CHAPTER 7

Thermal Stress

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INTRODUCTION

In the past, aviators in open cockpit aircraft had to perform flight tasks with little or no protection from the environment or protective systems to mitigate environmental stresses. With the advent of modern aircraft, protective clothing, and survival equipment, it would seem that thermal stress (heat or cold) would no longer be a significant concern for the modern aviator. However, present day protective systems and equipment used in aviation create new situations where aviators remain challenged by thermal stress. For example, closed cockpits can create heat stress due to the greenhouse effect from solar radiation. Protective clothing [G-suits, nuclear-biological-chemical (NBC) gear] add to the difficulty of performing a task and increase heat stress and the risk of dehydration. The proximity of flight crews or ground crews to heat generated by engines and/or reflected from the tarmac or flight deck is also of great concern. This heat stress is further exacerbated by the ambient environment itself when working (ground crews) or waiting outdoors (flight crews) during preflight, taxiing, or standby for takeoff. The combined effects of heat stress and dehydration over many hours for both ground and flight crews can alter cognitive function, delay reaction time, increase error rate, deteriorate physical stamina, impair cockpit management, and increase the risk of heat illness or injury. Although heat mitigation systems exist (air-conditioning, built-in clothing cooling systems), their cooling capacity is limited.

Ground crews and support personnel may also be exposed to cold climates. As with heat, exposure to cold for longer periods can degrade cognitive function such as decision making and physical performance, including manual dexterity, and can increase risk of injury. This is especially true for ground crews who are not only exposed to cold air but also use their hands to perform tasks, where heat loss can occur when touching metal tools, and may lose heat through their feet by standing on a cold tarmac or flight deck for long periods. In these scenarios, risk for frostbite and freezing injuries can be of concern, especially in the extremities (fingers, toes). Heat loss and the risk of cold injury are further aggravated by environmental factors such as wind and/or rain that increase the rate of body heat loss. Flight crews must also be concerned with cold environments during in-flight operations on aircraft with high airflows such as helicopters operating with open doors (Figure 7-1).

FIGURE 7-1 Aerospace personnel may be exposed to low ambient temperatures both during flight and upon planned or unplanned landings in cold climates.

The protection from the environment (cold or heat) afforded by the aircraft is lost when pilots are forced to land or ditch. Once on the ground or in the water, flight crews are fully exposed and a large part of survival depends on meeting environmental challenges. Understanding the factors that contribute to heat gain or heat loss, dehydration, and injury due to environmental exposure can be important not only for ground and flight crews but also for aeromedical personnel who must not only recognize signs of heat or cold injury and dehydration but must also be able to provide appropriate medical treatment. This chapter will outline the specifics regarding mechanisms of heat exchange, the physiological and cognitive responses to environmental stress and dehydration, guidance for operations in hot and cold environments, and will present the signs and symptoms of injuries and illnesses related to heat and cold exposure and provide treatment recommendations.

Biophysics of Heat Exchange

Changes in body core temperature are the result of either a positive or negative change in heat storage. If the body gains more heat than it dissipates, body core temperature will rise. Conversely, if heat loss exceeds heat gain, then heat storage will be negative and core temperature will fall. We can present these relationships between gain and loss mathematically as follows:

$$S = M - (\pm \text{Work}) - E \pm (R + C) \pm K$$

where S = heat storage, M = metabolic heat production, E = evaporation, R = radiation, C = convection, K = conduction, and W = external work (1). E, R, C, and K are the heat exchange pathways, explained in detail in the subsequent text. The mathematical equation contains positive and negative signs that indicate heat gain (positive sign) and heat loss (negative sign). It is important to understand that heat gain or loss by some of these exchange pathways are mathematical. Situations such as negative work (−W) may not occur in "real world" applications. Examples of heat gain and storage while on the ground and in the cockpit are depicted in Figures 7-2 and 7-3.

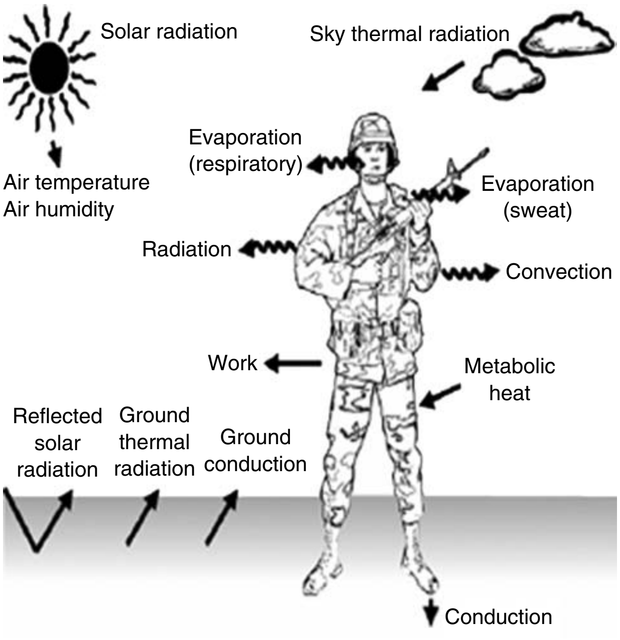

FIGURE 7-2 Sources of environmental cooling or heating on the ground.

During physical work, approximately 25% of energy expended goes toward performing the actual work and approximately 75% of energy expended is released in the form of heat. This heat is released from active skeletal muscles and transferred from the body core to skin, which then must dissipate the heat to the environment. Physical exercise can increase whole body metabolism by as much as 15 to 20 times above the resting metabolic rate in healthy young males. If heat production is not balanced by loss, body temperature will increase early in the work bout. In the cold climate, the opposite scenario occurs, where resting individuals must increase overall resting metabolic

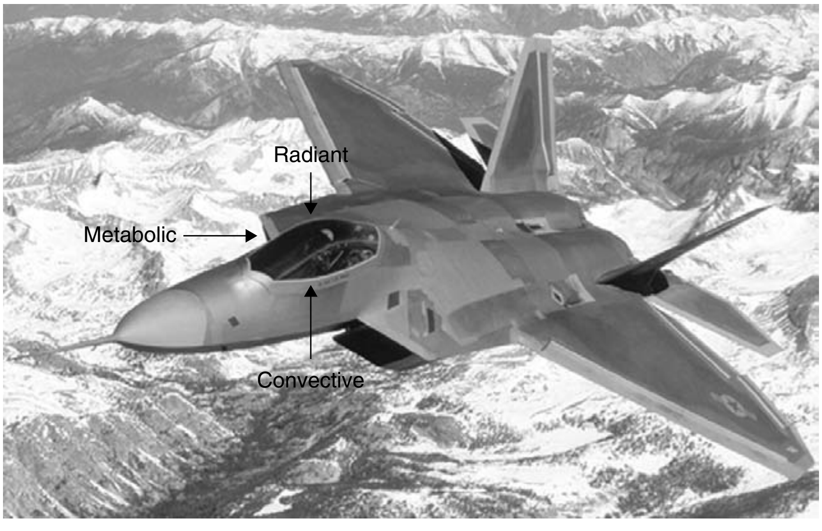

FIGURE 7-3 Examples of cockpit heat sources. Radiative heat from sun and electrical equipment; convective heat from air within cockpit and greenhouse effect; metabolic heat from pilot(s).

heat production (M) through mechanisms such as shivering, which can increase M by 3 to 5 times, in order to maintain normal body core temperature (37°C).

Convection is heat transfer by movement of air or fluid over the body, whether induced by thermal currents, body motion, or natural movement of air (wind) or water. Heat loss by convection occurs when the temperature of the air or water that is in contact with skin is below body temperature; conversely, heat gain by convection from air or water occurs when these temperatures approach or exceed that of the body. The primary means of moving heat from the core to the skin is by convection through blood flow (1).

Heat gain by radiation (solar, sky, large objects, and ground) occurs when radiative temperatures are higher than the body surface temperature. Heat loss occurs when surrounding objects or environments have temperatures lower than the body and the body will radiate heat to these objects and environments. Accordingly, temperature combinations of the sky, ground, and surrounding objects may exist which results in body heat gain due to radiation, although the air temperature is below that of the body. Radiative heat exchange is independent of air motion (1).

Conduction is heat transfer to or from solid objects through direct contact. In hot environments, conduction is usually minimal because little contact surface is involved. However, in the case of individuals such as aircrew, conduction can be more significant due to such factors as standing on hot tarmac, or contact with metal aircraft. Conversely, in the cold standing on cold tarmac, or a steel flight deck can result in conductive heat loss and contributes to extremity cooling.

When the ambient temperature is greater than or equal to skin temperature, evaporative heat loss accounts for all body cooling. Eccrine sweat glands secrete fluid onto the skin surface permitting evaporative cooling when liquid is converted to water vapor. Sweat glands respond to thermal stress primarily through sympathetic cholinergic stimulation, with catecholamines having a smaller role in the sweat response (2). The rate of sweat evaporation depends on air movement and the water vapor pressure gradient between the skin and the environment, so in still or moist air the sweat does not evaporate readily and collects on the skin. Sweat that drips from the body or clothing provides no cooling benefit.

The mechanism of heat loss depends on the ambient temperature. At low ambient temperatures (5°C—10°C), dry heat loss (i.e., heat loss from radiation and convection) is greater than heat loss through evaporation. At high ambient temperatures, evaporative heat loss predominates. Ambient water vapor pressure (relative humidity) also affects heat loss. When water vapor pressure is high, less sweat is able to evaporate from the skin to the environment, compared to a dry environment. Heat exchange between skin (or man) and the environment is influenced by air temperature; air humidity; wind speed; solar, sky, and ground radiation; and clothing.

Physiological Regulation in Hot Environments

Humans regulate their body core temperature within a narrow range (35°C–41°C). This is accomplished through behavioral and physiological regulation. Behavioral thermoregulation includes conscious actions such as altering physical activity, selecting appropriate clothing, adjusting indoor thermostats, and seeking shade, sun, or shelter. Physiological temperature regulation is typically independent of conscious behavior, but can be modified by it, and includes control of skin blood flow (Figure 7-4), sweating, and metabolic heat production (2).

Figure 7-4 schematically depicts the sensory and effector aspects of the human thermoregulatory system. Core temperature is the controlled variable under most conditions and must be maintained within defined limits. Signals regarding core temperature are integrated with skin temperature signals at the hypothalamus. If the core temperature signal deviates from the defined set point, appropriate effector responses (e.g., vasoconstriction or dilation, sweating or shivering) are elicited to either reduce or increase peripheral heat loss and metabolic heat production. For example, during exercise in the heat, core temperature is increased. This change in core

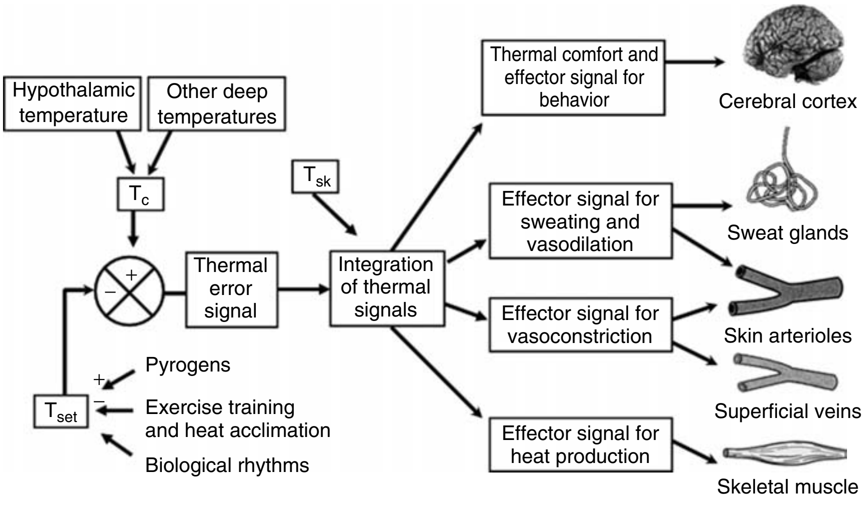

FIGURE 7-4 Schematic of human thermoregulatory control. Sawka MN, Young AJ. Physiological systems and their responses to conditions of heat and cold. In: Tipton CM, ed. *ACSM's advanced exercise physiology*. Philadelphia: Lippincott Williams & Wilkins, 2006:535–563.

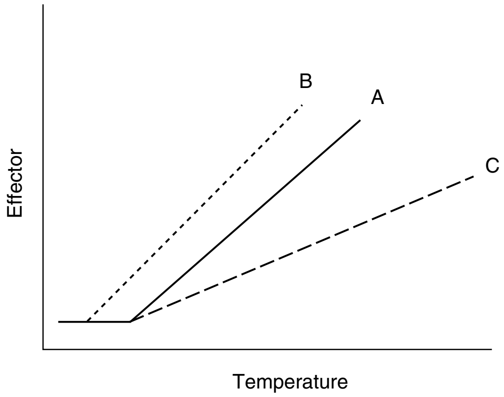

FIGURE 7-5 Proportional control system for two heat-dissipating effector responses (sweating and skin blood flow). Line A: This line demonstrates that the effector response increases as a function of temperature with a characteristic point where the response turns on (threshold) and the response increases as the temperature rises (slope or sensitivity). Line B: Change in the threshold (relative to A) of the effector response with no change in the slope. Line C: Change in the slope of the effector response (relative to A) with no change in the threshold.

temperature causes heat loss effector responses (sweating, vasodilation, and increased skin blood flow) to attenuate the rise in core temperature. These responses exhibit two control characteristics: (i) they turn on when reaching a particular core temperature threshold, and (ii) they exhibit a graded response as the controlled variable is further disturbed. This type of control system is called a *proportional control system*.

Figure 7-5 demonstrates the proportional control system for two heat-dissipating responses (sweating and skin blood flow). Note that there is a particular threshold when these physiological responses increase and then as the core temperature continues to rise, these responses increase linearly. Changes in the threshold of an effector response are generally thought of as a change in the set-point temperature (2). Any change in the slope of the relationship between core temperature and the effector response is considered as a change in the sensitivity of the system at a peripheral level (e.g., sweat gland). For example, dehydration will increase the body core temperature threshold for sweating, thereby delaying the onset of sweating.

Proportional control systems are modified by both thermal and nonthermal factors (3). Skin temperature, a thermal factor, changes the sensitivity of the relationship between sweating and core temperature. Therefore, at any given core temperature, sweat rates are greater when the skin is warm and lower when the skin is cool. Nonthermal factors that change the relationship between core temperature and heat loss responses include dehydration, acclimatization, circadian rhythms, and endocrine status (3,4). Table 7-1 presents the effects of these factors on thermoregulatory control of the heat.

Heat acclimatization is a classic example of how changes in thermoregulatory control impact overall health and performance. Sweating begins at a lower core temperature threshold, allowing earlier heat dissipation and a cooler skin temperature. Similarly, skin blood flow is higher at any given core temperature due to change in the threshold temperature at which cutaneous vasodilation begins to rise (5). Therefore, lower skin temperatures following heat acclimation reduce the volume of skin blood flow for heat exchange; however, acclimation initiates skin blood flow sooner so that dry heat loss (R + C) improves to an even greater extent. Higher sweating rates and skin blood flow, in concert, help explain why core temperature is lower after acclimatization; it is due to better evaporative, radiative, and convective heat loss.

Physiological Regulation in Cold Environments

One of the initial responses to cold exposure is peripheral vasoconstriction. Decreased blood flow to the shell (skin, subcutaneous fat, and skeletal muscle) in effect increases insulation, and reduces convective heat transfer between the body's core and shell (Figure 7-6), and skin temperature declines. Skin vasoconstriction begins when skin temperature falls below 33°C (95°F). As exposure to cold continues, vessels in underlying tissues vasoconstrict and thereby increase the insulating layer. Cooling of underlying inactive muscles can cause them to become stiff. Therefore, the vasoconstrictor

TABLE 7-1

Effect of Nonthermal Factors on Sweating and Skin Blood Flow Threshold and Sensitivity

	Sweating		*Skin Blood Flow*	
Factor	*Threshold*	*Sensitivity*	*Threshold*	*Sensitivity*
Dehydration	Increase	Decrease	Increase	Decrease
Acclimatization	Decrease	Increase	Decrease	Increase
Circadian rhythm	Increased at 4:00 pm and 8:00 PM vs. 12:00 AM and 4:00 AM	No time of day difference	Increased at 4:00 PM and 8:00 PM vs. 12:00 AM and 4:00 AM	Increased slope at 4:00 AM vs. 12:00 AM
Menstrual cycle phase	Higher during luteal phase vs. follicular phase	No difference between follicular and luteal phases	Higher during luteal phase vs. follicular phase	No difference between follicular and luteal phases

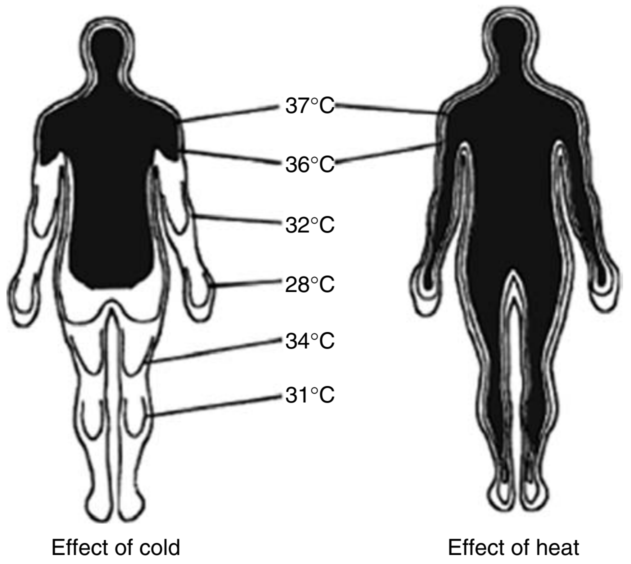

FIGURE 7-6 Effect of heat and cold on skin temperatures.

response to cold exposure helps retard heat loss and defend core temperature, but at the expense of a decline in peripheral tissue temperatures (6).

Another primary response to cold exposure is involuntary shivering, which increases metabolic heat production and voluntary behavior, that is, increasing physical activity (exercise, increased "fidgeting," etc.) which increases heat production. Shivering consists of involuntary, repeated, rhythmic muscle contractions (7), and may start immediately, or after several minutes of cold exposure, usually beginning in torso muscles and then spreading to the limbs (8). The intensity and extent of shivering varies according to the severity of cold stress. As shivering intensity increases and more muscles are involved metabolic rate increases, typically reaching approximately 600 to 700 mL/min during resting cold air exposure, and often exceeding 1,000 mL/min during resting cold water immersion (6). The highest oxygen intake reported is 2.2 L/min, recorded during cold water immersion, which was approximately six times the resting metabolic rate (50% $\mathrm{V}\text{O}_{2\mathrm{max}}$) for that subject (9).

A common response to cold exposure is cold-induced diuresis (CID), an increase in urine production associated with the central fluid shift induced by vasoconstriction (10). The fluid loss due to CID does not have the same effects on health and performance during cold exposure as a similar loss of fluid would during heat exposure. In fact, individuals who are dehydrated before cold exposure typically experience less CID than euhydrated individuals (11), that is, the diuresis is self-limiting. Furthermore, individuals who have free access to food and fluid will rehydrate upon returning to a warm environment. The fluid loss due to CID may be more important during heavy exercise in the cold environment when core temperature is elevated and blood flow to the skin increases to dissipate heat. If individuals in the cold environment are heavily clothed, they may overheat more readily and increase fluid losses due to thermoregulatory sweating. For these reasons, maintaining hydration is important during work in cold environments. Dehydration does not appear to increase risk of peripheral cold injury (11).

The vasoconstriction-induced reduction in blood flow and fall in skin temperature contribute to the etiology of peripheral cold injuries, particularly in the digits, ears, cheek, and nose. Cold-induced vasoconstriction has pronounced effects on the hands, fingers, and feet making them particularly susceptible to cold injury, pain, and a loss of manual dexterity (12) (Figure 7-6). Another vasomotor response, cold-induced vasodilatation (CIVD), can under some circumstances interrupt vasoconstriction in the fingers, toes, nose, cheeks and ears. Following the initial decline in skin temperature during cold exposure, an increase in blood flow may occur. The CIVD may be transient, resulting in periodic oscillations of skin temperature. The increased blood flow increases local tissue temperature and may protect against cold injury. Although initiated by local cooling, the CIVD response is also modulated by the central nervous system (13).

Wet Bulb Globe Temperature

Numerous environmental indices have been proposed for predicting thermal heat strain. The most widely used of these is the Wet Bulb Globe Temperature (WBGT) index, which was developed 50 years ago to provide guidance for controlling heat casualties among military troops in hot environments (14). Since this time, the index has also been adopted and popularized by occupational and sports governing authorities to promote safe environmental limits for work and exercise. The WBGT index is computed from measures of the natural wet-bulb temperature (Twb), black globe temperature (Tbg), and dry bulb air temperature (Tdb) using the following weighted formula:

$$\mathrm{WBGT} = 0.7\ (\mathrm{Twb}) + 0.2\ (\mathrm{Tbg}) + 0.1\ (\mathrm{Tdb})$$

When indoors the formula simplifies to $0.7\ (\mathrm{Twb}) + 0.3\ (\mathrm{Tbg})$. The equation emphasizes the strong influence of air water vapor content on human thermoregulation (sweat evaporation) in the heat, which is an extension of the same fundamental observation made more than a century ago (15). Because NBC protective clothing and body armor create situations where sweat evaporation is impaired, WBGT adjustments for clothing have also been established for the military (16).

In an effort to develop a thermal strain index specifically applicable to aviation, Harrison et al. (17) examined the relationship between ground weather and cockpit conditions across a broad range of WBGT at altitudes less than 3,000 ft. The following equation was developed from the relationship between ground WBGT (WBGTgr) and cockpit WBGT (WBGTcp):

$$\mathrm{WBGTgr} = (\mathrm{WBGTcp} - 0.333)/1.183$$

On the basis of WBGTgr and WBGTcp relationship, a practical thermal strain index for aviation was developed known as the *Fighter Index of Thermal Stress* (FITS) (18). The FITS assumes that Tbg is greater than Ta by 10°C (clear skies) and requires only two ground measurements to estimate cockpit thermal stress:

$$\text{FITS} = 0.83\,(\text{Twb}) + 0.35\,(\text{Ta}) + 5.08$$

FITS temperatures between 32°C and 38°C represent a "caution zone" where operations are permissible for pilots when adhering to proper precautions (18). FITS temperatures greater than 38°C represent a "danger zone" for flight operations that recommend cancellation of low-altitude missions and strict limits on high-altitude flights (18). It is important to remember that FITS provides only general guidance, but it does specifically address the unique occupational circumstances of aviators.

The following FITS procedures are designed to minimize heat stress impact (18):

1. FITS caution zone (between 32°C and 38°C)
    a. Encourage crews to drink water before cockpit entry, during standby, and in flight
    b. Be alert to symptoms of heat stress
    c. Avoid exercise 4 hours before takeoff
    d. Precool cockpits by means of air-conditioning the ground carts
    e. Assign alternate crewmembers to perform preflight aircraft inspection
    f. Keep the sun out of transparencies by using rolling roofs or fabric covers
    g. Transport crewmembers directly to the aircraft
    h. Limit the permitted duration of in-cockpit standby
2. FITS danger zone (temperatures >38°C)
    a. Keep the sun out of transparencies by using rolling roofs or fabric covers
    b. Allow only one change of aircraft before requiring return to ready room in cases of mechanical delay
    c. Optimized conditions for cooling and rehydration between flights
    d. Support self-assessment and empower crews to stand down when they judge that further flights would be unsafe

Wind Chill

Another environmental index that takes into account the cooling that can occur due to convectional flow of air is the Wind Chill Temperature (WCT) index (Table 7-2). The WCT integrates wind speed and air temperature to provide an estimate of the cooling power of the environment, as compared to calm conditions (19). Wind speed may vary locally depending on terrain features, but can also be increased during flight such as helicopter transport with open bays. Wind does not cause an object to become cooler than the ambient temperature, but causes objects to cool toward

TABLE 7-2

Wind Chill Temperature Index Frostbite Times are for Exposed Facial Skin

Wind Speed (mph) ↓	*Air Temperature (°F)*																	
	40	**35**	**30**	**25**	**20**	**15**	**10**	**5**	**0**	**−5**	**−10**	**−15**	**−20**	**−25**	**−30**	**−35**	**−40**	**−45**
5	36	31	25	19	13	7	1	−5	−11	−16	−22	−28	−34	−40	−46	−52	−57	−63
10	34	27	21	15	9	3	−4	−10	−16	−22	−28	−35	−41	−47	−53	−59	−66	−72
15	32	25	19	13	6	0	−7	−13	−19	−26	−32	−39	−45	−51	−58	−64	**−71**	**−77**
20	30	24	17	11	4	−2	−9	−15	−22	−29	−35	−42	−48	−55	−61	**−68**	**−74**	**−81**
25	29	23	16	9	3	−4	−11	−17	−24	−31	−37	−44	−51	−58	**−64**	**−71**	**−78**	**−84**
30	28	22	15	8	1	−5	−12	−19	−26	−33	−39	−46	−53	**−60**	**−67**	**−73**	**−80**	**−87**
35	28	21	14	7	0	−7	−14	−21	−27	−34	−41	−48	**−55**	**−62**	**−69**	**−76**	**−82**	**−89**
40	27	20	13	6	−1	−8	−15	−22	−29	−36	−43	−50	**−57**	**−64**	**−71**	**−78**	**−84**	**−91**
45	26	19	12	5	−2	−9	−16	−23	−30	−37	−44	**−51**	**−58**	**−65**	**−72**	**−79**	**−86**	**−93**
50	26	19	12	4	−3	−10	−17	−24	−31	−38	−45	**−52**	**−60**	**−67**	**−74**	**−81**	**−88**	**−95**
55	25	18	11	4	−3	−11	−18	−25	−32	−39	−46	**−54**	**−61**	**−68**	**−75**	**−82**	**−89**	**−97**
60	25	17	10	3	−4	−11	−19	−26	−33	−40	**−48**	**−55**	**−62**	**−69**	**−76**	**−84**	**−91**	**−98**

Frostbite times:
light gray—frostbite could occur in 30 minutes;
medium gray—frostbite could occur in 10 minutes;
dark gray—frostbite could occur in 5 minutes.
From the U.S. National Weather Service.

ambient temperature more rapidly than without wind. In humans, because heat continuously moves from core to skin, wind will increase heat loss. The WCT presents the relative risk of frostbite and the predicted time to freezing of exposed facial skin walking at 1.3 m/s (3 mph) (20). Facial skin was used because this region is most often unprotected; however, vasoconstriction results in a greater decrease in blood flow to the extremities, which may increase the susceptibility of fingers and toes to freezing. Wet skin exposed to the wind will cool even faster; therefore, under wet conditions the ambient temperature used for the WCT table should be 10°C lower than the actual ambient temperature (21). Note that frostbite cannot occur if the air temperature is above 0°C (32°F).

Operational Effectiveness

Operational effectiveness, that is, the ability to perform task requirements without being debilitated by the environment, depends on (i) proper assessment of the environmental threat (air temperature, wind speed, potential for precipitation or immersion); (ii) identification of increased susceptibility (due to physiological factors such as fatigue, or individual factors, such as dehydration, body composition, fitness level or illness); (iii) implementation of controls (appropriate clothing, fluid availability, work/rest cycles, ability to cool or warm, etc.); and (iv) heat and cold injury recognition, mitigation methods, and first aid.

Heat Stress

Flight crews encounter heat stress during preflight, engine start, taxiing out, and standing by for takeoff. Total ground time can be considerable even in fighter aircraft. In addition, the heat load experienced in the cockpit is more severe than on the ramp because of the reduced air velocity, personal equipment worn, and increased radiant heat load. The WBGT index may be increased as much as 20°F (11°C) or higher in the cockpit (22). Although fighter crews experience only limited physical workloads in the cockpit, flight clothing imposes a significant thermal burden for hot weather operations. The multilayered, protective clothing includes cotton underwear, fire-retardant coveralls, antigravity suits, parachute harness, boots, gloves, and helmet. A chemical defense layer may be added as underwear or incorporated into the coverall. The process of dressing in the ensemble, walking to the aircraft, and conducting preflight inspection on a hot ramp significantly raises core temperature (22). As a result, dehydration can be a factor resulting from increased sweating due to heat exposure, encapsulation, and increased work output due to protective clothing. Furthermore, because the flight crews are dressed in multiple clothing layers, and may have to wait for long periods on the runway to be cleared for takeoff, they may not drink fluid to avoid having to urinate. Therefore, it is an already warm and possibly dehydrated crew that enters the cockpit of a heat-soaked aircraft and goes through the sequences required for engine start. Moreover, in wartime, crews are expected to fly two, three, or more missions in quick succession with little change and cannot achieve full recovery in terms of body temperature and hydration status (22).

Dehydration and Performance

Dehydration refers to a loss of total body water (TBW) resulting in a fluid deficit. Under ordinary circumstances, body water is well maintained by physiological (fluid regulatory hormones) and social/behavioral factors (23). When a body water deficit occurs, plasma volume decreases and plasma osmotic pressure increases in proportion to the decrease in TBW (23). Plasma volume decreases because it provides the fluid for sweat, and osmolality increases because sweat is hypotonic relative to plasma. These changes combine to increase cardiovascular and thermoregulatory strain by a delay in the onset of sweating, reduced skin blood flow, and stroke volume. The deleterious consequences to exercise performance are well recognized when dehydration exceeds approximately 2% of body mass (~3% of TBW) and they are exacerbated by heat stress (23). The negative impact of dehydration on cognitive performance has also been established. Flight crews of high-performance aircraft have unique stressors that can interact with those of heat and dehydration. Specifically, aerial combat entails sequences of complex maneuvers with levels of accelerations (G-stress), which challenge human tolerance limits. Both heat stress and dehydration can lower the threshold at which the crew may lose consciousness.

Typical flying duties involve limited amounts of physical work (100–250 W) (18), but the mental workload associated with fighter missions and other flight scenarios can be substantial (23). The potential for dehydration, heat stress, or their combination to reduce cognitive function has been studied using multiple cognitive testing modalities. Interpretation of the many reports is difficult because the design of most studies does not allow distinction between the effect of thermal (or exercise) stress and that of dehydration. In one very well-designed study, Gopinathan et al. (24) determined the arithmetic ability, short-term memory, and visual-motor tracking in 11 men who, on separate days, had undergone dehydration levels of either 1%, 2%, 3%, or 4%. The subjects had ample rest in a thermoneutral environment once they reached the target level of dehydration. This allowed observation of the effects of dehydration *per se*, without fatigue or heat stress. The study revealed that, like physical performance, deterioration of mental functions occurs at a threshold level of 2% dehydration. More direct pilot performance measures like gray-out tolerance time also appear to be impaired by dehydration at high acceleration (7 G) (25), but this may not be a factor at lower levels of acceleration (3 G) (26). However, given the importance of mental function to the flight or high-performance aircraft, it is important to remember that even a small possibility of pilot error can have disastrous consequences.

Physiologic factors that contribute to dehydration-mediated cognitive and acceleration tolerance performance decrements have not been well elucidated. The relative hyperthermia associated with dehydration could diminish psychological drive (27) or perhaps alter central nervous system function independent of temperature. Cerebral blood flow is diminished in response to an orthostatic challenge by both prior heat stress and dehydration (28). This could impact cerebral oxygen availability, which itself is altered by G_z (29). It also appears that intracranial volume is altered in response to dehydration (30), although the exact functional consequence of this is unknown. It is recommended that pilots of high-performance aircraft do not become dehydrated by more than 1% of body mass (31). This would also assist in preventing body temperature from rising more than 1°C (18). When flying multiple sorties, proper postflight hydration practices (18) should foster a normal level of hydration. Drinking fluids until the flight briefing period will provide ample time for the bladder to empty before preflight and flight phases of the next sortie. Another approach is to mitigate heat strain in the taxi and flight phases to minimize dehydration through sweat losses. The interaction of dehydration and heat stress on $+G_z$ tolerance and cognitive functions are additive (23,31); therefore, active pilot cooling in a hot cockpit is essential.

Mitigation

Low-level flights in hot climates can produce environmental heat stress that exceeds FITS caution and danger limits (18). Modern fighter aircraft often have cockpit cooling during ground operations (standby and taxi). However, if protective clothing must also be worn the occupants receive limited benefit from in-cockpit cooling, and the added insulation and vapor resistance can impose additional heat stress and compromise thermoregulation and cognitive performance (32,33). In addition, cockpit cooling is limited, and typically, heat removal occurs so slowly that the aircraft is in combat or returning to base before cooling is complete. Microclimate cooling systems are an effective means of mitigating cockpit thermal heat stress.

Microclimate cooling systems remove body heat by conduction (ice), convection and conduction (perfused water), or convection and evaporation (compressed or conditioned air). Under ideal conditions for a given category of cooling system, the most popular form of cooling garment for the aviator (vest) can remove well above 100 W of body heat (34). Head cooling has also been tried and may improve thermal comfort (35), but by itself removes much less heat (25,35) and can produce headache if overcooled (36). In some flight circumstances, the use of microclimate heating—particularly heating of the extremities (warmed gloves and boots)—may be desirable, but the principle concern for the aviator is management of heat stress.

Figure 7-7 (34) depicts a modeling simulation (37) for the relationship between endurance time (minute) and cooling extraction rate (W) over a broad range of metabolic rates when wearing protective clothing in a hot, dry environment. At realistic metabolic rates for aviators (100–250 W) (18), work times without cooling improve from approximately 70 minutes to more than 300 minutes with the application of 100–150 W of microclimate cooling. All three categories of microclimate cooling systems will reduce heat stress and strain in a hot cockpit and improve performance whether worn beneath ordinary or protective clothing ensembles (38,39).

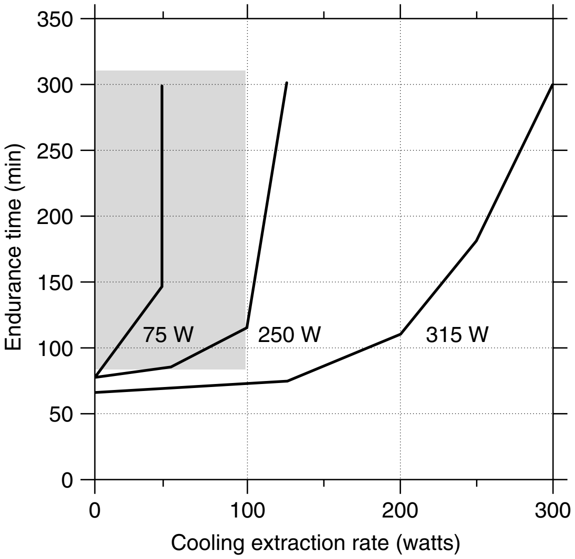

FIGURE 7-7 Modeling simulation of the relationship between endurance time and cooling extraction rate at various metabolic rates (75 and 315 W) in a hot, dry environment when donning protective clothing. Gray zone signifies improvement in endurance time from approximately 70 minutes to greater than 300 minutes with the application of 100 W of microclimate cooling at a metabolic rate consistent with the demands of aviation. (Modified from Pandolf KB, Gonzalez RR, Sawka MN, et al. *Tri-service perspectives on microclimate cooling of protective clothing in the heat*, Technical Report No.: T95–10, USAMRMC, 1995.)

Heat Acclimatization

Biological adaptations to repeated heat stress include heat acclimatization and acquired thermal tolerance, defined as adaptations that provide greater resistance to heat injury. The magnitude of both adaptations depends on the intensity, duration, frequency, and number of heat exposures. These adaptations are complementary as heat acclimatization reduces physiologic strain, and acquired thermal tolerance improves tissue resistance injury to a given heat strain. Heat acclimatization is induced when repeated heat exposures are sufficiently stressful to elevate core and skin temperatures and elicit profuse sweating. During initial heat exposure, physiologic strain will decrease each subsequent day of heat acclimatization. These adaptations include earlier onset of sweating and greater sweat volumes, better fluid balance, improved cardiovascular stability, and lowered metabolic rate. Overall, acclimatization will result in reductions in core temperature and perception of effort while performing physical work in the heat. The most important physiologic adaptation is improved sweating because earlier sweating and greater sweat volumes increase heat loss and lower cardiovascular strain. However, the use of protective clothing may hamper the evaporation of this greater sweating response.

Heat acclimatization is specific to the climate and activity level; therefore, if personnel will be working in a hot, humid climate, heat acclimatization should be conducted under similar conditions. Typically, approximately 2 weeks of progressive heat exposure and physical work should be allowed for heat acclimatization, with daily durations of at least 100 minutes. Individuals who are less fit or unusually susceptible to heat will require several days or weeks more to acclimatize. Highly fit individuals can achieve heat acclimatization in approximately 1 week. In addition, several weeks of living and working in the heat (seasoning) may be required to maximize tolerance to high body temperatures. Adequate water must be provided and consumption monitored during and after the acclimatization period. Heat acclimatization increases the sweating rate, and therefore increases water requirements. Heat acclimatization will be retained by approximately 1 week if heat exposure no longer occurs and 75% of the adaptation is lost by approximately 3 weeks (10).

Cold Stress

Cold stress is known to adversely affect both cognitive and physical performance. Physical performance tasks are more directly related to tissue cooling, which impairs muscle strength, slows nerve conduction velocity, and reduces joint mobility. Although local tissue cooling may initially degrade manual performance at skin temperatures as high as 20°C, an abrupt performance degradation occurs when skin temperature falls below 15°C (40), and another subsequent drop occurs at approximately 4°C as tactile sensitivity is impaired. A decreased core temperature is associated with degradation of cognitive and psychomotor tasks (41).

Although much data exist, it remains difficult to predict performance degradation in cold environments. Under some conditions, both cognitive and physical performance may be maintained during cold exposure, even with moderate decreases in core temperature. While it is suggested that the cold environment causes distraction, resulting in inattentiveness to the task at hand, Enander (42) suggests that arousal due to mild cold exposure could account for improved performance that sometimes occurs. Whether performance is degraded or even enhanced during cold exposure may be related to how the individual manages the pressure to perform and/or anxiety associated with the cold stress. It follows then that degradation in performance could be limited by training under stressful scenarios such as cold stress and while wearing cold-weather clothing, once the task has been learned under ideal conditions, to ensure optimal skill development. This strategy has been found to be effective for improving manual dexterity in cold environments that could prove useful for ground crews working outdoors.

In cold environments, humans rely heavily on "behavioral thermoregulation," which includes use of shelter, clothing, and physical activity to maintain body temperature. The most effective protection of course would be to go inside an enclosed, insulated, heated building. However, working in a climate-controlled hangar may not be available for many ground and flight crews. Different types of cold stress present different challenges for management. For example, during cold air exposure (10°C), individuals dressed only in shorts and socks can maintain their core temperature for more than 4 hours (43), whereas at the same temperature (10°C) the chest-deep cold water immersion causes a 1°C fall in core temperature within 90 minutes. During cold air exposure, the primary concern may be localized cold injury to exposed skin (e.g., frostbite at temperatures below freezing) or reduced manual dexterity due to extremity cooling (42), whereas during cold water immersion, the primary concern is hypothermia induced by rapid heat loss. The effective countermeasures in each of these scenarios may also differ. While exercise is effective for increasing extremity blood flow during cold air exposure, thereby improving thermal comfort and physical function and reducing risk of peripheral cold injury, exercise during cold water exposure less than 18°C is likely to increase the rate of heat loss and exacerbate core cooling.

Clothing—Creating a Microenvironment

The insulation value of clothing is primarily related to how much air is trapped between the fibers, as air is an excellent insulator. Table 7-3 presents clothing insulation values of typical uniforms. Air can also be trapped between layers of clothing and therefore increase insulation. An example of this can be seen in Table 7-4, where the addition of the nylon jacket and pants to the physical training uniform more than doubles the insulation, although nylon has little insulation value itself; the loose fit and wind-resistant property of the fabric increases the trapped air between the layers of clothing. On the other hand, the total insulation of a cold weather system is less than the sum of the garments that are worn because each layer actually adds some compression to

TABLE 7-3

Insulation Value of Different Pieces of U.S. Army and Air Force Clothing

Item	*Insulation value (clo)*
Improved physical fitness uniform	0.30
Improved physical fitness uniform + nylon jacket and pants	0.70
U.S. Air Force Nomex flight suit	1.15
Aviation fuel handler's protective coverall	1.25
U.S. Army desert battle dress uniform	1.32
U.S. Air Force Nomex flight suit + chemical protective undergarment	1.72
Gore-Tex parka and trousers	1.95
Fleece jacket, bib overall	2.37

TABLE 7-4

Time in Seconds to Reach a Finger-Skin Temperature of 32°F while Touching Various Materials at Different Temperatures

Material Temperature (°F)	*Aluminum (Seconds)*	*Steel (Seconds)*	*Stone (Seconds)*
32	43	>100	>100
23	15	50	>100
14	5	15	62
5	2	5	20
−4	1	2	7
−13	<1	<1	4

the layer underneath. The addition of chemical protective garments will not only increase overall insulation but can also limit evaporation of sweat if individuals are partially or fully encapsulated. The decision of what to wear is not necessarily straightforward and likely differs among individuals and may be dictated by conditions or mission tasks. Practice, particularly under varied environmental conditions, activity levels, and tasks, is critical for learning how best to use clothing to maintain comfort and performance.

In the extremities, blood flow is greatly reduced during cold stress, and there is little local metabolic heat production. Finger cooling can be exacerbated by touching cold objects, which is important for ground crews working outdoors. In a cold environment, touching tools, equipment, or the aircraft itself could result in a freezing tissue injury. Table 7-4 presents the time for finger skin to cool to freezing as bare skin contacts different materials. The high conductivity of aluminum is again apparent, with comparatively lower conductivity for steel and stone (Table 7-5). It illustrates the importance of anticontact gloves whenever the temperature falls below freezing. Ground crews should be aware that special precautions are required for handling fuel or petroleum products that remain liquid even at temperatures of −40°C or below. Contact of bare skin with these fuels can cause instantaneous frostbite; therefore, protective gloves are mandatory (Figure 7-8).

TABLE 7-5

Conductivity of Various Materials

Material	*Conductivity K (W/m·K)*
Air	0.024
Wood	0.1
Snow	0.1-0.3
Asphalt	0.2-0.5
Water	0.6
Concrete	0.8
Ice	1.6
Granite	2.2
Steel	50
Aluminum	205

FIGURE 7-8 Ground crew performing maintenance can lose heat through conduction to tarmac or flight deck, or through contact with hand tools or contact with the aircraft itself.

Thermal Stress and Microgravity

One particular challenge to thermoregulation during spaceflight is the restriction of conductive and evaporative cooling due to the design of the space suits worn. The development of protective garments such as the launch entry suit (LES) and advanced crew escape suit (ACES) were designed to provide protection against external element changes such as high cabin temperatures, cold water immersion, pressure changes, and any ambient gas changes (44). However, the microenvironments that these suits create by storing heat can also be detrimental. Despite new technology, the suits that are worn are bulky and difficult to move. Because all objects have mass, even in zero gravity, energy is required for movement, thereby increasing body temperature. A rise in the energy cost of ambulation, in addition to restricted evaporation due to encapsulation, increases the risk of hyperthermia.

The LES was the original garment worn by the astronauts and consisted of polypropylene underwear, an antigravity suit, a double-layer nylon exterior, and a helmet (45). While the suit prevents body heat losses in the event of water immersion, the LES also retained heat, detrimental in the hot cabin atmosphere, as it did not allow for evaporative or conductive cooling and resulted in increased core body temperatures. To aid in conductive thermoregulation, liquid cooling garments (LCGs) were developed that pass cool water through tubes lying against the skin, promoting heat loss from the skin through conduction. The outer layer of the newer ACES consists of a Gore-Tex shell, which theoretically allows the heat that is produced by the body to be released to the environment more readily than in previous suits (44).

An additional means of reducing the risk of hyperthermia in a zero gravity environment is maintenance of normal fluid balance. One exacerbating factor in maintaining fluid balance is a phenomenon that occurs in zero gravity where there is an acute upward shift of blood volume. This upward shift in blood volume stimulates central volume receptors and triggers hormones of fluid regulation, resulting in an increase in diuresis, negative fluid balance, and hypovolemia (46), effectively reducing thermoregulatory sweating. A hydration plan that helps to maintain normal fluid balance by increasing fluid intake before or during space flight might preserve thermoregulatory sweating. In a microgravity environment, with suits that allow for evaporation, this sweat would spread across the surface of the skin, effectively creating a large, wet surface, increasing evaporative cooling, and reducing risk of hyperthermia.

Exercise

By increasing body heat content, exercise is effective at elevating extremity temperatures, as well as core temperature, even in hypothermic individuals. Moderate exercise (e.g., walking at 3.5 mph) can be effective for maintaining finger temperatures during cold air exposure as low as −22°F when appropriate cold-weather clothing is worn. Clothing insulation must typically be reduced during exercise to avoid sweating because damp clothing has a lower insulation value and will increase conductive heat loss when exercise stops. Figure 7-9 presents the clothing insulation (clo) required over a range of cold conditions as metabolic rate increases due to activity.

Water Immersion

The conductivity of water is 25 times that of air, and hypothermia can be a concern even in water temperature as high as 70°F to 75°F. Risk of hypothermia depends on water temperature, immersion depth, and immersion duration. Exercise can increase heat loss as blood flow to extremities and working muscles increases; therefore, swimming to shore should only be attempted if the individual is confident of reaching land. Otherwise, heat conservation is the best strategy and is most effective by maintaining a posture that minimizes both the surface area in contact with the water and the movement, such as the H.E.L.P. position (Figure. 7-10). Immersion suits are designed to provide both floatation

FIGURE 7-10 H.E.L.P. position.

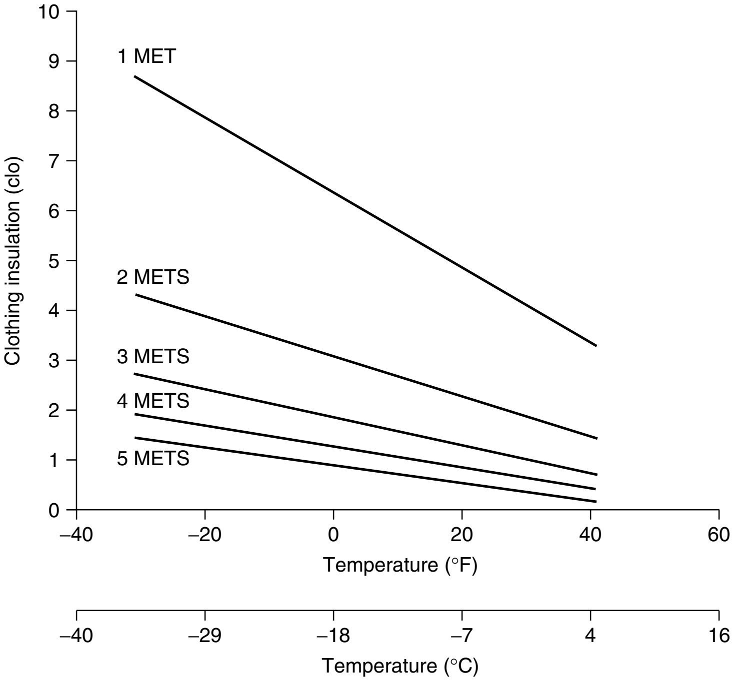

FIGURE 7-9 Interaction of clothing insulation (clo), environmental temperature (°F, °C), and exercise intensity (METS). The less the insulation factor of clothing, the greater the exercise intensity (metabolic heat production) required to maintain normal body temperature. The greater the insulation of clothing, the less metabolic heat production required.

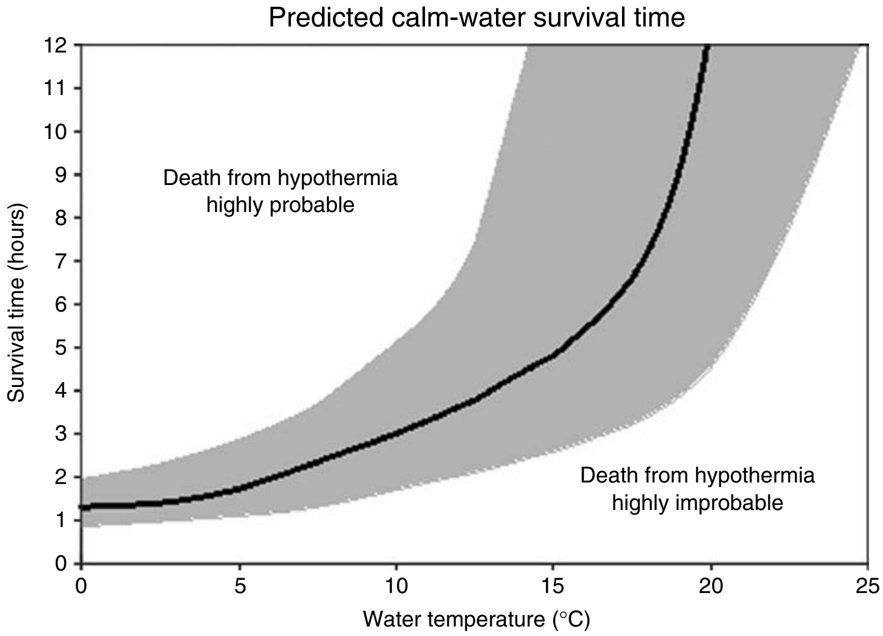

FIGURE 7-11 Average survival time in different water temperatures. Individuals who lose heat quickly (gray area below the line) will have significantly less time to survive versus individuals who cool at a slow to average rate (gray area above the line).

and insulation and can dramatically extend functional time in cold water. Recent research has demonstrated that motion sickness may increase the risk of hypothermia during cold water immersion by blunting both shivering and vasoconstrictor responses (47). Figure 7-11 shows the average survival time in different water temperatures. In calm water, at temperatures approaching approximately 20°C, survival rate increases dramatically. Individuals who lose heat quickly (gray area below the line) will have significantly less time to survive compared to individuals who cool at a slow to average rate (gray area above the line). For additional information about cold water survival, see the suggested readings for a cold water rescue attempt of a U.S. navy patrol aircraft.

Environmental Injury and Illness

Heat Illness and Injury

Minor heat illnesses include heat rash, heat cramps, and heat syncope, whereas serious heat illnesses include heat exhaustion, heat injury, and heat stroke. Factors that increase risk of serious heat illness or injury include lack of heat acclimatization, low physical fitness, dehydration, and high body fat/mass, and certain medications. However, serious heat illness can occur in low-risk persons who are practicing sound heat mitigation procedures.

Wearing encapsulated, protective clothing such as G-suits for prolonged periods can cause heat rash or prickly heat due to hygiene issues. Heat rash can interfere with heat exchange across the skin, thereby increasing the risk of heat exhaustion and heat stroke. Heat cramps are muscle pains or spasms in the abdomen, arms, or legs that may occur in association with strenuous activity. Heat cramps usually affect people who sweat profusely, typically during strenuous activity, and lose an appreciable amount of electrolytes, mainly sodium chloride, in their sweat. Heat syncope is a temporary circulatory failure due to the pooling of blood in the peripheral veins, particularly those of the lower extremity, resulting in a decrease in diastolic filling of the heart. Symptoms range from lightheadedness to loss of consciousness. Heat syncope typically occurs during prolonged standing in hot environments but can also occur if standing still after completing vigorous activity. Individuals suffering from heat syncope will recover rapidly once they sit or lie supine; however, complete recovery of stable blood pressure and heart rate may take a few hours.

Heat exhaustion is the most common form of serious heat illness. It occurs when the body cannot sustain the level of cardiac output needed to support skin blood flow for thermoregulation and blood flow for metabolic requirements of exercise. Signs and symptoms of heat exhaustion include syncope, headache, nausea, vomiting, loss of appetite, hypotension, tachycardia, muscle cramps, hyperventilation, and transient alteration in mental status.

Heat stroke is characterized by elevated body temperature (>40°C or 104°F) and profound central nervous system dysfunction that results in delirium, convulsions, or coma. Heat stroke is a catastrophic medical emergency that can result in multiorgan dysfunction. The onset of heat stroke may be preceded by headache, dizziness, drowsiness, restlessness, ataxia, confusion, and irrational or aggressive behavior, or may occur suddenly with symptoms of convulsions, delirium, vomiting, and unconsciousness. The skin may be hot and dry but can still be moist from sweat. Those suffering from heat stroke should be immediately taken to an emergency medical treatment facility. The most important treatment is rapid reduction of body core temperature. Cooling should begin in the field, where individuals are moved to a cool, shady place, clothes removed, and skin kept moist. The victim should be immersed in cool/cold water if possible, while waiting for transport. If not possible, spraying with cold water, and fanning while waiting for transport and/or during transport, can be effective in lowering body core temperature. For both heat exhaustion and heat stroke, active cooling should continue until the rectal temperature is less than 101°F (38.3°C) at which time cooling should stop to prevent hypothermia.

Cold Injury

Cold injuries are almost always preventable. Vigilance is required for early detection so that prompt treatment is effective. Cold injury can be life threatening, as in the case of hypothermia, or cause lifelong debilitation, as in the case of frostbite. Severe frostbite could require amputation of affected tissue.

Hypothermia is defined clinically as the core temperature below 35°C, at which point most individuals will have maximal shivering. Early signs of hypothermia include slurred speech and loss of coordination, and may be mistaken for intoxication. As hypothermia progresses, shivering increases and body temperature will fall rapidly; therefore, the time to begin rewarming is when the individual is vigorously shivering and able to still generate heat. Wet clothing must be removed because it greatly increases heat loss. Insulation and protection from wind is critical if rewarming in the field. If the individual is shivering, adding insulation and limiting further heat loss will allow shivering to be effective for rewarming. However, if shivering has ceased, external heat will have to be provided. Both pulse and respiratory rates may be difficult to detect in hypothermic patients because they are slow and shallow. Cardiopulmonary resuscitation (CPR) should only be initiated if these life signs are truly absent because heart arrhythmias can be initiated by the CPR procedure itself. Use of alcohol to "rewarm" an individual is contraindicated. Alcohol interferes with hepatic glucose production and causes hypoglycemia, which blunts the shivering response and causes vasodilation of skin blood vessels resulting in greater heat loss from the skin to the environment.

Peripheral Cold Injuries

Peripheral cold injuries can be divided into two categories: freezing (i.e., frostbite) and nonfreezing (trench foot and chilblain). The freezing point of skin is slightly below the freezing point of water due to the electrolyte content of the cells and extracellular fluid, with the skin surface reportedly freezing from −3.7°C to −4.8°C (48). Both wetness and wind will increase the rate of cooling. Frostbite is most common not only in exposed skin (nose, ears, cheeks, and exposed wrists) but also occurs on the hands and feet because peripheral vasoconstriction significantly lowers tissue temperatures (49). The wind chill equivalent temperature chart (Table 7-2) indicates the risk of bare skin freezing during exposure to different combinations of air temperature and wind speed, with guidance on how long it will take for skin to freeze under those conditions. The risk is greatly reduced by covering skin with appropriate clothing, and by monitoring signs and symptoms of frostbite. Individuals often report feeling a "wooden" sensation in the injured area. After rewarming, pain is significant. The initial sensations are an uncomfortable sense of cold, which may include tingling, burning, aching, sharp pain, and decreased sensation (50). The skin color may initially appear red and later it becomes waxy white. Buddy checks are important for prevention of frostbite because the loss of sensation often means that the injury is not perceived by the patient. Rapid rewarming (ideally in a warm water bath at 40°C) will minimize tissue damage; however, in field environments rewarming should not be attempted unless refreezing of the injury can be avoided because refreezing would damage tissues more than delayed rewarming. As mentioned previously, contact frostbite can occur rapidly at very cold temperature, and can occur in seconds in contact with metal objects and with petroleum fuels, oils, and lubricants having freezing points below −40°C.

Nonfreezing Cold Injuries

Nonfreezing injuries can occur at temperatures above freezing, particularly when skin or clothing is damp. Trench foot earned its name after its prevalence during World War I when soldiers were confined to sedentary positions with wet feet, either due to standing in water or simply from sweat-soaked socks. Trench foot typically occurs when tissues are exposed to temperatures between 0°C and 15°C (32°F–60°F) for prolonged periods of time (50), whereas chilblains, a more superficial injury, can occur after just a few hours of exposure to bare skin (50). Diagnosing nonfreezing cold injuries involves observation of clinical symptoms over time as different and distinct stages emerge days to months after the initial injury (51). Prevention requires frequent changing of socks to ensure that feet stay clean and dry. Physical movement is also important to maintain blood flow to the feet. If injury occurs, recovery can be prolonged. Chilblain produces swollen, tender, itchy, and painful skin that may continue for several hours after rewarming, but has no lasting effects.

Other medical issues related to cold exposure include cold-induced bronchospasm (CIB) or asthma, cold urticaria, and snow blindness. CIB can occur upon exposure to cold, dry air even in individuals who do not normally have exercise-induced asthma, and affects approximately 25% of elite winter athletes (51). This is attributed primarily to facial cooling rather than breathing cold air (52); however, while limiting facial cooling (e.g., by wearing a balaclava) could decrease the degree or incidence of CIB, some subjects may still experience symptoms. To minimize airway cooling, heat and moisture exchange (HEM) modules have been developed that are intended to help warm and humidify inspired air. Although these devices are of little value for reducing respiratory heat or moisture loss during cold exposure, they do have value for limiting cold-induced asthma (CIA) or CIB (53). Cold urticaria is probably the most common form of urticaria and is characterized by the rapid onset of itching, redness, and swelling of the skin (hives) within minutes of exposure to a cold stimulus (54). In extreme cases, anaphylactic shock may occur. Another concern is the glare of the sun on white snow that can cause snow blindness due to the reflective glare. This malady can be prevented with protective eyewear. Extensive treatment on the care and prevention of thermal illnesses and injury can be found in TB MED 507 and TB MED 508 (22,55).

Monitoring Body Temperature

In a situation of heat or cold illness or injury, measurement of core temperature is important to determine the extent of the change in body core temperature and to establish a course of treatment. Monitoring internal body core temperature (Tc) accurately requires invasive methodologies. The mercury thermometer is commonly used to measure oral temperature. Other Tc sites such as rectal and esophageal temperatures are commonly measured; esophageal temperature is performed more typically in research settings. Measurement of Tc at these as well as other sites may not be practical in the field. However, Tc measured at sites such as the axillary region, tympanic membrane, and body surface using other measurement devices may be more convenient but may not accurately assess true Tc. For example, oral and tympanic membrane temperatures are generally unreliable in cold environments; therefore, rectal temperature is generally used. Esophageal temperature is a better representation of central blood temperature and more responsive under changing conditions, but is difficult to obtain due to the invasiveness of the technique and the discomfort of the individual. Telemetric temperature pills can be a good alternative for ambulatory field conditions, but are expensive, require a data logging device, and would not be feasible for giving a patient orally upon suspecting hyper- or hypothermia. However, telemetric pills may be used as a suppository with individuals who are either unresponsive or may be convulsing, where use of a glass rectal thermometer may be dangerous. In the event that a patient has diarrhea, a flexible rectal thermistor may be better option. Overall, rectal temperature remains the most accurately available method for monitoring Tc during thermal illness.

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