高神大學醫學部 論文集 第3卷 第1號
The Journal of Kosin Medical College
Vol. 3, No. 1, March, 1987

DAILY ENERGY COST OF BREATH-HOLD DIVING

Y.S. Park, K. Shiraki* and S.K. Hong**

Departments of Physiology,
Kosin Medical College, Pusan, Korea

**Univerity of Occupational and Environmental Health,*
Kitakyushu, Japan
***State University of New York at Buffalo,*
Buffalo New York, U.S.A.

= Abstract =

Use of wet-suits by Korean women breath-hold divers enable them to prolong a diving work period with no marked drop in the body temperature in all seasons. Despite great increase in daily working time, the total energy cost of diving and the daily food intake of divers reduced remarkably after adoption of wet-suits. The pattern of heat exchanges during wet-suit diving in Japanese male breath-hold divers were generally similar to that of Korean women divers. However, seasonal changes in the diving energetics was different between the male and female divers.

The results are presented in relation to working conditions in the field and in terms of physiological mechanisms.

INTRODUCTION

Over the last 2,000 years professional breath-hold divers in Korea and Japan have harvested the ocean floor for shellfish, sea urchins, sea weeds and other marine organisms. It is estimated that in Korea and Japan today more than 20,000 practice this profession. Interestingly, while only women are engaged in this type of diving work in Korea, both men and women are involved in Japan. Traditionally these divers wore only cotton diving suits which provided no protection against eventual hypothermia during diving work. In 1960s and 1970s, however, they adopted wet suits to avoid this profession. Interestingly, while only women are engaged in this type of diving work in Korea, both men and women are involved in Japan. Traditionally these divers wore only cotton diving suits which provided no protection against eventual hypothermia during diving work. In 1960s and 1970s, however, they adopted wet suits to avoid cold water stress; thus their working time has been considerably prolonged and the energy cost of diving work reduced markedly. The present paper summarizes these changes documented for Korean women divers and compares energetics of wet-suit diving between male (Japan) and female (Korean) unassisted breath-hold divers.

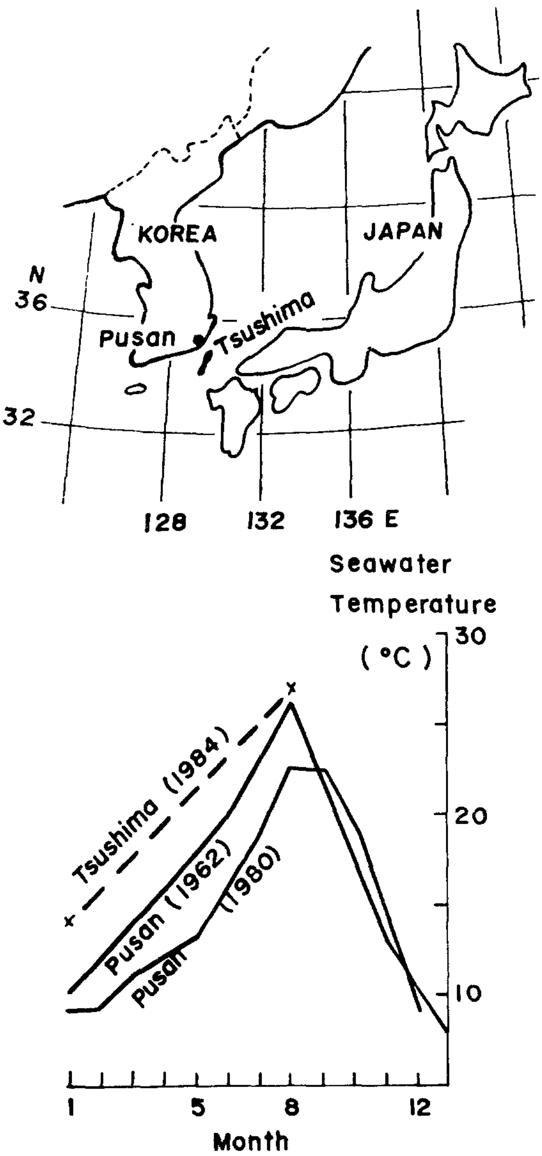

Fig. 1. Seawater temperature at the diving ground in Pusan, Korea and Tsushima Island, Japan

1. SEA WATER TEMPERATURE AND DIVING PATTERN

Fig. 1 depicts geographical location and the sea water temperature in Pusan, Korea and Tsushima Island, Japan where studies described in the present paper[3,4,5,6,9,10,11,12,13] have been conducted. In Pusan the sea water temperature changes from 9~10℃ in mid-winter (January-February) to 22~27℃ in mid-summer (August-September) and in Tsushima it change from 14℃ in January to 27℃ in August.

Because of such a great seasonal variation in the sea water temperature, working pattern of divers also change with season.[4,9,12] As summarized in Table 1, average duration of a work shift in previous Korean women cotton-suit divers varied from 60 min in summer to 20 min in winter. Since they worked 2~3 shifts in summer but only 1 or 2 shifts in winter, the total time for daily diving work decreased from 120~180 min in summer to 20~40 min in winter. Although such marked seasonal changes in working time are not seen in contemporary Korean women wet-suit divers, the duration of a work shift (and the total working time) is still shorter in winter (120 min) than in summer (180 min). A similar change in working time between warm and cold seasons is observed in Japanese male wet-suit divers.

Seasonal changes in the dive time and the surface time in male divers are of particular interest. The average duration of a dive is 15% shorter and

Table 1. Typical Diving Pattern of Korean Women and Japanese Male Breath-Hold Divers.

	Single			Duration of	Work Shift	Total
	Dive Time (sec)	Surface Time (sec)	S/D	Work Shift (min)	per Day	Working Time (min)
Korean Women Cotton-Suit Divers (1960s)[a]						
Summer	30	30	1	60	2 – 3	120 – 180
Winter				20	1 – 2	20 – 40
Korean Women Wet-Suit Divers (1980s)[b]						
Summer	32	46	1.44	180	1	180
Winter				120	1	120
Japanese Male Wet-Suit Divers (1980s)[c]						
Summer	39	42	1.08	138	2	276
Winter	33	47	1.42	80	3	240

a. Hong et al.[3] and Kang et al.[4]

b. Kang et al.[6]

c. Shiraki et al.[12, 13]

the surface time is 12% longer in winter than in summer; hence surface time to dive time ratio increases by 27% in winter as compared with summer. This change in diving pattern may have some bearing on the seasonal difference in the thermal insulation in the male divers (see below).

2. THERMAL COST OF DIVING IN KOREAN WOMEN DIVERS

A. Heat Exchanges during Diving Work

Fig 2 depicts body temperature changes during the work shift observed in previous cotton-suit divers[5] and in modern wet-suit divers.[6] In cotton-suit divers (dashed lines), rectal temperature (Tr) remained unchanged during the initial 5~10 min period, and then it declined steadily to approximately 35℃ in 30 min in winter (Tw=10℃) and in 45 min in summer (Tw=22℃), at which time they voluntarily terminated diving work. The mean skin temperature ($\bar{T}s$) dropped quickly from about 35℃ to the level of water temperature; hence the

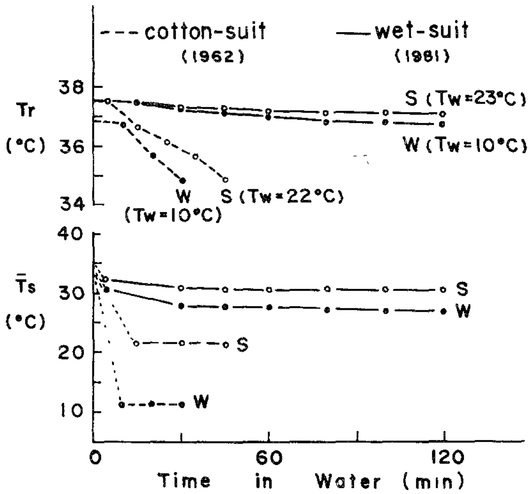

Fig. 2. Chanes in rectal (Tr) and mean skin (Ts) temperatures of Korean women cotton-suit (dashed curves) and wet-suit (solid curves) divers during diving work in summer (S) and in winter (W). Redrawn from Kang et al.[5,6]

reduction in mean body temperature ($Tb=0.6\ Tr+0.4\ \bar{T}s$) was much greater in winter (9.7℃) than in summer (6.1℃). These results indicate that the most important factor determining the working time of the cotton-suit divers was deep body cooling rather than absolute amount of body heat change.

In wet-suit diver (solid lines), Tr was not appreciably altered over the 2 h work period. The reduction in Tr in 2 h was only 0.4℃ in summer (Tw=23℃) and 0.6℃ in winter (Tw=10℃). Thus, Tr was of no major importance in the determination of the work period in wet-suit divers. The $\bar{T}s$ (and hence Tb) was also maintained at a level significantly higher than that in unprotected divers. The average $\bar{T}s$ and Tb at the end of 2h in water was 31 and 35℃ in summer and 28 and 33℃ in winter.

Fig. 3 compares metabolic responses to diving in cotton-suit (1962) and wet-suit (1981) divers In both groups, the oxygen consumption ($\dot{V}O_2$) increased rapidly during the first few minutes of diving work, the increment being greater in winter than in summer. After this initial rise, $\dot{V}O_2$ in cotton-suit divers increased further, whereas that in wet-suit divers remained unchanged during the rest of work period in all seasons. The extra $\dot{V}O_2$ during the diving work over the resting value will represent the extra amount of oxygen utilized to support the work itself (diving and swimming) and to cope with cold stress. The work load of diving may not be significantly different between cotton-suit and wet-suit divers. Thus, the relatively high $\dot{V}O_2$ in cotton-suit divers as compared with wet-suit divers may represent the higher degree of shivering in the former. In fact, cotton-suit divers shivered visibly even in summer, at the end of each work shift, as they returned to the shore to get warmed up by a fire[4] The higher level of $\dot{V}O_2$ in winter than in summer in wet-suit divers indicates that even with wet-suits, shivering takes place during the diving work

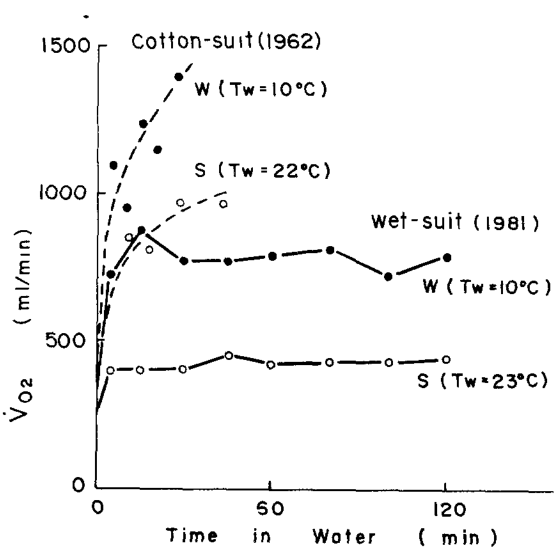

Fig. 3. Changes in oxygen consumption during diving work in summer (S) and in winter (W) in Korean women cotton-suit (dashed curves) and wet-suit (solid curves) divers. Based on the data of Kang et al.[5,6]

in the cold season. In this connection, it is important to point out that contemporary Korean women divers do not wear protective gloves even in cold winter. We therefore speculate that the exposure of hands and face to 10℃ water evoked shivering response in wet-suit divers. In fact, Van Someron et al.[14] have observed that local cooling of hands and feet stimulates the heat production in nude subjects immersed in 29℃ water.

Fig. 4 illustrates the cumulative extra heat production and the reduction in body heat content (i.e., heat debt) in water. The sum of these two values gives extra heat loss (i.e., thermal cost of diving). The extra heat production was calculated from the extra $\dot{V}O_2$ over the resting value ($\Delta\dot{M}=\Delta\dot{V}O_2\times 4.83$) and the heat debt from the change in Tb in water and the specific heat of the body ($\Delta S=\Delta Tb \times BW/BSA\times 0.83$). In cotton-suit divers (1962),

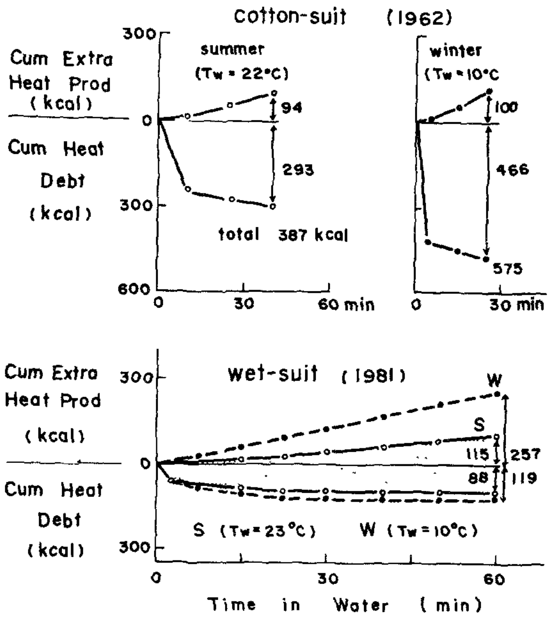

Fig. 4. Cumulative extra heat production and heat debt during diving work in summer(S) and in winter(W) in Korean women cotton-suit(Top) and wet-suit(Bottom) divers. Based on the data of Kang et al.[5,6]

both the extra heat production and the body heat debt at a given work period were greater in winter than in summer, as expected. In both seasons, however, the magnitude of heat debt was far greater than that of extra heat production, indicating that divers experienced severe degree of negative thermal balance during work and most of the heat loss was from the body heat storage.

The extra heat production and the heat debt in modern wet-suit divers (1981) appeared to be significantly smaller than those in cotton-suit divers. Furthermore, unlike the heat debt in cotton-suit divers, which was significantly greater in the cold season than in the warm season, that in wet-suit divers was only slightly different between the two seasons This indicates that the extra heat produced by shivering in winter is effectively utilized in maintaining thermal balance in wet-suit divers.

Fig. 5 depicts the cumulative extra heat loss during diving work. Irrespective of the season, the thermal cost in contemporary divers appeared to be considerably less than that in previous cotton-suit divers. In all cases the cumulative extra heat loss increased rapidly during the initial period, followed by a steady, slow increase. Thus, by extrapolating the steady portion of the curve we estimated that previous divers incurred the net thermal loss of approximately 550 kcal in a typical 20 min work shift in winter and 450 kcal in a 60 min work shift in summer. On the other hand, modern wet-suit divers, who usually engage in diving work for 2 h in a winter day and 3 h in a summer day, use only 370 kcal in winter and 260 kcal in summer in diving work.

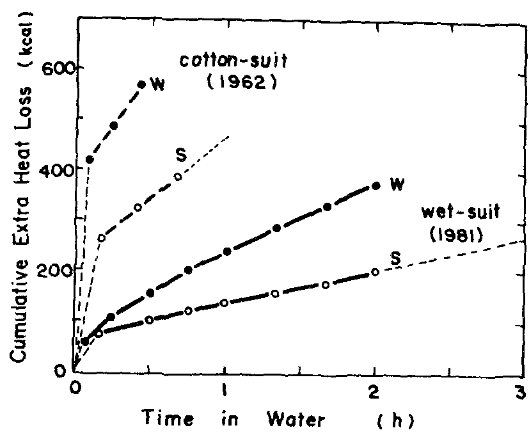

Fig. 5. Cumulative extra heat loss during diving work in summer (S) and in winter (W) in Korean women cotton-suit (dashed curves) and wet-suit (solid curves) divers. Based on the data of Kang et al.[5,6]

Evidently, such a great reduction of diving heat loss in contemporary divers is due to additional insulation provided by wet-suits. Calculations of thermal insulation using the value of Tr, Tw and the skin heat loss ($\dot{H}s=0,92\dot{M}$) during diving work ($I=[Tr-Tw]/\dot{H}s$) indicated that the overall insulation of the wet-suit diver (0.18−0.19℃/kcal/m²·h) was 2.5 times that of the previous cotton-suit diver (0.07℃/kcal/m²·h).[6]

B. Daily Energy Balance

Fig. 6 compares the energy cost of daily diving work and the amount of dietary intake in previous (1960) and contemporary (1980) Korean women divers. The energy cost was estimated from the net thermal loss during a work shift (Fig. 5) and the number of shift per day (Table 1) Previous divers lost 900 (2 shifts)-1,300 (3 shifts) kcal a day in summer and 550 (1 shift)-1,100 kcal (2 shifts) a day in winter for diving work. Thus, the energy cost of daily diving work was approximately 1,000 kcal in all seasons[5]. This amount of extra energy loss was compensated adequately by increasing the dietary intake and by heat gain upon returing to shore[5]. The amount of food intake was determined to be approximately 3,000 kcal/day in all seasons, which was approximately 1,000 kcal/day greater than that of the average Korean women at that time (2,000 kcal/day) The contemporary diver used 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 value for the non-diving housewife of similar socioeconomic level was 2,200 kcal/day[6] Thus, the amount of extra food intake by the diver (300 kcal/day) was in reasonable balance with the daily thermal cost of diving work.

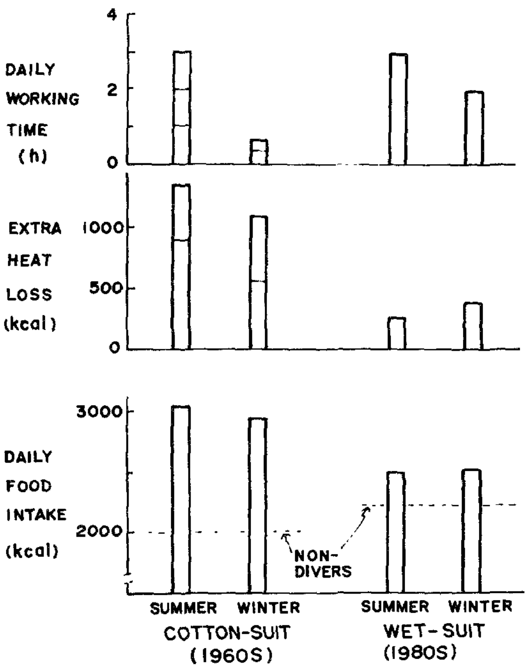

Fig. 6. Total daily diving time (Top), extra heat loss due to diving (Middle) and daily food intake (Bottom) in Korean women cotton-suit (1960s) and wet-suit (1980s) divers. Based on the data of Kang et al.[4] and Kang et al.[5,6]

Although food intake of divers reduced markedly their body fat content increased significantly after adoption of wet-suits. The average subcutaneous fat thickness of divers determined in 1980 was 8.9㎜ (skinfold thickness 21.8㎜) which was nearly 4 fold greater than that determined in 1962(2.2㎜, skinfold thickness 8.4㎜)[10,11]. Such a dramatic increase in body fat value can only be produced from a positive energy balance for some period of time. As described above, the thermal cost of divers for daily diving work reduced from 1,000 kcal in 1960 (cotton-suit diving) to 260 (summer)-370 (winter) kcal in 1980 (wet-suit diving). The diver's demand for energy may have decreased suddenly by wearing wet-suits, without a corresponding decrease of food intake because of their eating habits. If so, they were in a state of positive energy balance until the food intake was adjusted to match precisely the demand The extra energy taken in would have been converted to fat during this period of adjustment. Positive energy balance may also have been resulted from improvement in living conditions, such as house heating, quality of food, and transportation, as a consequence of nationwide economic growth during the last 20 years, as evidenced by the increase in subcutaneous fat thickness of nondiving Korean women (2.3 mm in 1960 to 9.0 mm in 1980) and their increased caloric intake (2,000 kcal/day in 1960 to 2,200 kcal/day in 1980)[10].

3. COMPARISON OF ENERGETICS OF WET-SUIT DIVING BETWEEN MALE AND FEMALE DIVERS

Fig. 7 illustrates courses of body temperature (Tr and T̄s) and metabolic rate (Ṁ) of male (Japanese) wet-suit divers during diving work in summer (Tw =27℃) and in winter (Tw=14℃). Average values during the work period are summarized in Table 2, along with values for female (Korean) wet-suit divers for comparison. In general, both the body temperature and metabolic changes were similar to those observed in female divers (see Figs 2 and 3). The final Tr and T̄s at the end of a work shift were 37.2 and 32.8℃ in summer (2h shift) and 36.0 and 28℃ in winter (90 min shift). The Ṁ maintained more or less constant during the entire work period. Interestingly, however, the level of Ṁ in winter (120 kcal/m²·h) was not higher but slightly lower than that in summer (140 kcal/m²·h), in contrast to that observed in female divers In the latter case, the Ṁ during diving work was 76% higher in winter (148 kcal/m²·h) than in summer (84 kcal/m²·h) due to shivering in winter (see Fig. 3 and Table 2). Presumably, shivering also occurred in male divers in winter, since their Tr and T̄s during diving work were comparable to female divers' (see Table 2). We therefore think that the exercise load of diving work in male divers was lower in winter than in summer.

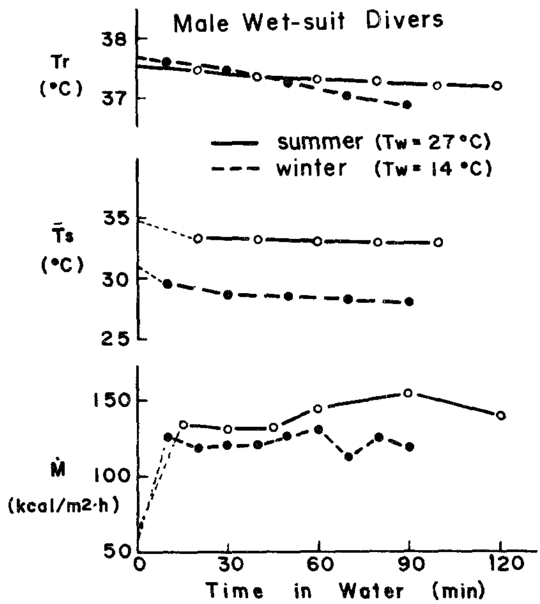

Fig. 7. Changes in rectal(Tr) and mean skin(Ts) temperatures and metabolic rate(M) during diving work in summer(solid curve) and in winter(dashed curve) in Japanese male wet-suit divers. Redrawn from Shiraki et al.[13]

Fig. 8 depicts cumulative extra heat loss during diving work calculated for male divers After initial rapid rise, the net heat loss rose slowly at a steady rate both in summer and in winter, as observed in female divers. Surprisingly, however, the value at a given work period was not significantly different between the summer and winter season, indicating that the thermal cost per unit time of diving work did not vary with the season Extrapolation of the steady portion of the curve indicated that the diver incurred a net thermal loss of approximately 350 kcal during the natural work shift of 140 min in summer and 230 kcal during the 80 min work shift in winter. Accordingly, the total amount of energy used for daily diving work was equivalent to 700 kcal in summer (2 shifts) and 690 kcal in winter (3 shifts). A dietary survey indicated that the average caloric intake of divers was 2,600 kcal/day[13]. This amount of food intake must be sufficient in maintaing diver's daily energy balance, since the body weight and fat content of divers did not undergo seasonal variation[13].

The rate of diving heat loss in male divers, estimated from the slope of the cumulative extra heat loss vs. time curve (Fig. 8), was approximately 85 kcal/m^2·h both in summer and in winter. Since the heat loss in water is determined mostly by the magnitude of skin heat flux, which is proportional to the body core to water temperature gradient and inversely proportional to the peripheral insulation ($\dot{H}s = [T_{core} - T_{water}]/I$), an equal diving

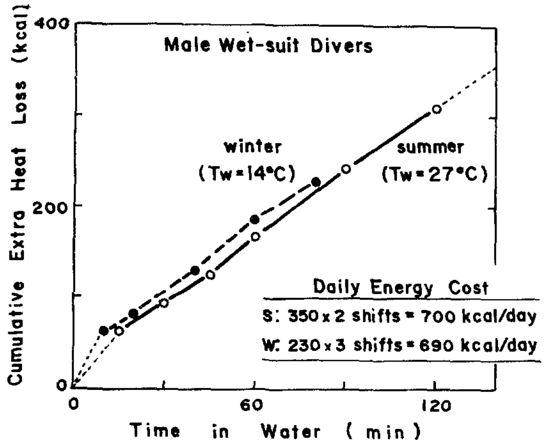

Fig. 8. Cumulative extra heat loss during diving work in summer (solid curve) and in winter (dashed curve) in Japanese male wet-suit divers. Redrawn from Shiraki et al.[13]

Table 2. Average body temperature, heat production, heat loss and thermal insulation during wet-suit diving.

		Male[a]		Female[b]	
		Summer	Winter	Summer	Winter
Measured values					
Tw	(℃)	27	14	23	10
Tr	(℃)	37.2	36.8	37.1	36.8
$\overline{T}s$	(℃)	33.1	28.4	31.5	27.5
$\dot{M}$	(kcal/m^2·h)	141	121	84	148
Calculated values					
△S	(kcal/m^2·h)	8	25	2	5
$\dot{H}$	(kcal/m^2·h)	149	146	86	153
$\dot{H}_s$	(kcal/m^2·h)	138	136	79	141
I_{total}	(℃/kcal/m^2·h)	0.074	0.168	0.178	0.190
I_{body}	(℃/kcal/m^2·h)	0.030	0.062	0.071	0.066
I_{suit}	(℃/kcal/m^2·h)	0.044	0.106	0.106	0.124

$\dot{M}$ (heat production) $= 4.83\,\dot{V}o_2$
△S (heat storage change) $= \triangle Tb \times 0.83 \times BW/BSA$
$\dot{H}$ (total heat flux) $= \dot{M} + \triangle S$
$\dot{H}_s$ (skin heat flux) $= \dot{H} - 0.08\dot{M}$
$I_{total} = (Tr - Tw)/\dot{H}_s$, $I_{body} = (Tr - \overline{T}s)/\dot{H}_s$, $I_{suit} = I_{total} - I_{body}$
a. based on data of Shiraki et al.[13]
b. based on data of Kang et al.[6]

heat loss (hence skin heat loss) between the two seasons in male divers requires that their thermal insulation increases in cold season. In fact, calculation of thermal insulation using the Tr, $\bar{T}s$, Tw and M during diving work (Table 2) indicated that overall insulation (I_{total}) of male divers in winter (0.168℃/kcal/m²·h) was 2-fold greater than that in summer (0.074), and this was due to changes in internal (I_{body}) as well as external (I_{suit}) insulation. The value of I_{body} and I_{suit} increased from 0.030 and 0.044℃/kcal/m²·h in summer to 0.062 and 0.106℃/kcal/m²·h in winter. Such a marked seasonal variation of thermal insulation has not been observed in female divers of Korea.

The change in I_{suit} between warm and cold seasons in male divers was partly accounted for by a change in attire In summer, the subjects wore 5 mm wet-suits, but in winter they wore 5.5~6.0 mm wet-suits and had additional protection with hoods gloves, and boots. Thus, the physical insulation external to the body was obviously increased in winter. However, this may not fully account for the observed change in I_{suit}. According to Goldman et al.[2], physical insulation of 4.76 and 6.35 mm neoprene wet-suits are only slight different (0.128 vs 0.139℃/kcal/m²·h). Perhaps the more important reason for the change in I_{suit} was a change in diving pattern between summer and winter. As mentioned above, the surface to dive time ratio of male divers increases in winter (see Table 1). The ratio for the subjects served for thermal study was on the average 50% higher in winter (1.97) than in winter (1.30). Since the physical insulation of the wet-suit is lower at depth than at the surface due to compression of trapped air[1], and the physiological insulation by wet-suits decreases with exercise due to increase in effective surface area for heat exchange[7] as well as heat convection under the suit[15], the average I_{suit} during breath-hold diving will increase as the surface to dive time ratio increases. The apparently high I_{body} in winter might also be attributed to the increase in surface to dive time ratio in winter. Since the body insulation in water undergoes dramatic reduction during exercise[7,8], I_{body} of divers would increase as the relative time of surface rest increases. In fact, a preliminary observation in two Korean women divers in summer (22℃ water) indicated that the average I_{body} increased from 0.062 to 0.075℃/kcal/m²·h and I_{suit} increased from 0.126 to 0.153℃/kcal/m²·h as their surface to dive time ratio was increased from 1 to 2 (Table 3). We therefore speculate that a significant fraction of the increase in thermal insulation of male divers in the cold season was a consequence of a behavioral adjustment of diving pattern, a mechanism with which divers conserve body temperature during diving work in cold water. This notion may be indirectly supported by the fact that in Korean women wet-suit divers, who do not change diving pattern throughout the year, there is no apparent seasonal variation of thermal insulation. The reason why such an adaptation has been aquired only in male divers is not clear at present.

Table 3. Effect of surface to dive time ratio on thermal insulation of wet-suit diver.

Surface/ Dive		I_{total}	I_{body} (℃/kcal/m²·h)	I_{suit}^{a}
1	#1	0.210	0.067	0.143
	#2	0.164	0.056	0.108
	Mean	0.187	0.062	0.126
2	#1	0.246	0.070	0.176
	#2	0.214	0.080	0.130
	Mean	0.230	0.075	0.153

a $I_{suit}=I_{total}-I_{body}$

Data represent two Korean divers working at 4-5m diving ground in summer (Tw = 22℃)

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