began to wear wet suits (since 1977 in Korean divers), which gave us an opportunity to study the time course of deacclimatization to cold through a series of longitudinal studies. In addition, the insulative value of wet suits while divers are engaged in underwater exercise has been critically reevaluated and some new important observations have been made.

COTTON-SUIT DIVERS

Figure 1 *A* depicts the average time course of changes in the rectal temperature of 4 cotton-suit divers during a diving work shift in summer (23°C water) and winter (10°C water) (1). There were considerable individual variations, but in general the rectal temperature remained unchanged during the initial 5–10-min period, and then declined steadily to approximately 35°C after 30 min in winter and after 60 min in summer, at which time the divers voluntarily terminated diving work. The mean skin

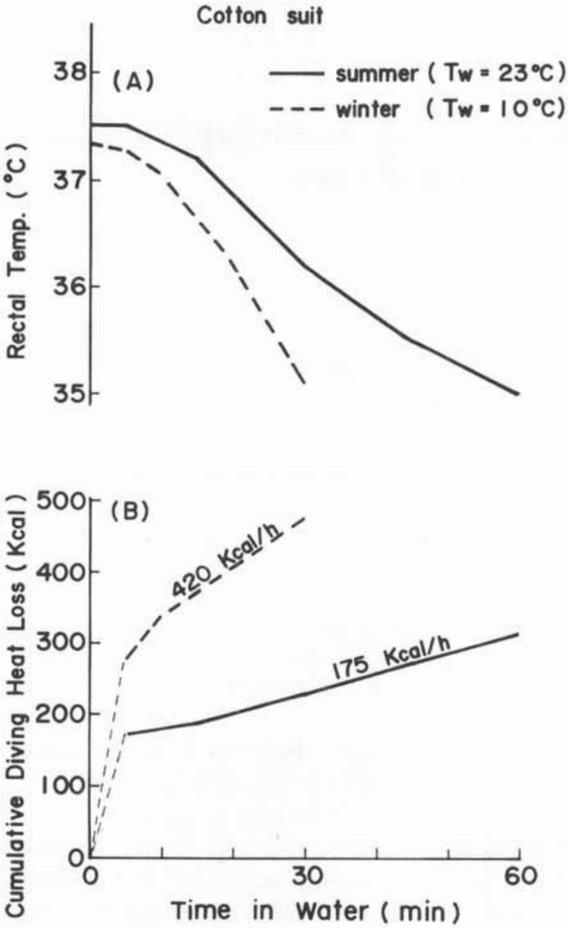

Fig. 1. Rectal temperature (*A*) and the cumulative heat loss (*B*) during diving work shifts in summer and winter. Redrawn from (1).

temperature dropped quickly from about 35°C to the level of water temperature; the reduction in mean body temperature was much greater in winter (8.4°C) than in summer (6°C). The calculated body heat debt was 28 and 119 kcal in summer and winter, respectively. These results indicate that the most important factor determining the working time is deep body cooling rather than the absolute amount of body heat loss.

Figure 1 *B* illustrates the cumulative extra heat loss during a diving work shift (1). The extra heat loss is the sum of the extra heat production over the resting value and the change in body heat storage; thus it represents thermal cost of diving work. In both summer and winter the thermal cost increased rapidly during the initial period, followed by a steady, slow increase. However, the rate of the steady heat loss (slope of the steady portion of the curve) was much greater in winter (420 kcal/h) than in summer (175 kcal/h), due to more intensive shivering in the winter. The total diving heat loss during a work shift appeared to be 320 kcal in summer (60-min shift) and 480 kcal in winter (30-min shift). Since they took three shifts a day in summer and one or two in winter, the average daily diving heat loss was estimated to be of the order of 1000 kcal (2, 3). Dietary survey indicated that the diver consumed approximately 3000 kcal/day in all seasons, which was 1000 kcal greater than that of the average Korean women (2, 3). To our knowledge this magnitude of daily voluntary heat loss has never been observed in any other group of human subjects.

Since these cotton-suit divers subjected themselves to such a great cold water stress throughout the year, they seem to have acquired a unique type of cold acclimatization. Figure 2 *A* shows that the basal metabolic rate of the diver increased markedly during the cold season (4, 5). In nondiving Korean women of similar age and socioeconomic status there was no such seasonal variation in the basal metabolic rate. Since the protein intake, erythrocyte counts, and hemoglobin concentration were not different between the 2 groups, it was concluded that the increase in basal metabolic rate in divers in the cold season is a manifestation of a metabolic acclimatization to cold stress.

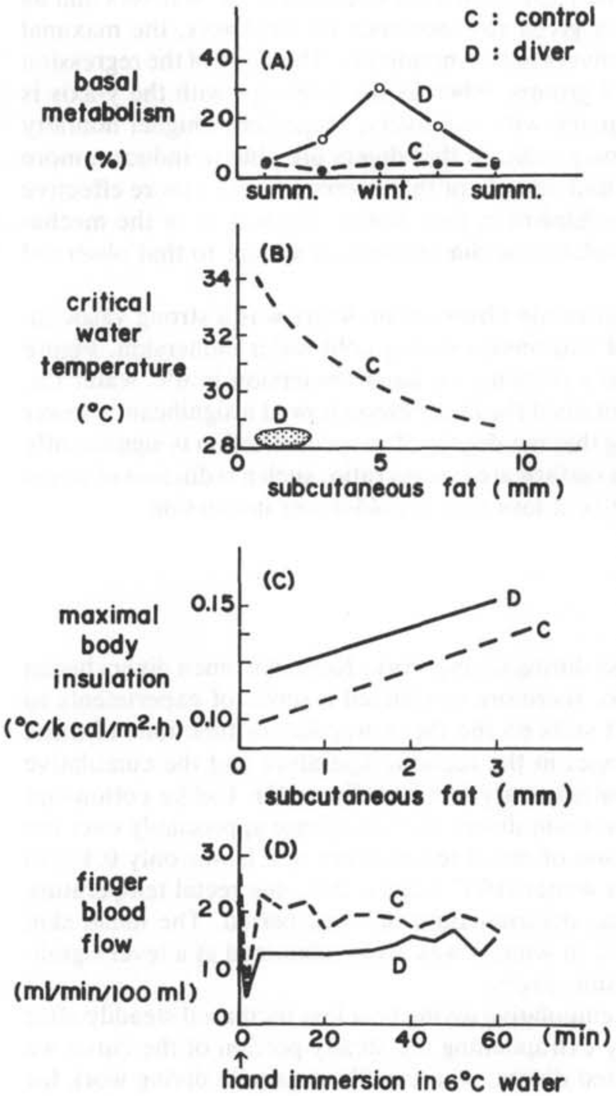

Fig. 2. Traditional cotton-suit divers compared with nondiving control subjects. Seasonal variations of basal metabolic rate (*A*), critical water temperature (*B*), and maximal body insulation (*C*) as functions of subcutaneous fat thickness, as well as finger blood flow while the hand was immersed in 6°C water (*D*). Data for *A* redrawn from (5), for *B* redrawn from (6), for *C* redrawn from (2), and for *D* redrawn from (9).

The shivering threshold of divers was much higher than that of nondivers (2, 6, 7). Figure 2 *B* depicts the critical water temperatures of divers and nondivers as a function of subcutaneous fat thickness (6). The critical water temperature was defined as the lowest water temperature one can tolerate for 3 h without shivering; thus, a lower critical water temperature is synonymous with an elevated shivering threshold. The critical water temperature decreased with subcutaneous fat thickness, as depicted for subjects from a nondiving population. It is seen that divers who were very lean tolerated without shivering much cooler water than nondivers of comparable fat thickness. Such an elevation of shivering threshold in the diver was observed in both summer and winter.

As a consequence of the elevated shivering threshold, these traditional Korean women divers could maintain a higher maximal body insulation than nondivers (2, 6, 7). The maximal body insulation is linearly correlated with the subcutaneous fat thickness. Figure 2 *C* compares the regression lines obtained from 30 divers and 89 nondivers (2). It is clear that, at a given subcutaneous fat thickness, the maximal body insulation is much greater in divers than in nondivers. The slope of the regression line is not different between the 2 groups, whereas the intercept with the y-axis is significantly higher in divers compared with nondivers, suggesting a higher nonfatty tissue insulation. These findings may indicate that divers are able to induce a more extensive vasoconstriction of the limb muscle or that divers possess a more effective countercurrent heat exchange mechanism in their limbs. Regardless of the mechanism, the basic pattern of this insulative acclimatization is similar to that observed in Australian aborigines (8).

Another feature of cold acclimatization observed in divers was a strong vasoconstriction in the most distal part of extremities during cold water immersion. Figure 2 *D* illustrates the finger blood flow response to hand immersion in 6°C water (9). During 1 h immersion, divers maintained the finger blood flow at a significantly lower level than in nondivers, suggesting that the degree of vasoconstriction is significantly greater. Since the finger has a high surface area: mass ratio, such a reduction of blood flow would effectively reduce the heat loss during cold-water immersion.

WET-SUIT DIVERS

To avoid severe cold water stress during diving work, Korean women divers began to wear wet suits in the 1970s. We therefore conducted a series of experiments to evaluate the effect of wearing wet suits on the thermoregulatory functions of these divers. Figure 3 summarizes changes in the rectal temperature and the cumulative diving heat loss observed in 4 contemporary wet-suit divers (1). Unlike cotton-suit divers, the rectal temperature in wet-suit divers did not change appreciably over the 2-h work period. The total reduction of rectal temperature in 2 h was only 0.4°C in summer (23°C water) and 0.6°C in winter (10°C water); thus, the rectal temperature was of no major importance in the determination of work period. The mean skin temperature (31°C in summer; 28°C in winter) was also maintained at a level significantly higher than that in cotton-suit divers.

In both summer and winter, the cumulative diving heat loss increased steadily after the first 30 min in water. Thus, by extrapolating the steady portion of the curve we estimated that the modern protected divers, who usually engage in diving work for

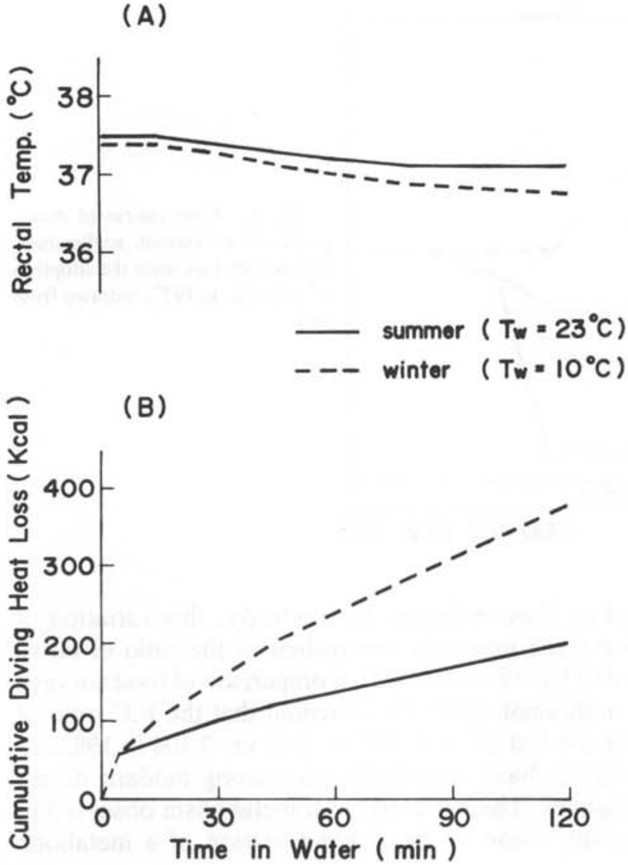

Fig. 3. Rectal temperature (*A*) and cumulative heat loss (*B*) during work in contemporary wet-suit divers; redrawn from (1).

3 h in a summer day and 2 h in a winter day, lose about 260 kcal in summer and 370 kcal in winter during a day. The rate of net heat loss, estimated from the slope of the steady portion of the curve, was approximately 80 kcal $\cdot$ h^{-1} in winter. These values are less than 35% of those observed in cotton-suit divers, indicating that the cold stress during diving work markedly decreased after divers adopted wet suits.

If the cold acclimatization observed in Korean women divers during the cotton-suit era (Fig. 2) was indeed developed through repeated exposures to severe cold water stress, it should disappear when the cold stress is removed by wearing wet suits.

Figure 4 summarizes the time course of deacclimatization of various thermoregulatory functions after wet suits were adopted in 1977 (10). The reversible increase in basal metabolic rate observed during cold seasons and the ability to maintain a high body insulation in cold water observed in both summer and winter had disappeared by 1980, i.e., within 3 yr of wet-suit diving. The mechanism of shivering suppression (i.e., a low critical water temperature) and the greater vasoconstriction of finger blood vessels during cold water immersion of a hand were sustained until Year 3 of wet-suit diving, but disappeared during the subsequent 3 yr.

A winter-high and summer-low type of seasonal variation of basal metabolic rate has also been documented among Japanese divers (11), although the magnitude was

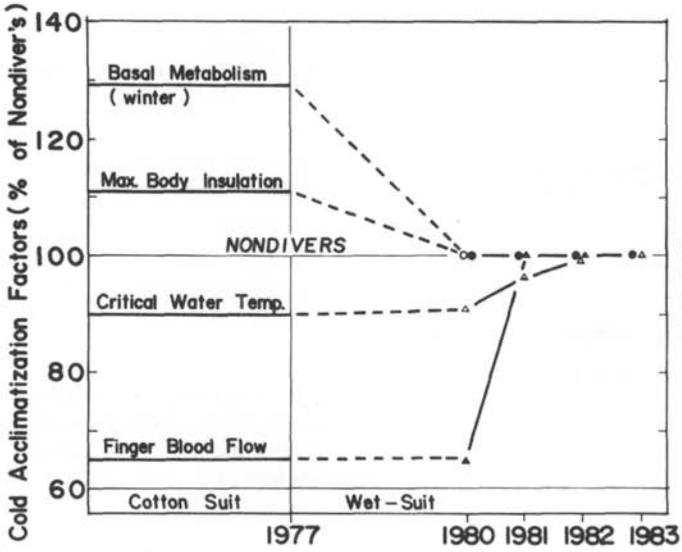

Fig. 4. Time course of disappearance of various acclimatization parameters since the adoption of wet suits in 1977; redrawn from (10).

much smaller than that observed in Korean divers. Interestingly, this variation of Japanese basal metabolic rate has been gradually diminished as the ratio of fat to carbohydrate (F:C ratio) in their diet has increased (12). Comparison of food surveys of contemporary divers (1) and traditional divers (3) indicated that the F:C ratio of Korean divers changed little over the last 20 yr (0.097 in 1962 vs. 0.104 in 1982) so the lack of seasonal variations in the basal metabolic rate among modern divers cannot be attributed to dietary changes. The elevated basal metabolism observed in previous divers during cold seasons seems to be a manifestation of a metabolic acclimatization to cold.

The attenuation of shivering mechanisms observed in the cotton-suit divers has been interpreted as an acclimatization process (2), and the mechanism underlying the shivering suppression is not clearly understood. However, our studies showed that when the shivering threshold of divers was higher than that of nondivers (such as in 1980), divers began to shiver at a lower core temperature than nondivers at the same cold water stress to the skin, and that during cold water immersion divers usually complained of internal chilling, not external chilling, whereas nondivers complained of external chilling (10). These facts may imply that the sensitivity of cutaneous cold receptors may be suppressed in divers, as has been observed in animals which are acclimatized to long-term cold (13).

A relatively high maximal body insulation in traditional cotton-suit divers was due to a higher insulation of the nonfatty shell than in nondivers (Fig. 2 *C*). Since the critical water temperature of divers was lower than that of nondivers (Fig. 2 *B*), passive cooling of the peripheral tissues (including muscles) might be greater, providing a thicker layer of nonfatty shell. In other words, the greater maximal body insulation observed in divers could be secondary to the elevation of their shivering threshold. However, the fact that the insulative acclimatization of the peripheral tissue disappeared in contemporary divers even faster than the mechanism of shivering attenuation suggests strongly that the elevation of the maximal body insulation is distinct from the elevation of shivering threshold. We therefore concluded that the insulative acclimatization of the peripheral tissue reflects a vascular acclimatization in which the diver could induce either a more extensive vasoconstriction of the limb musculature or a more effective countercurrent heat exchange in the limb (10).

Finally, reversal of the more intense vasoconstriction of the finger vessels during hand immersion in cold water took 4 yr. Perhaps this delayed return of the finger vascular response to normal was because the cold water stress to most parts of the body was immediately reduced by wearing wet suits but the cold stress to hands was not. Contemporary divers do not wear protective gloves even in winter, so their hands are still subjected to cold stress. This in turn suggests that the local vascular response observed in traditional divers had not been developed through the cold water stress to hands, but through the stress to the whole body. In this connection, it is important to point out that Gaspe fisherman (14) and British fish-filleters (15), who routinely expose their bare hands to cold water, have a considerably weaker finger vascular constriction during hand immersion than control subjects. Evidently, this type of acclimatization to local cold exposure is basically different from that of whole-body cold exposure.

The reduction of diving heat loss in Korean women divers after adoption of wet suits was apparently due to additional insulation provided by the suit. The overall thermal insulation (I_{total}) estimated in 4 divers using values of rectal-to-water temperature difference ($T_{re} - T_w$) and skin heat flux (H_{sk}) during diving work ($I_{total} = [T_{re} - T_w]/H_{sk}$) was approximately 2.5 times greater in wet-suit divers (0.170–0.193°C $\cdot$ kcal$^{-1} \cdot$ m$^{-2} \cdot$ h^{-1}) than in cotton-suit divers (0.068–0.081) (1). However, since the physical insulation of the wet suit may vary with the depth of diving due to compression of the trapped air in the suit (16), and since the physiologic insulation of the body may also decrease with exercise due to an increase in blood circulation to the working muscle (17), the overall insulation of the wet-suit diver will change with depth and workload.

Figure 5 depicts the effect of exercise on the steady-state insulation in nude (cotton-suited) (*A*) and wet-suited (*B*) subjects immersed in water of critical temperature (17). The subjects were immersed up to the neck in a circulating water bath and either rested for 3 h or exercised at a constant intensity using a submerged bicycle ergometer. As shown in Fig. 5 *A*, the body insulation declined progressively as the exercise intensity (expressed as a metabolic rate above resting value) increased. On the average, the insulation decreased to approximately 50% of the resting value with exercise at 2 Met (1 Met = 50 kcal $\cdot$ m$^{-2} \cdot$ h^{-1}). Thus, the skeletal muscle seems to provide as much as 80% of the total body insulation, with the subcutaneous fat and skin accounting for the remainder. This suggests that, for subjects immersed in cold water, the heat loss is controlled largely by blood flow to the skeletal muscle, with the subcutaneous fat and skin playing a less important role than commonly supposed.

The reason the skeletal muscle plays such an important role in providing insulation is that thermal control of blood flow, and hence insulation, is mostly accomplished in the extremities and not in the trunk (18). Cannon and Keatinge (19) have observed that in the subject immersed in water the thermal conductance of the hands and feet decreased drastically from 0.048 cal $\cdot$ cm$^{-2} \cdot$ min$^{-1} \cdot$ °C^{-1} at 35°C to 0.001 at 22°C. Over the same temperature range, the conductance of the chest decreased by only 36%, from 0.028 to 0.018 cal $\cdot$ cm$^{-2} \cdot$ min$^{-1} \cdot$ °C^{-1}. Barcroft and Edholm (20) observed that when an arm is immersed in 13°C water the forearm blood flow falls to only 0.5 ml $\cdot$ 100 ml$^{-1} \cdot$ min^{-1}, compared with 17.6 ml $\cdot$ 100 ml$^{-1} \cdot$ min^{-1} observed

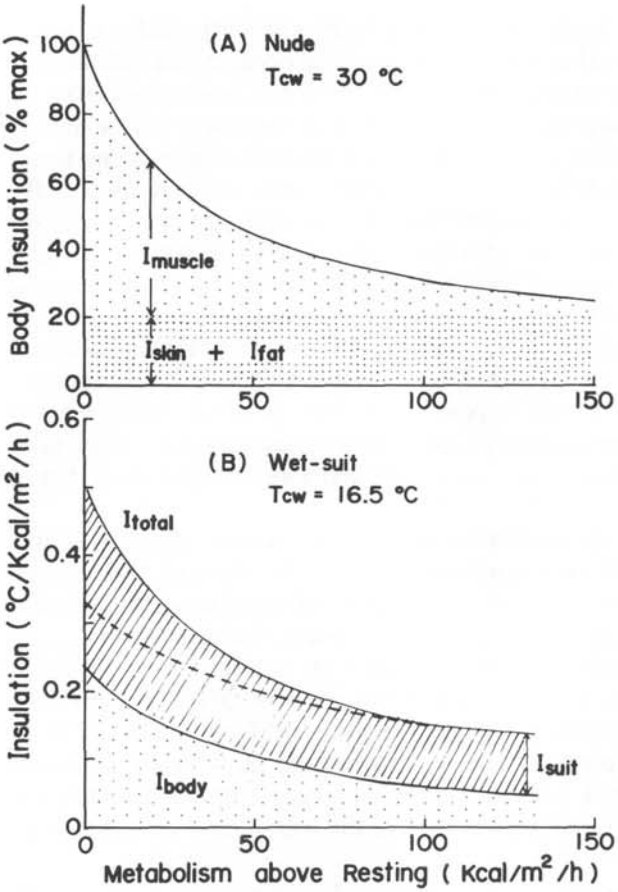

Fig. 5. Thermal insulations as function of metabolism above the resting level in water of critical temperature; cotton-suited (nude) in *A* redrawn from (17) and wet-suited in *B* redrawn from (23).

during immersion in 43°C water. Such a reduction in limb blood flow will not only retard heat transfer from the body core to the extremities but will also increase the efficiency of countercurrent heat conservation mechanisms, which are effective only when blood flow is sufficiently small (21). Therefore, most of the heat generated in the core of the subject while resting in cold water is lost through the trunk surface rather than through the limbs.

The counter-current mechanism may be even more important in wet-suited subjects. Since the physical insulation of foamed neoprene will decrease as the curvature of surface increases (22), the insulative value of wet suits will be much smaller in the limb than in the trunk. Furthermore, the design of diver wet suits is such that most of the trunk surface is covered by double sheets (pants and jacket) and the limbs by a single sheet. Thus, wet suits provide a good insulation to the trunk but a poor insulation to the limbs. Consequently, a restriction of blood flow to the limbs should greatly increase the efficiency of thermoregulation in the wet-suited diver. We have tested this hypothesis in a study on Korean women wet-suited divers (23).

As shown in Fig. 5 *B*, the overall (total) insulation decreased from about 0.5°C · $kcal^{-1} \cdot m^{-2} \cdot h^{-1}$ at rest to approximately one half at 2 Met and to one third of the resting value at 3 Met exercise. This decrease in total insulation (I_{total}) seemed to be due in part to the reduction in body insulation (I_{body}) and in part to the decrease in insulation afforded by wet suits (I_{suit}). The apparent I_{suit} estimated from the difference between the I_{total} and I_{body} (*striped area* in Fig. 5 *B*) was, on the average, 0.27°C · $kcal^{-1} \cdot m^{-2} \cdot h^{-1}$ at rest, but it decreased gradually with exercise intensity until it reached approximately 0.12°C · $kcal^{-1} \cdot m^{2} \cdot h^{-1}$ at 3 Met or above, similar to the physical insulation of 5-mm neoprene wet suit obtained using a copper manikin (24). Physical insulation of the wet suit should not change unless its thickness is changed. Since there was no apparent reason to expect a difference in the suit thickness between rest and exercise, we speculated that the unexpectedly high functional insulation of the wet suits in resting subjects is a consequence of physiologic regulation in cold water.

The skin temperature underneath the wet suit will become much lower in the extremities than in the trunk during immersion in cold water, so immersion with wet suits is analogous to exposing the limb to water colder than that to which the trunk is exposed. This will lead to a strong vasoconstriction in the extremities. Restriction of limb blood flow will greatly reduce the surface area for heat exchange, and most of the heat exchange between the body core and water will take place at the trunk surface where the suit insulation is relatively high (double sheets and low curvature). For these reasons, wet suits provide far greater physiologic insulation at rest than during exercise. Exercise hyperemia reduces not only the thermal insulation from the deep tissue to the skin but also the thermal insulation down the length of the limb, so much of the heat produced in the skeletal muscle is dissipated through the large surface area of limbs rather than returning to the body core. Figure 6 shows the effective heat exchange area A estimated in four Korean women wet-suit divers using the following formula (23): $A = I_{suit} \times 0.92\, M/(T_{sk} - T_w)$, where M is the steady-state metabolic rate in $kcal \cdot h^{-1}$, T_{sk} is the steady-state mean skin temperature, and I_{suit} is the physical insulation of wet suits, which was assumed to be constant at 0.12°C · $kcal^{-1} \cdot m^{-2} \cdot h^{-1}$ in all conditions. The area at rest was only 0.55 m^2, which

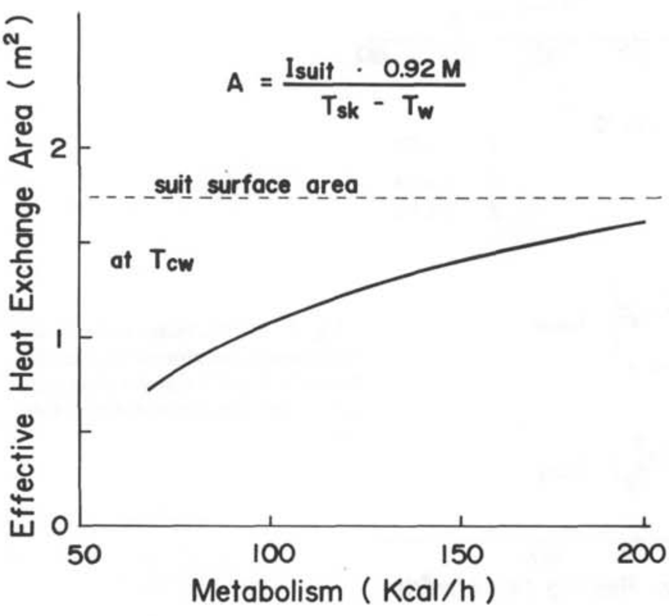

Fig. 6. Predicted changes in effective heat exchange surface area as function of metabolic rate in wet-suited divers. Metabolic rate was altered by adjusting the level of exercise in water of critical temperature; redrawn from (23).

was equivalent to 40% of the total suit surface area, but it increased with exercise and became identical to the actual suit surface area at a metabolic rate of approximately 200 kcal $\cdot h^{-1}$. This analysis strongly supports a notion that the relatively high apparent suit insulation in the resting subject may be due to a reduced surface area for heat exchange. One obvious practical implication of these findings is that if a wet-suited diver is in a situation where escape from the cold water is not possible, it is better to hold still than to swim if wasting of energy is to be prevented.

Figure 7 illustrates the effect of hydrostatic pressure on the thermal insulation in wet-suit divers (25). Subjects were immersed up to the neck for 2–3 h in 15°–16°C water in the wet-pot of a hyperbaric chamber. The chamber pressure was maintained at 1, 2, or 3 atm abs air. At all pressures, insulations declined inversely with exercise intensity. The I_{total}, either at rest or during exercise, decreased as the pressure increased. On the other hand, the I_{body} increased less at pressure than at the surface (1 atm abs). Consequently, the apparent I_{suit} (which is the difference between I_{total} and I_{body}) decreased as the pressure increased (Fig. 7 *inset*). The actual suit thickness reduced from 5-mm at 1 atm abs to 3.5 at 2 and 2.6 at 3 atm abs, so the physical insulation of the suit was decreased with pressure, and consequently skin surface under the suit was cooled more as the pressure increased. The mean skin temperature at rest was 27°C at 1 atm abs, <24.5°C at 2 atm abs, and 24.2°C at 3 atm abs. The

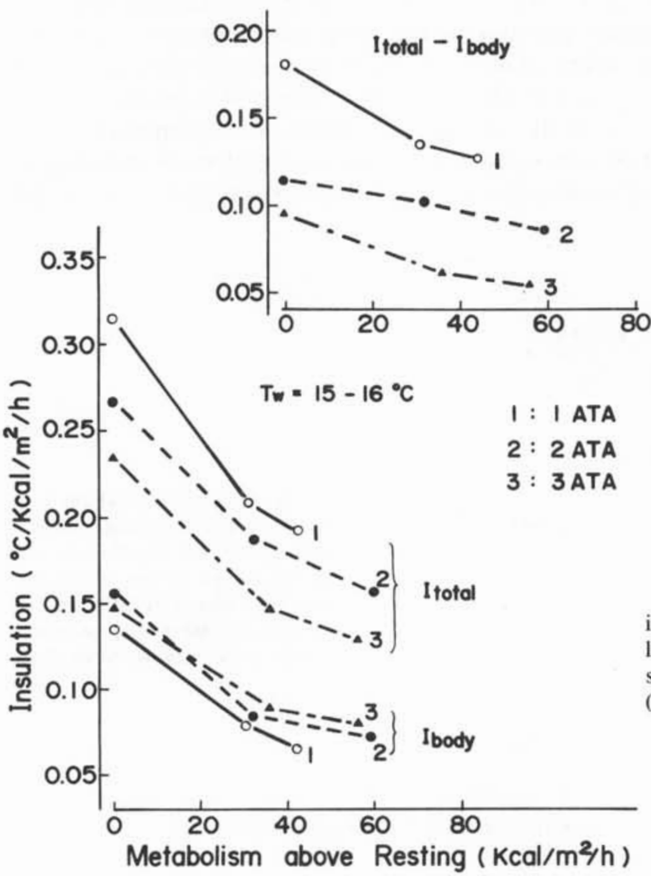

Fig. 7. Total, body, and wet-suit insulation as function of the metabolism at 1, 2, and 3 atm abs of air pressure in wet-suit divers; redrawn from (25).

relatively high I_{body} at 2 and 3 atm abs as compared with 1 atm abs may be attributed to more intensive peripheral vasoconstriction induced by the lower skin temperature at pressure.

In breath-hold diving, divers repeat the cycle of a dive and surface recovery, each lasting for 30–40 s in the case of Korean women divers. During surface recovery, divers are resting in a state of head-out water immersion, whereas during diving they exercise and are exposed to various degrees of hydrostatic pressure. Since the body insulation changes with exercise and the suit insulation decreases with pressure, as described above, the overall insulation of a breath-hold wet-suit diver will increase as the ratio of surface to dive time increases. Figure 8 summarizes the effect of voluntarily changing the surface to dive time ratio from 1 to 2 on the thermal insulation of two Korean women wet-suit divers. The average I_{body} increased from 0.062 to 0.075°C · kcal^{-1} · m^2 · h^{-1} and the I_{suit} from 0.126 to 0.153°C · kcal^{-1} · m^2 · h^{-1}; hence the overall insulation increased by about 23%. Thus, by adjusting the surface to dive time ratio one can prolong the working time without increasing heat loss during breath-hold diving. This wisdom of behavioral adjustment of diving pattern is actually observed in male wet-suit divers of Tsushima Island of Japan, whose surface to dive time ratio changes from 1.30 in summer to 1.97 in winter (26).

EFFECT OF WEARING GLOVES

Since contemporary Korean women divers do not wear protective gloves even during winter, we have evaluated the effect of wearing gloves on their thermal balance

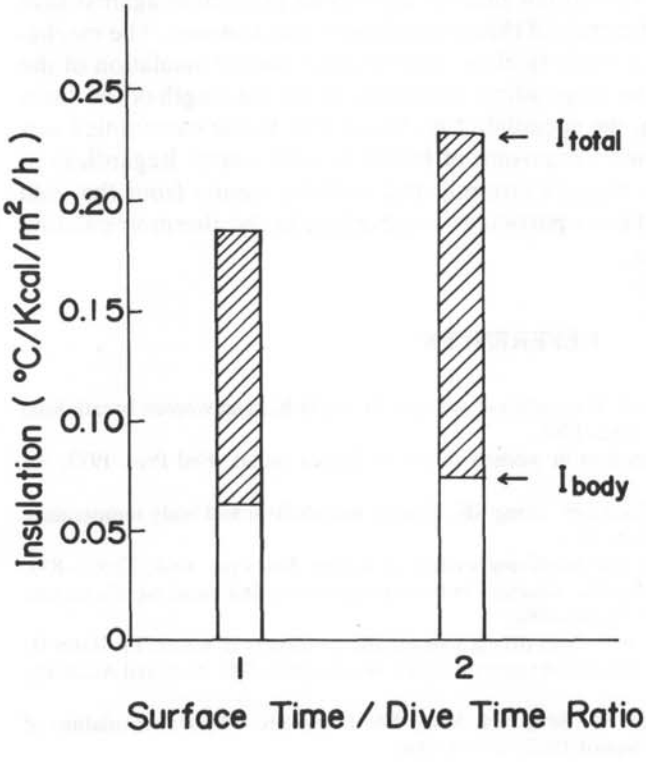

Fig. 8. Total and body insulation of wet-suit, breath-hold divers as function of the ratio of surface time to dive time from two women who dove to 4 or 5 m in summer; redrawn from (26).

TABLE 1
EFFECTS OF GLOVES DURING IMMERSION AT CRITICAL WATER TEMPERATURE[a]

	No Gloves	Gloves
Rectal temperature, °C	37.1	36.8[b]
Skin temperature, °C	28.5	27.9
Metabolic rate, $kcal \cdot m^2 \cdot h^{-1}$	44.8	49.0
Skin heat flux, $kcal \cdot m^2 \cdot h^{-1}$	46.7	54.7[b]
Total insulation, $°C \cdot kcal^{-1} \cdot m^2 \cdot h^{-1}$	0.43	0.36

[a]From Choi et al. (27). [b]Significantly different from the corresponding value without gloves.

during immersion in cold water (27). Subjects, clad with 5–6-mm-thick wet suits (jacket, pants, and boots) with or without wearing 3-mm-thick neoprene gloves, were immersed in water of critical temperature (17.3°C) and remained still for 3 h. Table 1 shows that the rectal temperature was slightly but significantly lower with gloves, and the skin heat flux was significantly higher. In both hands and forearms the regional heat flux, determined directly with a heat flux transducer, was higher and the thermal insulation index, calculated by dividing the rectal-to-local skin temperature difference with the local skin heat flux, was lower with gloves than without gloves (data not shown). Although gloves provided some additional insulation, their value was relatively so small that the total local insulation was still significantly lower than the tissue insulation alone without gloves. These results indicate that in wet-suited subjects resting in cold water, gloves do not provide additional protection against heat loss, but rather decrease the efficiency of thermoregulatory mechanisms. The mechanism for this phenomenon is not entirely clear, but because overall insulation of the body is mostly determined by the longitudinal regulation down the length of the limbs rather than the local insulation, we speculate that blood flow to the extremities was more effectively reduced by direct exposure of hands to cold water. Regardless of the mechanism, these findings suggest strongly that sensory inputs from the cold receptors in the distal extremities is particularly important in the thermoregulation during immersion in cold water.

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