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ENERGETICS AND THERMOREGULATORY FUNCTIONS IN KOREAN WOMEN WET SUIT DIVERS*

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= Abstract =

Korean women divers have dived for sea food in all seasons wearing only cotton swimsuits. Previous studies conducted in the 1960's indicated that these women divers subjected themselves to a daily cold water stress greater than that of any other human beings and that they had developed an unique pattern of cold acclimatization(2). However since 1977 Korean women divers have adopted wet suits to avoid cold water stress during diving work. We therefore conducted a series of experiments from 1980 to investigate the effect of wearing wet suits on the thermoregulation of contemporary women divers(5, 7). The results of some of these investigations are presented below.

ENERGETICS OF DIVING

Heat Exchanges during Diving Work

In 4 divers(average age 37 yrs, height 159cm, weight 51kg, BSA 1.51m^2) the heat exchange was studied while they were working in the sea both in summer(August, 1981) and in winter(February, 1982) using the same method as employed in a previous Korean diver study(4). In order to evaluate the effect of wet suits on the thermal balance, the subjects wore wet suit in one series (protected divers), and cotton suits in the other(unprotected divers).

Changes in Body Temperature

The most important factor determining the working time of the previous cotton suit diver was deep body cooling rather than absolute amount of heat loss (3, 4). Divers voluntarily terminated their work when the rectal temperature (T_R) fell to about 35℃, the time to reach this point being proportional to the sea water temperature (T_W). The amount of heat loss during a work shift was much greater in cold seasons than in warm seasons.

Exactly the same result was observed in unprotected divers in the present study. As depicted in Fig. 1, unprotected divers terminated diving at 60 min. in summer and at 30 min. in winter.

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However, the final T_R was 35℃ in both seasons. The mean skin temperature(T_S) calculated from the skin temperature measured at forehead(T_f), the chest(T_c) and a lower leg(T_l) ($T_S=0.05T_f+0.45T_c+0.5T_l$) dropped to 24℃ in summer and 13℃ in winter at the end of work period; hence the reduction in the mean body temperature($T_R=0.6T_B+0.4T_S$) was much greater in winter(8.4℃) than in summer(6℃). The loss of body heat content(i. e., heat debt=$\triangle T_B \times$body wt. $\times 0.83$) was calculated to be 240 and 363 kcal in summer and winter, respectively. These results confirm once again that T_R is the most critical factor determining the working time in unprotected divers.

In protected divers, T_R was not appreciably altered over the 2 hr work period. The reduction in T_R in 2 hr was only 0.4℃ in summer and 0.6℃ in winter. Thus, T_R was of no major importance in the determination of the work period in protected divers. The T_S(and hence T_B) was also maintained at a level significantly higher than in unprotected divers. The average T_S and T_B at the end of 2 hr in water was 31 and 35℃ in summer and 28 and 33℃ in winter. The calculated heat debt was 28 and 119 kcal in summer and winter, respectively.

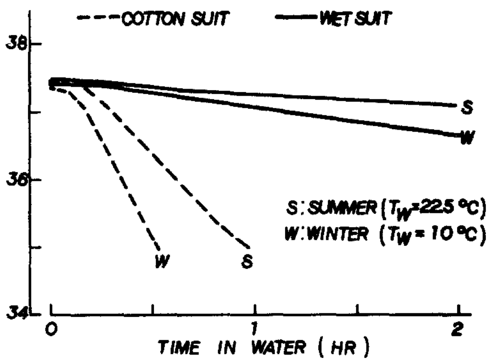

Fig. 1. Average time course of rectal temperature (T_R) of 4 divers during protected(wet suit) and unprotected(cotton suit) divings in summer(S) and winter(W). Values are based on Kang at. al., (5).

Heat Exchanges

Table 1 summarizes average values of heat production ($\dot{M}=4.83\ \dot{V}_{O_2}$) and heat loss ($\dot{H}=\dot{M}+\triangle T_B \times$ body wt. $\times 0.83$) of 4 divers during the work shift. In summer, $\dot{H}$ and $\dot{M}$ of protected divers were essentially equal (about 85 kcal/hr · m²), indicating that the subjects were in the thermal steady-state. Both the $\dot{H}$(167 kcal/hr · m²) and $\dot{M}$(105 kcal/hr · m²) in unprotected divers were higher than in protected divers, but in this case the $\dot{M}$ was only 60% effective in offsetting the H. The amount of excess heat production in unprotected divers over that in protected divers was about 20 kcal/hr · m². This amount may represent shivering thermogenesis (M_T), since the resting conditions during which the heat production was measured was comparable for all subjects. It is evident that even this small amount of shivering accelerates heat loss more than heat production in unprotected divers, and that its elimination by wearing a wet suit greatly reduces the waste of energy.

In winter, $\dot{M}$(148 and 210 kcal/hr · m² in protected and unprotected divers, respectively) and $\dot{H}$(153 and 335 kcal/hr·m² in protected and unprorected divers, respecrively) were approximately 2-fold higher than the corresponding values observed in summer. However, as in summer, the heat loss was nearly (95%) compensated by the heat production in protected divers, but was only 60% compensated in unprotected divers. The estimated M_T was 64 and 126 kcal/hr · m² in protected and unprotected divers, respectively. It is of interest to note that the degree of shivering was greater in protected divers in winter than in unprotected divers in summer (64 vs 21 kcal/hr · m²) although the T_R and T_S were higher in the former than in the later (see above). It is speculated that the exposure of the face and hands to the 10℃ water evoked the shivering response in protected divers. In fact, Van Someren et.al. (9) have observed that local cooling of hands and feet stimulates heat production in nude subjects immersed in 29℃ water. Regardless of mechanism, the effectiveness of shivering in maintaining thermal balance in protected divers

Table 1. Heat exchange (kcal/hr · m²) during diving work

	Summer		Winter	
	Wet suit	Cottom suit	Wet suit	Cotton suit
$\dot{H}$	86	167	153	335
$\dot{M}$	84	105	148	210
M_T	0	21	64	126

$\dot{H}$: total heat loss, $\dot{M}$: total heat production
M_T : shivering thermogenesis.
Values are based on Kang et al. (5).

is clearly evident in Table 1.

Evidently, the protective effect of wet suit on the thermal balance was due to the additional insulation provided by the suit. Calculations of overall shell insulation ($I=(T_R-T_W)/\dot{H}_S$, $\dot{H}_S$= skin heat loss) for present subjects during diving indicated that overall I of protected divers (0.182 ℃/(kcal/hr · m²)) was 2.5 times that of unprotected divers (0.075) in all seasons. The insulation of wet suit estimated in protected divers by subtracting the tissue insulation ($I_t=(T_R-T_S)/\dot{H}_S$) from the total insulation averaged about 0.1℃/(kcal/hr · m²). This is equivalent to the physical insulation of fat layer of 17mm thickness (0.1℃/(kcal/hr · m²) ÷ 0.006℃/(kcal/hr · m²) per mm fat = 17 fat). Such an increase in fat insulation would reduce proportionately the heat loss of divers for a given temperature difference between the central body and water.

Fig. 2 illustrates the cumulative extra heat loss during work. The extra heat loss is the sum of extra heat production over the resting value and the heat debt; thus it represents thermal cost of diving. Irrespective of the season, the thermal cost to protected divers appeared to be considerably less than that to unprotected divers, although the difference was much greater in winter than in summer. In all cases the cumulative extra heat loss increased rapidly during the initial period, followed by steady, slow increase. Thus, by extrapolating the steady portion of the curve to any time period, one can estimate the energy cost of diving work for that period. Such an estimation indicated that the mordern protected divers, who usually engage in diving for 3 hr in a summer day and 2 hr in a winter day, loses about 260 kcal in summer and 370 kcal in winter in daily diving work.

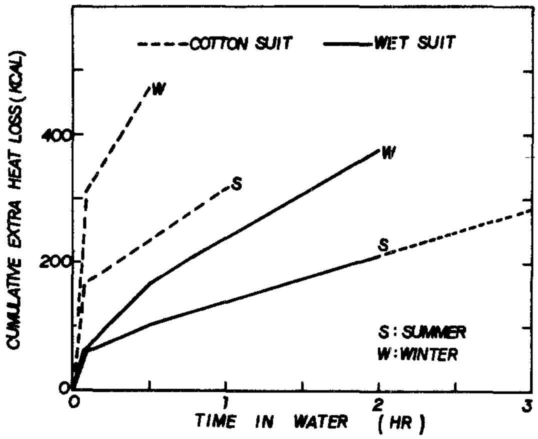

Fig. 2. Cumulative extra heat loss in protected (wet suit) and unprotected (cotton suit) divers. Values are from Kang et. al. (5).

Daily Energy Balance

In previous divers, the daily thermal cost of diving was estimated to be 1,000 kcal in all seasons, which was compensated adequately by increasing the dietary intake and by heat gain upon returning to shore (4). The amount of food intake of the diver was determined to be 3000 kcal/day which was 1,000 kcal/day greater than that of the average nondiving Korean women (2,000 kcal/day).

Table 2 compares the net thermal cost of diving work and the amount of dietary intake in previous (1960) and contemporary (1980) divers. Unlike the previous divers the contemporary divers incurred a net thermal loss of 260 kcal a day for diving in summer and 370 kcal in winter. Regardless of the season, their caloric intake was 2,500 kcal/day. The caloric intake of the nondiving housewife of similar socio-economic level was 2,200 kcal/day (5). Thus, the amount of extra dietary intake by the diver of 300 kcal/day was in reasonable balance with the daily thermal cost of diving work.

Prediction of the Limiting Diving Time

Since T_R of 35℃ appeared to be the maximal degree of hypothermia that women divers voluntarily tolerated, it was attempted to define the theoretical time limit of diving work in terms of deep body cooling.

In both protected and unprotected divers the rate of T_R decline after 10—20 min was proportional to the initial T_R-T_W difference; thus the cooling rate per unit T_R-T_W gradient was about 0.01 and 0.21℃/hr per ℃ (T_R-T_W) in protected and unprotected divers, respectively, in all seasons. Using these values and the initial delay in T_R change (t_i) the duration of diving work (t_{limit}) in which the T_R would decline to 35℃ was calculated.

$$t_{limit} = \frac{37℃-35℃}{(\text{cooling rate}/\triangle℃)\cdot(37℃-T_W)} + t_i$$

Such estimation for protected and unprotected divers for a wide range of T_W are illustrated in Fig. 3. This analysis indicates that it will take at least 15 hr in summer and 8 hr in winter before the T_R declines to 35℃ in mordern protected divers.

STATUS OF COLD ACCLIMATIZATION

Thermoregulatory functions of previous Korean women cotton suit divers were different from those of nondivers (see Ref 2). For instance, 1) their BMR was increased significantly during cold seasons; 2) resting $\dot{V}_{O2}$ increased significantly in response to exogenous norepinephrine in winter (i.e., apparent nonshivering thermogenesis), 3) the shivering threshold was always much higher than in nondivers; 4) the maximal tissue insulation was considerably higher than in nondivers; 5) during immersion in cold water the heat flux through extremities for a given blood flow was lower than in nondivers; 6) and the finger blood

Table 2. Thermal cost of diving work and food intake of Korean women divers

	1960[a] (Cotton suit)		1980[b] (Wet suit)	
	Summer	winter	Summer	winter
Number of Work shift	3	1-2	1	1
Duration of a Work shift (min)	70	16	180	170
Final Rectal Temperature (°C)	33	35	37.2	36.7
Total Extra Heat Loss (kcal)	1,000	500-1,000	260	370
Food Intake (kcal/day)	3,065	2,925	2,496	2,495

[a]Kang et. al. (4) and Hong(2)
[b]Kang et. al. (5)

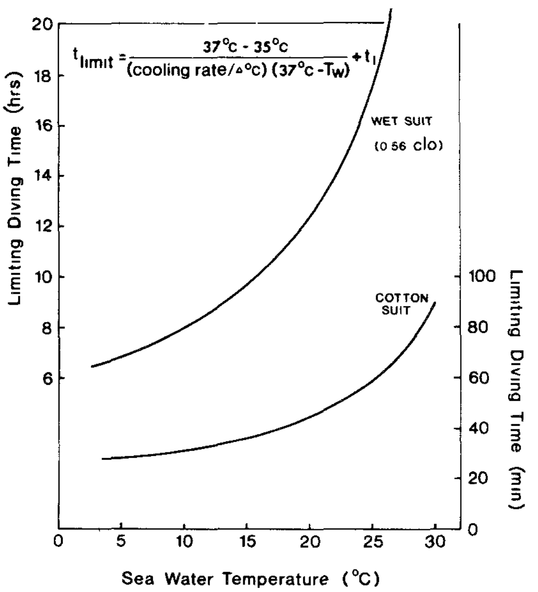

Fig. 3. A prediction of the limiting diving time in protected(wet suit) and unprotected(cotton suit) divers.

flow during hand immersion in 6℃ water was lower than in nondivers. These alterations in thermoregulatory functions in divers were taken as evidence for cold acclimatization (2).

If this pattern of cold acclimatization is indeed developed through repeated exposures to severe cold water stress, it should disappear when the cold stress is removed. As described above, the contemporary wet suit divers are no longer exposed to the severe cold water stress to which previous cotton suit divers were subjected daily (see Table 2). We therefore undertook the present series of investigations over a 4-year period (1980 — 1983) to reassess the cold acclimatization in these contemporary divers (7).

Eighteen each of divers and nondivers were recruited at random from a similar socio-economic level and their thermoregulatory functions were measured using techniques identical to those employed in previous series of diver studies (3, 6, 8). The results indicated that various types of cold acclimatization phenomena documented in previous Korean divers have gradually disappeared since divers started wearing wet suits in 1977.

Fig. 4 summarizes the time course of deacclimatization for each of several thermoregulatory functions. The reversible increase in BMR during cold seasons and the ability to maintain a higher tissue insulation in cold water had disappeared by 1980, i.e., within 3 years of wet suit diving. The mechanisms of shivering suppression and the greater vasoconstriction of finger blood vessels during cold water immersion were sustained until the third year of wet suit diving, but disappeared during the subsequent 2 years. This gradual return to normal physiological response to cold reinforces the original conclusion that cold acclimatization as manifested by earlier studies (2) did in fact exist prior to adoption of the wet suit.

A winter-high and summer-low type of seasonal variation of BMR has also been documented among Japanese (10) though the magnitude was much smaller than that in previous Korean divers. Interestingly, this variation of Japanese BMR has been gradually diminished as the ratio of fat to carbohydrate (F/C ratio) in their diet has increased (10). Comparison of food survey data of contemporary divers (5) and previous divers (4) indicated that the F/C ratio of Korean divers changed little over the last 20 years (0.097 in 1962 vs 0.104 in 1982). Thus the lack of seasonal variations in BMR among contemporary Korean divers can not be attributed to dietary changes. This in turn suggests that the elevated BMR in previous divers during cold seasons was a manifestation of metabolic acclimatization to cold.

Shivering mechanism of previous diver was attenuated as indicated by the lower critcal water temperature in divers than in nondivers, which has been interpreted as an acclimatization process economizing body heat balance of unprotected divers in cold water (8). The mechanism underlying the shivering suppression is not clearly understood. However, it was observed in the present study that when diver's shivering threshold was still higher than nondiver's (such as in 1980), at the same cold stress to the skin, divers began to shiver at a lower core temperature than nondivers, and that during cold water immersion, divers usually complained of internal chilling, not external chilling, whereas nondivers complained of external chilling. These facts may imply that the cold receptor sensitivity was suppressed in divers as observed in long-term cold acclimatized animals(1).

The maximal tissue insulation (I_{max}) attainable by previous Korean divers was much higher than that by nondivers. The overall tissue insulation consisted of insulations provided by unperfused skin, cutaneous fat and muscle layers in series. Since the physical insulations of fat and skin may not be different between divers and nondivers, the relatively high I_{max} in previous divers must be due to a relatively high muscle insulation (i.e., more intensive vasoconstriction in muscle layer, or an increased thickness of muscle shell). Such an insulative acclimatization in the muscle layer disappeared in contemporary divers even faster than the mechanism of shivering attenuation. This in turn suggests that the elevation of I_{max} in previous divers was distinct from the elevation of shivering threshold.

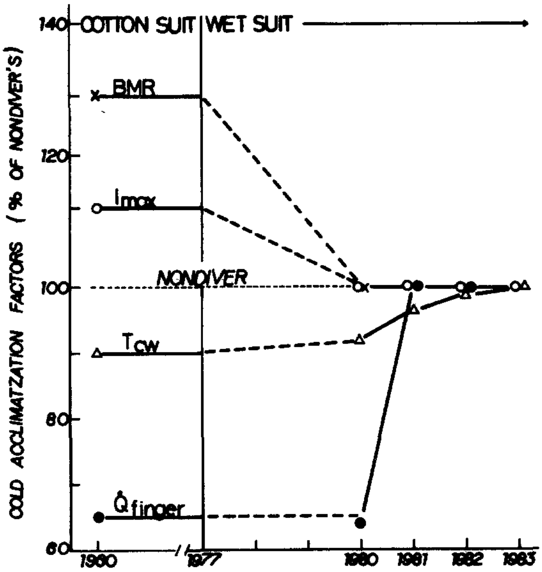

Fig. 4. Relative values of various thermoregulatory functions in previous (1960) and contemporary (1980's) divers. Values are based on Park et. al. (7) and unpublished data. BMR: basal metabolic rate, I_{max}: maximal tissue insulation, T_{cw}: critical water temperature, $\dot{Q}_{finger}$: finger blood flow during hand immersion in 6℃ water

Finally, reversal of the mechanism of more intense cutaneous vasoconstriction of divers during hand immersion in cold water took 4 years. Perhaps this delayed return of the cutaneous vascular response to normal was because the cold water stress to most parts of the body was immediately reduced by wearing wet suit, but the stress to hands was not. The contemporary divers do not wear protective gloves throughout the year, hence their hands are still subjected to cold water stress. This in turn suggests that the local vascular response observed in previous divers had not been developed through the cold water stress to hands, but through the stress to the whole body.

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