

Cold Adaptations

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Abstract: Nowadays, occupational and recreational activities in cold environments are common. Exposure to cold induces thermoregulatory responses like changes of behaviour and physiological adjustments to maintain thermal balance either by increasing metabolic heat production by shivering and/or by decreasing heat losses consecutive to peripheral cutaneous vasoconstriction. Those physiological responses present a great variability among individuals and depend mainly on biometrical characteristics, age, and general cold adaptation. During severe cold exposure, medical disorders may occur such as accidental hypothermia and/or freezing or non-freezing cold injuries. General cold adaptations have been qualitatively classified by Hammel and quantitatively by Savourey. This last classification takes into account the quantitative changes of the main cold reactions: higher or lower metabolic heat production, higher or lesser heat losses and finally the level of the core temperature observed at the end of a standardized exposure to cold. General cold adaptations observed previously in natives could also be developed in laboratory conditions by continuous or intermittent cold exposures. Beside general cold adaptation, local cold adaptation exists and is characterized by a lesser decrease of skin temperature, a more pronounced cold induced vasodilation, less pain and a higher manual dexterity. Adaptations to cold may reduce the occurrence of accidents and improve human performance as surviving in the cold. The present review describes both general and local cold adaptations in humans and how they are of interest for cold workers.

Key words: Cold, Adaptation, Acclimation, Acclimatization, Human

Introduction

Human is a tropical mammal which is rarely exposed to cold as spontaneously he uses different means to protect himself against cold environment: shelter, clothing, fire. But in some circumstances, he is exposed to cold stress, for example during occupational activities. Repeated or chronic cold exposures modify the thermophysiological cold reactions leading to a cold adaptation. Cold adaptation induces less discomfort, enhances dexterity, prevents general and local cold illnesses and injuries and improves surviving in a cold environment. This review will expose the thermoregulatory responses of persons chronically or repeatedly exposed to cold and will present the determinants and limits of the physiological adjustments exhibited. We will use the following terms in accordance with the “Glossary terms of thermo-

physiology”¹⁾: the term *adaptation* is referred to phenotypic or genotypic changes that reduce the physiologic strain produced by the cold, a *strain* relating to every change in the climatic condition^{2,3)}. The term *acclimation* relates to phenotypic changes in response to an experimentally and specific climatic condition such as temperature or windspeed. The term *acclimatization* describes the adaptative changes occurring within an organism in response to changes in the natural climate, combining different climatic conditions such as ambient temperature and humidity and windspeed. Acclimatization generally resulting from living or working in cold environments or acclimation induced by experimental modifications in environmental conditions can elicit new physiological responses or result in more pronounced physiological reactions or, at the opposite, in physiological reactions diminished in amplitude, a phenomenon known as *habituation*. These physiological adjustments appear in heightened, maintained or lowered thermogenic response to cold

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stress (metabolic adaptation) and/or in maintained or enhanced reactions for conserving body heat (isolative adaptation) during cold exposure.

As cold adaptations represent one of the means of prevention of the physiopathological effects of exposure to cold, we will consider the different characteristics of general and local cold adaptations. General cold adaptation relates to whole body cold adaptation whereas local cold adaptation refers only to the extremities, especially hands and feet.

General Cold Adaptations

Human is a homeo-endotherm and his thermo-physiological responses —increased metabolic heat production and/or decrease heat losses by peripheral cutaneous vasoconstriction— are often insufficient to maintain thermal homeostasis. Consequently, the natural and efficient strategy for protection against the effects of cold exposures is that of an adapted and precaution behaviour as migration, use of a protective clothing, shelter and external heat supply. All of these means, taken alone or combined, contribute to reduce or suppress the environmental cold stress. Therefore, general cold adaptation is rarely encountered in humans but several types of cold adaptation have been described over the 60 last years in studies carried out on natives in their natural environment (acclimatization) or on Caucasians in laboratory conditions (acclimation). In accordance with the well known qualitative classification of Hammel⁴⁾ based on the thermoregulatory reactions observed during a cold exposure, roughly four different qualitative types of cold adaptation have been described, taking into account the changes in core temperature (T_c), in mean skin temperature (\bar{T}_{sk}) and in the level of metabolism (M) (see reviews of Bittel⁵⁾ and Young^{6, 7)}).

Metabolic adaptation

It was described as a cold acclimatization in Alacaluf Indians of Tierra del Fuego^{8, 9)}, in Arctic Indians^{10–12)}, in Eskimos^{13–17)} as in Caucasians living in circumpolar regions^{18, 19)} or under laboratory conditions^{20, 21)} during cold acclimation. This type of cold adaptation is mainly characterized by:

- a higher metabolic heat production during cold exposure at a comparable (+60%¹⁹⁾) or a little lower level (+27%^{13–15)}) than the non-adapted one's, and even at the thermal neutrality^{10, 19)};
- a higher mean skin temperature (\bar{T}_{sk}) (+0.5 to +1°C) without change in core temperature (T_c).

The outcome was that the core to shell thermal conductance, calculated by dividing the metabolic heat production by the core to skin temperature gradient, is more

important at cold, allowing the extremities to be at a higher temperature but at the cost of a high level of expenditure of energy. It may be due to a more important shivering activity, to a high protein diet²²⁾ or to non-shivering thermogenesis²³⁾. Overall, people developing such a type of metabolic cold adaptation, generally by acclimatization, have adequate clothing and shelter to protect themselves from the surrounding extreme cold. Consequently, they probably do not experience in their way of life significant whole-body cooling, explaining the lack of dramatic changes in the thermoregulatory reactions. On the other hand, these people can experience periodic short-term cold exposures of the extremities, for example when gloves are removed to carry out a task requiring dexterity at a low risk because the high thermal conductance helps to maintain a high temperature of the hand. This type of acclimatization may frequently be retrieved in occupational activities.

Isolative cold adaptation

The thermoregulatory reactions of people developing such an adaptation are characterized by a preserved T_c , an roughly unchanged metabolic heat production, and a lower \bar{T}_{sk} when exposed to cold^{5–7)}.

This type of adaptation is encountered in Aborigines of the north coast of Australia²⁴⁾, in people naturally adapted to cold²⁵⁾ or in laboratory conditions²⁶⁾ or after repeated immersions in cold water^{27, 28)}.

Hypothermic cold adaptation

This type of cold adaptation is characterized by a reduced T_c with less metabolic compensation leading to a lesser mean body temperature (\bar{T}_b) whereas the changes in mean skin temperature are the same as in the non-adapted subjects^{5–7, 17, 29, 30)}.

This type of adaptation, evoked first by Carlson³¹⁾, was retrieved in Bushmen of the Kalahari Desert^{29, 30, 32, 33)}, in Quechua Indians living at altitude in the Andes³⁴⁾ and also in Caucasians living for a long time in subarctic areas^{20, 35)} or after acclimation^{25, 36–39)}.

Isolative hypothermic cold adaptation

This last type combines the characteristics of the two precedent types of adaptations with a lower T_c and \bar{T}_{sk} , the metabolism being almost unchanged^{5–7)}.

It was first described in the Aborigines of central Australia by Scholander¹⁷⁾ retrieved by Hammel^{8, 24)} confirming the works of Hicks⁴⁰⁾. It has also been described in nomadic Lapps¹⁵⁾. The important decrease in \bar{T}_{sk} is due to a pronounced vasoconstriction leading to a minimal thermal conductance between core and shell. Consequently, even if the core is better isolated from the cold stress, this is not sufficient to prevent a decrease in

core temperature, probably because of insufficient clothing and prolonged exposure especially during the night at a low ambient temperature⁷⁾. This type of adaptation has also been found in people repeatedly immersed in cold water as in professionals breath-hold divers like the Ama in Japan and Korea^{41–44)} or in Caucasians during acclimation or acclimatization studies by water immersion^{27, 28, 45, 46)}. In these subjects, the fall in T_c is more pronounced and more rapid than in the Aborigines. Furthermore, the threshold for shivering is increased as the reduced T_c (-1°C) at the threshold shows, whichever is the body fat content. This may be due to the development of the thermal counter-current exchanges in the limbs⁴⁷⁾ combined with a greater vasoconstriction in the skin⁴⁸⁾.

Quantitative classification of general cold adaptations

This previous classification proposed by Hammel⁴⁾ is only qualitative and based on the different changes of the thermoregulatory reactions during a cold exposure, eventually combined, and does not take into account all the components of the changes in the thermoregulatory reactions. Indeed, a change in the delay for onset of shivering is a good indication of the sensitivity of the thermoregulatory system. Taking into account the proposal of Bittel²⁶⁾ to use the heat debt measured during a cold stress test at 10°C to appreciate the degree of cold adaptation, Savourey *et al.*⁴⁹⁾ proposed a quantitative classification for the cold adaptations based on the relative changes in T_c , \bar{T}_{sk} and M during a standard cold air test (2 h at 1°C , at rest, lying on the back, nude, windspeed = $0.8 \text{ m}\cdot\text{s}^{-1}$) (Table 1).

Other physiological changes observed during general cold adaptations

General cold adaptations mainly modify the thermoregulatory responses without important changes in the cardio-ventilatory responses or in body fluid homeostasis. On the other hand, general cold adaptations induce changes in catecholamines and thyroid hormonal responses⁵⁰⁾.

Repeated expositions to cold induce lower plasmatic levels in FT3 and TT3 hormones without modification of TSH and T4. After a while, we can observe a decrease in FT4 sometimes associated with a decrease in TT4 and a rise in TSH setting up the “polar syndrome of T3”^{50–56)}. But the rise in TSH is inversely related to the intensity of the light, so it is not always retrieved⁵¹⁾. Last, the biological significance of these changes in the thyroid hormones is unknown⁵⁷⁾ and the relationship between this syndrome and one of a type of cold adaptation has yet to be defined^{58, 59)}.

Epinephrine is not modified by cold acclimation whereas the rise of norepinephrine occurring during a cold exposure is blunted because of habituation⁵²⁾ but this is not always retrieved, probably because of the differences in the methodology used⁵⁰⁾. As the thermogenic action of other hormones is discussed, few of them have been studied with cold adaptation and results are not specific to cold adaptation^{50, 52)}.

Factors of the different general cold adaptations

The different types of cold adaptation can be partly explained by many factors such as the various environmental conditions used to develop and test cold adaptation: continuous or discontinuous exposures to moderate or severe cold stress, number of expositions and the total time exposed to cold, the nature of cold exposure (natur-

Table 1. Quantitative classification of cold adaptations⁴⁹⁾

Variable	Change studied	Change observed	Type of adaptation
T_c ($^\circ\text{C}$)	ΔT_c (1)	> 0 or $=$	Normothermic
		< 0	Hypothermic
\bar{T}_{sk} ($^\circ\text{C}$)	$\frac{\bar{T}_{sk} \text{ (after adaptation)}}{\bar{T}_{sk} \text{ (before adaptation)}}$ (2)	< 1	Isolative
		$= 1$	Iso-isolative
		> 1	Hypo-isolative
M ($\text{W}\cdot\text{m}^{-2}$)	$\frac{M \text{ (after adaptation)}}{M \text{ (before adaptation)}}$ (3)	> 1	Metabolic
		$= 1$	Iso-metabolic
		< 1	Hypo-metabolic

(1) : difference between T_c observed at the end of the standard cold air and T_c at thermoneutrality.

(2) : values of \bar{T}_{sk} at the end of the standard cold air test.

(3) : M : mean value of metabolic heat production during the standard cold air test.

al or artificial), the effect of diet and body characteristics (physical fitness and body fat content)^{26, 49, 60} as other associated stresses as for example altitude in Peruvians Indians^{5, 22, 28}). Consequently, it is difficult to appreciate the cold stress undergone during cold adaptation as it must be taken into account the intensity and the time of exposure as well as physical activity or clothing and diet.

The influence of the characteristics of the cold exposure on the type of cold adaptation developed has been debated for a while^{5, 26}). From the different cold adaptations exposed above, we can postulate that: a metabolic adaptation is observed for a severe cold stress associated with the possibility of a high energy intake (Eskimos); an isolative adaptation is observed for a light cold stress with a low energy intake (Aborigines of the north coast of Australia); a hypothermic adaptation is observed for a moderate cold stress associated with a very low energy intake (Bushmen of the Kalahari desert) and an hypothermic — isolative adaptation is observed for a moderate cold stress undergone at night with a very low energy intake (Aborigines of central Australia) associated with a heat stress during the day. Adaptation of the hypothermic type appears to be the most advantageous as it maintains the energy reserves by delaying the onset of shivering but without risk of the development of a dangerous hypothermia³⁶).

Leblanc⁶¹) had another approach to the question and made a direct link between the characteristics of the exposition to cold stress and the thermophysiological reactions observed. For him, the prolonged exposition to a moderate or light cold stress leads, by a mechanism of habituation, to lesser reactions of defence against cold and a lesser perceived strain. In the case of repeated exposures to a severe cold, shivering activity is maintained as the lack of comfort perceived showing the lack of habituation confirmed by the high levels of norepinephrine retrieved. In this case, heat metabolic production is conserved with lesser body temperatures: this may due to the redistribution of blood flow from skin to muscles in favour of heat production. Last, repeated expositions to a severe cold of the extremities lead, also by a mechanism of habituation, to a local cold adaptation of the only exposed extremity. If the cutaneous surface of the extremities exposed to cold is sufficiently important (legs for example) and the cold intense (cold water immersion) the local cold acclimation may lead to general cold adaptation as Savourey *et al.*⁶²) showed. Launay *et al.*⁶³) have also recently demonstrated that an adaptation to heat developed after a sojourn in a tropical climate modify the thermoregulatory responses to cold attesting that a cross-adaptation heat/cold which could interact in the development of general cold adaptation.

Local cold adaptation

Local cold adaptation of the extremities is well documented⁶⁴). Many studies^{11, 65–72}) have been conducted both in natives of arctic regions and professionals groups exposed to cold in their extremities as in subjects in laboratory conditions. All of these studies showed that local cold adaptation is characterized during a local cold exposure of the adapted extremities by higher skin temperatures, a less vasoconstriction, less pain, and an earlier paradoxical vasodilatation (as known as «hunting reaction» or Lewis's reaction or cold induced vasodilatation) occurring at higher skin temperatures, a preserved dexterity, thus permitting the prevention of frostbite⁵⁸). All of these changes are based on an increase in the peripheral blood flow and not on a higher heat metabolic production⁴⁹). Repeated immersions of the extremities in cold water, for example 30 min in 5°C cold water, two times a day for one month, are sufficient to induce this adaptation^{49, 62, 73–76}). When it is associated with an isolative or hypothermic general cold adaptation, the paradoxical vasodilatation is reduced^{49, 77–79}).

This local cold adaptation is probably the most interesting cold adaptation from professional activities point of view as it is easy to get with a limited equipment. Moreover, the increase in manual dexterity is a preventive factor to maintain manual performance in workers exposed to cold conditions.

Conclusion

The different types of cold adaptations are related to the intensity of the cold stress and to individual factors such as body fat content, level of physical fitness and diet. All of these elements influence the cold strategy developed during cold adaptations. The various types of general cold adaptations are today well described whereas their origin (intensity or/and type of cold constraint, duration of exposure, hormonal changes implied...) are not well documented. The hypothermic general cold adaptation seems the most beneficial for surviving in the cold but the interest of the development of general cold adaptation in workers in the cold are questionable since occupational activities can be organized to avoid cold disturbances (shelter, clothes, heat sources, time sharing). On the other hand cold adaptations of the extremities are beneficial for cold workers since this adaptation is easy to develop and it improves manual dexterity and limits pain by developing the cold induced vasodilatation. However it is necessary to point out the fact that human physiological abilities against the adverse effects of cold are limited even in general/local cold adapted people and that technical supplies are necessary to avoid medical accidents such as an accidental hypothermia or frostbites.

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