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THERMOREGULATION IN WET SUIT DIVERS†

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= Abstract =

Thermoregulation of wet suit divers were studied during breath-hold diving in the sea and during exercise in temperature regulated water bath in 1, 2 and 3 ATA.

1) During breath-hold diving, heat loss in Korean women wet suit divers was more than 96% compensated by heat production, thus rectal temperature was decreased by only 0.4℃ in summer (22.5℃ water) and 0.6℃ in winter (10℃ winter) during 2hr diving work.
2) During immersion in cold water (14~19.5℃), total thermal insulation of the wet suit diver decreased as an exponential function of the exercise intensity, thus the steady state rectal temperature was not different whether the subject exercised or not
3) The apparent insulation afforded by the wet suit decreased as a function of pressure, and at the same pressure it decreased as a function of exercise intensity.
4) Practical consequence of these results will be discussed.

Maintenance of normal body temperature is a critical problem for divers working in cold water. Because of the high heat conductivity and heat capacity of water, body heat is rapidly lost from the skin to the adjacent layer of water. This drain of body heat is the principal problem of divers and, in fact, the dive time of unprotected divers is primarily determined by this loss of body heat[8,10]

As reported elsewhere[9] the thermal cost of diving in Korean women divers decreased remarkably since they adopted wet suits probably due to additional insulation provided by the suit. In breath-hold diving, divers repeat the cycle of a dive and surface recovery each lasting for 30~40 sec in the case of Korean women divers[11]. During surface recovery, divers are resting in a head-out water immersion, whereas

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during dives they exercise and are exposed to various degrees of hydrostatic pressure. As discussed by Rennie in the preceeding paper, insulation of the human body undergoes a dramatic reduction during exercise in water. Moreover, physical insulation of the wet suit changes with pressure due to compression of trapped air[1]. Therefore, overall thermal insulation (and hence heat balance) of breath-hold wet suit divers will be changed cyclically during the course of diving work

In the present paper, we will first present data of heat exchanges obtained in Korean women wet suit divers during their natural divng work, and then describe effects of exercise and pressure on the thermal insulation of wet suit divers in cold water.

Thermal Balance during Breath-Hold Diving

In 4 Korean women wet suit divers the heat exchange was studied while they were working in the sea (4~5 m depth)[9]. In order to evaluate the effect of wet suits on the thermal balance, the subjects wore wet suits (5 ㎜ thick neoprene jacket, pants, hood and boots) in one series and cotton suits (traditional diving suits of previous Korean women divers) in the other.

Fig. 1 compares the time course of rectal (T_R) and the mean skin ($\bar{T}_S$) temperatures of wet suit and cotton suit divers during diving work in summer (22.5 ℃ water) and in winter (10 ℃ water). In cotton suit divers, the T_R declined to about 35 ℃ in 30min in winter and in 1 hr in summer, at which time divers did not want to continue diving work any longer. The $\bar{T}_S$ dropped to 24 ℃ in summer and 13 ℃ in winter at the end of the work period, hence the reduction in mean body temperature ($\bar{T}_B = 0.6\, T_R + 0.4 \bar{T}_S$) was 8.4 ℃ in winter and 6 ℃ in summer. The loss of body heat content ($\Delta S = \Delta \bar{T}_B \times$ body wt x 0.83) was calculated to be 240 and 363 kcal in summer and winter, respectively. These results confirm the earlier notion that the most important factor determining the working time in unprotected divers is deep body cooling[8,10].

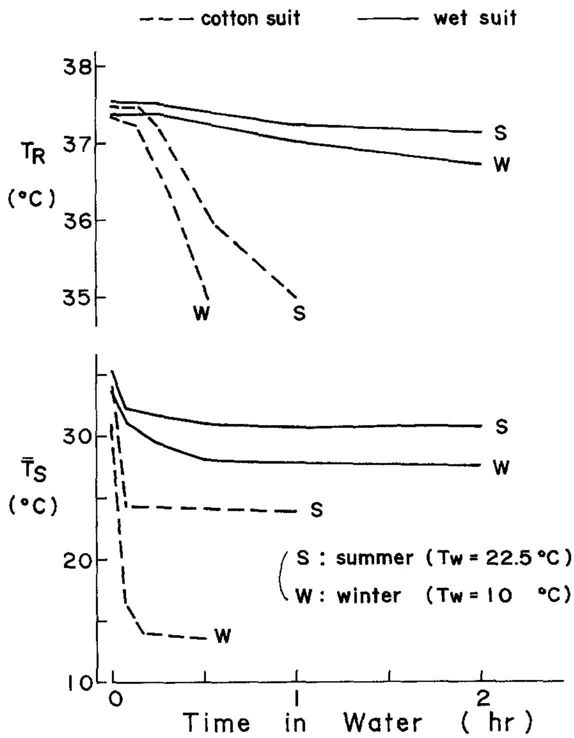

Fig. 1. Average time course of rectal (T_R) and mean skin ($\bar{T}_S$) temperatures of 4 women divers during wet suit and cotton suit divings in summer (S) and winter (W) Data based on Kang et al.[9]

During wet suit diving, divers did not experience such a hypothermia. The fall in T_R in 2hr was only 0.4 ℃ in summer and 0.6 ℃ in winter. Thus T_R was of no major importance in the determination of work period. The $\bar{T}_S$ was also maintained at a level significantly higher than that in cotton suit divers, but it is important to notice that $\bar{T}_S$ in winter was still well below the comfortable range (30~33 ℃). Values of $\bar{T}_S$ and $\bar{T}_B$ at the end of 2 hr work period were 31 and 35 ℃ in summer and 28 and 33 ℃ in winter, respectively. The calculated body heat debt was 28 and 119 kcal in summer and winter, respectively.

Fig. 2 summarizes average hourly values of heat production ($\dot{M}=4.83\ \dot{V}_{O_2}$) and heat loss ($\dot{H}=\dot{M}+\Delta\bar{T}_B\times$body wt$\times 0.83$) of 4 divers during the work shift. In summer, heat production and heat loss of wet suit divers were approximately equal (about 85 kcal/m²·hr), indicating that the subjects were in thermal steady-state However, in cotton suit divers the heat production (105 kcal/m²·hr) was only 60% effective in offsetting the heat loss (167 kcal/m²·hr). The amount of excess heat production in cotton suit divers over that in wet suit divers was about 20 kcal/m²·hr, which may represent shivering thermogenesis It is evident that even this small amount of shivering

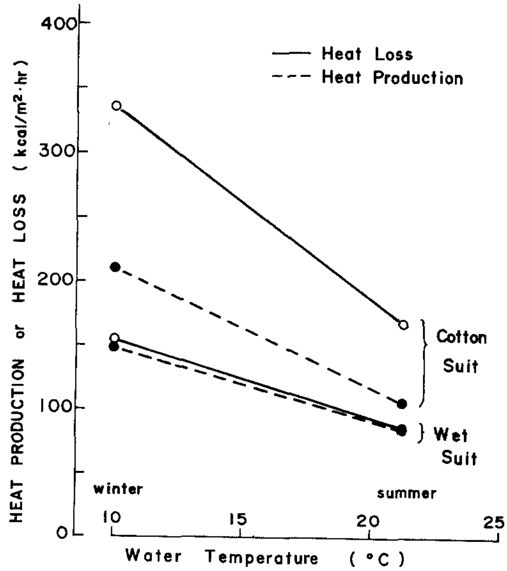

Fig. 2. Average heat production and heat loss of 4 women divers during wet suit and cotton suit divings in summer and winter Data based on Kang et al.[9]

accelerated heat loss more than heat production in unprotected divers, and that its elimination by wearing wet suits greatly improved the thermal economy of divers.

As expected, when water temperature decreased in winter, heat production (148 and 210 kcal/m²·hr in cotton suit and wet suit divers, respectively) and heat loss (153 and 335 kcal/m²·hr in cotton suit and wet suit divers, respectively) increased in both wet suit and cotton suit divers However, as in summer, the heat loss was nearly (95%) compensated by the heat production in wet suit divers, but only 60% compensated in cotton suit divers

The estimated shivering thermogenesis in winter was 64 and 126 kcal/m²·hr in wet suit and cotton suit divers, respectively It is of interest to note that the degree of shivering was greater in wet suit divers in winter than in cotton suit divers in summer (64 vs 21 kcal/m²·hr) although the T_R and $\bar{T}_S$ were higher in the former than in the latter (see Fig 1). Since the present subjects (also other Korean women divers) did not wear protective gloves even in the cold season, we speculated that the exposure of the hands to cold (10° C) water potentiated the shivering response in wet suit divers. In fact, Van Someren et al.[11] have observed that selective cooling of hands and feet stimulates heat production in subjects immersed in 29 ℃ water. Regardless of the mechanism, the effectiveness of shivering in maintaining thermal balance in wet suit divers is clearly evident in Fig. 2.

Evidently, the reduction of heat loss by wearing wet suits was due to additional insulation provided by the suit. As illustrated in Fig. 3, the total insulation estimated from the rectal to water temperature difference and skin heat loss ($I_{total}=(T_R-T_W)/\dot{H}s$) appeared to be 2.1 to 2.8 times greater in wet suit divers in summer and winter, respectively (0.170 vs 0.193 ℃/kcal/m²·hr in summer vs winter) than in cotton suit divers (0.081 vs 0.068 in summer vs winter). However, the tissue insulation ($I_{body}=(T_R-\bar{T}_S)/\dot{H}_S$) was not significantly different between the two conditions (approximately 0.07 ℃/kcal/m²·hr). Consequently, the additional insulation afforded by wet suits ($I_{suit}=I_{total}-I_{body}$) was 0.10 − 0.13 ℃/kcal/m²·hr. Since the physical insulation of wet suits may vary with the depth of diving and the physiological insulation provided by wet suits decreases with exercise (see below), the values of suit insulation obtained in working breath-hold divers, as described above, may only represent the average insulation during divig work. In any event, such a value of extra insulation is equivalent to the insulation that can be provided by the 17 mm fat layer (0.1 ℃/kcal/m²·hr÷0.006 ℃/kcal/m²·hr per mm fat=17 mm fat). Such an increase in subcutaneous fat insulation would reduce proportionately the heat loss of divers for a given temperature difference between the central body and water.

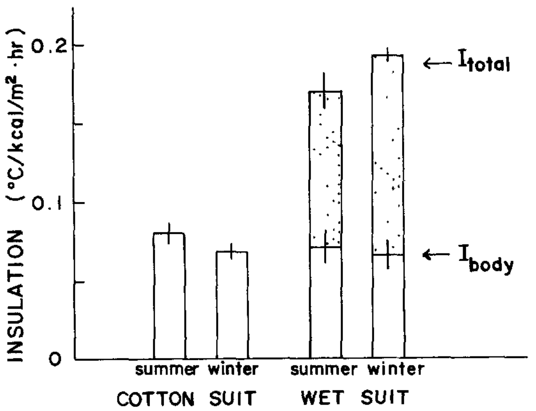

Fig. 3. Total and body insulations (I) during diving work in wet suit and cotton suit divers in summer and winter. The stippled portion of the bar represents the insulation provided by wet suits Each value represents the mean (±SE) of 4 women divers. Data based on Kang et al.[9]

Effect of Exercise on Thermal Balance of Wet Suit Divers

It is well known that exercise in cold water increases heat loss more than heat production in an unprotected individual.[4,7] In order to evaluate the effect of exercise on the thermal balance of wet suit divers we have measured heat exchanges in 4 Korean women wet suit divers at rest and during exercise in cold water. Subjects were clad in their personal wet suits (jacket, pants and boots of 5~6 mm thick) and were immersed up to the neck in a circulating water bath. The subject rested for 3 hr in a seated position or exercised for 2 hr at a constant intensity using a bicycle ergometer submersed in the bath. In order to prevent convective heat

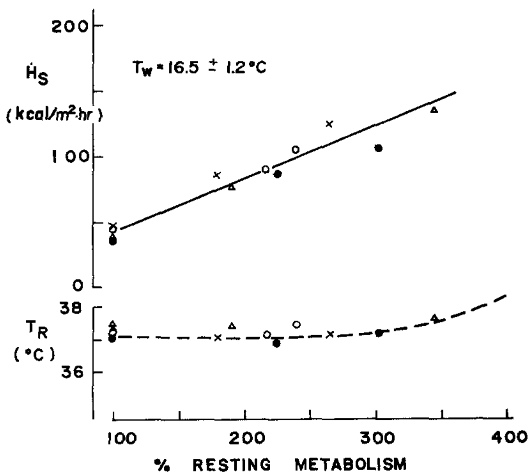

Fig. 4. Steady-state skin heat loss ($\dot{H}_S$) and rectal temperature (T_R) of 4 female wet suit divers as a function of exercise intensity (% resting metabolism) in water of critical temperature (T_{cw}). Each symbol represents an individual diver Dotted line represents T_R calculated using the following formuls : $T_R=T_W+(I_{total}\times 0.92\dot{M})$

loss from under the suit[15] we tapped the suit at the ankles and the wrists. For each subject the water temperature was adjusted to the critical temperature (Tcw, the lowest water temperature a resting subject could tolerate for 3 hr without shivering) in order to evaluate the thermal insulation at the maximal degree of peripheral vasoconstriction. The average Tcw with wet suits was 16.5±1.2 (SE) ℃.

Fig. 4 depicts average skin heat loss ($\dot{H}_S$) and rectal temperature (T_R) over the final 1 hr at rest or during exercise. The exercise intensity was expressed as a percentage of the resting metabolic rate. The $\dot{H}_S$ at rest was on the average 45 kcal/m²·hr, but it increased linearly with the exercise intensity. However, the T_R was not different whether the subjects were resting or were exercising at the various levels tested (less than 3.5 Met). These results indicate that thermal insulation decreased inversely with exercise intensity.

As shown in Fig. 5, the calculated overall insulation ($I_{total}=(T_R-T_W)/\dot{H}_S$) decreased from about 0.5 ℃/kcal/m²·hr at rest to approximately one half at 2 Met and to one third of the resting value at 3 Met. This decrease in I_{total} appeared 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. The I_{body} declined exponentially from 0.23 ℃/kcal/m²·hr at rest to 0.06 at 3 Met. The apparent suit insulation estimated from the difference between the total and body insulation ($I_{suit}=I_{total}-I_{body}$, stippled area) was on the average 0.27 ℃/kcal/m²·hr at rest, but it decreased gradually with exercise intensity until it reached approximately 0.1 ℃/kcal/m²·hr at above 3 Met. The latter value of I_{suit} is similar to the physical insulation of 5 mm neoprene wet suits obtained using a copper manikin[5]. Since there was no apparent reason for change in thickness (and hence physical insulation) of wet suits between rest and exercise we speculate that the unexpectedly high functional insulation of wet suits in resting subjects is a consequence of physiological regulations in cold water

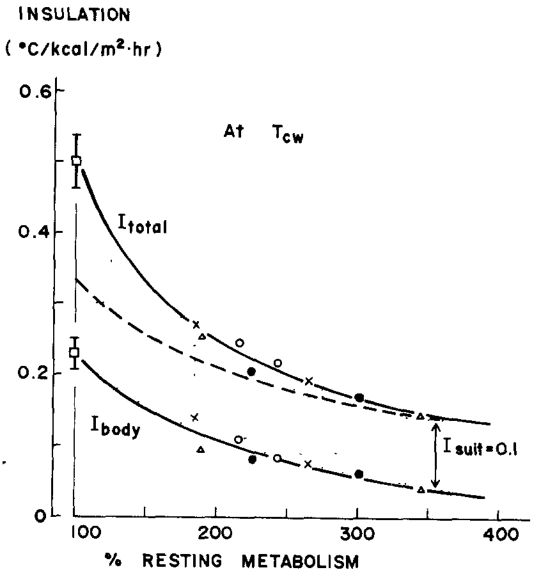

Fig. 5. Steady-state insulations (I) of 4 female wet suit divers as a function of exercise intensity in water of critical temperature In each subject, values of I_{total} and I_{body} were normalized against the corresponding mean value at rest Each symbol represents an individual diver Stippled area represents the insulation afforded by wet suits (I_{suit}). Dashed line represents the I_{total} calculated by adding an I_{suit} value of 0 1 to I_{body} at various exercise levels

When exposed to cold, the human body increases thermal insulation through peripheral vasoconstriction. As schematically illustrated in Fig. 6, this regulation of thermal insulation is mostly accomplished in the extremities and not in the trunk.[2,3,7] Infrared thermography studies by Hayward et al.[6] indicated that the highest skin temperatures following prolonged resting in water are lateral thorax, upper chest and groin. The constriction of limb blood vessels in cold water may occur also in wet suited subjects. Since the physical insulation of foamed neoprene will decrease as the curvature of surface increases[13], the insulative value of wet suits will be much smaller in the limb than in the trunk. Furthermore, the design of 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 good insulation to the trunk surface, but poor insulation to the limbs. As a consequence, the skin temperature underneath the suit will become much lower in the extremities than in the trunk during immersion in cold water (31.3 ℃, chest vs 26 ℃, leg in the present study).

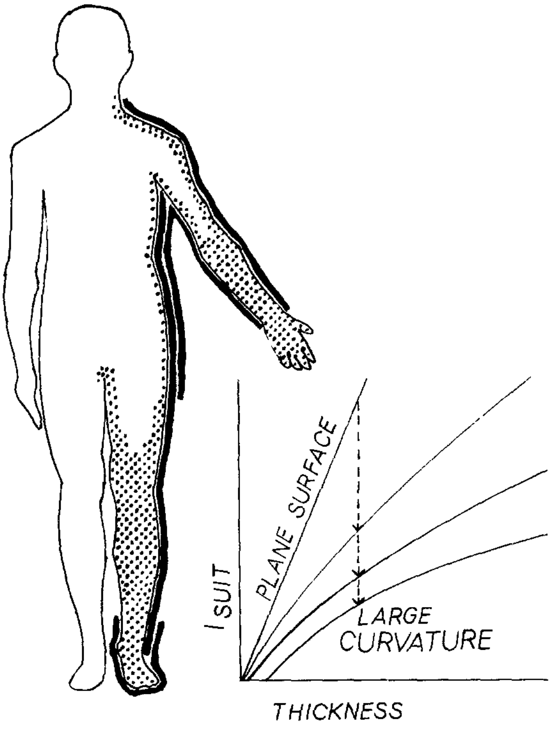

Fig. 6. A schematic illustration of the insulative shell (stippled area) of a wet suited subject in cold water. Note that the trunk is covered by double sheets (pants and jacket) and the limbs by a single sheet of the suit. Insetillustrates schematically changes in clothing insulation as a function of thickness and curvature (after Van Dilla et al. (12).

In other words, immersion with wet suits is analogous to exposing the limb to water colder than that exposing the trunk. This will lead to 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 suit insulation is relatively high. For these reasons, wet suits provide far greater physiological insulation at rest than during exercise The exercise hyperemia reduces not only the thermal gradient from the deep tissues to the skin but also thermal insulation down the length of the limb. Therefore, 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. Since the insulative value of wet suits is relatively low in the limbs because of its design (single sheet) and the high curvature, the effect of exercise is to increase the area for heat exchange over a poorly insulated region in parallel to the trunk. Added to this is increased convective heat loss from the escape of heated water at wrist, ankle and neck seals[15]. Estimation of the heat exchange area ($A = I_{suit} \times 0.92\dot{M}/(\bar{T}_S - T_W)$, $\dot{M}$ is metabolic rate in kcal/hr), assuming that I_{suit} is constant at 0.12 ℃/kcal/m^2·hr, indicates that the area at rest is only 0.66 m^2, which is equivalent to 40% of the total suit surface area (Fig 7). The heat exchange area increases with exercise and becomes almost identical to the actual suit surface area at $\dot{M}$=200 kcal/hr.

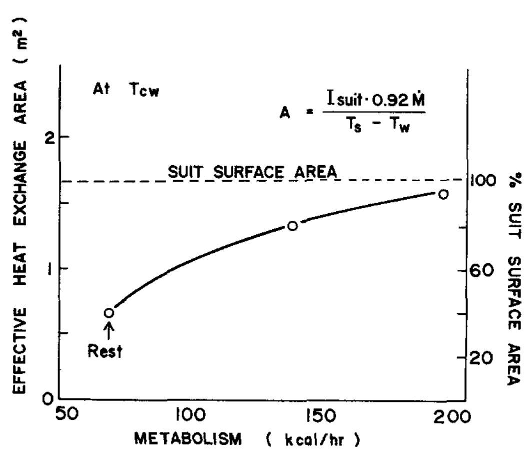

Fig. 7. The effect of heat exchange area of wet suits (A) at rest and at two levels of exercise. The formula for A is shown in the inset The value of I_{suit} was set at 0 12 ℃/kcal/m²·hr, which was observed for the 5 mm neoprene wet suit using an electrically heated manikin[11]

This analysis clearly indicates that the relatively high apparent suit insulation in the resting subject is due to reduced surface area for heat exchange.

Effect of Pressure on the Thermal Insulation of Wet Suit Divers

Having established the pattern of thermal exchange in wet suit divers at the surface of the water, we next investigated the effect of hydrostatic pressure on the thermal balance of divers.

Three male wet suit divers were immersed in 15~16 ℃ water in the wetpot of a hyperbaric chamber up to the neck. The chamber pressure was maintained at 1,2 or 3 ATA air. Subjects rested for 3 hr or exercised for 2 hr using a bicycle ergometer. The I_{total}, I_{body} and I_{suit} were estimated as described above when the body temperature change was minimal during the final hour of immersion. The actual thickness of suit reduced from 5 mm at 1 ATA to 3.5 at 2 ATA and 2.6 at 3 ATA Thus, the physical insulation of the suit might be decreased with pressure, and consequently skin surface underneath the suit was cooled more as the pressure increased. The $\bar{T}_S$ at rest was approximately 27 ℃ at 1 ATA, 24.5 ℃ at 2 ATA and 24.2 ℃ at 3 ATA. Fig. 8 illustrates thermal insulations at rest and during exercise in water at 1, 2 and 3 ATA air. The degree of exercise was expressed as the metabolism above resting. At all pressures, insulations declined inversely with exercise intensity The I_{total}, either at rest or during exercise, decreased as the pressure increased.

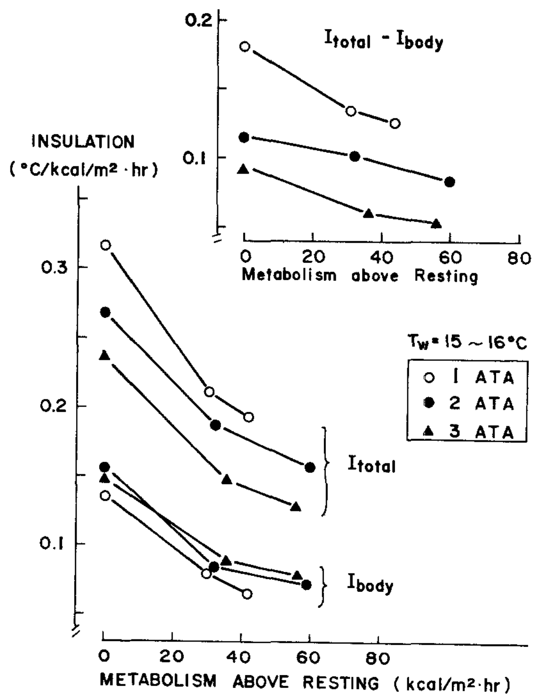

Fig. 8. Insulations (I) of wet suit divers at rest and during exercise in 15~16 ℃ water at 1, 2 and 3 ATA air Values represent the mean of 3 male divers

On the other hand, I_{body} increased slightly at pressure than at the surface (1 ATA). Consequently, the difference between I_{total} ant I_{body} (i.e., I_{suit}) decreased as pressure increased (inset). The relatively high I_{body} at 2 and 3 ATA as compared with 1 ATA may be attributed to more intensive peripheral vasoconstriction induced by the lower skin temperatures at pressure.

A practical implication of these findings is that if a wet suit diver is in a situation when escape from the cold water is not possible, he is better off to move to the surface and hold still than to swim if wasting of energy is to be prevented. Even with wet suits, exercise increases heat loss as much as heat production in cold water

Changes in Wet Suit Insulation with Surface to Dive Time Ratio in Breath-Hold Diving

Since the functional insulation of wet suits changes with exercise and pressure, as described above, the protective effect of wet suits in a breath-hold diver will increase as the surface to dive time ratio increases. In fact, a preliminary observation in 2 Korean women divers in summer (23 ℃ water) indicated that the apparent I_{suit} increased from 0.126 to 0.153 ℃/kcal/m²·hr as their surface to dive time ratio was changed from 1/1 to 2/1. Thus, by adjusting the surface to dive time ratio one can prolong the working time without increasing heat loss during breath-hold diving in cold water. This wisdom of behavioral adjustment of diving pattern (depending on water temperature) is actually observed in male divers of Tsushima Island, Japan, as will be presented by Shiraki in the following paper.

REFERENCES

1. Beckman EL : Thermal protection during immersion in cold water In : Underwater Physiology Vol Ⅱ, Lambertson CJ and Greenbaum LJ eds. Publ. 1181, National Academy of Sciences-National Research Council, Washington D C., 1963, pp. 247~266
2. Burton AC, Edholm OG : Man in Cold Environment. Hafner Pub. Co, New York and London, 1969
3. Cannon P, Keatinge WR : The metabolic rate and heat loss of fat and thin men in heat balance in cold and warm water. J Physiol 154 : 329, 1960
4. Crittenden G, Morlock JF, Moore TO : Recovery parameters following underwater exercise. Aerospace Med 45 : 1225, 1974
5. Goldman RF, Breckenridge JR, Reeves E, Beckman EL : "Wet" versus "dry" suit approaches to water immension protective clothing. Aerospace Med 37 : 485, 1966
6. Hayward JS, Collis M, Eckerson JD : Thermographic evaluation of relative heat loss areas of man during cold water immersion. Aerospace Med. 44 : 708, 1973
7. Kang DH, Kim PK, Kang BS, Song SH, Hong SK : Energy metabolism and body temperature of the ama. J Appl Physiol 20 : 40, 1965
8. Kang DH, Park YS, Park YD, Lee IS, Yeon DS, Lee SH, Hong SY, Rennie DW, Hong SK : Energetics of wet suit diving in Korean women breath-hold divers. J Appl Physiol 54 : 1702, 1983
9. Kang BS, Song SH, Suh CS, Hong SK : Chages in body temperature and basal metabolic rate of the ama. J Appl Physiol 18 : 483, 1963
10. Keatinge WR : Survival in Cold Water, Blackwell Scientific Pub., OXford and Edinburgh, 1969

11. Park YS, Rahn H, Lee IS, Lee SI, Kang DH, Hong SY, Hong SK : Pattern of wet suit diving in Korean women breath-hold divers. Undersea Biomed Res 10 : 203, 1983
12. Van Dilla M, Day R, Siple PA : Special problem of hands. In : Physiology of Heat Regulation and the Clothing, Newburgh LH ed, Philadelphia, Saunders, 1949, pp. 374~388
13. Van Someren RNM, Coleshaw SRK, Mincer PJ, Keatinge WR : Restoration of thermoregulatory response to body cooling by cooling hands and feet. J Appl Physiol 53 : 1228, 1982
14. Wolff AH, Coleshaw SRK, Newstead CG, Keatinge WR : Heat exchanges in wet suits. J Appl Physiol 58 : 770, 1985