*Journal of Physiology* (1988), **396**, *pp.* 349–363
*With 7 text-figures*
*Printed in Great Britain*



# HUMAN ADAPTATION TO REPEATED COLD IMMERSIONS

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(*Received 30 April 1987*)

SUMMARY

1. The present investigation was designed to examine human adaptation to intermittent severe cold exposure and to assess the effect of exercise on any adaptation obtained.

2. Sixteen subjects were divided into two equal groups. Each subject performed ten head-out immersions; two into thermoneutral water which was then cooled until they shivered vigorously, and eight into water at 15 °C for 40 min. During the majority of the 15 °C immersions, one group (dynamic group) exercised whilst the other (static group) rested.

3. Results showed that both groups responded to repeated cold immersions with a reduction in their initial responses to cold. The time course of these reductions varied, however, between responses.

4. Only the static group developed a reduced metabolic response to prolonged resting immersion.

5. It is concluded that repeated resting exposure to cold was the more effective way of producing an adaptation. The performance of exercise during repeated exposure to cold prevented the development of an adaptive reduction in the metabolic response to cold during a subsequent resting immersion. In addition, many of the adaptations obtained during repeated resting exposure were overridden or masked during a subsequent exercising immersion.

## INTRODUCTION

Despite the large number of studies performed, no single picture of human adaptation to cold has been consistently described. At least three different patterns of human adaptation to cold have been defined: 'metabolic', 'insulative' and 'hypothermic' (Hammel, 1963).

Some authors, (Scholander, Hammel, Andersen & Loyning, 1958) have suggested that man can develop a 'metabolic adaptation' to cold in which the metabolic response to a cold stress is higher in the adapted compared to the unadapted state. Others (Hong, 1973) have reported an 'insulative' adaptation to cold, in which skin temperature is allowed to fall to lower levels during cold exposure whilst core temperature and metabolic rate remain closer to pre-exposure levels in the adapted compared to unadapted individual. Finally, a 'hypothermic' adaptation has been identified in which the fall in core temperature is larger, and the metabolic response smaller, during cold exposure following adaptation (Stanton-Hicks & O'Connor, 1938; Young, Muza, Sawka, Gonzalez & Pandolf, 1986).

Despite such evidence, doubt still exists about the capacity of humans to achieve whole-body physiological adaptation to cold. This doubt originates both from a confusion in terminology and the wide variety of studies performed. Evidence for human adaptation to cold has been sought in: different ethnic groups (Stanton-Hicks & O'Connor, 1938; Hong, 1963); cold-exposed sportsmen (Pugh & Edholm, 1955; Golden, Hampton & Smith, 1980); people on expedition to cold regions (Budd & Warhaft, 1966); individuals following seasonal exposures (Yaglou, 1927); laboratory-based studies both in air (Glaser, 1949; Davies, 1961) and water (Boutelier, Bougues & Timbal, 1977).

The differing patterns of adaptation reported may be partly explained, therefore, by the variety of experimental approaches. Work with animals (Le Blanc, 1967) has suggested that different types of cold exposure may result in different types of adaptation: intermittent severe exposure producing hypothermic adaptation and continuous moderate exposure, metabolic adaptation.

The variety of experimental approaches has inevitably resulted in poor methodological standardization. Perhaps the most poorly controlled variable has been exercise, more particularly its effect on the fitness of individuals and their responses to cold. An increase in fitness has been shown to alter the responses of individuals to cold in a way that resembles both metabolic (Adams & Herberling, 1958) and hypothermic adaptation to cold (Baum, Bruck & Schwennicke, 1976). In addition, human metabolic adaptation to cold has only been reported in individuals who have exercised during exposure to cold.

The aim of the present study was to examine human adaptation to intermittent severe cold exposure and to assess the influence of exercise on any adaptation obtained.

## METHODS

The experimental protocol was approved by a local ethical committee prior to subject recruitment.

Sixteen healthy male volunteers, aged between 17 and 34 years, acted as experimental subjects; none had a history of cold exposure or had recently altered their habitual levels of exercise. Following a full medical examination, which included a twelve-lead electrocardiogram (ECG), and before giving his written consent, each subject was fully informed about the nature and potential risks of the experiment by an independent physician.

The physical characteristics of the subjects were determined prior to the experiment; total percentage body fat was calculated following caliper assessment of skinfold thickness at four sites (Durnin & Womersley, 1974) and surface area was obtained from height and weight using the formula of Du Bois & Du Bois (1916).

At least 2 days before their first immersion the maximal oxygen consumption ($\dot{V}_{O_2,max}$) of each subject was assessed on a treadmill (P. K. Morgan, Kent), using a pneumotachograph and expiratory gas analysis system (Fenyves & Gut Ergospirostar, Basel, Switzerland). The $\dot{V}_{O_2,max}$ of the subjects were re-assessed following their final immersion.

Each subject performed three types of head-out immersion, in well-stirred water, wearing only swimming trunks. (1) Shivering threshold immersion. Subjects were initially immersed in thermoneutral water (35–35·5 °C); after 10 min, the bath water was cooled at an average rate of 1 °C every 4·9 (S.D. 0·9) min. The cooling profiles for the first and last immersion of each subject were the same. Cooling continued until the subjects were shivering vigorously, as indicated by (a) subject comment, (b) visual assessment and (c) respiratory recordings including oxygen consumption and minute ventilation. The subjects rested throughout the immersions. (2) Resting immersion. The subjects remained at rest throughout a 40 min period of immersion in water at

15 °C. (3) Exercising immersion. The subjects were also immersed in water at 15 °C for 40 min, but within 15 s of immersion they began to exercise on a modified electronically braked bicycle ergometer (Siemens, Erlangen, F.R.G.) and continued cycling for the whole of the immersion period. The work load (watts) at which the ergometer was set was determined separately for each subject by dividing his $\dot{V}_{O_2,max}$ (l $min^{-1}$) by 0·05. During the immersions the subjects cycled at a rate of 60 r.p.m.; each subject exercised, therefore, at the same relative workload.

TABLE 1. Experimental protocol

| Day... | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Dynamic group activity | 1st STI | 1st RI | 1st EI | 2nd EI | 3rd EI |
| Static group activity | 1st STI | 1st EI | 1st RI | 2nd RI | 3rd RI |
| Week-end | — | — | — | — | — |
| Day... | 6 | 7 | 8 | 9 | 10 |
| Dynamic group activity | 4th EI | 5th EI | Last EI | Last RI | Last STI |
| Static group activity | 4th RI | 5th RI | Last RI | Last EI | Last STI |

STI, shivering threshold immersion; EI, exercising immersion; RI, resting immersion.

The subjects were divided into two groups of eight: a 'dynamic' and a 'static' group. Subjects in both groups performed ten immersions at the corresponding time on separate days, within two successive weeks. The order in which the subjects of both groups performed their immersions is shown in Table 1.

Prior to each immersion the subjects rested in air (24–28 °C) for 20 min with their legs covered with a blanket. They sat on a board placed on top of the immersion tank and were supported during the rest period in the same semi-recumbent posture that they would assume during the subsequent immersion. Support was provided by two 50 cm wide straps (helicopter rescue strops), one placed around the back the other around the knees. At the end of the rest period the board was removed from beneath the subjects and they were lowered into the water at a rapid, reproducible rate by means of an electric winch to which the straps were attached.

During the shivering threshold and resting immersions the subjects remained in the semi-recumbent posture with their arms folded across their chests and their legs almost straight and together. A similar posture was assumed for the exercising immersions with the exception that the legs were used to cycle. At the end of each immersion the cold water was rapidly drained from the immersion tank and replaced with hot water (40 °C). The subjects remained in the hot water until their core temperatures approximated pre-immersion levels.

Prior to immersion the subjects rested and did not smoke or consume caffeinated drinks.

*Experimental measures.* Rectal temperature was measured throughout each experiment by a rectal thermistor (Series 400 Probe, Yellow Springs Instruments, OH, U.S.A.) inserted 15 cm into the rectum, and connected to a single-channel DC amplifier (Gould, OH, U.S.A.). Aural temperature was measured using a zero-gradient aural thermometer (Muirheads Ltd, Kent) inserted into the external auditory meatus of the left ear, as close as possible to the tympanic membrane. Skin temperature was recorded every 5 min with thermistors (EU Thermistors, Edale Instruments, Cambridge) attached by single pieces of waterproof tape at ten sites; forehead, chest, upper arm, abdomen, back of hand, front thigh, front calf, top of foot, lower back and back of thigh. Mean skin temperature was obtained by an unweighted division of the ten skin temperatures. Water and air temperature were also recorded every 5 min using EU thermistors. From rectal and mean skin temperature, mean body temperature was calculated using the following formula: mean body temperature = 0·64 rectal temperature + 0·36 mean skin temperature (Burton & Edholm, 1955).

Heart rate was recorded every 5 min from a three-lead ECG obtained by telemetry (Siemens Telecust 36, Erlangen, F.R.G.).

Oxygen consumption ($\dot{V}_{O_2}$) was assessed by open-circuit spirometry where expired air was collected in Douglas bags and analysed for oxygen and carbon dioxide concentrations (OM11 and LB2 analysers, Beckman, IL, U.S.A.). The volume of expired air ($\dot{V}_E$) was determined by evacuating the Douglas bags through a gas meter (Parkinson & Cowan, Birmingham) onto which an optical incremental encoder had been attached (Leine & Lind, Stranganas, Sweden), permitting a digital read-out of volume to 0·1 l. Douglas bags were collected for 3 min after 5 and 15 min of rest, for the first minute of cold immersion (first 3 min of the shivering threshold immersion), and for 3 min prior to every tenth minute of immersion.

The fractional concentration of end-tidal carbon dioxide ($F_{ET,CO_2}$) was measured by continuously sampling expired air at the mouthpiece and analysing for carbon dioxide concentration (LB2 analyser, Beckman, IL, U.S.A.).

Inspiratory volume ($\dot{V}_I$) and respiratory frequency ($f_R$) were obtained from a pneumotachograph and integrator unit (P. K. Morgan, Kent). These were recorded continuously and examined over the same period that Douglas bag collections were being made. Subjective assessments of thermal comfort were recorded using a sliding scale, at each end of which were marked the extremes of the comfort continuum (extremely comfortable–extremely uncomfortable). The assessments of the subjects could be quantified from graduations displayed on the back of the scale (unseen by the subjects).

Statistical analysis attempted to identify alterations in the responses of subjects between their first and last shivering threshold, exercising and resting immersions. The non-parametric tests performed upon the experimental data were: the Wilcoxon matched-pairs signed-ranks test for related samples and the Mann–Whitney $U$ test for independent samples. In addition, a statistical model was constructed which approximated the $\dot{V}_{O_2}$ and mean body temperature data for the subjects in both groups during the final 20 min of their first and last resting immersion. Within the model it was assumed that $\dot{V}_{O_2}$ and mean body temperature were linearly related within the range of mean body temperature values recorded, and that this relationship was, on the first and last resting immersion of a given subject, approximately parallel. An analysis of covariance was performed to assess the significance of the factors stated in the model.

## RESULTS

The static and dynamic groups of subjects were evenly balanced in respect of physical characteristics. The mean (S.D.) subject data of the groups were as follows. Dynamic group: age 22 (5) years; height, 182 (7) cm; weight, 74 (15) kg; percentage fat, 14·6 (5·0); $\dot{V}_{O_2,max}$, 3·868 (0·732) l min$^{-1}$; surface area, 1·93 (0·21) m$^2$. Static group: age, 23 (3) years; height, 177 (4) cm; weight, 73 (8) kg; percentage fat, 14·4 (4·8); $\dot{V}_{O_2,max}$, 3·763 (0·656); surface area, 1·90 (0·1) m$^2$. There was no significant difference in the $\dot{V}_{O_2,max}$ between groups. The $\dot{V}_{O_2,max}$ reorded before and after the experimental period were also not significantly different in either group.

### *First and last shivering threshold immersions (day 1 and 10)*

The resting data obtained before the first and last shivering threshold immersions were not found to differ significantly in the dynamic or static group. Likewise, the data recorded on immersion were not found to differ significantly in either group. The duration of immersion to reach shivering threshold was longer ($P < 0·01$) in both groups during the last shivering threshold immersion (dynamic group: 82 min cf. 67 min; static group: 80 min cf. 61 min).

Figure 1 shows the $\dot{V}_{O_2}$ responses of both groups at four different mean body temperatures. The $\dot{V}_{O_2}$ responses of the dynamic group were significantly lower ($P < 0·01$) during the last compared to first shivering threshold immersion at a mean

body temperature of 33 °C, but not at the other three temperatures. The same result was found with the static group ($P < 0.025$). During the shivering threshold immersions the fall in mean body temperature was primarily due to falling mean skin temperature, which itself was determined by water temperature. In the dynamic group, thermal comfort was only significantly increased during the last immersion at

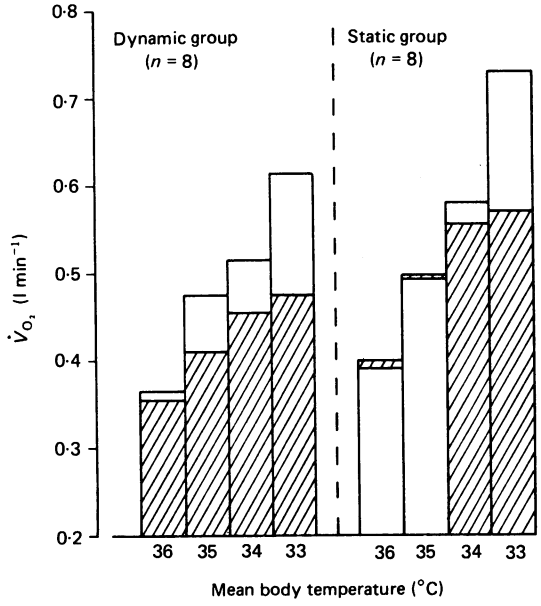


Fig. 1. The relationship between oxygen consumption and mean body temperature for the dynamic and static groups during the first and last shivering threshold immersions. □, day 1; ▨, day 10.

the lower mean body temperatures of 34 ($P < 0.025$) and 33 °C ($P < 0.05$). In the static group, thermal comfort was significantly increased ($P < 0.01$) at 35, 34 and 33 °C mean body temperature.

*First and last resting and exercising immersions (days 2–9)*

No significant differences were found for either group in the variables recorded during the rest periods prior to the first and last resting and exercising immersions.

*Initial responses to cold water immersion.* The heart rates recorded during the first minute of the last resting immersion were found to be significantly lower than those recorded during the corresponding period of the first resting immersion for both the dynamic ($P < 0.05$) and the static group ($P < 0.01$). They were also found to be significantly lower during the last compared to first exercising immersion of both the dynamic ($P < 0.025$) and the static group ($P < 0.05$). The mean heart rates recorded during the first minute of immersion on days 2–9 of the static group are shown in Fig. 2 (regrettably the heart rate data, on immersion, of one subject was lost on one occasion).

An attempt was made to determine whether the lower heart rates, seen in both

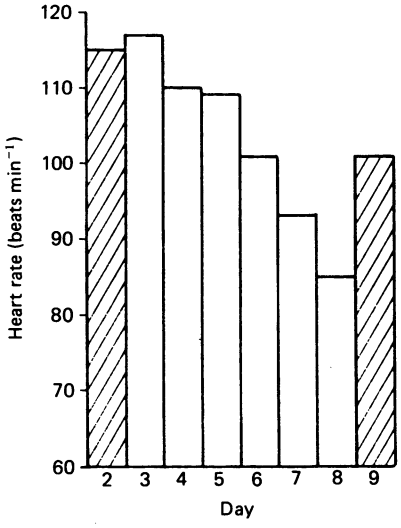


Fig. 2. Heart rate of the static group during the first minute of immersion on days 2–9 ($n = 7$). □, resting immersion; ▨, exercising immersion.

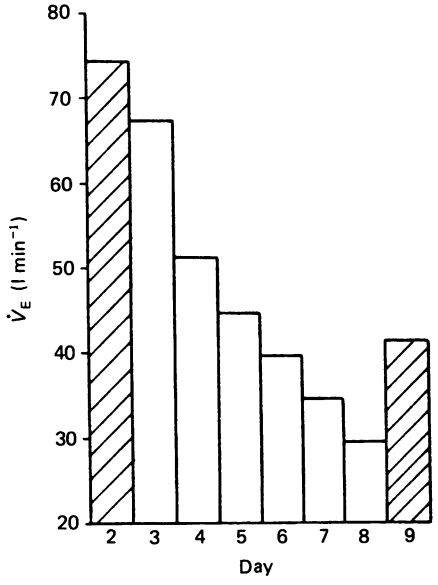


Fig. 3. Ventilatory volume of the static group during the first minute of immersion on days 2–9 ($n = 7$). □, resting immersion; ▨, exercising immersion.

groups during the later immersions, were due to a diminished response to the cold stimulus or due to a quicker return towards resting levels. The number of heart beats for each 5 s interval in the initial 30 s of the first and last resting immersion was therefore examined for both groups. The dynamic group showed no significant reductions in the number of heart beats recorded. In the static group, the number of beats was found to be significantly lower ($P < 0{\cdot}05$) for every 5 s interval in the first 30 s.

The $\dot{V}_E$ recorded during the first minute of the last compared to first resting immersion, were found to be significantly lower in both the dynamic and the static group ($P < 0{\cdot}01$). They were also found to be significantly lower during the last compared to first exercising immersion in both the dynamic ($P < 0{\cdot}05$) and the static

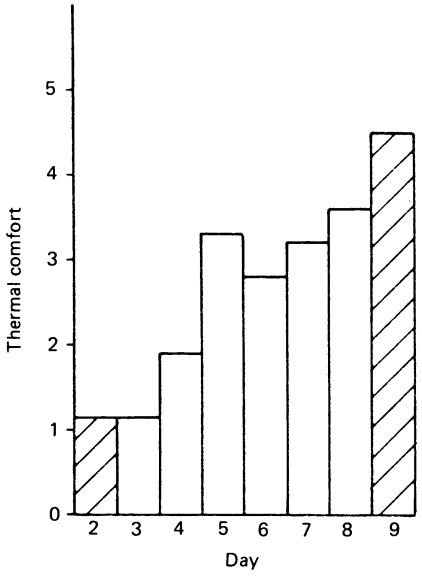


Fig. 4. Thermal comfort of the static group during the first minute of immersion on days 2–9 ($n = 8$). □, resting immersion; ▨, exercising immersion.

group ($P < 0{\cdot}01$). Figure 3 shows the mean $\dot{V}_E$ of the static group (except for one subject whose data was lost on one day) during the first minute of immersion on days 2–9.

The volume of air inspired by each subject during each 15 s interval of the initial 2 min of the first and last resting immersion was determined. The dynamic group showed no significant reductions in $\dot{V}_I$ during the first 15 s period of the last resting immersion, but showed a significant reduction ($P < 0{\cdot}05$) during each of the following 15 s periods. In the static group, $\dot{V}_I$ was found to be significantly lower for every 15 s interval of the first 2 min of the last compared to first resting immersion ($P < 0{\cdot}05$).

In the dynamic group, $f_R$, tidal volume ($V_T$) and $\dot{V}_{O_2}$ were found to be significantly lower during the first minute of the last compared to first resting immersion ($P < 0{\cdot}05$) and $F_{ET,CO_2}$ was significantly increased ($P < 0{\cdot}01$). No significant differences were found in these variables between the first minute of the first and last exercising immersion. In the static group all of these variables were significantly lower during the first minute of the last compared to first resting immersion ($P < 0{\cdot}02$) and exercising immersion ($P < 0{\cdot}05$), with the exception of $F_{ET,CO_2}$ which was significantly higher ($P < 0{\cdot}01$).

The thermal comfort of the dynamic group after 1 min of immersion was significantly higher ($P < 0{\cdot}025$) during the last compared to first resting immersion and during the last compared to first exercising immersion ($P < 0{\cdot}01$). Figure 4 shows

the corresponding data for the static group; again thermal comfort was significantly higher ($P < 0.01$) after 1 min of immersion during the last compared to first resting and exercising immersions.

*Responses to prolonged cold immersion.* The rectal temperatures of both groups did not differ significantly at the start of the first and last resting or exercising immersions. The fall in rectal temperature between the 10th and 30th minute of

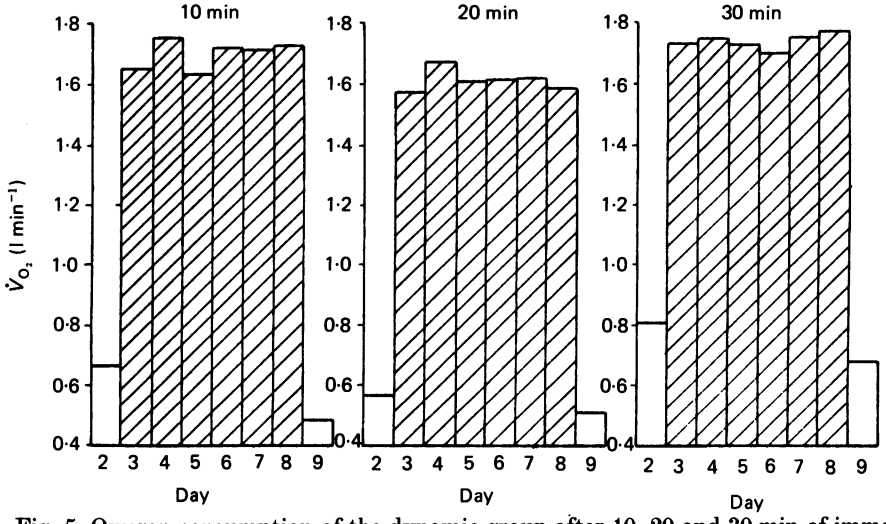


Fig. 5. Oxygen consumption of the dynamic group after 10, 20 and 30 min of immersion on days 2–9 ($n = 8$). □, resting immersion; ▨, exercising immersion.

immersion was analysed, as this was the period during which it was falling at a relatively constant rate in the majority of subjects. The fall in rectal temperature during this period was significantly smaller ($P < 0.02$) for the dynamic group in the last compared to first resting immersion (−0·83 cf. −0·61 °C). In the static group the rectal temperature during this period fell by a greater amount during the last compared to first resting immersion (−0·28 cf. −0·41 °C), but the difference was only significant at the 10% level. In both groups, core temperature fell by a greater amount ($P < 0.01$) during resting immersion (these findings are the subject of a separate paper, Golden & Tipton, 1987). No significant differences were found in either group between the mean skin temperatures recorded at corresponding 10 min intervals during the first and last resting or exercising immersions.

In both groups, the mean $\dot{V}_{O_2}$ after 30 min of their first resting immersion was 0·867 l min$^{-1}$ (22% of $\dot{V}_{O_2,max}$), and 1·776 l min$^{-1}$ (46% of $\dot{V}_{O_2,max}$) after 30 min of their first exercising immersion. The $\dot{V}_{O_2}$ of the dynamic group was significantly lower ($P < 0.01$) during the last compared to first resting immersion after 10 min, but was not significantly different for the remainder of the immersion. No significant differences were found between the $\dot{V}_{O_2}$ recorded at corresponding times during the first and last exercising immersions. Figure 5 shows the mean $\dot{V}_{O_2}$ of the dynamic group against time.

The $\dot{V}_{O_2}$ of the static group was significantly lower ($P < 0.05$) throughout the last

compared to first resting immersion, with the exception of the readings taken at 20 min where the significance level was $P < 0{\cdot}1$. As with the dynamic group, no significant differences were found in the $\dot{V}_{O_2}$ recorded at corresponding times during the first and last exercising immersions. Figure 6 shows the mean $\dot{V}_{O_2}$ of the static

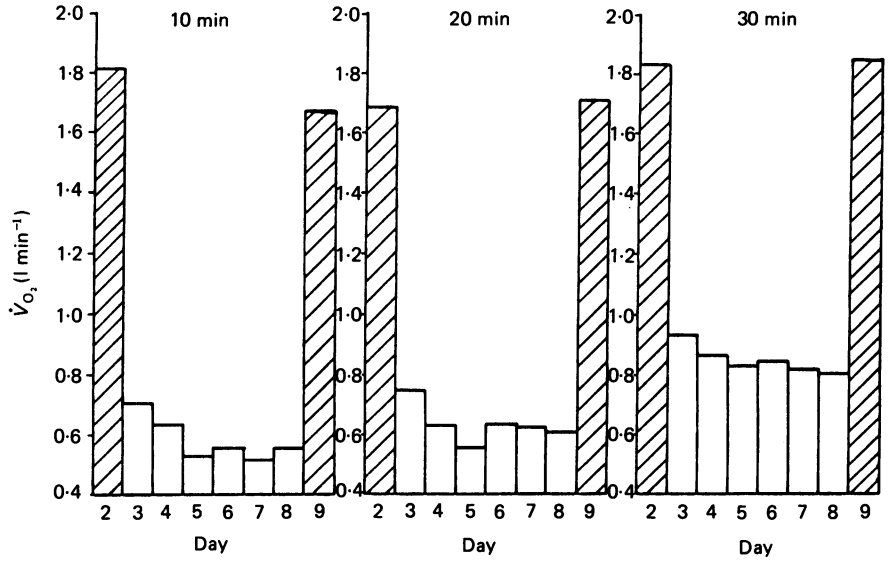


Fig. 6. Oxygen consumption of the static group after 10, 20 and 30 min of immersion on days 2–9 ($n = 7$). □, resting immersion; ▨, exercising immersion.

group against time. Three of the subjects in the dynamic group had an upward, and five a downward shift in their $\dot{V}_{O_2}$/mean body temperature relationship between the first and last resting immersion. The three subjects showing the upward shift were those with the highest $\dot{V}_{O_2,max}$. In the static group, every subject showed a downward shift in this relationship.

The analysis of covariance performed on the $\dot{V}_{O_2}$ data (averaged over subjects and adjusted for mean body temperature) revealed a significant difference ($P < 0{\cdot}01$) between the two groups with regard to the changes in the $\dot{V}_{O_2}$ response between the first and last resting immersion. The average estimated decline in $\dot{V}_{O_2}$ (for the same equivalent mean body temperature in each subject) was 0·049 l min$^{-1}$ for the dynamic group, and 0·296 l min$^{-1}$ for the static group. A two-tailed Student's $t$ test showed that the reduction in the $\dot{V}_{O_2}$ response of the dynamic group was not significant, whilst that of the static group was ($P < 0{\cdot}01$).

The thermal comfort of the dynamic group was not significantly higher during the last compared to first resting immersion at 10 min, but was after both 20 ($P < 0{\cdot}05$) and 30 min ($P < 0{\cdot}025$). During the last compared to first exercising immersion, thermal comfort was found to be significantly higher ($P < 0{\cdot}025$) after 10 and 20 min, but not after 30 min. In the static group thermal comfort was significantly higher during the last resting immersion after 10 min ($P < 0{\cdot}025$) and 20 min ($P < 0{\cdot}05$) but not 30 min. Thermal comfort was significantly higher ($P < 0{\cdot}025$) throughout the last compared to first exercising immersion of this group.

The thermal comfort data obtained from all of the subjects after 10, 20 and 30 min of their first exercising immersion were combined and compared to the data obtained after the corresponding periods of resting immersion. No significant differences were found in thermal comfort between the resting and exercising immersions after 10 min;

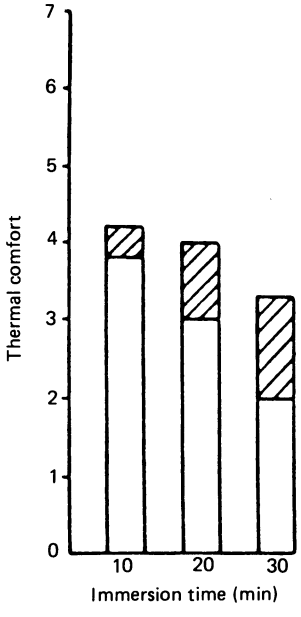


Fig. 7. Thermal comfort of the static and dynamic group at 10, 20 and 30 min of the first resting compared to first exercising immersion ($n = 14$). □, first resting immersion; ▨, first exercising immersion.

however, thermal comfort was significantly higher in the exercising immersions after 20 ($P < 0{\cdot}05$) and 30 min ($P < 0{\cdot}01$, Fig. 7). The same procedure was completed for the last resting and exercising immersions. Thermal comfort was significantly ($P < 0{\cdot}01$) higher at each of these times during the last exercising compared to resting immersions. A summary of the results is presented in Table 2.

## DISCUSSION

The initial responses to cold immersion have been reported by several authors (Keatinge & Evans, 1961; Keatinge, McIlroy & Goldfien, 1964; Goode, Duffin, Miller, Romet, Chant & Ackles, 1975). Few, however, have examined the alterations in these responses following repeated immersion. Keatinge & Evans (1961) reported that repeated immersions into water at 15 °C reduced or abolished the initial respiratory, heart rate and metabolic responses to immersion, and increased $F_{ET,CO_2}$ and thermal comfort levels. The results of the present study confirm these findings for repeated resting immersions and extend them, with regard to the heart rate and respiratory responses, to include repeated exercising immersions. To the authors' knowledge no information has been published regarding the time course of such alterations.

TABLE 2. Summary of results of both groups in which their last exercising and resting immersions are compared to their first

| Last shivering threshold immersion | Dynamic group | | Static group | |
|---|---|---|---|---|
| Duration (min) | ↗ *** | | ↗ *** | |
| $\dot{V}_{O_2}$ (l min$^{-1}$) at a $\bar{T}_b$ of 33 °C | ↙ *** | | ↙ ** | |
| Thermal comfort at $\bar{T}_b$ of 33 °C | ↗ * | | ↗ *** | |
| | Last resting immersion | Last exercising immersion | Last resting immersion | Last exercising immersion |
| Initial responses | | | | |
| HR (beats min$^{-1}$) | ↙ * | ↙ ** | ↙ *** | ↙ * |
| $\dot{V}_E$ (l min$^{-1}$) | ↙ *** | ↙ * | ↙ *** | ↙ *** |
| $f_R$ (breaths min$^{-1}$) | | | | |
| $\dot{V}_T$ (l) | ↙ * | n.s. | ↙ ** | ↙ * |
| $\dot{V}_{O_2}$ (l min$^{-1}$) | | | | |
| $F'_{ET,CO_2}$ (%) | ↗ *** | n.s. | ↗ *** | ↗ *** |
| Thermal comfort | ↗ ** | ↗ *** | ↗ *** | ↗ *** |
| Responses to prolonged immersion | | | | |
| Change in $\dot{V}_{O_2}$ (l min$^{-1}$) response | n.s. | n.s. | ↙ *** | n.s. |

$^*P < 0{\cdot}05$, $^{**}P < 0{\cdot}025$, $^{***}P < 0{\cdot}01$.

$\bar{T}_b$, mean body temperature; HR, heart rate; $f_R$, respiratory frequency. n.s., not significantly different.

Examination of the day-to-day reductions in the heart rate and ventilatory responses of the static group (Figs 2 and 3) reveals that the greatest portion of the adaptive reduction in these responses occurred over the initial resting immersions for the ventilatory response and over the later resting immersions for the heart rate response. In addition, by the last resting immersion of the static group the heart rate recorded on immersion approximated that recorded during the initial minute of immersion in thermoneutral water. The $\dot{V}_E$ of the same group during the initial minute of the last resting immersion was still, however, approximately 2·5 times higher than the response recorded during the initial minute of thermoneutral immersion. It is possible that by the last resting immersion the heart rate response to cold was close to reaching its capacity for habituation, whereas the ventilatory response was not, either because it has a longer time course of adaptation or, because it does not possess the same capacity for adaptation.

Taken together, these findings suggest that larger differences than were once thought may exist between the pathways which initiate and produce adaptation in these responses. Certainly, recent work (Tipton & Golden, 1987) has suggested that differences may exist in the body regions most effective at initiating these responses.

In the present investigation, there was evidence that the mechanisms producing adaptation in the initial responses may not have been identical for the two groups. In the static group, heart rate recorded over the first 5 s of immersion and ventilation recorded over the first 15 s were lower in the last compared to first resting immersion; this was not the case with the dynamic group. In addition, the static group showed a reduction in all of the initial responses to their last exercising immersion; the dynamic group did not.

A reduction in the metabolic response to cold, as seen in the static group during their last resting immersion, is probably the most widely reported adaptation to cold and, as in this study, is often associated with greater falls in core temperature (hypothermic adaptation). The nature of human alterations in the shivering response to cold is not clear. Stanton-Hicks & O'Connor (1938) believed that if the cold-adapted Aborigines were cooled enough they would show a normal metabolic response to cold. The results of the present study suggest that the adaptations obtained by the subjects were fairly specific to the temperature to which they were exposed. Oxygen consumption and thermal comfort for example, were only found to be significantly reduced during the last shivering threshold immersion at the lowest mean body temperatures.

In man, a decrease in the shivering threshold with no change in the sweating threshold has been observed after intermittent exposure to cold air (Bruck & Zeisberger, 1978). In the present study, core and mean body temperature at rest were regulated at the same temperature following cold adaptation. These results, together with those of Bruck & Zeisberger (1978), suggest that a shift in the hypothesized thermoregulatory 'set point' does not occur in this form of adaptation. The human response to resting intermittent severe cold adaptation would seem to be characterized, therefore, by a decreased shivering threshold and unchanged sweating threshold. A widening of the 'interthreshold zone' occurs (Bruck, Wunnenburg & Zeihm, 1970) and results in a decrease in the sensitivity of the thermoregulatory system to cold.

The performance of exercise during repeated exposure to cold would appear to

prevent a reduction, or produce an increase (metabolic adaptation), in the metabolic response to resting cold exposure of some individuals, even when the exercise performed does not alter their maximal oxygen consumption. There are several possible explanations for this. Firstly, during the exercising immersions the core temperatures of subjects did not fall as low as during the resting immersions (Golden & Tipton, 1987). It is possible that the adaptation of some responses, including the metabolic response, requires repeated reductions in core as well as skin temperature. It has been reported (Park, Rennie, Lee, Park, Paik, Kang, Suh, Lee, Hong & Hong, 1983) that since wearing wet suits, which maintain their core temperatures during dives, the diving women of Korea have lost their peripheral adaptation to cold, despite the fact that the suits do not protect their hands and feet.

The dynamic group may have acquired an adaptation to falling skin temperatures: their initial responses adapted and they showed a diminished $\dot{V}_{O_2}$ during their last shivering threshold immersion. Both of these sets of responses were primarily determined by falling skin, rather than a falling core temperature. They would, however, only have become adapted to relatively small falls in core temperature. Thus, during their last resting immersion, when core temperatures fell to lower levels than during the repeated exercising immersions, they responded with an unadapted metabolic response to cold or, more specifically, to falling core temperature.

Central nervous structures do exist which might mediate a 'differential' adaptation to cold. Single-unit studies on animals (Wit & Wang, 1968; Boulant & Bignall, 1973) have demonstrated hypothalamic units which respond to a change in their own temperature with an alteration in firing rate (thermosensitive), and others which are thermoinsensitive but respond to changes in skin temperature with an increase in their firing rate (thermoresponsive).

A second possible explanation for the finding that the dynamic group did not show a reduction in the metabolic response to their second resting immersion may involve the effect which exercise had on the thermal comfort of subjects. Exercising immersions were reported to be more thermally comfortable than resting immersions (Fig. 7). This may have been due to the higher core temperatures during the exercising immersions, but even those subjects who had similar falls in core temperature reported being more comfortable whilst exercising. Other authors (Craig & Dvorak, 1968) have reported similar findings. A mechanism for this non-thermal effect of exercise on thermal comfort in the cold has not been postulated. It may simply be that exercise diverts attention away from the cold. Alternatively, exercise may increase local temperatures and reduce the afferent input from cold receptors which help determine thermal comfort.

Another possible explanation involves the endogenous opiods; these have been reported to be released in man during exercise (Colt, Wardlow & Frantz, 1981) producing an analgesic effect which takes several minutes to occur. Interestingly, it was only after several minutes of exercise that the thermal comfort scores of individuals were found to be significantly higher during their exercising immersions compared to resting immersions (Fig. 4). Whatever the mechanism, the relative discomfort experienced by the dynamic group during the last resting immersion may have increased their anxiety levels. Several authors (Glaser & Hervey, 1952; Scholander, 1961) have reported that anxiety can return a habituated response to its unhabituated level.

The three subjects in the dynamic group who showed an upward shift in their $\dot{V}_{O_2}$/mean body temperature relationship during their last resting cold immersion (metabolic adaptation) were those with the highest $\dot{V}_{O_2,max}$. It may be that the effect which performing exercise during cold exposure can have on the metabolic response to a subsequent resting cold exposure, is fitness dependent. Other authors (Bittel & Cure, 1983) have reported that the physical characteristics of an individual can influence the type of adaptation to cold he develops.

From a practical viewpoint, two short-term methods of producing alterations in the responses of individuals to cold have been described. A reduction in the initial responses to cold would be advantageous in all situations, particularly on accidental cold water immersion where they represent a serious threat to life. A reduction in the responses to prolonged immersion will improve performance on tasks requiring fine motor actions, which otherwise would be affected by shivering. Additionally, the improvement in thermal comfort will improve the mood and morale of individuals. Faster rates of fall of core temperature (hypothermic adaptation) may, however, represent a deleterious effect of human resting 'intermittent severe' cold adaptation, allowing individuals to become hypothermic more quickly and not respond behaviourally because of their higher levels of thermal comfort.

With regard to the choice of method of intermittent severe cold adaptation, both resting and exercising immersions reduce the initial responses to cold immersion at rest. However, repeated resting immersions appear to be the most effective method of decreasing the initial responses to cold immersion with exercise. Repeated resting immersions also appear to be more effective than repeated exercising immersions at producing adaptation to prolonged cold exposure at rest. Many of these responses are overridden or obscured, however, during a subsequent cold exposure with exercise, the exception being thermal comfort which seems to be enhanced.

The authors would like to thank the subjects for their cooperation and the personnel of the Institute of Naval Medicine, in particular Mr T. Beames and the members of the Survival and Thermal Medicine Department, for their invaluable assistance. This work was supported by the Medical Research Council and The Royal Navy.

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