The Coat of Arms

1818
Medical Department of the Army

A 1976 etching by Vassil Ekimov of an original color print that appeared in The Military Surgeon, Vol XLI, No 2, 1917
The first line of medical defense in wartime is the combat medic. Although in ancient times medics carried the caduceus into battle to signify the neutral, humanitarian nature of their tasks, they have never been immune to the perils of war. They have made the highest sacrifices to save the lives of others, and their dedication to the wounded soldier is the foundation of military medical care.
Textbooks of Military Medicine

Published by the

Office of The Surgeon General
Department of the Army, United States of America

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The environments that face combatants on modern battlefields.

Art: Courtesy of US Army Research Institute of Environmental Medicine, Natick, Massachusetts
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Foreword

Earth’s environments have always influenced the planning and conduct of military operations. Past campaigns have been impacted by heat, cold, and altitude, as well as the changes in barometric pressure that divers face in special operations. During the 20th century alone, US armed forces have been involved in terrestrial military operations in hot climates in the North African campaign and Pacific theater operations during World War II, the Vietnam and Persian Gulf wars, and military and humanitarian operations in Panama, Haiti, Grenada, Rwanda, and Somalia. Our major military operations involving cold climates during the past century include World War I and World War II, the Korean War, and most recently in Bosnia and Kosovo. Medical Aspects of Harsh Environments, Volume 1, treats the major problems caused by fighting in heat and cold.

The topics of Medical Aspects of Harsh Environments, Volume 2, are the effects of altitude, especially as experienced in mountain terrain and by aviators, and the complex interactions between humans and the special environments created by the machines used in warfare. Our warfighters were exposed to mountain terrain during World War II, the Korean War, in military and humanitarian efforts in South America, and most recently in the Balkans. Military action has also occurred in some of the environments considered “special” (eg, on and below the water’s surface) in every war that this country has fought, whereas other special environments (eg, air—flights not only within Earth’s atmosphere but also beyond it, in space) have become settings for the havoc of war only as a result of 20th-century technology. The second volume also contains a discussion of the personal environment within the protective uniforms worn by service members against the fearsome hazards of chemical and biological warfare. This microenvironment—that protects the wearer—is in some ways different from but in others similar to all closely confined, manmade environments (eg, the stresses that divers face in coping with the changes in barometric pressure). Whatever the environment, this point needs to be kept in mind: indifference to environmental conditions can contribute as much to defeat as the tactics of the enemy.

Medical Aspects of Harsh Environments, Volume 3, emphasizes the need for a preventive approach to decrease attrition due to harsh environments, such as predicting the likelihood of its occurrence and stimulating awareness of how specific factors (eg, gender, nutritional status) are sometimes important determinants of outcome. The third volume concludes with reproductions of two of the classics of environmental medicine: the lectures given by the late Colonel Tom Whayne on heat and cold injury, respectively, at the Army Medical School in 1951; for decades these have been unavailable except as mimeographed handouts to students attending specialized courses.

Military and civilian experts from the United States and other countries have participated as authors of chapters in this three-volume textbook, Medical Aspects of Harsh Environments. The textbook provides historical information, proper prevention and clinical treatment of the various environmental illnesses and injuries, and the performance consequences our warfighters face when exposed to environmental extremes of heat, cold, altitude, pressure, and acceleration. The contents are unique in that they present information on the physiology, physical derangements, psychology, and the consequent effects on military operations together in all these harsh environments. This information should be a valuable reference not only for the physicians and other healthcare providers who prepare our warfighters to fight in these environments but also for those who care for the casualties. Military medical personnel must never forget that harsh environments are great, silent, debilitating agents for military operations.

Lieutenant General James B. Peake
The Surgeon General
U.S. Army

Washington, DC
December 2001
Preface

On 1 July 1941, as part of Hitler's attack of the Soviet Union, the XXXVI Corps of the German army crossed the Finnish–Soviet border and began what was planned as a rapid advance some 50 miles to the east, where lay the strategically important railroad that linked the Arctic Ocean port of Murmansk with the Russian hinterland to the south. The German soldiers in their heavy woolen uniforms were greeted not only by determined Soviet resistance, but also by an unexpected enemy: the day was hot, with temperatures in the high 80s (°F), and there were swarms of ferocious mosquitoes. During the next 3 weeks the temperature rose above 85°F on 12 days and twice reached 97°F, and it was soon obvious that military operations were possible only in the relative cool of the “night.” By the end of July, after advancing only 13 miles, the attack was called off, with the XXXVI Corps being denounced as “degenerate” by the German high command. Higher commanders obviously never considered that low combat effectiveness might result from the hazardous environmental factors: the heat, insects, and 24 hours of constant light. After all, who would have thought that heat stress might impair combat operations occurring 30 miles north of the Arctic Circle.

The German experience in northern Finland was anything but unique; military history is full of examples where weather conditions influenced the outcome of military campaigns. In fact, the earliest recorded instance of weather’s having a direct effect on the outcome of a battle dates back to the Old Testament:

And it came to pass, as they fled from before Israel, and were in the going down to Beth-horon, that the Lord cast down great stones from heaven upon them unto Azekah, and they died: they were more which died with hailstones than they whom the children of Israel slew with the sword.

The mission of the US Army Research Institute of Environmental Medicine, Natick, Massachusetts, is both to understand how soldiers react to military environmental and occupational stresses and to devise materiel and doctrinal solutions that are protective and therapeutic. The publication of the three volumes of Medical Aspects of Harsh Environments will ensure that both healthcare providers and military line commanders do not repeat the mistakes of countless commanders of the past who have underestimated the threats that harsh environments pose to their soldiers. I strongly recommend that all commanders and healthcare personnel become acquainted with the volumes of the Textbooks of Military Medicine dealing with harsh environments to better protect and preserve our sons and daughters during their deployments around the world.

The volumes of Medical Aspects of Harsh Environments became a reality because of the dedication and hard work of Kent B. Pandolf, PhD, and Robert E. Burr, MD, then a Lieutenant Colonel, Medical Corps, US Army, the specialty editors of this three-volume textbook. Dr. Burr was primus inter pares in the group that performed the critically important tasks of deciding on the subject matter and finding appropriate authors; when Dr. Burr left the Army, Dr. Pandolf brought the project to fruition. This first volume, which deals with hot and cold environments, owes its completion to the willingness of its section editors—C. Bruce Wenger, MD, PhD, and Robert S. Pozos, PhD—well-known experts in the fields of heat and cold stress, respectively, to perform the seemingly endless tasks necessary to assure the scientific accuracy of the text. In addition, the Specialty and section editors wish to thank Rebecca Pincus for her invaluable help during this book’s formation. The forthcoming second and third volumes deal with mountains and special operations environments, and sustaining health and performance during military operations. It is not too much to hope that the labors of the volumes’ editors and many authors will lighten the burdens of our military personnel in the years to come.

Brigadier General Russ Zajtchuk
Medical Corps, US Army, Retired
Editor in Chief, Textbooks of Military Medicine

December 2001
Washington, DC


The current medical system to support the U.S. Army at war is a continuum from the forward line of troops through the continental United States; it serves as a primary source of trained replacements during the early stages of a major conflict. The system is designed to optimize the return to duty of the maximum number of trained combat soldiers at the lowest possible level. Far-forward stabilization helps to maintain the physiology of injured soldiers who are unlikely to return to duty and allows for their rapid evacuation from the battlefield without needless sacrifice of life or function.
Rudolph Von Ripper  
*Filling Craters Near Pantellaria*  
1943

Pantellaria (also spelled Pantelleria) is a tiny, rocky island in the Mediterranean Sea between Tunisia and Sicily, the occupation of which was considered essential for the planned invasion of Italy in the summer of 1943. Accordingly, the Allied air forces and the Royal Navy were called in to soften up the Italian defenders, a process they performed with great gusto:

In one of the greatest examples of overkill of the war the air forces in three weeks dropped 6,400 tons of bombs ... on Pantelleria.1(p215)

After the island had been captured and so that air facilities could be established in time for the invasion of Sicily, the vast multitude of craters left on Pantellaria by the bombs and shells had to be quickly filled by hard, manual labor in Sahara-like heat. Surviving records, however, do not indicate whether heat casualties were a significant problem.

Chapter 1

INTRODUCTION TO HEAT-RELATED PROBLEMS IN MILITARY OPERATIONS

RALPH F. GOLDMAN, PhD*

INTRODUCTION

PROBLEMS OF DEFINITION AND COMPREHENSION
Terminology of Heat Effects
Epidemiology of Heat Illness

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CONCLUSIONS

ATTACHMENT

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INTRODUCTION

As an introduction to the heat illness section of Medical Aspects of Harsh Environments, this chapter considers the effects of heat in the format of the classic epidemiological triad: the agents, the disease, and the host factors. First, the physical and physiological factors that are responsible for heat illness, especially in a military environment, are delineated. Second, insofar as possible, the physical and physiological factors that have affected military operations in the past are described, often by those who were directly involved.

Recognition that people can be killed by exposure to heat is documented in the earliest writings of man. The Bible reports the death of the young son of a farmer from exposure to the midday heat during the harvest in his father’s fields (in about 1000 BC): he “went out to ... the reapers, said unto his father, ‘my head, my head,’” and died in his mother’s lap.1 Sunstroke is specifically mentioned later in the Bible. Judith’s husband, Manasseh, was out in the fields, supervising the binding of the barley sheaves: “he got sunstroke, and took to his bed and died.”2 The effects of heat on fighting men are also noted in the Bible: when the “sun stands still in the heavens,” it helps the Hebrews fighting the more heavily armored Canaanites.3

The most critical time of year for heat stress was clearly identified millennia ago. By 3000 BC the appearance of the dog star, Sirius, representing the nose of the constellation Canis Major, was recognized as ushering in the “dog days” of summer. Sirius, described by ancient Egyptians, Greeks, and Romans as bringing on fever in men and madness in dogs, was introduced into medical literature as siriass, the medical term for all types of heat illness well into the 20th century. In Homer’s Iliad (ca 1100 BC), King Priam muses, while watching red-haired Achilles advance,

blazing as the star which comes forth at harvest time, shining amid the host of stars in the darkness of the night, the star men call Orion’s Dog. Brightest of all, but an evil sign, bringing much fever on hapless men.4(p401–402)

Reports on the effects of heat on military operations have recurred repeatedly since then. King Sennacherib of Assyria had problems with heat while attacking Lashish, about 720 BC. In about 400 BC, Herodotus provided one of the first reliable reports on the effects of heat on military operations. He describes the effects of the interaction among the load carried, protective clothing worn, and heat stress, when he states that both the Athenian attackers and Spartan defenders were worn out by “thirst and the sun,” and when he reports on the discomfort of fighting in full armor under the summer sun, citing Dienekes the Spartan, at Thermopylai, in 480 BC, who, when told that the multitude of incoming Persian arrows would blot out the sun, calmly replied, “Then we might have our battle with them in the shade.”5(p551)

In 332 BC, Alexander the Great’s military advisors insisted that a march across 180 miles of the wind-blown Libyan Desert was too risky; if the army should use up its water supplies, they would experience great thirst for many days. At that time the camel, which could travel for 3 to 4 days without drinking while carrying a significant load of water for the troops, was already recognized as superior to horses, donkeys, or oxen, which had to drink several times a day. In any event, as Plutarch suggested, the gods were extremely kind, providing plentiful rains, which relieved the fear of thirst and made the desert moist and firm to walk on. (According to studies carried out at the US Army Research Institute of Environmental Medicine [USARIEM], Natick, Massachusetts, the latter characteristic may have cut the heat production of Alexander’s soldiers by as much as 50%). In the summer of 330 BC, while pursuing Persian King Darius after his crushing defeat at the Battle of Arbela, water supply became a problem as Alexander approached what is now the Turkmenistan border. When a foraging party finally returned to camp with water, Alexander, who was almost choked with thirst, again won the hearts of his troops when, offered a helmet of water (according to Plutarch), he

took the helmet in his hands, and looking about, when he saw all who were near him looking earnestly after the drink, he returned it without tasting a drop of it. “For,” said he, “if I alone drink, the rest will be out of heart.”6(p113)

In midsummer 327 BC, Alexander split his 40,000 foot soldiers, sending one group through the Khyber Pass while leading the rest on a more difficult route into India. Troop movement was slow, and Alexander realized that the problem was not only the environment and terrain but also the heavy weight
of booty accompanying them. One dawn, after all the freight was loaded, Alexander set fire to his personal baggage wagon and then commanded that his soldiers’ wagons be burned too. Thus unencumbered, the troops continued the march much more rapidly. But by 325 BC, his troops, demoralized by years of fighting away from home, were unwilling to continue. Unable to inspire his troops to continue across the Hyphasis River, and after receiving a face-saving report from his soothsayers that the omens suggested that the gods did not want him to cross the river, Alexander started the march back. He started in September with about 20,000 in his entourage, many of whom were family members and camp followers. According to Plutarch, after 2 months of extreme heat, lack of water, and the trackless desert, only about 5,000 survived to reach the Persian palace at Pura, 200 miles from the southern border of what is now Iran. As has often been observed subsequently, the problem was not an effect of heat but the lack of water (and, in this case, of food also).

Three hundred years later, in 24 BC, a Roman legion led into Arabia by Aelius Gallus suffered a malady that proved to be unlike any of the common complaints, but attacked the head and caused it to become parched, killing forthwith most of those who were attacked.

The Roman legionary used an early form of auxiliary cooling, inserting rushes into his headgear and keeping them wet with water. The Roman legions made extensive use of auxiliaries to carry as much of the legionnaires’ load, and do as much of the engineering digging as possible, thus sparing the fighting edge of the legion. In the 1930s, during Italy’s invasion of Eritrea, the descendants of the legionnaires (who were advised by Aldo Castellani, a leader in 20th-century military medicine) made similar use of auxiliaries.

In the Middle Ages, the crusaders to the Holy Land had severe heat problems compared with the Saracens; the final battle of the Crusades was lost by heavily armored crusaders fighting under King Edward. The loss is usually attributed to an advantage of the native Arabs who, as a result of living in the heat, were, in theory, better acclimatized to heat than were the European crusaders. However, the 20th-century experience of oil companies hiring native workers in Bahrain, who suffered more heat casualties by far than their nonnative workers, appears to support the sentiment in Noël Coward’s song that “mad dogs and Englishmen go out in the mid-day sun,” that is, the Arabs benefited from having learned to avoid working in the heat rather than better heat acclimatization, which would have been acquired by gradually increased levels or durations of work, or both, in the heat. Modern understanding of the problems of military operations in the heat would suggest that the weight and impermeability of the protective armor worn by the crusaders were the primary problems. Active fighting, while wearing crusaders’ armor, would have been stifling. Indeed, many combatants were reported to have been “suffocated.” When unhorsed, such knights had to be “cracked open and broken like lobsters” to be dispatched. (The reference to lobsters perhaps applied equally to the skin color of the knights as to their shell-like casing.)

The potentially epidemic nature of heat illness was documented in Rome in 1694 by Baglivi. In July 1743, 11,000 people died in Peking, China, during a 10-day heat wave. In the 1800s, heat affected Spanish military operations in the New World; the Dutch suffered while taking the East Indies and the British while taking India; nevertheless, all these campaigns were successful. And during the 20th century, many heat deaths occurred among pilgrims making the Hajj to Mecca in years when it coincided with high temperatures. However, although severe heat exposures can and have produced many casualties, reported losses in military effectiveness and lives are difficult to clearly separate between heat, per se, and other causes in reports made before the 20th century.

PROBLEMS OF DEFINITION AND COMPREHENSION

Terminology of Heat Effects

One of the problems with delineating the effects of heat on military operations from the literature before the 1950s, and even with some more recent reports, is that of terminology. The implied differential diagnosis of siriasis (ie, heatstroke) from sunstroke confounds many of the reports. In the 19th and early 20th centuries, siriasis was believed to be caused by the “actinic rays” of the sun and mandated wearing actinic orange underwear, a spine pad, and solar topee (a cork or pith helmet) to pre-
vent these rays from penetrating to the brain and spinal cord. Even today, heatstroke may not be properly differentiated from “physical heat exhaustion,” “heat exhaustion collapse,” or “hyperventilatory blackout” unless a patient dies—in which case it is almost always considered a heatstroke death, albeit it was not necessarily so. US military medical reports lumped all heat ailments under the term “sunstroke” during the American Civil War, as “heatstroke” during the Spanish–American War, as “effects of excessive heat” during World War I, and defined as three categories of heat illness during World War II: “ill-defined effects of heat,” “heat exhaustion,” and “heatstroke.” Because deaths occurred in all three categories, it seems clear that a problem of definition existed.

Unfortunately, such problems of definition still exist. For example, during one of the many field studies that I helped design and conduct, a 2:00 AM trip to a forward aid station was required to prevent a young medical officer from classifying militarily ineffective soldiers as “heat casualties” (a term used then in place of Leithead and Lind’s “transient heat fatigue” — despite ambient temperatures in the 10° range. Tired, cold, dehydrated, and demoralized after many hours in chemical–biological protective clothing, yes; but not the usual “heat” casualties.

Even more difficult to assess than terminology is determining the consequences of long-term exposure in the tropics or, as Huxley is said to have defined heat acclimatization, “getting used to not getting used to the heat.” In the 1920s, the Italian, Aldo Castellani, wrote on the importance of rotating white men from the tropics back to temperate climates to avoid an ill-defined syndrome, termed “heat fatigue.” In the 1930s, Castellani was appointed the Chief Health Consultant in East Africa for the Italian Campaign in Ethiopia, where he introduced one of the first cohesive programs for avoidance and treatment of heat casualties. In 1944, Douglas H. K. Lee evaluated troops of the Australian Army and Air Force for “tropical fatigue” and its detrimental effects on the health and performance of troops. Hans Selye’s formulation in 1949 of the concept of “stress” and the “generalized adaptation syndrome” may be the best explanation for such vague, but real, malaise.

**Epidemiology of Heat Illness**

A second problem is the lack of understanding of the epidemiology; that is, the role played by various host and agent (environmental and operational) factors, and the nature of the diseases broadly termed “heat illnesses.” Military operations are particularly likely to produce large numbers of heat problems, as discussed below. However, because of (a) the select nature of most military forces (ie, troops are usually young, fit, well conditioned, and at least partially heat acclimatized as a result of their physical conditioning); and (b) generally good, informed command and control by the military leadership, death due to heatstroke tends to occur as an isolated case. In the Israeli Armed Forces, for example, a heatstroke death is considered a failure of command control. In my own experience with heat death in civilian workers, when heatstroke is not a direct result of supervisory failure, it may be associated with increased susceptibility of the individual as a result of

- dehydration, often as a sequel to high alcohol consumption;
- febrile onset as a result of infection or recent immunizations; or
- loss of physical condition or acclimatization, or both, as a result of extended absence from the job, whether from illness or vacation.

It has been suggested (but not in the open literature) that individuals with low innate fitness (eg, those with <2 L/min of maximum oxygen uptake [as a result of small cardiac stroke volume due to either small heart size or low maximum heart rate, usually a concomitant to aging]), have unique susceptibility to all forms of heat illness.

**THE SIX “AGENTS” OF HEAT EFFECTS**

Air temperature per se is seldom the cause of heat problems; it is only one, and rarely the most important, of the six factors—or, in terms of the epidemiological triad, the “agents”—that result in heat stress as it affects military operations. Four of these six are environmental factors:

1. ambient air temperature ($T_a$);
2. air motion, or wind velocity (WV);
3. air relative humidity (rh), expressed more relevantly as the vapor pressure of the moisture in air ($P_v$); and
4. mean radiant temperature (MRT).
Introduction to Heat-Related Problems in Military Operations

The details of their measurement and calculation are outside the purview of this chapter, but interested readers can consult the chapter by Santee and Matthew, Evaluation of Environmental Factors, in the third volume of Medical Aspects of Harsh Environments, and other textbooks that discuss the subject.

In considering the effects of heat on military operations, rarely are any of these four environmental factors as important as two behavioral factors:

5. the amount of metabolic heat (M) produced by the body; and
6. the clothing worn, and its insulation (clo) and moisture permeability (I_m), and how these change with wind or body motion or both (as characterized by a “pumping” coefficient).

These behavioral factors can be considered agent rather than host factors because they tend to be established by the operation rather than by the individual, particularly in a military setting. Thus, any consideration of thermal stress should explore these six key factors.

Environmental and Behavioral Tradeoffs

Tradeoffs have been established between these six factors with respect to their effects on human comfort. It is useful to examine the tradeoffs among these for comfort, and then infer from them the effects of five (in relation to the sixth, air temperature), as epidemiological “agents” for heat illness:

1. rh: a 10% change can be offset by a 0.5°F change in T_a;
2. WV: a change in wind speed of 20 feet per minute (fpm) is equivalent to a change of 1°F (up to a maximum of 5°F) in T_a;
3. MRT: a change of 1°F can be offset by a 1°F change in T_a;
4. clo: a change of 0.1 clo has the effect of a 1°F change in T_a, up to 2.5 met (the unit of measure for metabolic rate) of activity, and 2°F at higher levels; and
5. M: an increase of 25 kcal/h is equivalent to a 3°F increase in T_a.

The normal comfort range is a 6°F-wide band of air temperature between 72°F and 78°F when the following conditions are met for the other five agents:

- rh is 40%;
- WV is 44 fpm (ie, 0.5 mph);
- MRT = T_a;
- clo = 0.6; and
- M = 1 met.

The clo unit of clothing insulation was defined so that an average man with 1.8 m² of body surface area must transfer 10 kcal of heat per hour (by radiation and convection) per Centigrade degree difference between the air temperature (T_a) and skin temperature (T_sk), typically 35°C when warm. A long-sleeved shirt and trousers provides 0.6 clo; the surface air layer next to the body adds another 0.8 clo, to bring the total insulation to 1.4 clo units. Thus, the total insulation that limits heat loss, without sweat evaporation, is about 1.4 clo for a soldier who is wearing a fatigue ensemble; this increases to about 2.5 clo when a chemical protective ensemble (which also usually offers increased resistance to sweat evaporative cooling) is worn. As a result, maximum nonevaporative heat loss is about 72 kcal/h at 25°C with 1.4 clo [ie, (35°C – 25°C) • 10/1.4], but only 40 kcal/h with 2.5 clo. Note that at rest, producing 90 kcal/h, about 25% of M (~ 22 kcal/h) is lost by respiration and evaporation of the normal, nonsweating, moisture diffusing from the skin, so that heat balance (ie, heat production [90 kcal/h] – heat loss [72 + 22 kcal/h]) is achieved without sweating, and an individual is comfortable at 25°C (77°F) with 1.4 clo of total clothing and still air insulation. This helps explain why the comfort range for office workers is 72°F to 78°F, while soldiers can get heat illness at these same temperatures.

Metabolic rate (M) is expressed in mets. One met, the resting heat production, is defined as 50 kcal/h per square meter of body surface area; or, for an average 1.8 m² man, 90 kcal/h, which equals 105 watts (W). M increases with the pace of military operations, and load carried, to levels of as much as 10 met, which can only be sustained for a short time (~ 15 min). The metabolic demand of marching at 3.25 mph on a blacktop road can be estimated as 2 kcal/h per pound of body weight plus load weight (eg, a 165-lb infantryman carrying a 60-lb load [clothing, weapon, pack, etc] will produce ~450 kcal/h, or 5 met). Marching over sand will more than double this heat production, to the 10-met level, which will rapidly result in physical exhaustion.

To better understand why military operations are so susceptible to being affected by heat, we can estimate the comfort temperature range for combat
infantrymen on an approach march (i.e., 5 met, or 450 kcal/h) with a total of 2.0 clo of insulation (helmet, body armor, battle dress uniform, pack, etc). In an otherwise comfortable environment, with $T_a$ of 20°C (68°F) and 60% rh, with high wind and an increase in MRT of 7°C (13°F, which is typical for full sun exposure), the tradeoff analysis gives an equivalent air temperature of 55.4°C (132°F) (Exhibit 1-1).

**Exhibit 1-1**

**Tradeoff Analysis**

Soldiers performing military operations are vulnerable to the effects of heat. The tradeoff analysis—a stepwise arithmetical process—demonstrates how the cumulative effects of working in the sun in uniform can change an exposure from benign to unbearably hot:

1. 20.0°C (68°F) $T_a$
2. + 0.5°C (1°F) for the extra 20% rh
3. + 7.0°C (13°F) for the MRT effect
4. − 2.8°C (5°F) the maximum “wind” benefit
5. + 6.7°C (12°F) for the extra 0.6 clo (5 met)
6. + 24.0°C (43°F) for the extra 360 kcal/h

= 55.4°C (132°F) equivalent air temperature

clo: unit of clothing insulation; MRT: mean radiant temperature; rh: relative humidity; $T_a$: ambient temperature; met: unit of measure for resting metabolic rate

However, worldwide weather extremes are much less severe than those that can occur inside crew compartments in military armored fighting vehicles (Table 1-1), where the average increase in interior temperature above the ambient outside is 13 Fahrenheit degrees, with peak increases exceeding 26 Fahrenheit degrees. In addition, whereas the highest ambient air temperatures (e.g., > 100°F) are never accompanied by high humidity, the even higher air temperatures in crew compartments can be accompanied by quite high humidity as occupants’ evaporated sweat accumulates. Finally, the fully saturated (100% rh), trapped air next to the skin of soldiers encapsulated in heavy clothing with reduced moisture permeability, or in light but impermeable protective clothing, routinely produces heat casualties.26 (The ratio of the index of permeability to moisture to the insulation provided by clothing [$Im / clo$] is discussed later in this chapter.) Heat casualties should be anticipated in less than 1 hour at ambient air temperatures above 30°C (86°F) even at low activity levels and, given the introduction of reduced permeability membranes in combination with the high insulation of the latest Extended Cold Weather Clothing System (ECWCS), possibly with only a few hours’ heavy work even at –30°C (–22°F).

**Heat Production Extremes**

Many aspects of the military setting result in sustained periods of extremely high heat production. First, the pace of work is seldom set by the individual, and often not even by his immediate unit leaders, but by a remote commander or by the enemy. The well-known military tradition of “hurry up and wait” is a natural consequence. The problem was stated by John Pringle, Surgeon General to the English army, in 1752:

> The life of a foot soldier is divided between two extremes of labour and inactivity. Sometimes he is ready to sink beneath fatigue, when, having his arms, accoutrements and knapsack to carry, he is obliged to make long marches, especially in hot or rainy weather.27

Second, almost all individuals taken into the military are given extensive training to bring them to peak ability to perform heavy work, despite some evidence that most troops are seldom exposed to anything like the sustained high work levels experienced during their training. This very demanding training, and an initial lack of acclimation or acclimatization to work in the heat, accounts in part for the high incidence of heat casualties suffered by
recruits during military training. (The term “acclimatization” pertains to the physiological adjustment to an environment in nature, whereas “acclimation” pertains to physiological adjustment to environmental conditions in a controlled setting.) Of greater importance in the overall issue of heat stress during military operations is the unreasonably heavy loads carried by combat troops. Mules may have developed their reputation for stubbornness as a result of their adamant refusal to move when overloaded. Troops are less resistant to excessive loads and, despite peacetime loads that

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Location</th>
<th>Ambient Temp (°F)</th>
<th>Average (°F)</th>
<th>Maximum (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M114 ARV</td>
<td>Driver compartment</td>
<td>91–114</td>
<td>13</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Crew compartment</td>
<td></td>
<td>14</td>
<td>30</td>
</tr>
<tr>
<td>M50 APC</td>
<td>Crew compartment</td>
<td>100</td>
<td>—</td>
<td>40</td>
</tr>
<tr>
<td>M113 APC</td>
<td>Crew compartment</td>
<td>105–108</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>M106A1 SPM</td>
<td>Crew compartment</td>
<td>90–102</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>M557 CPC with CPV</td>
<td>Crew compartment</td>
<td>102</td>
<td>—</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Crew compartment</td>
<td>90–100</td>
<td>20</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Driver compartment</td>
<td></td>
<td>21</td>
<td>35</td>
</tr>
<tr>
<td>M701 MVCV</td>
<td>Turret</td>
<td>100</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Squad compartment</td>
<td></td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Driver compartment</td>
<td></td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>LVTPX 12</td>
<td>Driver compartment</td>
<td>95–109</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Commander’s compartment</td>
<td></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Cargo compartment</td>
<td></td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td>T98EI SPH</td>
<td>Turret</td>
<td>94–107</td>
<td>18</td>
<td>53</td>
</tr>
<tr>
<td>T19EI SPH</td>
<td>Turret</td>
<td>97–101</td>
<td>23</td>
<td>30</td>
</tr>
<tr>
<td>M109 SPH</td>
<td>Crew compartment</td>
<td>99–111</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Driver compartment</td>
<td></td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>MSSI AR/AAV</td>
<td>Turret</td>
<td>104–110</td>
<td>13</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Driver compartment</td>
<td></td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>M41M Tank</td>
<td>Turret</td>
<td>94–111</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>M48 Tank</td>
<td>Turret</td>
<td>95–107</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>T45 Tank</td>
<td>Turret</td>
<td>96–107</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>M 60 AI Tank</td>
<td>Turret</td>
<td>90–113</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>M43EI Tank</td>
<td>Turret</td>
<td>93–107</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Turret bustle</td>
<td>99–102</td>
<td>55</td>
<td>57</td>
</tr>
</tbody>
</table>

Notes:
- Add + 10°F for positive pressure (few of these vehicles could be overpressurized but the limited data on overpressurized vehicles [the USSR approach] suggests adding 10°F to interior temperatures)
- Ambient Temperature Range: 90–114
- Approximate Average Temperature Above Ambient: 13.1 23.7

*Add + 10°F for positive pressure (few of these vehicles could be overpressurized but the limited data on overpressurized vehicles [the USSR approach] suggests adding 10°F to interior temperatures)
approximate the 45 pounds recommended by a British Royal Commission in 1847, often carry almost twice that weight into combat. Each pound (whether of body or load) moved when walking at a normal pace (about 3.25 mph) requires a heat production of 2 kcal/h, and even more as load weights exceed about one third of body weight, or as speed increases. The effects of such heavy loads in exhausting the soldier and inducing casualties have been a focus of attention since Roman times. Lothian reviewed the soldier’s load from the classical Greek hoplite era through 1918; I have expanded Lothian’s chart up to the Vietnam era (Figure 1-1). S. L. A. Marshall, in his essay “The Soldier’s Load and the Mobility of the Nation,” provides an extensive critique of the effects of the excessive loads imposed on a soldier. Indeed, tables describing the energy costs of various tasks characterize identical caloric costs for a given task differently for the military population than for a civilian work force (eg, a task rated at the same number of calories will be characterized as “light” for a military population, but “moderately hard” for civilian workers who usually are older, generally less fit, and often include workers who would have been screened out by any military selection process). Finally, Kennedy and Goldman in a report on the design of load carriage equipment, suggest that load carriage capacity, and even uniform pockets, should be minimized to reduce the traditional accumulation of trophies (or loot) common to the combat soldier since earliest history.

**Clothing Extremes**

As the effectiveness of weapons increased there was a natural desire to provide increasing protection against them, insofar as possible. An example of this is the blue paint daubed on Zulu warriors by their witch doctors to repel the British bullets. At least this psychological prop did not degrade the performance capabilities of the wearer, unlike most items of modern protective clothing and equipment. Concerns for heat stress in four groups of fighters have formed a major portion of this writer’s career: the military, firefighters, hazardous-waste site workers, and football players. Football players are at increased risk of heat illness because of the impermeable plastic protective shoulder padding and helmet worn, in combination with their high, albeit intermittent, levels of heat production. Hazardous-waste site workers are at risk because of the impermeability ($I_m < 0.12$) of their thin (clo ~ 1.0), encapsulating, protective ensembles. Firemen typically wear about 3 clo of insulation, with varying degrees of reduced permeability from water-repellent treatments or “breathable” waterproof membranes, or both, which have an $I_m$ of less than 0.3. The resulting approximately 0.1 $I_m$/clo, coupled with high radiant or ambient temperatures, or both, and short periods of very heavy exertion, result in significant heat stress problems.

Military personnel body armor is essentially impermeable as well as highly insulating. It adds enough weight and impedance of movement that, it has been argued, it slows the wearer down and makes him an easier target. However, there is some evidence that the increase in protection afforded military personnel and firefighters leads both groups to take greater risks than they otherwise would. Finally, nuclear, biological, and chemical (NBC) protective clothing, which was developed initially during World War II, was resurrected after reports during the late 1950s that facilities were being constructed at Russian airfields for the storage of chemical munitions. This led to 25 years (1959–1984) of intense research and development focus on the effects of wearing chemical protective clothing (Table 1-2), on development of more permeable chemical protective clothing, on heat stress and tolerance time limitations for military performance, and on models to predict them.

Recognition that troops on today’s battlefields wearing body armor and chemical protective clothing have limits on load carriage and sweat evaporative cooling similar to those of the armored crusaders of the Middle Ages has led to development programs for advanced combat infantry clothing (Generation II and 21st Century Land Warrior [21CLAW]). However, further development of the auxiliary cooling systems included in earlier programs (eg, the Soldier Integrated Protective Ensemble [SIPE]) has been rejected as impractical. At the same time, the most recent versions of the battle dress overgarment (BDO) provide about 20% less potential for sweat evaporative cooling than earlier versions (eg, $I_m$/clo now = 0.12, vs 0.15). Thus we can expect questions to continue on the effects of heat stress on military operations.

The sources of heat that most seriously affect military operations are (1) a sustained, high metabolic heat production; and (2) high temperature and humidity, particularly in crew compartments of armored fighting vehicles, where the interior temperatures average 7 Centigrade degrees above ambient and can be as much as 17 Centigrade degrees higher. These are complicated by (3) difficulty in losing this heat through the heavier insulation of protective clothing. Of these, the third, that of pro-
Introduction to Heat-Related Problems in Military Operations

Light Troops

South

1907

1914

1918

Crimea

Napoleonics

Middle 18th

Early 18th

Late 17th

Ironside

Pikeman

Archer

Fanti

Freeman

Byzantine

Heavy

Light

Shotman

Hostage

Freeman

Imperial

Rise of Anglo Saxons

Prosperity

Reduction

Hastings

Increasing

Use of Body Armor

Use of Body Armor

The Knight

Hoplite

Byzantine

Legionary

Peltast

Rise of organized Greek Armies

Elimination of Auxilary Transport

Necessaries Standardised

Use of Armours

Tends to Disappear

Packs Introduced and

Effects of Gustavus

Fig. 1-1. The soldier’s load: estimated, recommended, and actual. This chart, presented by N. W. Lothian in 1922, was updated by R. F. Goldman in 1969 to include data for the late 1940s through the Korean War in 1951; the subsequent, noncombat Cold War; and the Vietnam War in 1967. The chart shows that despite recognition of the adverse effects of heavy load carriage on military operations as early as the introduction of the armor of the Greek hoplite, and the recommendation of a British Royal Commission in 1867 that 45 lb represented the limit carried by average troops without distress, the cycle of increasing the soldier’s load in wartime—until it becomes clear that he is at a severe disadvantage against more lightly loaded opponents—has continued over the last two millennia and seems likely to continue into the third. The combat load, close to the 45-lb recommendation in peacetime, and the existence load (i.e., tentage, sleeping bag, poncho, etc., carried on a march), which hovers around 65 lb in peacetime, both increase dramatically during wartime, to the soldier’s detriment. According to the US Army Research Institute of Environmental Medicine, the current nomenclature and recommended weights for soldiers are as follows: fighting load, 41.5 lb; approach load, 67.5 lb; and sustainment load, 97.5 lb. Sources: (1) Xenophon. *Anabasis*. 3.4.48. (2) British Royal Commission. *The Influence of Accoutrements on Health*. Cited by: Lothian NW. The load carried by the soldier. *J Roy Army Med Corps*. 1921;37:241–263, 324–351, 448–458, and 1922;38:9–24. Distributed by: Washington, DC: Office of The Quartermaster General, Research and Development Branch, Textile, Clothing and Footwear Division. Tentage and Equipage Series Report 11. Released for public information by The Office of Technical Services, US Department of Commerce; 1954:7. (3) Marshall ISLA. *The Soldier’s Load and the Mobility of a Nation*. Washington, DC: Combat Forces Press; 1950. (4) Pandolf KB. Senior Research Scientist, US Army Research Institute of Environmental Medicine, Natick, Mass. Personal communication, 11 May 2000. Chart: Adapted with permission from Goldman RF. Physiological costs of body armor. *Mil Med*. 1969;134(3):239.
TABLE 1-2
SELECTED CHRONOLOGY OF TESTING NUCLEAR, BIOLOGICAL, AND CHEMICAL PROTECTIVE CLOTHING

<table>
<thead>
<tr>
<th>Year</th>
<th>Study or Event</th>
<th>Site or Testing Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1915</td>
<td>First use of gas, Germans</td>
<td></td>
</tr>
<tr>
<td>1918</td>
<td>AEF #1433; Defense Against Gas. Troops Need Practice</td>
<td>Wearing Respirator for Longer Periods</td>
</tr>
<tr>
<td>1959</td>
<td>Evaluation of CB protection during the Cold War</td>
<td>Camp Pickett, Va; Fort Knox, Ky; EPRD*</td>
</tr>
<tr>
<td>1960</td>
<td>Copper Man Studies of NBC Clothing</td>
<td>USARIEM†</td>
</tr>
<tr>
<td>1961</td>
<td>Climatic Chamber Studies</td>
<td>USARIEM†</td>
</tr>
<tr>
<td>1961</td>
<td>Effects of Hycar Underwear on Heat Stress</td>
<td>Edgewood Arsenal, Md</td>
</tr>
<tr>
<td>1961</td>
<td>Responses Wearing Protective Clothing in Hot-Dry</td>
<td>Dugway Proving Ground, Utah</td>
</tr>
<tr>
<td>1962</td>
<td>Fort Lee Field Studies</td>
<td>USARIEM†</td>
</tr>
<tr>
<td>1962</td>
<td>Project Samples-Mask Studies</td>
<td>Fort McClellan, Ala</td>
</tr>
<tr>
<td>1962</td>
<td>Jackpot</td>
<td></td>
</tr>
<tr>
<td>1963</td>
<td>Road Operations in a Toxic Environment (Panama)</td>
<td>USARIEM†</td>
</tr>
<tr>
<td>1963</td>
<td>Samples</td>
<td>Fort McClellan, Ala</td>
</tr>
<tr>
<td>1964</td>
<td>Road Operations in a Toxic Environment</td>
<td>Fort Ord, Calif; CDEC*</td>
</tr>
<tr>
<td>1965</td>
<td>IPR CB Protective Overgarment</td>
<td>NARADCOM</td>
</tr>
<tr>
<td>1966</td>
<td>Mandrake Root (Computer Study)</td>
<td>MUCOM; OPRESG*</td>
</tr>
<tr>
<td>1967</td>
<td>Mandrake Root Addendum Study</td>
<td>United States; USSR*</td>
</tr>
<tr>
<td>1967</td>
<td>Mission Degradation</td>
<td>MUCOM</td>
</tr>
<tr>
<td>1966–1968</td>
<td>Effectiveness in a Toxic Environment–METOXE</td>
<td>CDC; CAG (many sites)*</td>
</tr>
<tr>
<td>1969</td>
<td>US Amphibious Assault 69-10</td>
<td>NMFRL</td>
</tr>
<tr>
<td>1969</td>
<td>Doctrinal Guidance for NBC Wear</td>
<td>USARIEM†</td>
</tr>
<tr>
<td>1970</td>
<td>Copper Man Evaluations</td>
<td>USARIEM</td>
</tr>
<tr>
<td>1971</td>
<td>Gum Tree</td>
<td>United Kingdom, Malaysia</td>
</tr>
<tr>
<td>1971</td>
<td>Chillitog</td>
<td>United Kingdom, NW Europe</td>
</tr>
<tr>
<td>1971</td>
<td>Reducing heat stress in NBC ensembles</td>
<td>TTCP/Edgewood</td>
</tr>
<tr>
<td>1971</td>
<td>DCGE/DREO 2/71</td>
<td>Canada</td>
</tr>
<tr>
<td>1972</td>
<td>Jeremiah</td>
<td>United Kingdom (done in Suffield, Canada)</td>
</tr>
<tr>
<td>1973</td>
<td>Grand Plot III</td>
<td>CDEC; IDF</td>
</tr>
<tr>
<td>1975</td>
<td>US/CDA/UK Companion Study</td>
<td>Dugway Proving Ground, Ut*</td>
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<tr>
<td>1976</td>
<td>Unit Chem. Defense (SCORES-MIDEAST)</td>
<td>TRADOC, Fort Monroe, Va</td>
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<tr>
<td>1977</td>
<td>USAF Chem. Defense</td>
<td>TAC OPS Eglin Air Force Base, Fla*</td>
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<tr>
<td>1977</td>
<td>Ill Wind (CPX)</td>
<td>Fort Benning, Ga</td>
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<td>1978</td>
<td>Wetted cover to reduce heat stress in NBC</td>
<td>USARIEM†</td>
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<tr>
<td>1978</td>
<td>XM-29AH and the AH-Is Sight</td>
<td>Fort A. P. Hill, Va*</td>
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<tr>
<td>1979</td>
<td>Performance Degradation Modeling (PDGRAM)</td>
<td>AAMF Industries</td>
</tr>
<tr>
<td>1980</td>
<td>Heat Stress for XM-I CVC in CW Protection.</td>
<td>USARIEM†</td>
</tr>
<tr>
<td>1980</td>
<td>Heat Stress in USN Carrier Flight Operations</td>
<td>USARIEM†</td>
</tr>
<tr>
<td>1980</td>
<td>Early Call III</td>
<td>APRE, Aldershot, United Kingdom</td>
</tr>
<tr>
<td>1980</td>
<td>Australian Infantry Performance in NBC</td>
<td>Australia*</td>
</tr>
<tr>
<td>1980</td>
<td>Thermal Stress in M-I Tank With NBC</td>
<td>APG, USARIEM†</td>
</tr>
<tr>
<td>1981</td>
<td>Mobility Through Contaminated Areas (MOCAT)</td>
<td>CDCEC, Fort Ord, Calif*</td>
</tr>
<tr>
<td>1981</td>
<td>CW Protective Posture Performance (CPW3)</td>
<td>CDCEC, Fort Ord, Calif*</td>
</tr>
<tr>
<td>1981</td>
<td>Auxiliary Cooling and Tank Crew Performance</td>
<td>USARIEM†</td>
</tr>
<tr>
<td>1981–1982</td>
<td>Forward Area Refuel/Rearm Performance (FARP)</td>
<td>AAMRL, Brooks Air Force Base, Tex*</td>
</tr>
<tr>
<td>1982</td>
<td>Thermal Stress and Flight Performance</td>
<td>US Air Force; AMRL†</td>
</tr>
<tr>
<td>1983</td>
<td>Tank Crew Performance with Auxiliary Cooling</td>
<td>USARIEM; APG†</td>
</tr>
<tr>
<td>1983</td>
<td>Heat Stress and Performance in Nuclear Reactor Repair</td>
<td>GPUN/TMI-2*</td>
</tr>
<tr>
<td>1983–1984</td>
<td>Cane I</td>
<td>CDCEC</td>
</tr>
</tbody>
</table>

*Author involved as consultant or collaborator
†Author ran the study

AAMRL: Army Aviation Medical Research Laboratory, Dothan, Ala
AEF: Army Expeditionary Force
AMAF: American Machine and Foundry (contractor)
AMRL: Armored Medical Research Laboratory, Fort Knox, Ky
APG: Aberdeen Proving Ground, Aberdeen, Md
APRE: (Royal) Army Personnel Research Establishment
CDC/CAG: Combat Development Command, Combined Arms Group
CDCEC: Combat Development Command Experimentation Center, Fort Ord, Calif
CDCEC.IDF: Combat Development Command Experimentation Center and Israeli Defence Force (at Fort Ord)
EPRD: Environmental Protection Research Division, Natick, Mass
GPUN/TMI-2: General Public Utilities Nuclear, Three Mile Island Facility
MUCOM/OPRESG: Munitions Command, Operations Research Group
NARADCOM: US Army Natick Research and Development Command
NBC: Nuclear, Biological, and Chemical
NMFRL: US Navy Medical Field Research Laboratory, Camp Le Jeune, NC
TAC OPS: tactical operations
TRADOC: Training and Doctrine command, Fort Monroe, La
TTCP: Tripartite Technical Cooperation Program (US, UK, Canada)
protective clothing insulation as a limit to cooling, is the most insidious. The potential for soldiers wear protective clothing that is heavily insulated or relatively impermeable, or both, to become overheated is further compounded by such clothing’s limitations on sweat evaporative cooling. This limitation results not only from the reduced permeability to moisture (Im) of any clothing (even for ordinary civilian clothing, Im values are ~ 0.45) but also from the need for the evaporating sweat to pass through the insulation. The actual fraction of maximum evaporative cooling a wearer might be able to obtain in any given environment is determined by the ratio, Im/clo. For example, with multilayered protective ensembles, such as cold weather clothing, which range up to 3 clo, even if moisture permeability is not reduced by waterproof materials or water-repellent treatments, the Im/clo ratio of 0.45/3 means that the wearer can get only 15% of the maximum evaporative cooling power of the environment. And the insulation of the US Army’s arctic clothing can reach 4 clo.

HEAT ILLNESS: THE “DISEASE” SPECTRUM

During World War II, considerable effort was spent in trying to categorize various forms of heat illness. A more modern approach is to consider heat illness not as a single disease but as a continuum of accumulating effects of heat, with specific disease entities defined as specific organs or systems are affected. In particular, I have found it possible to differentiate “heat exhaustion collapse” (ie, a soldier, temporarily unconscious, falls to the ground until the blood, not having to fight gravity, can again flow to the brain) from “physical heat exhaustion,” in which a soldier remains standing but is “obtunded” (ie, unable to respond to a direct order, unaware of what is going on around him or where he is, albeit still trying to keep moving). In the latter condition, troops have been known to walk into vehicles, off ledges, and the like.

Both heat exhaustion collapse and physical heat exhaustion (previously termed “transient heat fatigue”18) (Table 1-3) can be viewed, simplistically, as an inability of the body to

- maintain sufficient cardiac output (blood flow) to deliver oxygen to the brain, muscles, and other body tissues;
- remove heat and products of metabolism from the tissues; and
- transfer heat to the skin so that it can be lost to the environment, if allowed by clothing, ambient temperature and vapor pressure, and air motion.

A useful basis for understanding why heat accumulates in the body, producing this continuum of heat illness, is suggested by three simple equations, which show that cardiac output is the most important determinant, with removal of tissue heat and metabolic by-products and heat transfer from skin to environment both secondary. These avoid any medical differential diagnosis but characterize, simplistically, the physiological basis for the categories of heat illness as a disease. The first equation states that cardiac output of blood (ie, the volume of blood [L/min] pumped by the heart), at rest or work in any environment, is simply a function of heart rate and stroke volume:

$$\text{Heart rate} \times \text{Stroke volume}$$

The maximum heart rate (ie, the maximum number of beats per minute) is primarily a function of age (220 beats per minute minus the subject’s age in years). The stroke volume (ie, the amount of blood pumped per beat) is a function of the size of the heart (primarily set by genetic inheritance, but heart size can be somewhat increased by physical conditioning), assuming that the volume of blood returned from the body to the heart is sufficient to fill it in the time between beats.

The second equation states that the volume of oxygen (VO2, in L/min) supplied to the various body organs (brain, muscles, heart, etc) is simply the product of cardiac output multiplied by the difference between the oxygen concentration in the arterial blood (CaO2), as it is circulated to these organs, and the oxygen in the venous blood (CvO2) as it leaves them:

$$\text{Cardiac output} \times (\text{CaO2} - \text{CvO2})$$

The third equation states that the maximum amount of heat (in kcal/min) that can be transferred from the body’s core (ie, muscles and other organs) to the skin is a function of the cardiac output multiplied by the difference between the temperature of the body’s core (Tc), which is the primary site of heat production during work, and the temperature of the skin (Tsk):

$$\text{Skin blood flow} \times (\text{Tc} - \text{Tsk})$$

Almost all the heat produced by the body must be
TABLE 1-3
HEAT STRESS

<table>
<thead>
<tr>
<th>Heat Stress Disorder</th>
<th>Cause and Problem</th>
<th>Signs and Symptoms</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Cramps</td>
<td>Failure to replace salt lost through sweating</td>
<td>Painful muscle cramps</td>
<td>Drink lightly salted water, lemonade, tomato juice, or “athletic” drinks</td>
</tr>
<tr>
<td></td>
<td>Electrolyte and muscle problems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyperventilation</td>
<td>Overbreathing</td>
<td>Dizziness; tingling around lips; carpopedal spasm; blackout</td>
<td>Slow, deep rebreathing from paper bag</td>
</tr>
<tr>
<td></td>
<td>Low blood CO₂ level problem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Exhaustion</td>
<td>Excessive heat strain with inadequate water intake</td>
<td>Weakness, unstable gait, extreme fatigue; wet, clammy skin; headache, nausea, collapse</td>
<td>Rest in shade and drink lightly salted fluids</td>
</tr>
<tr>
<td></td>
<td>Cardiovascular problem (inadequate venous return, filling time)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orthostatic hypotension problem</td>
<td></td>
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<tr>
<td></td>
<td>Excessive work in heat problem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dehydration/Physical</td>
<td>Failure to replace water loss</td>
<td>Excessive fatigue; weight loss</td>
<td>Replace fluids; rest until weight and water losses are restored</td>
</tr>
<tr>
<td>Exhaustion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heatstroke</td>
<td>High $T_c$ typically $&gt;105^\circ F$</td>
<td>Mental status changes, including irrational behavior or delirium; loss of consciousness, convulsions, and/or shivering may occur</td>
<td>Rapid, immediate cooling by cold-water immersion, or wrap in wet sheets and fan vigorously. Continue until $T_c$ is $&lt;102^\circ F$. Treat for shock if necessary once temperature is lowered. Heat stroke is a medical emergency. Brain damage and death can result even if treatment is timely.</td>
</tr>
<tr>
<td></td>
<td>Damage to or dysfunction of multiple organ systems is frequent</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$T_c$: core body temperature

Delivered to the skin before it can be lost, through any clothing, to the environment by convective, radiant, or evaporative heat transfer, separately or in combination.

These three equations suggest that there is competition for cardiac output between (a) the need to transport oxygen to the muscles (and other organs in the body’s core) and the brain and (b) the need to transport heat from the body’s core to the skin. (This competition is discussed in greater detail in Chapter 2, Human Adaptation to Hot Environments.) The first line of defense for the body against heat stress is to increase blood flow to the skin, thus raising skin temperature. The second line of defense is to increase the “wetness” of the skin by initiating sweating as skin temperature reaches 35°C, and increasing the amount of sweat produced as the body’s requirement for evaporative cooling increases. Bear in mind, however, that the interpretation of these equations needs to be tempered by a consideration of the following factors: (a) although the sustainable sweat rate is only about 1 L/h, under severe heat stress up to 3 L/h can be produced; (b) at least initially, almost all the sweat produced represents fluid drawn from the circulating blood volume; (c) the average adult has only about 5 liters of blood; and (d) when we are inactive and hot, blood tends to pool in the skin. Obviously, the com-
petition for cardiac output (implied by the three equations above) is increased, particularly if water intake is less than sweat loss.

A fourth equation,

\[
(4) \quad \text{Maximum heat loss from the skin} = \frac{10}{\text{clo}} \cdot (36 - T_a) + \frac{22 \cdot I_m}{\text{clo}} \cdot (44 - P_a)
\]

establishes the maximum heat transfer (kcal/h) at any environmental or ambient air temperature \((T_a)\) and vapor pressure \((P_a)\) of the moisture in air from a warm \((36^\circ C)\), fully sweating \((P_a = 44 \text{ mm Hg})\) skin to the environment through \((a)\) clothing insulation (in clo units) as radiative and convective heat loss, and \((b)\) the clothing’s resistance to evaporative heat loss. (Clothing resistance to evaporative heat loss is expressed by the relation \(\text{clo}/I_m\), the inverse of the evaporative potential, \(I_m/\text{clo}\).)

Overheating in humans can be compared to overheating in automobiles, although in humans the process is more complex (Exhibit 1-2). These simple analogies should help the reader understand the causes of the “diseases of heat” that affect military operations, and the interactions that make a continuum of these disorders. Figure 1-2 summarizes the heat illnesses and their etiology and adds less common heat ailments, such as tetany associated with hyperventilation (panting).

**“HOST” FACTORS IN HEAT ILLNESS**

Unlike studies in laboratory animals in which there is little inbred variability, studies of the human responses to heat show large differences between individuals. As discussed above, host factors of concern include heart size, physical fitness, skin eruptions, initial body temperature elevation from anxiety, fever (or prefebrile state) associated with many diseases (or inoculations against them), and dehydration.

**Heart Size**

As indicated above, small heart size implies lower cardiac output; this results in lower work capacity (ie, maximal oxygen uptake, \(\dot{V}O_{2\text{max}}\)) and greater problems under heat stress. Indeed, it has been suggested that individuals with a \(\dot{V}O_{2\text{max}} < 2.5 \text{ L/min}\) cannot perform hard work in the heat.

**Physical Fitness**

Lack of physical fitness, whether a result of genetics (inadequate selection pool or criterion for military recruits) or lack of adequate training (intensity, duration, and frequency of exercise), cardiac or respiratory disease, and so forth, will reduce heat tol-