SUSCEPTIBILITY TO FROST-BITE

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(*Received* 3 *March* 1966)

The body protects its susceptible parts *e.g.*, hands and feet from cold injury by allowing a surge of blood to flow through them on exposure to severe cold. This occurs through alternate vasodilatation and vasoconstriction known as Lewis Hunting Reaction. This phenomenon is influenced by several factors, which indirectly may also affect individual susceptibility to cold injury. The role of nutrition, adequate insulation of the body and positive heat balance in relation to the protective mechanism have been reviewed and discussed. Available literature on various factors has been surveyed and discussed in the light of recent advances in the physiology of cold exposure. Certain tests based on the present knowledge, to be developed and standardised for screening susceptible individuals to frost-bite have been suggested.

Protection of extremities against cold has assumed special importance as our Armed Forces have to operate under conditions of severe cold, violent air movements and oxygen deficiency encountered at high altitudes in the vast mountainous terrains of our northern frontiers. Further, it is essential to maintain joint function, mobility, neuromuscular function and comfort by adequate protection to the extremities in order to enable the troops to keep fit for active operations.

Extremities contain very little tissue which is capable of heat production. Heat, therefore, has to be supplied either by blood circulation or from an external source. The arterial blood supply to the foot is relatively poor and is further reduced to a marked extent on exposure to cold because of vasoconstriction[1,2]. Due to a very small blood flow to the foot, it follows the same cooling curve as if it was an inanimate object[3]. A temperature gradient exists along the body and the blood loses its effective heating power relatively as it travels from the heart to the lower extremities. Further, from surface area consideration the foot forms only a small part of the total body, yet it is difficult to insulate it because of its shape. Foot sweats more than other body areas[4]. The accumulation of sweat decreases the thermal insulation of the footgear and poses an additional problem. Due to these factor foot is more susceptible to frost-bite than hand.

Suceptibility to cold/cold injuries depends on the following factors: (*i*) acclimatization to cold: if troops stationed in regions of warm climate are suddenly induced to extreme cold existing at high altitude, they do not have sufficient time to get acclimatized to the new environment and are therefore more prone to injuries due to cold (*ii*) racial and ethnic differences: personnel of the Indian Armed Forces are recruited from different regions where food habits, social customs and weather conditions differ widely and as such there may be variations in their physiological responses to cold exposure which may vary their susceptibility to cold. Observations in Korea indicated higher incidence of frost bite among Negros as compared to Whitemen[5].

Studies have confirmed that people chronically exposed to cold exhibit peripheral heat regulating mechanism which enables them better to succeed in their environment[6—10]. These physiological adjustments may result from direct cold exposure to both experimental or natural cold stresses. The present paper deals with the various factors which influence susceptibility to frost-bite. These factors may form the basis to formulate simple tests to exclude individuals susceptible to frost-bite from participating in operations to be conducted in extreme cold.

There are two schools of thought with regard to pathogenesis of frost-bite (*i*) damage is produced by direct action of cold upon tissues (*ii*) damage occurs as a secondary effect of cold induced vascular changes. The recent trend is towards a combination of the two. Considering the above, susceptibility to frost-bite also has two main aspects (*i*) capacity to resist freezing by supercooling the tissue fluids. Thus the damage to the tissues by formation of ice crystals and disruption of the morphological structure of the cells and the cell bridges is avoided (*ii*) body's mechanism to maintain the temperature of the tissues higher than the freezing point by a pronounced cold induced vasodilatation. It is with this latter aspect in view that we propose to standardise physiological parameters to predict susceptibility to frost-bite in human subjects.

PROTECTIVE MECHANISM OF THE BODY

When the extremities are allowed to cool down to 18°C there is a vasoconstriction and the blood flow decreases. Between 18°C and 10°C the blood flow remains constant at the minimum level. If the temperature of the extremities falls below 10°C, a protective action of the body occurs which allows a surge of blood to flow through the extremities. This was first observed by Lewis[11] on the basis of skin temperature measurements and he termed the alternate constriction and dilatation as 'hunting reaction'. This is a cyclic phenomenon and is usually triggered at temperatures below 10°C. The cold induced vasodilatation prevents the extremities to cool further by losing more heat at the expense of the thermal economy of the body. It is more marked in hands than in feet. Other body areas which are normally exposed to cold *e.g.*, ear, forearm and the elbow also show the dilator response. The cold induced vasodilatation does not depend upon the integrity of the sympathetic nervous system or sensory nerves but is caused by cold directly acting on the vessel walls[12]. The Lewis phenomenon may be reduced by several variable factors such as total body cooling or emotional state and anxiety. On the other hand adaptation to cold is associated with rapid onset of vasodilatation, resulting in greater blood flow and quicker rewarming. Physical fitness, nutritional status as well as age may also influence the protective mechanism of the body against cold and therefore are of importance for persons required to function in the cold environment[13].

PHYSICAL FITNESS AND AGE

The importance of physical fitness and physical training programme has been emphasized for various reasons. It has been shown by Adams & Heberling[14] that prolonged physical training significantly increases the physical fitness scores. When these subjects were exposed to cold after the training programme, the average level of the heat production was 15 Cal/meter^2/hour higher and the foot and toe temperatures 3—4 °C higher with no significant difference in the average body temperature than the controls[14,15]. These data indicate that physical training may provide enhanced protection to the extremities. The actual factors responsible for higher metabolic rate and higher temperature of the extremities are not well defined. It may be that the increased heat production during the period of physical training persists for a period longer than 24 hours after the training programme[16] or the protein intake and utilization in the body is improved as a result of vigorous exercise[17].

The blood flow through the extremities changes little with age although the vasomotor variation in flow is diminished in the elderly[18]. There may be a rise in the resistance of the vascular bed resulting from the rise in systemic arterial pressure with age[19]. Spurr *et al*[20] observed that the hunting reaction occurred less frequently in the older age group. The rate of cooling and rewarming appeared to be more rapid in the younger age group.

NUTRITIONAL STATUS AND DIET

In extreme cold climate the caloric requirements are enhanced and an inverse relationship has been observed between the caloric requirements and environmental temperature[21]. Our studies[22] have shown that caloric requirements for the same daily routine are enhanced at high altitude in cold. This additional requirement may be met by adding more fat to the diet. At high altitudes even high fat diet may be well tolerated without any evidence of ketosis and its sequelae[23]. This may be in accordance with the conclusion of Mitchell & Edman that protein intake does not increase tolerance to cold while high carbohydrate and fat diet are of value[24].

The nutritional status of an individual also seems to influence the thermal protection afforded to the body against cold. Impietro & Bass[25] have reported that the ability to maintain body core temperature is impaired by marked restriction of food intake. In such cases the cold induced heat production is decreased during prolonged exposure to cold thus necessitating a higher insulative protection for the body. A fall in the core temperature affects the cold induced vasodilatation[26, 27]. Under operational conditions such marked restrictions of food intake should not normally arise. But at times when parties of individuals are cut off from their parent units and run short of supplies they are prone to caloric deficiency for short periods. Recently Eagan[7] tested the thermal responses of six subjects who had undergone a regimen of starvation for five days outdoors in interior Alaska. The starvation group did not differ from the control in average temperature of the finger although temperatures were obviously higher for the controls at the end of the test. The slightly lesser pain in the starvation group was accounted for their cold experiences during the starvation regimen. How far such mild changes of nutritional status and fatigue will effect the protective mechanism of the body needs further investigation.

The question of alcohol and high SDA diet to provide quick calories during cold exposure is worthy of consideration. German workers[28] recommended moderate quantities of alcohol as a protective measure against the Russian winter. The recommendations were mainly based on the assumption that ready calories provided by alcohol would help in the maintenance of the body temperature. Recently a study on thermal balance showed that deep body temperatures generally showed no fall in individuals given moderate quantities of alcohol. Only in a few the rectal temperatures showed a slight fall[29]. However, alcohol produced other deleterious effects on the central nervous system which may summate with those of high altitude hypoxia. The role of alcohol and high SDA diet need to be further investigated.

As regards the effects of deficiency and extra supplement of various vitamins, the results are conflicting. There is some evidence of increased resistance to cold in animals given extra amounts of vitamin C[30]. No beneficial effects have so far been demonstrated in human beings exposed to cold. However, in view of the fact that fresh vegetables and fruits are difficult to provide at high altitudes, it is preferable to supplement the diets with vitamin C. There is a need to determine the influence, if any, of vitamin supplements and deficiencies especially of nicotinic acid to the incidence of experimental frost-bite in animals.

INSULATION OF BODY AND POSITIVE HEAT BALANCE

The cold induced vasodilatation patterns are related more to the central thermal state of the body than the finger temperature[31]. If the body is in a condition of heat debt to the extent of 10–15 per cent the Lewis hunting reaction is sufficiently weakened or totally abolished [26,27]. This finding has an important bearing on the question of frost-bite. The extremities lose heat at the expense of the central thermal economy. If the heat loss exceeds to an extent of 10–15 per cent of the metabolic heat production, the vasodilatation will be totally abolished and the temperature of the extremities will start falling. Either the body should be in a position to increase its heat production to meet the demand of the extremities or it will have to sacrifice them in order to preserve itself. It has been shown that adequate heating of the body will maintain temperature of the extremities[32]. It is also interesting to note that face warming is capable of increasing blood flow to the hands[33]. These experimental results indicate the necessity of adequate thermal insulation of the body to minimise the thermal losses from the body. Veghte[34], on the other hand, observed that heavy insulation of the body with unprotected extremities does not enhance tolerance of the extremities to cold for most persons at a temperature of 0°C or less in cold chambers. This implies intense vasoconstriction of the vasculature of the extremities due to local responses of the peripheral receptors. If the extremities are also protected adequately, the body is able to tolerate low environmental temperatures for long periods.

No simple physical method is available at present to indicate whether an individual has a positive or negative heat balance. It is only the subjective feeling of discomfort which acts as a guiding factor. It has been mentioned that the habituated individual feels less discomfort due to cold for the same degree of cold stress[35—37] and this confidence may induce him to over expose himself to cold. As such, to be on the safer side, it is always better to keep oneself physically active as far as possible and restore the heat balance by periodic exercises.

GENERAL COLD ACCLIMATIZATION

Human adaptation to cold has been the subject of numerous studies most of which are concerned with field observations of metabolism and body temperature of people accustomed to a cold climate since birth. These studies have revealed various thermo-regulatory processes in response to cold. At one extreme Australian aborigines are there who sleep naked through a considerable cold night without recourse to increased metabolism The adaptation of this group to non-freezing cold is characterised by low body temperature and low tissue thermal conductance[8, 38]. In the midspectrum are the white persons living in temperate climates, who expend a great deal of metabolic heat trying to maintain normal body temperature during cold exposure and are unable to decrease tissue conductance as much as the aborigine can[39]. On the other extreme appears to be the Alaskan Eskimo who, when cold stressed, has a higher metabolism and warmer skin[40] than the non-Eskimo. Rennie *et al*[41] observed that the Eskimo, when at rest, consistently produced more heat to the extent of 15–20 Cal/meter^2/hour. The high metabolism has been shown to be caused mainly by the specific dynamic action of their high protein diet. The elevated metabolism cannot be cold adaptation in case it is due to dietary factors. Their tissues conduct heat physically at a rate of 60 per cent above that of non-Eskimo, which is a result of their relative lack of fat insulation. This loss of heat results in a warmer skin, a greater heat loss and a greater fall of rectal temperature. The value of high metabolism and high tissue conductance of a fully clothed Eskimo would lead to better convection of heat to the distal extremities since average skin temperatures under their clothing are comparable to those of the unclothed Eskimo in room temperature exceeding 28°C. If the Eskimo was not well clothed in his natural habitat this excess heat loss would prove fatal. Therefore, their active heat loss reflexes are not detrimental to overall body temperature but in fact may be beneficial in warming skin surfaces exposed to subzero temperatures and in this way prevent local cold injury.

Repeated cold exposures produce changes in man which acclimatize him to cold environment. These changes are reduction in the adrenergic responses which are evidenced by a weak pressor action in the case of cold water immersion and a decreased vasoconstriction in case of cold air exposure[42]. The metabolic adaptation is also observed as shown by non-shivering thermogenesis in cold adapted individual[43]. Joy[44] has given evidence of an increased metabolic action of nor-adrenaline in cold adapted men.

There is no direct evidence suggesting a marked difference in the susceptibility of extremities to cold injury in the cold adapted and non-acclimatized individuals. Information from the records of frost-bite cases during the recent Sino-Indian operations did not throw any light on the relative susceptibility of the acclimatized or the non-acclimatized individuals[45]. Also no mention was made in the reports of frost-bite cases during the operations in Korea[5]. Presumably, all the soldiers were fully acclimatized to cold. The question of cold acclimatization assumes importance for the Indian forces as it is often necessary to transport the soldiers from the plains to the combat areas at high altitudes. In a tropical country it is likely that most of these soldiers would often not be in a state of cold acclimatization at the time of arrival in the field areas. The question arises whether the extremities of these soldiers will be unduly susceptible to frost-bite. If this be true, it would be necessary to ensure that the soldier is cold acclimatised by artificial or natural means for a period of four to six weeks prior to his assignment in high altitude operations.

LOCAL COLD ACCLIMATIZATION

There is enough evidence to show that the deteriorating effect of cold on the sensory and neuromuscular functions of the hand can be lessened by acclimatization[37,46]. This may at least partly be due to an improved peripheral blood circulation in the hand. Differences in the vascular responses to cold have been found by several workers [31,47—49]. It is well established fact that onset of cold induced vasodilatation is quickest in people habituated to life in the cold[50]. Evidence is also available that man may develop a greater blood flow through the hands at low temperatures as a result of previous exposure to cold[51]. Krog *et al*[50] could not confirm this observation in studies on hand circulation of Lapps and North Norwegian fisherman. However, they suggested that the greater blood flow in the cold acclimatized persons is only found when the experimental subjects are investigated at ambient temperatures low enough to produce an increased general vasoconstriction tonus. Evidence in favour of this hypothesis was brought forward by Elsner *et al*[49] who studied heat output from the hands of Arctic Indians. They found markedly lower heat output from the hands of whitemen than of Indians in cool environment. Hellstrom & Andersen[52] could not find any significant difference of the mean heat output between Arctic fishermen and young men not habituated to work in the cold when they were either in general heat balance or heat debt. Their results do not agree with the view that men habituated to work in the cold with their hands show an increased blood flow in the cold when studied under environmental temperature low enough to produce a general vasoconstriction. Studies on tolerance of Gaspe fisherman[40] to cold water showed a greater heat flow and higher finger temperature than the control subjects from the same vicinity. With one hand immersed in water, the pressor response was greater in control subjects. Skin biopsies showed no difference in skin thickness and in cell size but there was a significantly greater number of mast cells in the fisherman's skin. On the basis of these results LeBlanc[48] suggested that thermoreceptors, hypothalamus, cortex and effector organs are the sites of local adaptation.

Adams & Smith[31] were able to produce local cold conditioning in the right index finger of Caucasian subjects from a temperate climate by immersing in ice water bath for 20 minutes four times daily for one month. In addition to this Eagan[53] found that chronic exposure of hands to cold air for 12 hours every day results in decreased finger cooling rate after about 10 days. However, Miller & Irving[54] have pointed out they individuals subjected to cold stress need not all be acclimatized and it is not necessary that adaptive changes may occur in all such individuals.

Although direct evidence of proneness to frost-bite of locally acclimatized extremities is not available yet the changes produced may be considered protective in nature. The German authorities recommended alternate exposure of the extremities to cold water bath and rubbing with snow as a protective measure against frost-bite[55]. It may be worthwhile to include similar exercise in the training programme of the soldier even though he may be considered in a condition of general cold acclimatization.

General cold acclimatization even to moderate cold necessarily imparts some degree of local cold acclimatization. The parts of the body which are frequently exposed to cold *e.g.* hands, are better locally adapted to cold. Feet which are covered with socks and shoes for most of the time do not show the same degree of cold adaptation. It has been shown in sojourners to Antarctica that people who have stayed there for more than one year show better general and local cold acclimatization[56–59]. In experiments conducted by Massey[46] eighteen persons (fourteen were new and four had attended one year camp in Antarctica) developed primary frost-bite of the fingers.

It is not known how far local cold acclimatization would help general cold acclimatization of the body, but if LeBlanc's view that the centres of local cold acclimatization are hypothalamus, cortex, thermoreceptors and effector organs is correct, it may be conjectured that the locally cold adapted individual can stand cold stress better than the unadapted. This view may be compared with the cold acclimatization of the Eskimo who is more conditioned to the loss of heat from the extremities and other exposed parts of the body rather than conservation of the thermal energy. It is the Eskimo rather than the Australian aborigine who lives in an environment capable of freezing the extremities.

ACCLIMATIZATION TO HIGH ALTITUDE HYPOXIA

Acclimatization to high altitude hypoxia is a slow process. Individuals who reach high altitudes rapidly suffer from the hypoxic effects for a considerable length of time. Under hypoxic conditions, there may be a general vasodilatation associated with local vasoconstriction of the extremities[60]. The sensitivity of cold receptors in the skin is also reduced[61]. Further hyperventilation results in greater respiratory heat losses[62]. Hypoxia inhibits shivering reflexes through the chemoreceptors[63]. In animals, the core and skin temperatures decrease under hypoxia and cold[64] but no such changes occur in man[65]. Kottke[66], however, observed a fall in the core temperature in man. Oxygen administration has been shown to suppress functional changes particularly of the legs in animals exposed to cold water bath for 30 hours [67]. In our studies, high altitude hypoxia decreased tolerance to cold by impairing the fraction of non-shivering thermogenesis. Further stay of about a year at high altitudes produced only slight degree of cold acclimatization as compared to Tibetans as evidenced by cold induced oxygen consumption, shivering and cold tolerance. Tibetans also maintained a higher foot temperature on cold exposure[68]. Similarly Cavanagh[69] found no evidence of local cold habituation upto a period of 62 days at high altitudes. This contrasts with experiments in cold environment alone where habituation could be demonstrated within six weeks [46, 70]. Incidence of frost-bite is particularly to be high at high altitude [71] although the mechanism by which hypoxia aggravates cold injury is not clear at present. Pitchotka *et al*[72] examined the effect of hypoxia on local cold injury in the rabbit. From their observations it was clear that exposure to hypoxia after cold injury increased the degree of injury. They suggested that tissues not irreversibly damaged by the cold injury are further damaged by diminished oxygen supply. The duration of hypoxia before injury does not seem to be related with the extent of the damage.

Experiments on heat output from the hand immersed in cold water bath at 4°C have indicated a decreased heat output in hands at high altitudes of the same individual when compared at sea level[73]. Further experiments are in progress to determine as to what factors are responsible for this marked reduction of the cold induced vasodilatation at high altitudes.

It is surprising that slow and gradual acclimatization to hypoxic conditions accelerates the cold adaptation. Hale & Meffered[74] concluded from their experiments on rats at 380 mm of *Hg* that in many respects the results at high altitude were closer to the ideal than those at ground level which suggests that chronic hypoxia acts to accelerate adaptive changes to temperature.

Tissular and chemical acclimatization to hypoxia results in increased capilarity which helps in physical diffusion of oxygen from the blood to the cells. An increase [75,76] in the levels of myoglobin, energy rich phosphates and ATP—ase activity has also been reported in high altitude reared animals as compared to those at seal level. These changes during acclimatization are expected to be helpful in cold acclimatization also. However, data in this respect on human subjects are lacking. Investigation on human beings may throw more light on the protective changes that take place during cold exposure.

RACIAL AND ETHNIC DIFFERENCES

Racial and individual differences in vascular response to cold have been found to exist. Negroes maintain a lower finger temperature on immersion in ice water as compared to Alaskan natives[77]. Compared to white subjects, Negroes showed a more severe digital response on exposure to intense cold. They also showed a significantly less rise in cold induced metabolism[78]. During the Korean operations frost-bite cases were higher in the Negroes than whitemen[5]. It could not be established whether this difference was due only to increased susceptibility to frost-bite or other factors like personal hygiene, motivation and training as well. In India, the personnel of the armed forces are recruited from different regions which differ widely in environmental conditions. Variations in food habits, personal and social customs also exist. As such it would be interesting to study the variations in their ability to acclimatize to cold. These studies will provide valuable information on their susceptibility to local cold injury and the amount of insulative protection they require.