Chapter 1

INTRODUCTION TO HEAT-RELATED PROBLEMS IN MILITARY OPERATIONS

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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 siriasis, 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(pp401–402)]

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[5] 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 advisers 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[6] 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[7] 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."[8(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.[8(p129)]

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.[9] 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.[10]

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.[11]

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"[12(p163)]; 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."[13(p30)] When unhorsed, such knights had to be "cracked open and broken like lobsters"[13(p30)] 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.[14] In July 1743, 11,000 people died in Peking, China, during a 10-day heat wave.[15] 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.[16] 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 prevent 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,[17] 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"[18(Table 30-6)]—despite ambient temperatures in the 10°C 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.[11] 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.[19] Hans Selye's formulation in 1949 of the concept of "stress" and the "generalized adaptation syndrome"[20(p837)] 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 sequela of 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_a); and
4. mean radiant temperature (MRT).

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[21] 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)[22] and moisture permeability (I_m),[23] 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 at 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[24] 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 m^2 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] $\simeq$ 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 m^2 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).[25] Marching over sand will more than double this heat production,[7] 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

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

infantrymen on an approach march (ie, 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).

Exacerbating Aspects of Military Operations

During military operations these six "agents" (air temperature, wind velocity, relative humidity, mean radiant temperature, metabolic heat production, and clothing insulation) that contribute to heat illness can, in turn, be exacerbated by the occurrence of unusually extreme environmental exposures, and by extremes of heat production and clothing; the former can seldom be avoided, and the latter are an inescapable component of battle.

Environmental Extremes

The civilian population is seldom exposed to extremes of any of the four environmental factors introduced above. Avoidance of extremes of heat is ingrained in semitropical and tropical cultures, and embedded in such traditions as the afternoon *siesta.* 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 (eg, > 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 [I_m/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

TABLE 1-1

INTERIOR TEMPERATURES* IN ARMORED FIGHTING VEHICLES IN HOT–DRY ENVIRONMENTS

Vehicle	Location	Ambient Temp (°F)	Interior Temperature, Degrees Above Ambient	
			Average (°F)	Maximum (°F)
M114 ARV	Driver compartment	91–114	13	29
	Crew compartment		14	30
M50 APC	Crew compartment	100	—	40
M113 APC	Crew compartment	105–108	10	14
M106AI SPM	Crew compartment	90–102	21	25
M557 CPC with CPV	Crew compartment	102	—	37
	Crew compartment	90–100	20	34
	Driver compartment		21	35
M701 MVCV	Turret	100	17	19
	Squad compartment		17	21
	Driver compartment		17	19
LVTPX 12	Driver compartment	95–109	6	14
	Commander’s compartment		10	20
	Cargo compartment		12	25
T98EI SPH	Turret	94–107	18	53
T19EI SPH	Turret	97–101	23	30
M109 SPH	Crew compartment	99–111	11	16
	Driver compartment		14	20
MSSI AR/AAV	Turret	104–110	13	25
	Driver compartment		7	12
M41M Tank	Turret	94–111	5	11
M48 Tank	Turret	95–107	7	13
T45 Tank	Turret	96–107	6	9
M 60 Al Tank	Turret	90–113	9	20
M43EI Tank	Turret	93–107	10	18
	Turret bustle	99–102	55	57
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)

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 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[12] 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,"[28] 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[29] 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,[30] it slows the wearer down and makes him an easier target. It has also been argued[30] 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.[31]

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 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-

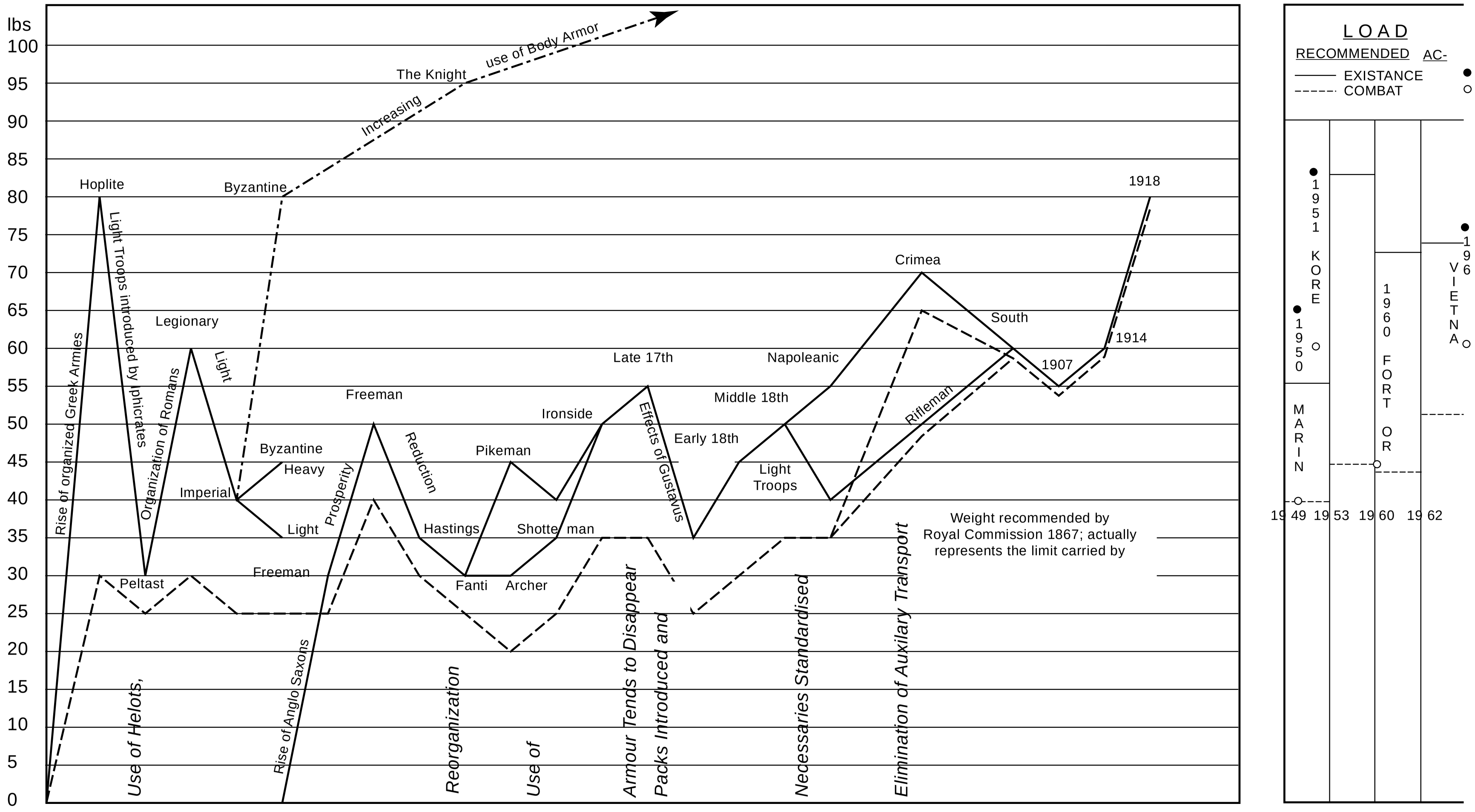

Fig. 1-1. The soldier's load: estimated, recommended, and actual. This chart, presented by N. W. Lothian in 1922, was updated by R. F. Goldman in 1969 to include data for the late 1940s through the Korean War in 1951; the subsequent, noncombat Cold War; and the Vietnam War in 1967. The chart shows that 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,[1] and the recommendation of a British Royal Commission in 1867[2] 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 (ie, 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.[3] 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.[4] 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 SLA. *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):209.

TABLE 1-2

SELECTED CHRONOLOGY OF TESTING NUCLEAR, BIOLOGICAL, AND CHEMICAL PROTECTIVE CLOTHING

Year	Study or Event	Site or Testing Organization
1915	First use of gas, Germans	
1918	AEF #1433: Defense Against Gas. *Troops Need Practice Wearing Respirator for Longer Periods*	
1959	Evaluation of CB protection during the Cold War	Camp Pickett, Va; Fort Knox, Ky; EPRD[*]
1959	Protect I	Fort McClellan, Ala; Dugway Proving Ground, Ut
1960	Copper Man Studies of NBC Clothing	USARIEM[†]
1961	Climatic Chamber Studies	USARIEM[†]
1961	Effects of Hycar Underwear on Heat Stress	Edgewood Arsenal, Md
1961	Responses Wearing Protective Clothing in Hot-Dry	Dugway Proving Ground, Utah
1962	Fort Lee Field Studies	USARIEM[†]
1962	Project Samples-Mask Studies	Fort McClellan, Ala
1962	Jackpot	Fort McClellan, Ala
1963	Road Operations in a Toxic Environment (Panama)	USARIEM[†]
1963	Samples	Fort McClellan, Ala
1964	Road Operations in a Toxic Environment	Fort Ord, Calif; CDEC[*]
1965	IPR CB Protective Overgarment	NARADCOM[*]
1966	Mandrake Root (Computer Study)	MUCOM; OPRESG[*]
1967	Mandrake Root Addendum Study	United States, USSR[*]
1967	Mission Degradation	MUCOM[*]
1966–1968	Effectiveness in a Toxic Environment–METOXE	CDC; CAG (many sites)[*]
1969	US Amphibious Assault 69-10	NMFRL[*]
1969	Doctrinal Guidance for NBC Wear	USARIEM[†]
1970	Copper Man Evaluations	USARIEM
1971	Gum Tree	United Kingdom, Malaysia
1971	Chillitog	United Kingdom, NW Europe
1971	Reducing heat stress in NBC ensembles	TTCP/Edgewood[*]
1971	DCGE/DREO 2/71	Canada
1972	Jeremiah	United Kingdom (done in Suffield, Canada)
1975	Grand Plot III	CDCEC; IDF[*]
1975	US/CDA/UK Companion Study	Dugway Proving Ground, Ut[*]
1976	Unit Chem. Defense (SCORES-MIDEAST)	TRADOC, Fort Monroe, Va[*]
1977	USAF Chem. Defense	TAC OPS Eglin Air Force Base, Fla[*]
1977	Ill Wind (CPX)	Fort Benning, Ga
1978	Wetted cover to reduce heat stress in NBC	USARIEM[†]
1978	XM-29AH and the AH-IS Sight	Fort A. P. Hill, Va[*]
1979–1980	Reducing Heat Stress in a CB Environment	TRADOC, Fort Monroe, Va; Field Manual 21-40
1979	Performance Degradation Modeling (PDGRAM)	AMAF Industries[*]
1980	Heat Stress for XM-I CVC in CW Protection.	USARIEM[†]
1980	Heat Stress in USN Carrier Flight Operations	USARIEM[†]
1980	Early Call III	APRE, Aldershot, United Kingdom
1980	Australian Infantry Performance in NBC	Australia[*]
1980	Thermal Stress in M-I Tank With NBC	APG, USARIEM[†]
1980–1982	Rapid Runway Repair (R3) in NBC	US Air Force[*]
1981	Mobility Through Contaminated Areas (MOCAT)	CDCEC, Fort Ord, Calif[*]
1981	CW Protective Posture Performance (CWP3)	CDCEC, Fort Ord, Calif[*]
1981	Auxiliary Cooling and Tank Crew Performance	USARIEM[†]
1981–1982	Forward Area Refuel/Rearm Performance (FARP)	AAMRL, Brooks Air Force Base, Tex[*]
1982	Thermal Stress and Flight Performance	US Air Force; AMRL[*]
1983	Tank Crew Performance with Auxiliary Cooling	USARIEM; APG[†]
1983	Heat Stress and Performance in Nuclear Reactor Repair	GPUN/TMI-2[*†]
1983–1984	Cane I	CDCEC[*]

[*] 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)
USARIEM: US Army Research Institute of Environmental Medicine, Natick, Mass

tective 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 (I_m) of any clothing (even for ordinary civilian clothing, I_m 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, I_m/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 I_m/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:

$$\text{(1)}\quad \text{Cardiac output (C.O.)} = \text{heart rate} \bullet \text{stroke volume}$$

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 ($\dot{V}O_2$, 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 (Cao_2), as it is circulated to these organs, and the oxygen in the venous blood (Cvo_2) as it leaves them:

$$\text{(2)}\quad \dot{V}O_2 \text{ delivery to organs} = \text{C.O.} \bullet (Cao_2 - Cvo_2)$$

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 (T_c), which is the primary site of heat production during work, and the temperature of the skin (T_{sk}):

$$\text{(3)}\quad \text{Maximum heat delivery to skin} = \text{skin blood flow} \bullet (T_c - T_{sk})$$

Almost all the heat produced by the body must be

TABLE 1-3

HEAT STRESS

Heat Stress Disorder	Cause and Problem	Signs and Symptoms	Treatment
Heat Cramps	Failure to replace salt lost through sweating Electrolyte and muscle problems	Painful muscle cramps	Drink lightly salted water, lemonade, tomato juice, or "athletic" drinks
Hyperventilation	Overbreathing Low blood CO_2 level problem	Dizziness; tingling around lips; carpopedal spasm; blackout	Slow, deep rebreathing from paper bag
Heat Exhaustion	Excessive heat strain with inadequate water intake Cardiovascular problem (inadequate venous return, filling time) Orthostatic hypotension problem	Weakness, unstable gait, extreme fatigue; wet, clammy skin; headache, nausea, collapse	Rest in shade and drink lightly salted fluids
Dehydration/Physical Exhaustion	Failure to replace water loss Excessive work in heat problem	Excessive fatigue; weight loss	Replace fluids; rest until weight and water losses are restored
Heatstroke	High T_c, typically > 105°F Damage to or dysfunction of multiple organ systems is frequent	Mental status changes, including irrational behavior or delirium; loss of consciousness, convulsions, and/or shivering may occur	Rapid, immediate cooling by cold-water immersion, or wrap in wet sheets and fan vigorously. Continue until T_c is < 102°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.*

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-

EXHIBIT 1-2

OVERHEATING IN HUMANS AND AUTOMOBILES

Humans, like automobiles, overheat faster when

- the air temperature is close to the radiator (skin) temperature
- fluid, trapped in the radiator (skin), is not circulating
- the radiator (skin) is covered with dirt (clothing)
- radiator fluid (blood volume) is low
- too little fluid returns to the pump (heart), or the pump is too small, too weak, or leaks
- the radiator (skin) is partially blocked (skin eruptions)
- they start with warmer radiator (body) temperature

Humans, unlike automobiles, also heat faster when

- clothing is impermeable, heavy, or both (ie, low I_m/clo)
- environmental vapor pressure is near 44 mm Hg
- the body's control of blood flow or sweating is impaired by alcohol, drugs, disease, or inoculations to prevent it
- sweating is impaired by skin eruptions

petition for cardiac output (implied by the three equations above) is increased, particularly if water intake is less than sweat loss.

A fourth equation,

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

establishes the maximum heat transfer (kcal/h) at any environmental or ambient air temperature (T_a) and vapor pressure (VP) of the moisture in air (P_a) from a warm (36°C), fully sweating (VP = 44 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 clo/I_m, the inverse of the evaporative potential, I_m/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[32] 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, $\dot{V}O_2$max) and greater problems under heat stress. Indeed, it has been suggested[33] that individuals with a $\dot{V}O_2$max < 2.5 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-

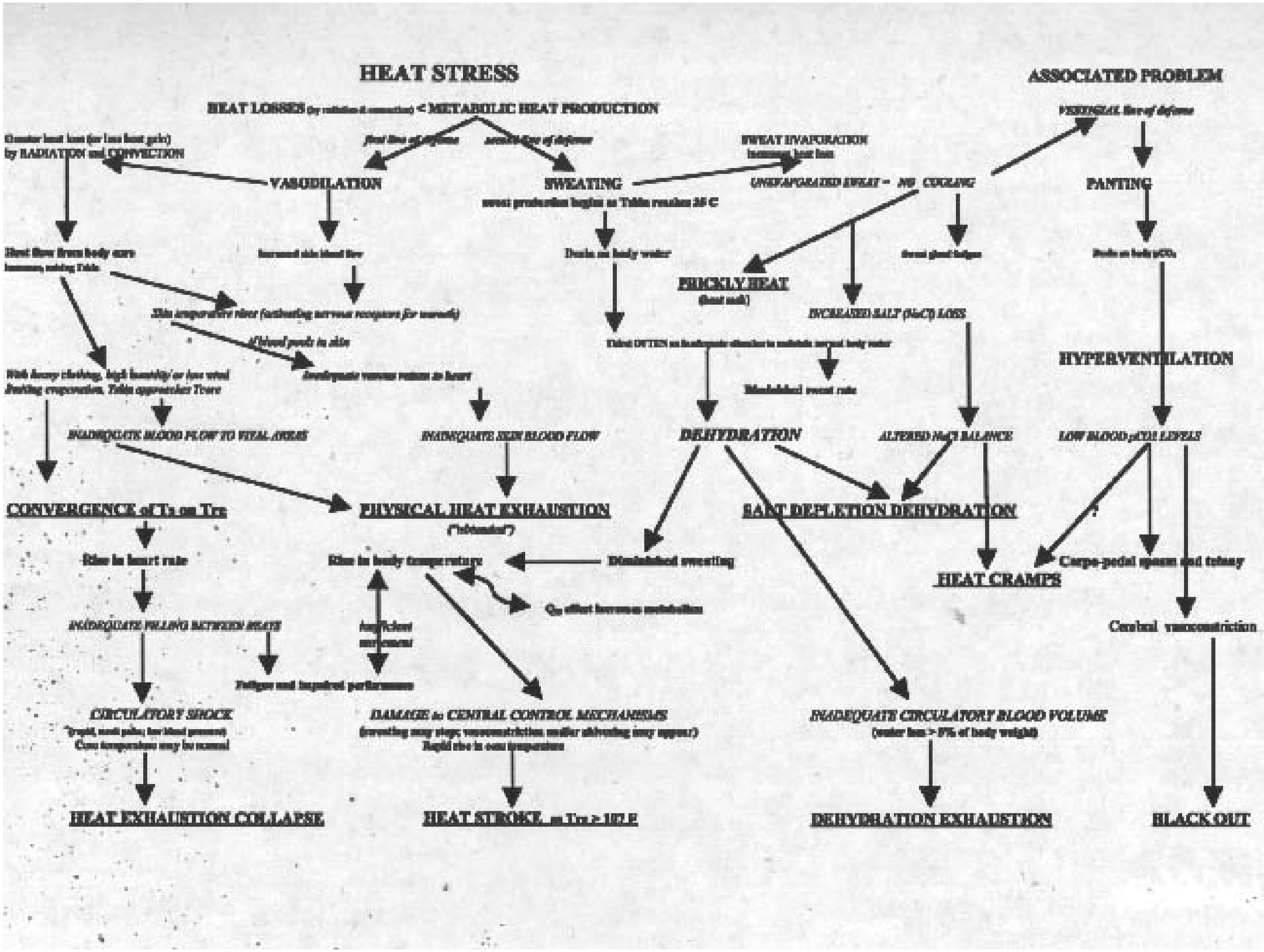
HEAT STRESS
ASSOCIATED PROBLEM
HEAT LOSSES (by radiation & convection) < METABOLIC HEAT PRODUCTION
first line of defense
second line of defense
Greater heat loss (or less heat gain)
by RADIATION and CONVECTION
VASODILATION
SWEATING
sweat production begins as Tskin reaches 35 C
SWEAT EVAPORATION
increases heat loss
UNEVAPORATED SWEAT = NO COOLING
VESTIGIAL line of defense
PANTING
Heat flow from body core
increases, raising Tskin
Increased skin blood flow
Drain on body water
Sweat gland fatigue
Drain on body pCO2
PRICKLY HEAT
(heat rash)
Skin temperature rises (activating nervous receptors for warmth)
INCREASED SALT (NaCl) LOSS
if blood pools in skin
Thirst OFTEN an inadequate stimulus to maintain normal body water
With heavy clothing, high humidity or low wind
limiting evaporation, Tskin approaches Tcore
Inadequate venous return to heart
Diminished sweat rate
HYPERVENTILATION
INADEQUATE BLOOD FLOW TO VITAL AREAS
INADEQUATE SKIN BLOOD FLOW
DEHYDRATION
ALTERED NaCl BALANCE
LOW BLOOD pCO2 LEVELS
CONVERGENCE of Ts on Tre
PHYSICAL HEAT EXHAUSTION
SALT DEPLETION DEHYDRATION
Rise in heart rate
Rise in body temperature
Diminished sweating
Carpo-pedal spasm and tetany
HEAT CRAMPS
Q10 effect increases metabolism
INADEQUATE FILLING BETWEEN BEATS
Insufficient
movement
Cerebral vasoconstriction
Fatigue and impaired performance
CIRCULATORY SHOCK
(rapid, weak pulse; low blood pressure)
Core temperature may be normal
DAMAGE to CENTRAL CONTROL MECHANISMS
(sweating may stop; vasoconstriction and/or shivering may appear)
Rapid rise in core temperature
INADEQUATE CIRCULATORY BLOOD VOLUME
(water loss > 5% of body weight)
HEAT EXHAUSTION COLLAPSE
HEAT STROKE, as Tre > 107 F
DEHYDRATION EXHAUSTION
BLACK OUT

Fig. 1-2. Heat stress and its associated physiological responses and pathologies. If troops cannot get rid of the heat that they produce, then their body temperature must rise. As the individual becomes hotter, the body has only two mechanisms—vasodilation and sweating—by which to rid itself of the extra heat. The heart beats faster, pumping more blood from the muscles to the skin, to help get rid of the heat; that will not work if the skin cannot lose the heat through the clothing to the environment. The skin can also increase the amount of sweat it releases, putting out as much as 2 to 3 L of sweat per hour, at least for the hour or so before a trooper suffers heat exhaustion or dehydration exhaustion (ie, the loss of more water from the body than is replaced by drinking). Sweat also contains salts, and if too much salt is lost from the body, a variety of heat illnesses result.[1] Although these heat illnesses can be differentially diagnosed and categorized, they tend to represent a continuum of effects rather than separate entities.

Heat Exhaustion. As the heart rate increases to greater than 160 to 180 beats per minute, there is no longer enough time between beats to completely refill the heart; with each beat it pumps a little less blood to the brain, and the worker begins to feel dizzy, nauseous, and weak. If one sits down to take a break, or slows down enough that too much blood is out in the skin, not being pumped back into the central circulation by body activity, then not enough blood returns to the heart to fill it. As a result, there is not enough blood to be pumped to the brain. The individual is then said to have *heat exhaustion collapse,* and faints or blacks out. Blood flow to the brain is restored when one is lying on the ground, and splashing cold water on the body and massaging the legs and arms may help return blood to the central circulation. The troopers might be able to resume their mission but the heat stored in the body has not yet been removed; if they are allowed to return to work, there is an increased risk of a second collapse from heat exhaustion, or of heatstroke, which could be fatal.

Dehydration Exhaustion. Individuals who lose much more water than they drink will be among the first to be distressed. An adult man has only about 5 liters of circulating blood; most of it is water and most of the sweat produced comes, initially, from this circulating blood reservoir. If the soldier does not replace this lost water by drinking enough water, then *dehydration exhaustion* and collapse are more likely.

Although the tremendously tired feeling that accompanies heat exhaustion, and the collapse that can occur, is frightening, it is not in itself terribly dangerous. Some men have suffered heat exhaustion collapse during exercises in the field for 5 or 6 consecutive days with no residual damage.[2] However, they were allowed to recover completely (cold shower, full rehydration, and overnight rest) before being reexposed to work in the heat the next day.

Heatstroke. The most serious risk of the body's inability to rid itself of heat is not heat exhaustion collapse but that individuals—from those in the best to those in the worst physical condition—may reach core temperatures (T_c) above 41°C. This represents a serious risk because the body is unable to cope with such high temperatures and may suffer permanent damage to its ability to sweat, increase blood flow to the skin, and thermoregulate. If T_c is high enough, and stays high long enough, *heatstroke* can be fatal, from the brain damage that temperatures above 41°C can produce.[3]

Heat Cramps. Individuals whose food intake is inadequate, or who do not add extra salt to their food during the first few days of hard work in the heat, may lose enough body salt that their muscles become sore and *heat cramps* ensue. These muscle cramps can occur simultaneously in a number of sites and can be completely disabling. Salt pills are not the answer. Drinking more, lightly salted, water will prevent heat cramps and, in most instances, cure them if they occur.

Salt Depletion Dehydration. Failure to replace the body's salt losses, and prolonged, daily exposure to heat stress can cause a serious but relatively infrequent condition. The body may reach a new, abnormal balance of salt and water, *salt depletion dehydration*, a condition that is difficult to treat. The body may not recognize that it is short of either salt or water and simply "dump" the extra provided. Ensuring that extra salt is ingested by heavy use of a salt shaker with meals during the first few days' work in the heat, will maintain body salt levels.

Hyperventilation. Some individuals exposed to heat stress (particularly in hot–humid environments) will attempt to pant (like a dog) to rid themselves of extra body heat. However, humans do not lose heat by panting; instead, they may exhale so much of the carbon dioxide normally in the blood that they feel dizzy, tingling of the lips, and faint. The small muscles of the hand may cramp and render the hand useless. Slow, deep rebreathing from a paper bag may be necessary to recover from *overbreathing* (hyperventilation).

(1) Minard D. Physiology of heat stress. In: *The Industrial Environment: Its Evaluation and Control.* Cincinnati, Ohio: National Institute of Safety and Health; 1973. (2) Joy RJT, Goldman RF. A method of relating physiology and military performance: A study of some effects of vapor barrier clothing in a hot climate. *Mil Med.* 1968;133:458–470. (3) Bynum GD, Pandolf KB, Schwette WH, et al. Induced hyperthermia in sedated humans and the concept of critical thermal maximum. *Am J Physiol.* 1978;4:R228.

Figure legend adapted with permission from Goldman RF. Standards for human exposure to heat. In: Mejkavik IB, et al, eds. *Environmental Ergonomics.* New York, NY: Taylor and Francis; 1988: 106, 108–109.

erance. Hard physical conditioning (eg, running for 2 h/d to near exhaustion, for several months) will maximize an individual's cardiac output, while also weeding out less fit individuals who may have met the requirements for military induction but still lack the genetic potential to be fully conditioned to work in the heat. Generally, the most that can be expected from even the best conditioning programs is an increase of about 15% in maximum work capacity, or, in the case of extremely sedentary individuals, who are well below their genetic normal level of fitness owing to their sedentary life-style, perhaps 25% to 30%.

Weight

It is relatively easy to predict the energy expenditure (and hence the heat production) of an individual who is carrying a load while either standing or walking. Energy expenditure for standing or walking on a firm, level surface is shown by the following equation[34]:

$$(5) \quad M = 1.5\ B + 2.0\ (B + L)\ (L \div B)^2 + 1.5\ (B + L)\ V^2$$

where *M* represents metabolic rate, in watts; *B* represents body weight, in kilograms; *L* represents load carried, in kilograms; and *V* represents walking speed, in meters per second.

Equation 5 is the sum of three components. The first is a linear function of body weight, and is the energy expenditure associated with standing without a load. The second is the additional energy expenditure associated with supporting a load while standing. Although the second component is negligible for small loads, it increases with the square of the load. The third component is the additional energy expenditure associated with walking rather than standing still, and increases with the square of the speed of walking.

Obviously, heavier individuals will have a higher heat production than lighter ones, but this is balanced by the heavier individual's greater surface area for heat loss. However, lighter individuals carrying the same weight loads have a higher heat production and, as loads exceed one third of body weight, the risk of physical exhaustion (from accumulating lactate buildup) or heat exhaustion (as skin temperature rises toward the core temperature), or both, increases (see Table 1-3). Obesity, although not generally a problem in the military, is a major risk factor for heat illness in the civilian workforce. If a march is not on a level, paved road the effect of more-difficult terrain becomes another multiplier for the third component above; marching in light brush increases metabolic rate by 30%, in heavy brush by 60% to 80%, and on soft sand by more than 200%. The effects of terrain and increased march rate when carrying loads are also easily seen and, using the simplistic ratio discussed at the start of this chapter—that each increase of 25 kcal/h in heat production is roughly equivalent to 1.67 Centigrade degrees (3 Fahrenheit degrees) in the perceived temperature—it is easy to see the need to reduce the soldier's load, march rate, and the interval between rest breaks to lower the hourly average heat production. Table 1-4 presents the metabolic heat production demands for a variety of typical military activities.

Gender

The classic belief has been that women are less able than men to tolerate work in the heat. Indeed, after attempting to regulate work in heat for the American workforce, the National Institute for Occupational Safety and Health (NIOSH) recommended[35] a considerable differential between male and female workers. It now appears that the perceived difference was primarily one of social and cultural differences; as a group, women had tended to be less physically conditioned and had less exposure than men to conditions that would induce full heat acclimatization.

Subsequent studies[36] suggest that if women are physically conditioned and fully acclimatized to heat, they may have a slight advantage over men under hot–humid conditions, and be at a slight disadvantage under hot–dry conditions, as an effect of their generally smaller body size and ratio of surface area to mass. Any gender differences are a matter of variation within an otherwise comparable group, with some men being less able to work in heat than most women.

Age

Because of the concomitant reduction in maximum heart rate with age, heat tolerance will also be reduced with increasing age, but there are large interindividual differences in physiological, as opposed to chronological, age. The capacity to meet the demands for military tasks is presented in Table 1-5, which shows the decreasing work capacity for troops (both men and women) as a function of age and level of fitness. In this regard, it is important to note that the level of voluntary hard work sustainable by an individual for 3 to 4 hours is 45% of maximum capacity.[37] Work demands that represent 60% of the work capacity can be sustained for only

TABLE 1-4

ESTIMATION OF HEAT PRODUCTION BY ACTIVITY LEVEL*

Work Rate	Activity	Watts (W)	kcal/h
Very light (105–175 W)	At rest, lying down	105	90
	Standing in a foxhole/riding in a truck	116	100
	Guard duty	137	118
	Flying a plane	145	125
	Driving a truck	163	140
Light (175–325 W)	Cleaning a rifle	198	170
	Walking on hard surface at 1 m/s (2.25 mph):		
	no load	210	180
	with 20-kg load	255	219
	with 30-kg load	292	251
Moderate (325–500 W)	Walking on soft sand at 1 m/s (2.25 mph):		
	no load	326	280
	Walking on hard surface at 1.56 m/s (3.5 mph):		
	no load	361	310
	with 20-kg load	448	385
	Scouting patrol	454	390
	Working with pick and shovel/crawling with pack	465	400
	Field assaults	477	410
Heavy (> 500 W)	Walking on hard surface		
	at 1.56 m/s (3.5 mph): with 30-kg load	507	436
	at 2.0 m/s (4.5 mph): no load	525	451
	Digging emplacements	540	465
	Bayonet drill	616	530
	Walking on soft sand at 1 m/s (2.25 mph):		
	no load	642	552

*for a 70-kg, young, physically fit soldier

Source: Adapted from US Army Research Institute of Environmental Medicine. *Heat Illness: A Handbook for Medical Officers.* Natick, Mass: USARIEM; June 1991. Technical Note 91-3 (AD A238974).

about 1 hour before physical exhaustion occurs without any complications from heat per se.

In the military, a more serious effect of age is the perceived need for younger, and also for older, troops to prove that they can cope with heat and, in general, perform as well as the rest of the unit. This factor may be more responsible than physiological differences for the greater incidence of heat casualties observed in both younger and older individuals. This may be particularly relevant for younger and older unit leaders; in one field study on the effects of chemical protective uniforms on a platoon's ability to set up hasty defensive positions, all the unit leaders suffered heat exhaustion collapse during the first few hours. Of course, the extra physical work of leaders in trying to ensure that the entire area was prepared as rapidly and as well as possible may have been a contributing factor.[38]

TABLE 1-5

MAXIMUM WORK CAPACITY (IN WATTS*) BY AGE AND FITNESS LEVEL

	Fitness Level				
Age	**Poor**	**Fair**	**Average**	**Good**	**Excellent**
Men					
17–19	< 924	948–1,042	1,066–1,161	1,185–1,256	> 1,279
20–24	< 829	853–924	948–1,066	1,090–1,232	> 1,256
25–29	< 805	829–900	924–1,042	1,066–1,184	> 1,208
30–34	< 782	805–877	900–1,019	1,042–1,137	> 1,161
35–39	< 758	782–829	853–971	995–1,090	> 1,113
40–44	< 711	734–805	829–900	924–1,042	> 1,066
45–49	< 663	687–758	782–829	853–1,019	> 1,042
50–54	< 616	640–711	734–782	805–995	> 1,019
Women					
17–19	< 782	805–900	924–995	1,019–1,113	> 1,137
20–24	< 758	782–853	877–948	971–1,066	> 1,090
25–29	< 711	734–805	829–924	924–1,019	> 1,042
30–34	< 663	687–758	782–877	900–971	> 995
35–39	< 616	640–711	734–829	853–924	> 948
40–44	< 577	592–663	687–782	805–877	> 900
45–49	< 521	545–616	640–734	758–829	> 853
50–54	< 474	497–569	592–687	711–782	> 805

*To convert these values from watts to kcal/h, multiply by 0.86.
Adapted by Goldman RF, from a table that was developed at US Army Research Institute of Environmental Medicine, Natick, Mass; circa 1975.

Type of Task

The effects of heat on physical task performance can be inferred from those seen previously in Table 1-4. Decrements in psychological task performance, on the other hand, are more difficult to assess but they can be offset by training, experience, leadership, and motivation to a much greater degree than the decrements in physical work tasks. However, failures in such cognitive tasks as perception, judgment, and decision making can be far more deadly, particularly if troop leaders are affected. Exhibit 1-3 suggests levels of rectal temperatures at which a variety of physical and psychological task capacities may be adversely affected.

Skin Diseases

Only one common skin disease of military relevance, prickly heat (miliaria rubra), has been shown to reduce heat tolerance.[39] Any impairment of sweat gland function (eg, delayed onset of sweating, congenitally fewer sweat glands), by exposure to chemical warfare agents or antidotes, or total absence of sweat glands, will reduce heat tolerance.

Race

Although the concept of "race" was first articulated by Kant in the 1800s, and race is difficult to define as a distinct grouping of characteristics, it has been suggested that, as a group, "blacks" are less heat-tolerant than "whites." This is certainly supported by US Army medical reports, as analyzed by Colonel Tom F. Whayne, later in this chapter. Although the incidence of heat illness among black troops was less than it was for white troops during the American Civil War, Spanish–American War, World War I, and World War II, the severity of heat illness and the death rates during those same wars

EXHIBIT 1-3

PHYSIOLOGICAL LEVELS OF CONCERN

1. Rectal Temperature (with elevated skin temperature)

Physical Tasks

38.2°C	NIOSH limit (discomfort)[*]
39.2°C	25% risk of heat casualties[†]
39.5°C	50% risk of heat casualties
40.0°C	100% casualties (“heat ineffectives”)

Cognitive Tasks

37.7°C	Threshold of decrement
38.2°C	Slowed cognitive function
38.5°C	Increased errors in judgment
39.6°C	Suggested functional limit

Motor Tasks

37.9°C	Decreasing manual dexterity
38.8°C	Loss of tracking skills

2. Heat Storage

Level	Effect
80 kcal	Discomfort
120 kcal	Performance degrades (T_{re} ~ 39°C)
160 kcal	Tolerance time limit (50% risk)
> 200 kcal	Potential damage

3. Heart Rate[‡]

Level	Effect
≥ 120 bpm	Discomfort (8-h tolerance)
≥ 140 bpm	4-h limit
≥ 160 bpm	2-h limit
> 170 bpm	Potential damage (*f* age)

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[*] Recommended (but not formally approved) upper limit proposed for civilian workforce.

[†] Actual heat exhaustion and heat collapse casualties will be about half the number at risk, if the operational scenario allows the level of activity (M) to be reduced as troops approach heat exhaustion.

[‡] For a civilian workforce of uncertain fitness and age, an increase in heart rate > 30 bpm above the individual’s resting level is to be avoided.[1]

bpm: beats per minute; *f:* function of; NIOSH: National Institute for Occupational Safety and Health; T_{re}: rectal temperature

(1) Brouha L. *Physiology in Industry.* New York, NY: Pergamon Press; 1960.

were significantly higher among black troops. A similar situation appears in British army medical reports in reference to Indian troops. However, analyses with prediction models for heart rate and rectal temperature responses to rest, work, and recovery in the heat, developed at USARIEM by Goldman and associates,[40,41] show that prediction models developed primarily on data from white soldiers provide an equally good fit to the responses of black mine workers in South Africa.[42] This suggests that social, rather than physiological, differences may be responsible for this variability in heat injury.

Acclimatization and Acclimation

Seven to 10 days of work in the heat, for 2 h/d, is generally considered sufficient to produce “full” acclimatization to heat exposure that is no more severe than the conditions of heat and exercise that produced the acclimatization. A large part of the beneficial effect of acclimatization is a result of increased sweating (due both to earlier onset of sweating and to increased secretory capacity of the sweat glands). Under conditions in which sweat can freely evaporate, acclimatization can result in a dramatic improvement in heat tolerance. However, if sweat evaporation is limited, either by lower-permeable or heavier protective clothing (lower I_m/clo) or elevated ambient vapor pressure, the benefits of heat acclimatization may be sharply decreased. Wearing body armor has been equated[43] to an increase of about four Centigrade degrees (seven Fahrenheit degrees) in the wet bulb globe temperature (WBGT) index, while complete encapsulation in chemical–biological protective ensembles (mission-oriented protective posture [MOPP 4] gear) has been equated to an increase of about 5.5 Centigrade degrees (10 Fahrenheit degrees).

With such heavy protective clothing it is conceivable that heat acclimatization could turn into a liability; the more rapid fluid loss will result in greater dehydration, without any real gain in sweat evaporative cooling. A well-conditioned soldier (ie, one in the best physical condition allowed by his genetic potential for $\dot{V}O_2$max) will have roughly the equivalent of an induced acclimatization after 3 days of work in the heat, just from his or her superior cardiovascular conditioning. However, the full benefit of 7 days of work in the heat cannot be obtained from work, no matter how hard, without concomitant heat exposure.

For the military, the psychological and behavioral adaptations developed by exposure to work in the heat may be more important than the physiological changes, in a manner somewhat analogous to what the British used to term "blooding the regiment," particularly if we consider the limitations imposed by protective clothing. Troops, and especially leaders, who are experienced in the problems of heavy work in the heat can take a variety of steps to reduce the potential heat stress: reducing the heat production (reduced load, rotation of heavy tasks, more frequent rests—in shade rather than in sun) and increasing water intake by command control (predrinking, provision of extra canteens and, most effective, requiring water intake at every rest break) are more beneficial than acclimatization when wearing protective clothing. In one field exercise, troops who were briefed on the potentials for heat stress and given a simple field instrument with which to identify high-risk conditions were able to operate with minimal heat casualties, compared with troops lacking such briefing or instruments.[44]

Hydration

Maintaining normal levels of body water, and even prehydration by ingesting 1 or 2 pints of water, is an important factor in resistance to heat illness. The effects of dehydration are explicated later in this chapter.

Electrolyte (Sodium Chloride) Intake

For this discussion, sodium is the essential electrolyte. The daily intake of salt pills during World War II was perhaps the worst possible doctrine to accompany the doctrine of water discipline. Supplementary salt *may* be useful for unacclimatized troops during the first few days of work in heat, before they become fully acclimatized, if they are not eating normally. However, any supplementary salt intake can interfere with one aspect of the heat acclimatization process: a decreasing content of sodium in the sweat.

The normal US military diet usually contains ample—even excessive—salt; supplements are usually unnecessary. Dasler and associates,[45] who conducted research studies on salt intake and heat acclimatization for the US Navy in the early 1970s, suggested that supplementary salt intake—beyond the already high salt content of a normal diet—retarded development of heat acclimatization. Unfortunately, the late-20th-century marketing success of "sports drinks," which contain large amounts of electrolytes and glucose, seems certain to continue to provide funds to (1) support research proving the benefits of such drinks and (2) attempt to convince the military that purchase of such drinks would be beneficial to troops. These commercial marketing attempts may well prevail despite ample evidence that such drinks represent unnecessary—and possibly detrimental—supplements to a normal military diet, which typically contains large amounts of salt.

Initially Elevated Body Temperature

Any heat produced (M) or received (H_R [radiant] or H_C [convective]) by the body that cannot be eliminated from the skin through the protective clothing to the ambient environment, must be stored in the body. The temperature of an average 70-kg body increases by one Centigrade degree for every 60 kcal of heat that it must store. Resting heart rate also increases with heat storage. Thus, any initial increase in body temperature means that there is simply that much less capacity to store additional heat before suffering heat exhaustion collapse (see Table 1-3 and Exhibit 1-3).

Body temperature elevations produced by any of the following will cause problems with heat to occur sooner and to be more severe:

- bacterial, viral, or parasitic diseases, or inoculations against them;
- previous activity with inadequate recovery, identified by a greater rate of increase in heart rate on reexposure to activity than the initial rate of rise[46]; or
- dehydration, a frequent sequela of even moderate alcoholic beverage ingestion during the preceding 24 hours.

In addition, a destabilizing effect of alcohol intake on the body's vasomotor control of blood pressure has also been observed[47,48] as a result of the accompanying dehydration (personal observation). Indeed, although there are no data on heat casualties during the US Revolutionary War, the comments of Dr. Benjamin Rush, a signer of the Declaration of Independence and physician who served during the American Revolutionary War, seem remarkably prescient:

> What should I say to the custom of drinking spiritous liquors which prevails so generally in our Army? I am aware of the prejudices in favor of it. It requires an arm more powerful than mine; the Arm of a Hercules to encounter it. The common apology for the use of rum in our Army is that it is necessary to guard against the effects of heat and cold. But I maintain that in no case whatever does rum abate the effects of either of them upon the constitution. On the contrary, I believe it always increases them. The temporary elevation of the spirits in the summer, and the temporary generation of warmth in the winter, produced by rum, always leave the body languid, and more likely to be affected with heat and cold afterward.[47(p6)]

EFFECTS OF HEAT ON MILITARY OPERATIONS

Having explored the usual epidemiological triad of agent, host, and disease, we now turn to the observed effects of heat on military operations in the heat. The primary sources of information are experimental studies of the effects of heat on humans and analyses of heat illness in the civilian population, medical analyses of wartime heat casualties, and afteraction reports of military operations in the heat.

Experimental and Analytical Studies

Most experiments and analytical studies were carried out to answer questions that were generated by wars. World War II generated questions on heat, cold, and altitude; the Korean War turned the focus to cold; and the Vietnam War and the later involvements in Iraq redirected the focus to heat. Most of the relevant studies were conducted in military laboratories or under contracts funded by the military. As might be expected, the US Army Research Institute of Environmental Medicine (USARIEM) and its predecessor organizations, the Environmental Protection Research Division (EPRD) of the Office of the Quartermaster General, at Natick, Massachusetts, and the Office of The Surgeon General's Armored Medical Research Laboratory (AMRL), at Fort Knox, Kentucky, were primary centers for these studies. (For interested readers, a short description of the origins and kinds of heat-related research done at USARIEM is attached to the end of this chapter.) Two themes dominated the heat studies: the effects of work under hot conditions and the role of dehydration in military operations.

Physiological Effects of Dehydration

In the 1950s, the US Army Quartermaster and Engineers, charged with delivering potable water to the troops, developed a chart entitled "Daily Water Requirements for Three Levels of Activity" (Figure 1-3). Although more extensive studies have been conducted subsequently,[49] these still seem reasonable guidelines. Doctrine promulgated in 1981, entitled "Water Intake, Work/Rest Cycles During Field Operations for Heat Acclimated Units," also supported these guidelines (Exhibit 1-4), and the Quartermaster group also developed a set of graphs entitled "Insufficient Water Intake and Impairment of Operational Effectiveness" (Figure 1-4). The guidance contained

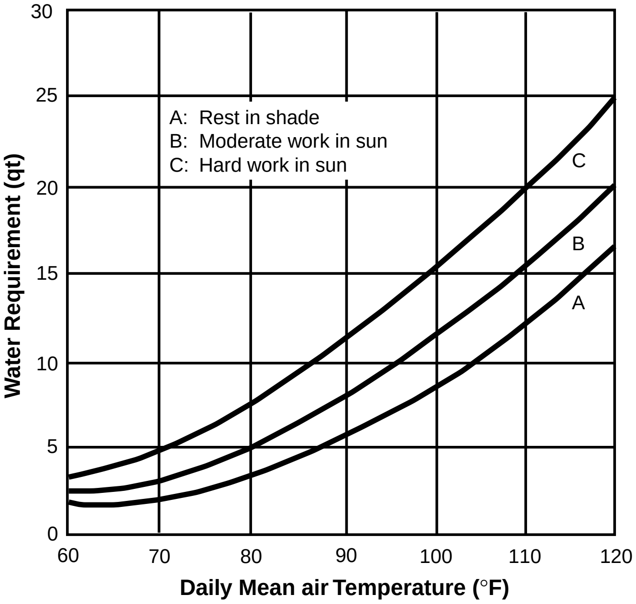


Fig. 1-3. Daily water requirements for three levels of activity. This graph shows theoretical water needs, in quarts per day, for men at rest and at work in sun and shade, in relation to the daily mean air temperature measured in degrees Fahrenheit. Curve A: rest in shade; Curve B: moderate work in sun; Curve C: hard work in sun. For example, if a man does 8 hours of hard work in the sun (Curve C) when the average temperature of the day is 100°F, then his water requirements for that day will be approximately 15 qt. Adapted with permission from Adolph EF, Brown AH. Economy of drinking water in the desert. In: Wulsin FR. *Response of Man to a Hot Environment.* Washington, DC: Climatic Research Unit, Research and Development Branch, Military Planning Division, Office of The Quartermaster General; 1 Aug 1943: Figure 10. First published in the present format in Environmental Protection Research Division. *Environment of South East Asia*. Natick, Mass: US Army Natick Laboratories; Aug 1953. EPRD Report 219.

EXHIBIT 1-4

WATER INTAKE, WORK/REST CYCLES DURING FIELD OPERATIONS FOR HEAT-ACCLIMATIZED UNITS*

Heat Condition	Botsball WGT (°F)†	Water Intake (qt/h)	Work/Rest Cycle (min)
Green	80°F–83°F	0.5–1.0	50/10
Yellow	83°F–86°F	1.0–1.5	45/15
Red	86°F–88°F	1.5–2.0	30/30
Black	≥ 88°F	2.0	20/40‡

*Provisional doctrine, April 1981; guidance for unacclimatized troops was given in Headquarters, Department of the US Army. *Prevention, Treatment and Control of Heat Injury.* Washington, DC: HQ, DA; July 1986. Technical Bulletin Medicine 507.

†WGT is a successor to WBGT (see below); to convert WGT to WBGT, add two Fahrenheit degrees. Below 80°F, drink up to 0.5 qt/h; 50/10 work/rest cycles.

‡Depending on the condition of the troops.

WBGT: wet bulb globe temperature; WGT: wet globe temperature

To maintain physical performance:

1. Drink 1 quart of water in the morning, at each meal, and before any hard work.
2. Take frequent drinks because they are more effective than drinking all at once. Larger men need more water.
3. Replace salt loss by eating three rations per day.
4. As WGT increases, rest periods must be more frequent, work rate lowered, and loads reduced.
5. Use water as a tactical weapon and maintain top efficiency by drinking each hour.

NOTE: The Botsball was developed in 1971 by James Botsford, an industrial hygienist working for ALCOA, to measure the heat stress in the area around metal-smelting furnaces. The Botsball is a small (3″), hollow cylinder covered with a thin, black, cotton fabric, which is kept wet by the water in a cylinder (6″ x 2″) stem at the top of the 3″ cylinder. A standard metallic stem dial thermometer is inserted into the 6″ stem so that its sensing tip is sited at the center of the now-wetted black globe. Thus, this wet globe thermometer (WGT) provides a single numerical reading for the combined effects of thermal radiation, ambient temperature and humidity, and air motion. Goldman adapted Botsford's device to incorporate the green, yellow, red, and black sections for the numerical readings on the dial, and was able to get triservice agreement to adopt this device as a useful measure of heat stress in 1978. The WGT is obviously much easier to obtain, read, and interpret than the conventional wet bulb globe temperature (WBGT). Although vastly simpler than the conventional WBGT, and so portable that it can be carried and used on a march, its use has been questioned as a less-accurate index by some laboratory scientists. How a simple color indication of the actual heat stress conditions at the site where troops are working can be deemed "less accurate" than an index calculated by a weatherman reading three separate instruments and providing a numerical value for conditions at a weather station some distance away (usually at an airfield) is an interesting scientific sophistry. For further information, interested readers can see Onkaram B, Stroschein LA, Goldman RF. Three instruments for assessment of WBGT and a comparison with the WGT (Botsball). *Am Ind Hyg Assoc J.* 1980;41:634–641.

Adapted with permission from Goldman RF. Heat stress in industrial protective encapsulating garments. In: Levine SP, Martin WF, eds. *Protecting Personnel in Hazardous Waste Sites.* Stoneham, Mass: Butterworth Publishers; 1985: 246.

in Exhibit 1-4 was reevaluated in the late 1990s because of an increasing incidence of water intoxication in military basic trainees. Although that guidance recommended water consumption of more than 1.5 qt/h in heat categories 4 and 5 (red and black flag conditions), it was found that requirements for fluid replacement never exceeded 1.5 qt/h, at least when the prescribed work/rest cycles were followed.[50] Based on this work, the army's policy on water replacement requirements during training have been revised to incorporate the recommendations in the paper by Montain, Latzka, and Sawka.[50] The new water replacement guidelines are also discussed in Chapter 7, Clinical Diagnosis, Management, and Surveillance of Exertional Heat Illness; see Exhibit 7-7 in that chapter.

Data from physiological studies on human volunteers (1) reaffirm that ad libitum water intake is inadequate to maintain full hydration and (2) sug-

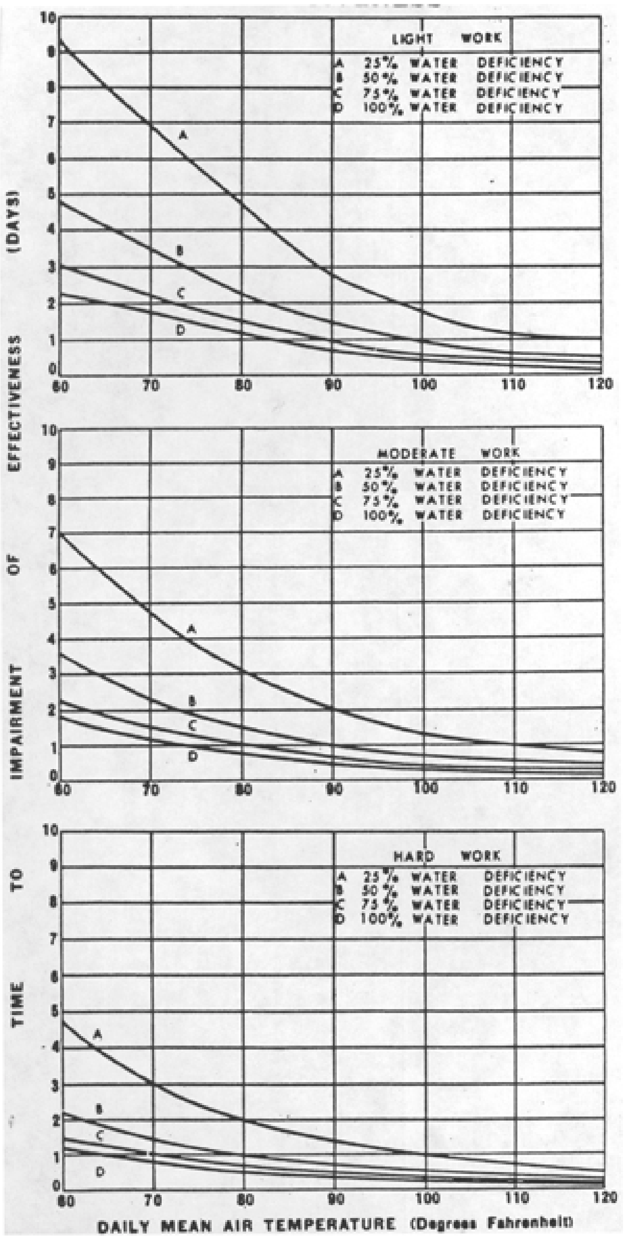


Fig. 1-4. Insufficient water intake and impaired operational effectiveness. Dehydration occurs when water intake is not adequate to replace the water lost from the body. When the amount of body water lost exceeds 5% of the body weight (about 3.5 qt), operational effectiveness is impaired. The three graphs, which represent, from top to bottom, light, moderate, and hard work, show the time required for impairment of effectiveness at various average daily temperatures. Reprinted from Environmental Protection Research Division. *Environment of South East Asia.* Natick, Mass: US Army Natick Laboratories; Aug 1953. EPRD Report 219.

gest that rectal temperature (T_{re}) is elevated by about 0.15 Centigrade degree for each 1% of dehydration above the threshold 2% (little effect is seen at the threshold level). The corresponding rise in heart rate is about 3.5 beats per minute per percentage of dehydration, whereas sweat rate falls by about 100 mL/h per percentage of dehydration.

Effects of Work and Temperature

A number of studies have been conducted throughout the world on conditions that produce significant discomfort at different work rates (ranging from the metabolic heat production of 90 kcal/h at rest up to 425 kcal/h), as well as on the inability of highly motivated, physically fit, young men to tolerate at least 4 hours of work without collapse. The results, plotted in Figure 1-5 as a function of the effective temperature index (ET, the air temperature at 100% humidity with minimal air motion, at which different combinations of T_a, rh, and air motion would *feel* the same as the ET), clearly show the linear relationship between heat production and ambient heat. The effect of "significant discomfort" can be seen to begin at an ET of about 78°F (25.5°C) while working at about 450 kcal/h; this level of work represents a "voluntary, self-paced, hard work" level sustainable for 3 to 4 hours.[37] An ET of 78°F is somewhat above the upper boundary of thermal comfort for sedentary workers ($M \approx 125$ kcal/h) reported in the American Society of Heating Refrigerating and Air-conditioning Engineers Comfort Standard 55; at this level of heat production, "significant discomfort" is shown to be about 92°F (33°C). At rest ($M = 100$ kcal/h), "4-hour tolerance" is shown at 97°F (36°C), whereas 88°F (31°C) appears as the 4-hour limit for work at 425 kcal/h.[51] These severe discomfort and 4-hour tolerance limits for fit young men (frequently soldiers) can be compared with "Permissible Heat Exposure Threshold Limit Values" that were proposed in 1970 for an average American worker by the American Conference of Government Industrial Hygienists (ACGIH)[52] (Table 1-6).

Laboratory research studies on more severe heat conditions were conducted between 1923 and 1967 in a number of countries on "heat tolerance" (ie, the time, during exposures of up to 3 h of heat, to reach T_{re} 39.2°C at rest, or 39.5°C during work, or a heart rate of 170 to 180 beats per minute). The data show remarkable agreement when plotted as a function of the Oxford Index, WD (or wet–dry), calculated as

$$0.85\ (T_{wb}) + 0.15\ T_{db}$$

where T_{wb} represents the wet bulb thermometer

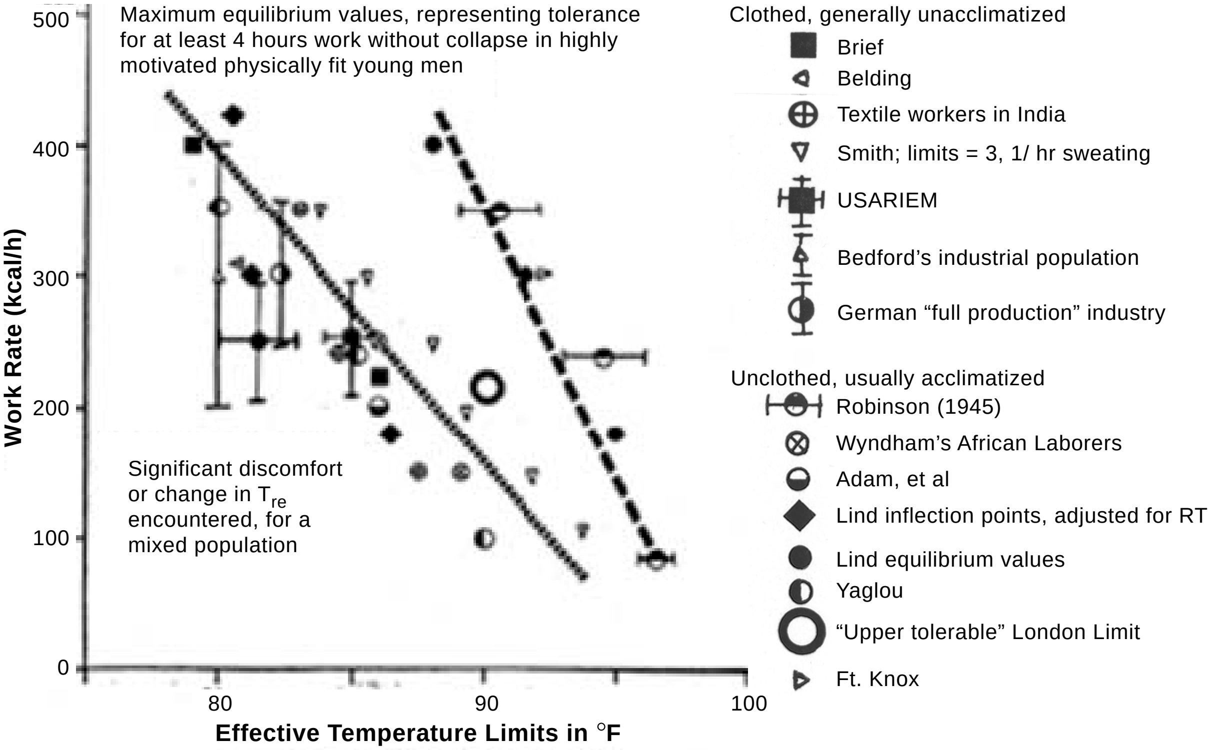


Fig. 1-5. The effective temperature limit at a given work rate, resulting in "significant discomfort" (dotted line) or "tolerance for at least 4 hours" (dashed line). "Mixed" refers to mixed military and civilian, or very fit and less fit, populations. Adapted with permission from Goldman RF. Heat stress in industrial protective encapsulating garments. In: Levine SP, Martin WF, eds. *Protecting Personnel in Hazardous Waste Sites.* Stoneham, Mass: Butterworth Publishers; 1985: 249.

Sources for data points:

Clothed, generally unacclimatized: (1) Brief RS, Confer RG. Comparison of heat stress indices. *Am Ind Hyg Assoc J.* 1971;32:11–16. (2) Belding HS, Hentig BA, Riedesel ML. Laboratory simulation of a hot industrial lab to find effective heat stress and resulting physiologic strain. *Am Ind Hyg Assoc J.* 1960;21:25. (3) Mankiber NS, ed. *Thermal Stress in the Textile Industry.* New Delhi, India: Government of India; 20 July 1957. Ministry of Labor and Employment Report 17. (4) Smith FE. *Indices of Heat Stress*. London, England: Her Majesty's Printing Office; 1955. Medical Research Council Report 29. (5) Iampietro PF, Goldman RF. Tolerance of men working in hot humid environments. *J Appl Physiol.* 1995;20:73–76. (6) Goldman RF, Iampietro PF, Green EB. Tolerance of hot, wet environments by resting men. *J Appl Physiol.* 1965;20:271–277. (7) Bedford T, Warner GC. Observations on the working capacity of coal miners in relation to atmospheric conditions. *J Ind Hyg*. 1931;13:252–260. (8) Ehrismann O, Hasse A. Uber die zulassige Arbeitszeit bei hoher Temperatur und Luftfeuchtigkeit [On the allowable work time at elevated temperature and humidity. In German.]. *Archives Gewerbepath & Gewerbehyg*. 1938;8:611–638. (9) Hasse A. Leistung und klimatische Bedingungen in Berban [Performance and climatic conditions in mining. In German.]. *Arbeitsphysiologie*. 1935;8:459–475.

Unclothed, usually acclimatized: (1) Robinson S, Turrell ES, Gerking SD. Physiologically equivalent conditions of air temperature and humidity. *Am J Physiol.* 1945;143:21. (2) Wyndham CH, Strydom NB, Morrison JF, et al. Criteria for physiological limits for work in heat. *J Appl Physiol.* 1965;20:37. (3) Adam JM, Jack JW, John RT, MacPherson RK, Newling PSB, You PS. *Physiological Responses to Hot Environments of Young European Men in the Tropics, IV: The Response to Hot Environments of Young Men Naturally Acclimatized to Tropical Conditions.* London, England: Medical Research Council; 1953. Royal Naval Personnel Report 53/767. (4) Adam JM, Jack JW, John RT, MacPherson RK, Newling PSB, You PS. *Physiological Responses to Hot Environments of Young European Men in the Tropics, II and III: Further Studies on the Effects of Exposure to Varying Levels of Environmental Stress.* London, England: Medical Research Council; 1955. Royal Naval Personnel Report 55/831. (5) Lind AR. Determination of environmental limits for everyday industrial work. *Ind Med Surg*. 1960;29:515. (6) Lind AR, Hellon RF. Assessment of physiologic severity of hot climates. *J Appl Physiol*. 1957;11:35. (7) Yaglou CP. Indices of comfort. In: Newburgh LH, ed. *Physiology of Heat Regulation and the Science of Clothing.* Philadelphia, Pa: Saunders; 1949.

Upper tolerable London limit: (1) McArdle B, Dunham W, Holling HE, et al. The prediction of the physiologic effects of warm and hot environments: The P4SR Index. *Medical Research Council (London), Royal Navy Personnel Report.* 1947;47:391.

Fort Knox: (1) Nelson N, Eichna LW, Horvath SM, Shelley WB, Hatch TF. Thermal exchanges of man at high temperatures. *Am J Physiol.* 1947;151:626. (2) Hatch TF. Assessment of heat stress. In: Hardy JD, ed. *Temperature, Its Measurement and Control in Science and Industry.* Vol 3. New York, NY: Reinhold. 1963: 307.

TABLE 1-6

HEAT EXPOSURE THRESHOLD LIMIT VALUES FOR THE AVERAGE AMERICAN WORKER

	Work Load (at WBGT [°C])		
Work/Rest Regimen	**Light**	**Moderate**	**Heavy**
Continuous work	30.0	26.7	25.0
75% work/25% rest*	30.6	28.0	25.9
50% work/50% rest	31.4	29.4	27.9
25% work/75% rest	32.2	31.1	30.0

*percentage of each hour (ie, 75% work = 45 min; 25% rest = 15 min)
WBGT: wet bulb globe temperature
Adapted with permission from Goldman RF. Heat stress in industrial protective encapsulating garments. In: Levine SP, Martin WF, eds. *Protecting Personnel in Hazardous Waste Sites.* Stoneham, Mass: Butterworth Publishers; 1985: 243.

temperature and, as before, T_{db} represents the ambient temperature. As shown in Figure 1-6, tolerance times at rest exceed 3 hours for WD < 98°F (~ 37°C), and fall steeply to < 40 minutes as WD increases to 108°F (~ 42°C). Although these WD levels are extreme for outside ambient conditions, they are not uncommon inside buttoned-up (ie, fully closed) armored fighting vehicles, where interior temperatures average 13 Fahrenheit degrees (7 Centigrade degrees) above outside air temperatures, and can reach as high as 30 Fahrenheit degrees (17 Centigrade degrees) above, while the tankers' sweat also elevates interior humidity. A WD of 37°C may also occur as the microclimate within heavy, less-permeable protective clothing ensembles during hard work under warm dry bulb temperature conditions.

At moderately hard work levels (280–350 kcal/h, for a civilian work force), tolerance time is limited to about 3 hours at a WD of 91°F (33°C), a condition regularly found in clothing microclimates, crew compartments, and shelters without air conditioning. Physically trained, young, military troops may not have as much problem at this WD and work level, but tolerance times will drop to 40 minutes at a WD of 98°F (36.7°C) and thereafter approach 10 minutes as WD approaches 120°F (49°C), even in the fittest individuals. The human body appears to tolerate up to 20 minutes of exposure, at rest or at work; the lag in rectal temperature response associated with the mass of an adult body[40] accounts for this 20-minute minimum tolerance time to the most severe heat conditions, as long as skin temperature remains below the pain threshold for skin (at T_{sk} of ~ 45°C). Note the very high correlation coefficient (r = 0.96) shown for the combined rest and work data points when plotted as a log-log function of tolerance time (scaled differently for work and rest) and WD. This implies that > 90% of the tolerance time response is a direct effect of WD, which is consistent with the observation that interindividual and intraindividual human variability dramatically diminishes with increasing heat stress. An important meaning of this finding is that when a military unit suffers more than one or two heat casualties during an operation, the remaining troops have a high probability of becoming heat casualties *if* they are doing comparable tasks, at comparable rates, and the first few casualties were not unusually impaired by preexisting problems (eg, dehydration, infection, lack of acclimatization, etc).

Finally, Figure 1-7 shows the predicted times, at elevated WBGT levels, at which a 50% risk of heat casualties will occur[38] under the most severe heat exposures apt to be experienced by military personnel while wearing chemical protective ensembles, either in

- closed suit (MOPP 4): wearing gas masks with protective hoods, gloves, and overboots, with all openings sealed to provide as complete encapsulation as possible against chemical–biological agents, or
- open suit (MOPP 1): without the hood, gloves, and overboots, and with neck and wrists as open as possible.

At the sustainable level of voluntary hard work for 3 to 4 hours in fit, young soldiers (M = 450 kcal/h), any difference in a 60-minute time to 50% risk of heat casualties for both open and closed suits is negligible at WBGT levels above about 86°F (30°C). At lower WBGT levels, the predicted differences between ensemble configurations during light work become more meaningful, with 60 minutes at a WBGT of 70°F (26°C) in a closed suit versus about 90 minutes in an open suit. In the studies on which these predictions were based,[38] regardless of open or closed suit configuration, 25% of the troops were stopped for safety reasons when their rectal temperatures reached 39.5°C, before they suffered heat exhaustion collapse (ie, loss of consciousness), and 25% of the troops had already collapsed (hence, the specification of 50% risk). For moderate work (M = 325 kcal/h), the predicted time to incur 25% frank heat casualties, with another 25% having been stopped for safety reasons, at a WBGT of 80°F (26.5°C), is about 2 hours in the closed suit but about 4 hours in the

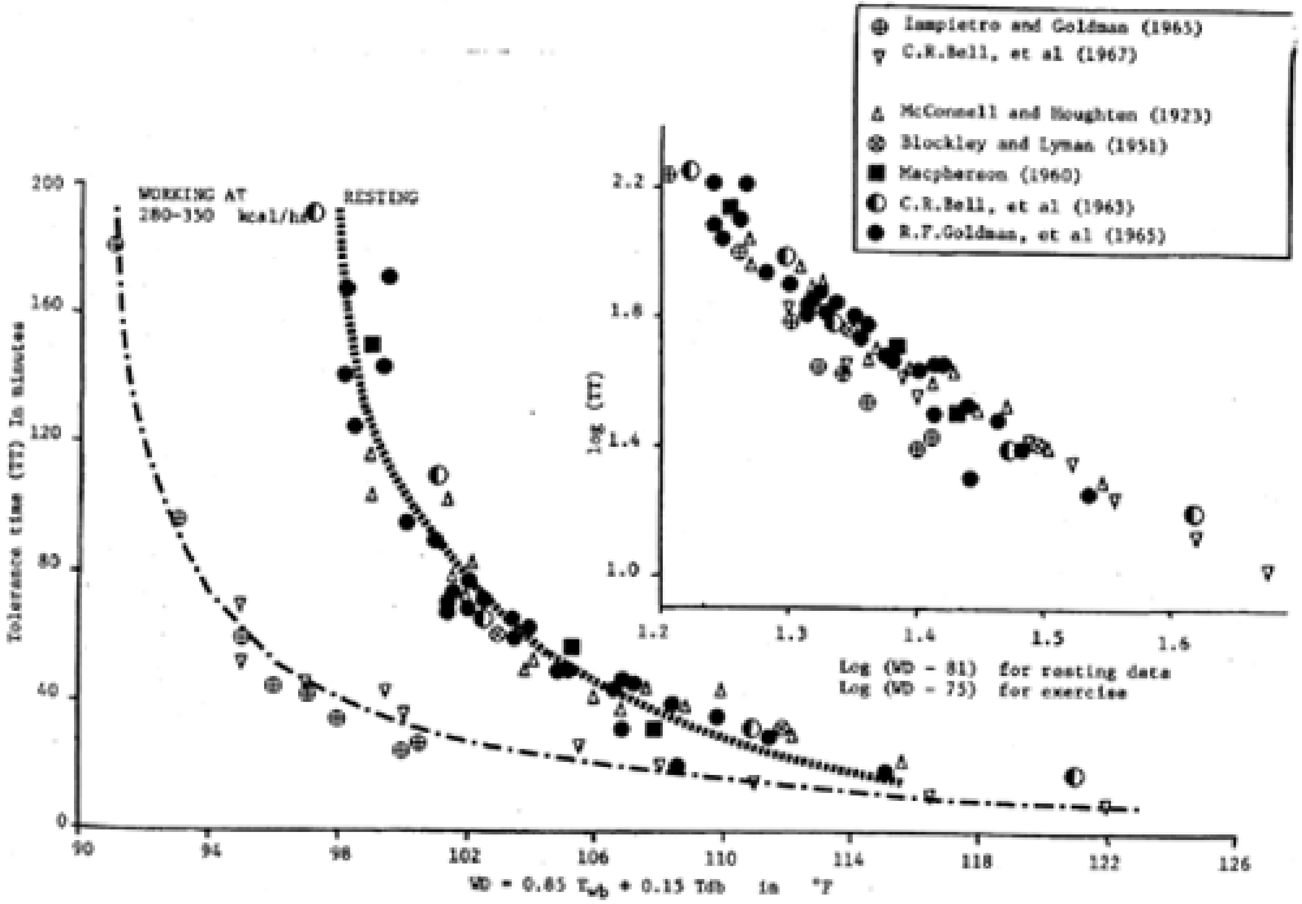
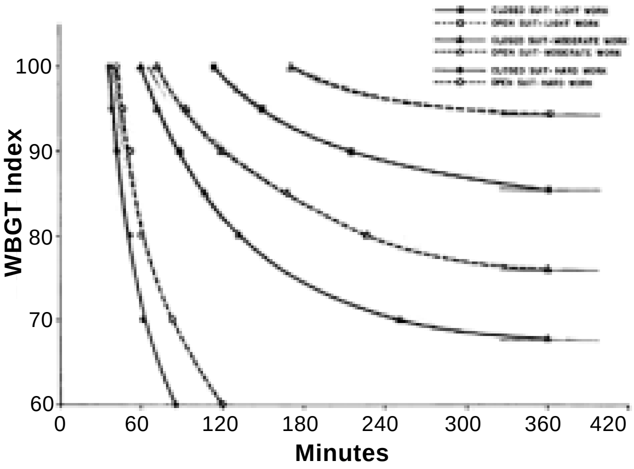


Fig. 1-6. Tolerance time (defined as minutes to reach a deep body temperature [T_{re}] of 39.5°C [103°F] or a heart rate of 180 beats per minute, or both) at rest (| | | | | line) or at work (metabolic rate = 280–350 kcal/h, — • — • — • line), expressed as a function of the wet–dry (WD, or Oxford index = 0.85 T_{wb} + 0.15 T_{db}) Index. The outstanding agreement between the data from these seven studies, conducted between 1923 and 1965 in several countries, suggests the uniformity of response under conditions of high heat stress (WD > 90°F) at rest, and at moderate work (280–350 kcal/h) levels. This suggestion is supported on examination of the inserted log-log plot, which shows that work data can be combined into a single line by simple adjustment of the log of the WD index (ie, WD –81 at rest, and WD –75 at moderate work). The correlation coefficient (r) for these combined data points to the log-log line is 0.96, which indicates that 92% (r^2) of the tolerance time is accounted for by the WD index, with only 8% associated with other factors such as individual variability. Adapted with permission from Goldman RF. Heat stress in industrial protective encapsulating garments. In: Levine SP, Martin WF, eds. *Protecting Personnel in Hazardous Waste Sites.* Stoneham, Mass: Butterworth Publishers; 1985: 250.

Sources for data points: (1) Iampietro PF, Goldman RF. Tolerance of men working in hot humid environments. *J Appl Physiol.* 1965;20:73–76. (2) Bell CR, Walters JD, Watts AN. *Safe Exposure Times for Men Working in Hot and Humid Conditions.* London, England: Royal Navy Personnel Research Committee, Medical Research Council; 1967. RNPRC Report RNP 67/1092. (3) McConnell WJ, Houghton FC. Some physiological reactions to high temperatures and humidities. *American Society of Heating and Ventilating Engineers Transactions.* 1923;29:125–129. (4) Blockley WV, Lyman J. *Studies of Human Tolerance for Extreme Heat.* Dayton, Ohio: Wright Patterson Air Force Base; 1950. USAF Materiel Command Technical Report 5831. Blockley WV, Lyman J. *Studies of Human Tolerance for Extreme Heat, IV: Psychomotor Performance of Pilots as Indicated by a Task Simulating Aircraft Instrument Flight.* Dayton, Ohio: Wright Field Air Development Command, Aeromedical Laboratory; 1951. (5) MacPherson RK, Ellis FP. *Physiological Responses to Hot Environment.* London, England: Medical Research Council, Her Majesty's Stationery Office; 1960. (6) Bell CR, Hellon RF, Hiorns RW, Nicols PB, Provins KA. *Exposure to Very Hot Conditions.* London, England: Royal Navy Personnel Research Committee, Medical Research Council; 1963. RNPRC Report RNP 63/1035. (7) Goldman RF, Green EB, Iampietro PF. Tolerance of hot, wet environments by resting men. *J Appl Physiol.* 1965;20:271–277.



Closed suit (MOPP 4): CBR protective ensemble worn with gas mask with protective hood, gloves, and overboots, with all openings sealed to provide as complete encapsulation as possible against chemical–biological agents and nuclear radiation.

Open suit (MOPP 1): CBR protective ensemble worn without the hood, gloves, and overboots, and with neck and wrists as open as possible.

MOPP: mission-oriented protective posture gear

WBGT: wet bulb globe temperature (= 0.7 T_{wb} + 2 T_{globe} + 0.1 T_{db})

Fig. 1-7. Predicted time to 50% heat casualties when chemical, biological, radiological (CBR) protective suits are worn. When wearing CBR protective clothing, whether the protective ensemble is worn fully closed (MOPP 4) or open (MOPP 1, with the mask but with the neck and wrist areas not buttoned closed and even with sleeves rolled up above the wrists), the mismatch between the heat produced during hard work and the heat that can be lost by the body to the environment is very severe at WBGT > ~ 75°F. There is only a marginal reduction of heat stress by exposing so much area to possible CBR agents: about 12 minutes during hard work at 75°F in the predicted time to 50% heat casualties (ie, heat exhaustion collapse of 25% of the troops, with another 25% at high risk of it). Even at WBGT of 60°F, predicted time to 50% risk of unit heat casualties is only about 90 minutes in MOPP 4, and 120 minutes in MOPP 1 at sustained hard work (eg, > 450 kcal/h). At moderate work levels (~ 300 kcal/h), the difference in MOPP levels is predicted to result in an offset of about 10 Fahrenheit degrees in WBGT, with 50% risk of heat casualties occurring in 4 hours (240 min) at about 78°F WBGT in open suit, and about 68°F WBGT in MOPP 4. At light work, there should be little risk of heat casualties at WBGT < 85°F in MOPP 4, or < 95°F in MOPP 1. Finally, after 6 hours of exposure, *if* troops are kept fully hydrated, the risk of heat casualties appears to have reached a plateau at light and moderate work levels. The shaded areas on the graph represent an estimate (and only an estimate) of variability around the curve. The straight lines on both sides of the last four data points suggest the asymptotic nature of the curves at those points. Reprinted with permission from Joy RJT, Goldman RF. A method of relating physiology and military performance: A study of some effects of vapor barrier clothing in a hot climate. *Mil Med.* 1968;133:469.

open suit. At very light work (M = 125 kcal/h), predicted tolerance time is about 2 hours at a WBGT of 100°F (38°C) with closed suits, and about 3 hours with open suits; such an extreme WBGT might occur in a buttoned-up armored fighting vehicle sitting in the sun with its engine running. Combat-ready tank crews in MOPP 4, serving as subjects in the field research that led to introduction of air conditioning for the latest US tank,[53] had to be helped out of the tank after 80 minutes of rest interrupted by several short firing missions, during which they had to hand-crank the gun turret into position. Each crew member had lost more than 3 L of sweat during the 80 minutes, as WBGT rose above 90°F inside the tank.

The predicted tolerance times shown in Figure 1-7 for wearing chemical–biological protective clothing in the heat can be compared with those shown in Table 1-7, which is compiled from various research done in the United States, the United Kingdom, and USSR.[54–59]

Although three different temperature indices were used in Figures 1-5 through 1-7 (ET, WD, and WBGT, respectively), they are all comparable at higher levels. Thus, the data from all three figures

TABLE 1-7

SAFE EXPOSURE PERIODS FOR MODERATE WORK* WHILE WEARING CHEMICAL PROTECTIVE UNIFORM SYSTEMS

Air Temperature (°F)	Safe Wear Time (h) (closed suit)†
< 30	8
30–50	5
50–60	3
60–70	2
70–80	1.5
80–85	1.0
85–90	0.5
> 90	0.25

*250 kcal/h

†MOPP 4 (mission-oriented protective posture gear): wearing gas masks with protective hoods, gloves, and overboots, with all openings sealed to provide as complete encapsulation as possible against chemical and biological agents

Adapted with permission from Goldman RF. Heat stress in industrial protective encapsulating garments. In: Levine SP, Martin WF, eds. *Protecting Personnel in Hazardous Waste Sites.* Stoneham, Mass: Butterworth Publishers; 1985: 246.

represent a spectrum of temperature conditions from ET levels of 80°F to 95°F, WD levels from 91°F to 122°F, and WBGT levels while wearing chemical–biological protection, of 60°F to 100°F (ie, a range of index temperatures from about 20°C to 50°C). The various discomfort and tolerance times presented cover exposures lasting from 20 minutes to more than 4 hours. Major difficulties in maintaining control of activity, food and water intake, and the like, during longer periods seriously limit the reliability of data from more extended studies (eg, Project CANE [Combined Arms in a Nuclear Environment][60]). Thus the factors leading to heat illness cannot be as clearly delineated in historical events, such as the military medical reports and afteraction reports that follow, as they have been in controlled clinical investigations.

Whayne's Analyses of Military Medical Reports

The military medical reports of heat casualties incurred during various wars provide, at best, a very limited look at the true effects of heat on military operations. There are few or no reliable data prior to the 1800s, and the data reported even in the latest large-scale military operation in the heat, the Persian Gulf War (1990/91), appear to be subject to the same problem as earlier data: failures in differential diagnosis of heat illness among heat exhaustion collapse, heatstroke, and "ill-defined effects of heat" confound the data. An even more serious problem is that the number of cases of heat illness treated at a medical treatment facility, and thus recorded, probably under-represents by at least 3-fold the number of soldiers who were treated at forward aid stations or in the field.[61]

On 9 June 1951, Colonel Tom F. Whayne delivered a lecture entitled "History of Heat Trauma as a War Experience" as part of the Medical Service Officer Basic Course at the Army Medical Service Graduate School, Army Medical Center (now Walter Reed Army Medical Center), Washington, DC. In his lecture, Colonel Whayne analyzes the available medical information on the effects of heat on military operations of US fighting forces from the Revolutionary War to the end of World War II. The text of the lecture has been available only as a mimeographed handout distributed to a relatively few students, or bound, with other lectures delivered during the course, in a volume housed in the main library at Walter Reed Army Institute of Medicine, Washington, DC.[62] The editors of this textbook believe that the Whayne lecture deserves a wider readership; it is reprinted in its entirety as Appendix 1 to Volume 3 of *Medical Aspects of Harsh Environments*.

Readers should keep in mind, however, that medical reports are unable to portray even the major losses of military effectiveness that occurred among troops who did not receive, or may not have needed, treatment for heat problems. Whayne presents numerous tables and graphs to bolster his analyses and repeatedly makes two points: (1) the races respond differently to heat, and (2) the effects of heat on soldiers are not severe enough to compromise the particular military operations selected. A few relevant excerpts from the Whayne lecture follow.

American Civil War

> [Whayne's] Figure 3 presents the admission rates for sunstroke per thousand mean strength per year for white and colored troops of the United States Army (Union forces). For the year 1861, only the months of May and June were recorded but these were calculated as an annual rate. Even when reduced to the proper proportions, the admission rate for that year was higher than for the two succeeding years … probably a reflection of a lack of acclimatization or physical conditioning and, unquestionably, to the added stress of combat during hot weather. The rates for 1862 and 1863 are appreciably lower and are probably to be expected for a seasoned army operating for the most part in Maryland, Virginia and Pennsylvania. The higher rate for 1864 is probably associated with penetration of Northern forces further to the South. …
>
> Data was recorded on admissions for the colored troops only from 1864. … [T]he colored troop rate was lower than for the white troops … a phenomenon that appears … in all of the wars in which American forces took part, with the possible exception of World War II.
>
> As one considers the magnitude of these admission rates, however, it is obvious that "sunstroke" was not a medical or tactical problem of great significance. … The maximum rate recorded (1864) is only approximately four per thousand per year and could have had little influence in the overall prosecution of the war if, indeed, these data represent the true picture. The annual admission rate for the total period was 3.1, which included both white and colored troops.[63(p7)]

Spanish–American War

> [H]eat trauma came under the diagnosis of "heatstroke."…
>
> . . . .

> The total number of cases, white and colored, for the entire Army was only 748. The total number of deaths was nine. The admission rate for 1898 was 3.68, and for 1899, 1.93 or a total for the two years of 2.95. No deaths occurred in 1899, but for 1898 the case fatality rate was 1.65. …
>
> For the white troops, the rates per thousand per year were 3.79 for 1898 and 2.04 for 1899, while for the colored troops these rates were 1.62 and 0.43 respectively. When the case fatality rate is calculated for the year 1898, however, the white rate was 1.5 as compared to the colored rate of 8.3. … As for the Civil War, it is again demonstrated that within the limitations of the diagnosis for heat stroke, heat trauma was not of great medical or tactical importance.
>
> In neither the Civil War nor the Spanish–American War have we any estimate as to mild casualties from the effects of heat, or of the role of high temperature in lowering efficiency and physical and mental effectiveness in such a way as to interfere with optimum military performance.[63(pp7–11)]

World War I

> Effects of "excessive heat" presumably covered the total range of heat injury. … The data … is more complete and its analysis provides some estimate of the cause of the malady. [There were 3,623 cases of "excessive heat" among white enlisted men, a rate of 1.00/1,000/y, with 3 deaths, giving a case fatality rate of 0.08; for black troops, there were 210 cases, for a rate of 0.73/1,000/y, with a case fatality rate of 0.475.—R.F.G.]
>
> . . . .
>
> [T]he relationship between the admission rates and case fatality rates already commented upon holds true in World War I. Whereas white admission rates were about one, colored admission rates were 0.73. Conversely, the white case fatality rate was 0.08, whereas the colored case fatality rate was 0.475. Here again, we note a ratio of approximately one white death to six colored deaths on a percentage basis. [Of the total 3,880 cases of excessive heat, 3,200 of them occurred in the United States (the Zone of the Interior), which pointedly illustrates heat injury as a Zone of the Interior malady.—R.F.G.]
>
> . . . .
>
> Total days lost from disease or injury is a measure of its military cost. During World War I in the total Army ... including officers and enlisted men—there were 31,532 days lost. For white enlisted men, days lost were 28,093; for colored, 2,166. … Among the enlisted men in the U.S., 22,107 days were lost by white enlisted men and 1,863 by colored …, again demonstrating the prevalence of heat injury in the Zone of the Interior. The over-all non-effective rate from heat injury for the total war period was 0.02. Days lost per case … for white enlisted men [was] 7.75; and for colored enlisted men, 10.3. … [T]he time lost per case for colored soldiers is consistently longer than for white soldiers and may corroborate the impression gained from case fatality rates that the severity of the injury in colored men affected may be greater. …
>
> [A]dmission rates [including World War II] as between troops in the United States and overseas … [show] that, except for the Civil War, the over-all admission rates for the total war period in the United States are reasonably close. [They were 2.96 for the Civil War, 1.63 for the Spanish–American War, 1.61 for World War I, and 1.85 for World War II.—R.F.G.]
>
> Based on available data, heat injury in the United States Army was not an important cause for loss of time and had no great medical or tactical significance up to the time of World War II. … [E]xcept for the Spanish–American War, admission rates were relatively high in the Zone of the Interior and low … overseas.[63(pp11–13)]

World War II

Three categories—heat exhaustion, heatstroke, and ill-defined effects of heat—were used for all heat injuries during World War II.

> The year 1940—a … peacetime year prior to World War II—shows annual heat injury admission rates per thousand for the Army in the United States of 0.5, … in Panama, 1.4, and … in the Philippines, 1.3. Line officers believed in "water discipline" and … that the drinking of water during work in the heat was harmful. …
>
> . . . .
>
> [I]n some of the training in the tropics prior to the war, men were required to wear wool shirts because it was thought that they were cooler than cotton. …
>
> There was a desperate urgency to train men for operations … in many of the hottest regions on earth, … about which opinion and tradition had fostered the impression that the white man could not endure. …
>
> . . . .
>
> [H]ow the American soldier … performed … is, he did well after he had learned several fundamental rules and after those who were responsible for his

training … [understood] the proper corrective measures: … acclimatization, proper use of water, proper intake of salt, control of activity, physical fitness, adequate sleep and rest, adequate nutrition, proper clothing, previous and associated illnesses, and appropriate education.

[D]efects of these data … are apparent from the records.

1. We have data only on cases severe enough to be admitted to a medical installation. These are inadequate indices … because they fail … to record unknown numbers of men who were not sufficiently incapacitated to report to sick call, but were not well enough to perform their duties efficiently. Some of these men were confined to quarters, others stuck it out, while others, because of injury or intercurrent disease, were carded for these causes, and mild heat injury was not recorded. …
2. Criteria for diagnosing heat injury were not generally … understood. …
3. Heat casualty has a seasonal incidence; … calculation of annual admission rates, which includes the cool months, may not reflect the magnitude of the problem.
4. Study of heat injuries on the basis of theaters, rather than on the cost … in small units, gives a false picture of the potentialities of heat trauma as a tactical military problem.

Figure 10 shows admissions and admission rates for effects of heat other than burns and sunburn in the United States Army. …

Heat casualties in WW II were more frequent in the United States than in any other theater, and casualties were most frequent among men who were overweight or obese, in the older age groups, and for those whose service in the Army had been of short duration. … While the highest rate was reached in 1942, proportionately there was a greater number of cases for the year 1943 when training activities were the heaviest. … [63(pp13–15)]

. . . .

Heat casualties in this country begin to be a problem in May and slacken off … by October. [In my experience, whether dealing with hazardous-waste site workers, football players, firefighters, the military, or civilian populations, the first few weeks of exposure to hot conditions generate the majority of heat problems, especially the initial few days following the first day of a heat wave.—R.F.G.][63(p17)]

. . . .

It was in the desert area and more specifically, in the Persian Gulf Command … that most of the overseas heat casualties occurred. The annual admission rate for 1943 reached 20.78 per thousand. The total case load was 1,102 and in July and August of that year the incidence rates reached 57.26 per thousand per year and 88.58 per thousand per year, respectively. This was indeed a medical problem of some significance and a potentially hazardous military tactical problem. In 1944, a striking decrease occurred. The annual rate per 1000 mean strength was 4.03; the highest monthly rate was 26.73 for July. The total case load for the year was only 183 cases.

This remarkable decrease … was achieved even though the summer of 1944 was as hot as the summer of 1943, and even though the Command broke all records for moving supplies. The experience of the Persian Gulf Command was especially important, since it was the hottest theater in which American troops functioned for long periods, and it was a dry heat rather than a humid heat.

It was the final consensus of the Command that once proper living conditions were instituted, proper working hours adhered to, and troops

FIGURE 10 [FROM WHAYNE LECTURE]

ADMISSIONS FOR EFFECTS OF HEAT (OTHER THAN BURNS AND SUNBURN) IN THE US ARMY BY NATURE OF TRAUMATISM AND BY AREA, 4-YEAR PERIOD, 1942–1945

Nature of Traumatism	Total Army	United States	Overseas
	(Number)		
Heat Exhaustion	18,128	12,151	5,977
Heatstroke	1,676	1,315	361
Other Effects of Heat	15,558	13,814	1,744
Total Effects of Heat	35,362	27,280	8,082
Annual rate per 1,000 mean strength:			
Heat Exhaustion	.71	.82	.56
Heatstroke	.07	.09	.03
Other Effects of Heat	.61	.94	.16
Total Effects of Heat	1.39	1.85	.75

Reprinted from Whayne TF. History of heat trauma as a war experience. Lecture delivered 9 June 1951. In: US Army Medical Service Graduate School. *Notes: Medical Service Company Officer Course 8-0-1 (b)*. Vol 2. Washington, DC: US Army Medical Service Graduate School; 1951: 15. Walter Reed Army Institute of Medicine, Washington, DC: Library call number RC971/.U5/v.2.

> handled in a way most likely to protect them from heat injury, then effective and efficient work could be maintained without significant injury from heat in spite of the very hot summers. This experience was duplicated in [China, Burma, and India,] a hot, humid region.[63(p25)]

Military medical reports from other nations, as well as from subsequent US wars, add little to the information above, which Colonel Whayne so superbly detailed in his lecture.

Afteraction Reports

Another source of information is the ex post facto reviews of various military activities. Some were written by participants, others by concerned reviewers trying to explain or understand what happened, and why. In modern terminology, these are called "afteraction reports." They are usually far less detailed than the type of analysis presented by Colonel Whayne, but highlight the impressions of participants or narrators who wrote shortly after the event.

American Revolutionary War

One of the earliest American military experiences indicated an effect of heat on military operations. British infantrymen, wearing their tall, heavy, black headgear and carrying full packs on a hot summer day, attempted to take a field fortification, erected on top of a hill, by the direct assault common to that era: advancing in line to a drumbeat, pausing only to level and fire their heavy muskets. The advance was broken three times by the American militiamen holding the position, despite frantic efforts of the British officers to steady the troops, who were carrying 80 pounds, uphill, on a hot June day. After General Gage ordered the British to doff their helmets and packs, they drove the Americans off. The extent to which relief from heat stress, versus the Americans' running out of ammunition, contributed to the British taking Bunker Hill in Boston, Massachusetts, cannot be determined, but this unusual order from a British general officer in that era certainly reflects his estimate of the effects of heat trauma on his troops. The attackers lost 1,054 officers and men out of a total of 2,500; the defenders lost 441 in killed, wounded, and prisoners.

War of 1812: Napoleon in Russia

The War of 1812–1813 took a terrible toll on Napoleon's forces in the Russian campaign. Almost all military historians are aware of the effects of the severe cold, as reported by his chief surgeon, Larrey (only about 10,000 of the 100,000 troops who left Moscow reached the Niemen River en route back to France).[64] Far fewer are aware of Larrey's reports on the effects of the unseasonably warm weather during the advance to Moscow with about 250,000 men. Napoleon began his advance into Russia when he crossed the Niemen River, the boundary between the French and Russian empires, on 24 June 1812. By the end of the first month of the campaign, after winning several minor battles and detaching more than 100,000 troops to guard his return line, Napoleon's army had lost well over half its men from heat, drought, lack of food, desertion, and disease—although the significant fighting (at the great battles of Smolensk and Borodino) was still to come. On 28 July Napoleon halted the remaining 175,000 troops near Vitebsk, a 20-day march from Moscow, and waited for Czar Alexander to sue for peace. The weather turned "stifling hot" and the exhausted, half-starved troops lacked water, fighting each other to drink from muddy puddles during the 20-day wait. Then, as Napoleon moved on to Smolensk with only 145,000 troops left, vodka contributed to the problems of young soldiers, weakened by hunger, heat, and fatigue, with only limited amounts of muddy water to drink. Arriving in Viazma on 28 August, the men continued to fight over water in mud puddles. Napoleon reached Borodino on 15 September with only 130,000 men.[64,65]

As is always the case with battles fought earlier than the 20th century, it is difficult or impossible to sort troop losses according to battle, disease, heat or cold, desertion or detachment; nevertheless, it is clear that heat, and especially the lack of drinking water, was a problem. Complicating the problem was, doubtless, the reduction in French recruiting standards, as continuing wars reduced the available supply of sturdy farmers and increased recruitment from the cities. The minimum standard height for the French military was 5 feet 5 inches in 1776, and 5 feet 4 inches in 1792, but was reduced to just under 5 feet in 1813.[66] This reduction in fitness may have been part of the basis for Napoleon's dictum that the essentials of the fighting man comprise his arms and ammunition, trenching tool, knapsack, and 4 days' rations[67]; note that the water bottle (canteen) was not included, although the British had called for one beginning in about 1655 for campaigns in the West Indies.[68]

American Civil War (1861–1864)

> [1861.] On the morning of July 21st, ... we halted in the shade, as the day, even thus early, promised to

> be one of the hottest of the season. While observing the troops passing … I perceived that our troops marched at double quick, and some at full run, while many, overcome by the heat, threw away their blankets and haversacks. I expressed my opinion to the General, that owing to their rapid movement, the men would be exhausted before they arrived on the scene of action. … [H]e directed the men not to run; but, as the Officers behind … constantly repeated the command to close up, the troops were kept at the run a great part of the way. The weather was excessively hot, and, as one of the causes of the Bull Run failure, I desire to express my belief that the exhaustion of our forces, by the long and forced march, contributed as much as anything else to the disasters of the day. … [O]n several occasions where our men faltered … or did not pursue an advantage … it was manifestly owing to complete exhaustion rather than any want of spirit or courage … [T]heir failure … was from inability for further exertion.[69(p3)]

> [1864.] During a march many cases of sunstroke come under the hands of the regimental surgeons. I have seen about forty cases of different grades of severity, from slight dizziness, with inability to walk straight, to violent … convulsions and almost immediate death. … Cases of heat apoplexy have also occurred during marches on hot sultry summer nights.[70(p199)]

> [1864. On 26 June,] a very large number … of men in the command judged by the Medical Officers incapable of performing a forced march … were sent to hospital. … At four o'clock PM … [t]he Corps was pushed on so rapidly that the twenty ambulances following each division were very speedily filled with exhausted men, and straggling took place by the roadside to a far greater extent than is usual even in day marches, when hot sun combines with fatigue to overcome the men.[71(p187)]

> [1864. On 25 July, t]he day was oppressively hot, so much so, that although the men had only marched a couple of miles, a very large number were utterly exhausted … . Many were insensible; some in convulsions; four I saw dead. … [A]bout an hour and a half elapsed before all the cases of sunstroke could be carried to the rear.[72(p188)]

Official and Anecdotal Reports

Crimean War

During the Crimean War, attention focused on the heart and lung lesions that resulted from the combination of heavy loads being carried and the shift from sturdy yeomen to less physically fit urban recruits. The load carried by French troops was reduced by 12 pounds after the war because of the "high incidence of emphysema of the lungs."[73(p8)] A British Royal Commission also addressed these issues, pointing out that it was not just the net exertion, but the fact that the exertions are maintained, not with open necks and rolled sleeves, nor in specially adapted costume like the sportsman, but at the utmost possible disadvantage as regards the weight carried and the entire arrangement of dress and equipment.[74(p7)]

World War I

The huge load carried during World War I was also linked to cardiac overstrain in soldiers, and in particular in Macedonia where men weakened by malaria and from marching in irregular, mountainous terrain developed heart lesions to such an extent that the cumulative effects of marching while weakened by malaria were studied in the field. During 4 weeks of marching, some 9% of the troops engaged became heat casualties, but of the individuals afflicted with malaria, no less than 22% were afflicted with heat effects; thus, although they formed less than 11% of the total personnel involved, the men with malaria contributed 25% of the total casualties.[75(p9)] Lothian, writing in 1921, reports that

> apart from actual acute heat effects, such as heatstroke and derangement of the heat regulating system, such hurtful conditions may cause a lot of inefficiency not perhaps so noticeable at the time, but tending to cumulative injury as well as immediate exhaustion.[75(p9)]

Arab–Israeli War (1956)

Perhaps the most numerous loss of troops during a 24-hour period from the effects of heat on military operations was experienced by the Egyptians on 2 November, the sixth day of the Arab–Israeli War of 1956. A new Egyptian commander reached the 2,500- to 3,000-man garrison holding the two main ridges east of Abu Agueila in the Sinai just before it was surrounded by Israeli forces. Cut off from food and water, the commander announced that it was every man for himself. Starting that night, the Egyptians fled into the desert in a vain attempt to escape to El Arish, 52 miles across the desert dunes. The number of deaths from heat and dehydration, rather than from the knives of Bedouins seeking loot, is undocumented, but only about 700 Egyptians were eventually captured by the Israelis.[76(p139)]

The British in Kuwait: Operation Vantage

A nonclassified summary of a report detailed the health and efficiency of troops on "Operation Vantage," a 1961 British expedition into Kuwait. Despite humidities of 6% to 11%, the WBGT index between the hours of 1130 and 1430 approximated 31°C, with an ambient temperature of 45°C and globe temperatures from 50°C to 55°C; inside armored vehicles the conditions were considerably worse (WBGT to 38°C, T_a to 50°C with peaks to 70°C, and wet bulb temperatures in the 30°C range). There were 132 heat casualties treated at a base hospital, indicative of a total of approximately 400 to 500 heat casualties during the first 47 days; the maximum number of heat casualties reached the base hospital during the first 5 days of the expedition. Water requirements averaged 4 to 6 gallons per day, or about 125 tons of water per day for 5,000 troops.[61]

Vietnam War

A letter from Vietnam in May 1970 shows the continuing effects of heat on military operations:

> Along the Cambodian border troop units are being relocated and shuffled to new areas; often without any or enough canteens. This battalion had been moved a couple of days earlier from their old base in the delta where they had been fighting in relatively easy rice paddies (dry season) and were now required to hack their way through thick jungle with machetes, which made a big difference in terms of the energy required. Short (ie, 1–3 day) patrols need continuous air re-supply, especially water, but air assets are in critical supply and working continuously. Yet in the space of a couple of hours I saw 5 men of one squad dusted off back to the relocated base camp and several others from that one company dusted off for heat casualties—all within the space of a couple hours on May 6th. The temperature was hotter than anything I'd ever experienced outside of a foundry or hay mow; in the adjacent FSB [fire support base] someone reported 126°F. As I departed, I heard there were more heat casualties on the way in and I was worried about their supply of intravenous fluids.
>
> These heat casualties were promptly cared for by the competent medics and doctor by fanning, I.V.s, oral fluids and rest. About [one third] had *severe* cramps and [two thirds] had severe weakness, palpitations, fever and near collapse; the latter's skin was hot and dry and red but no temps were taken.
>
> So I can personally confirm that heat stress influenced this mission (company sized patrol, grunts only) and may have prevented its accomplishment. I will attempt to get some information that is better than this anecdotal material.[77]

EFFECTS OF DEHYDRATION ON MILITARY OPERATIONS

US Army, Texas, 1877

One of the best descriptions of severe dehydration in troops appears in the report of Company A, Tenth Cavalry, which lost its way and spent 3.5 days without water during July 1877, in an arid area of Texas 140 miles from Fort Concho. The terrain—dry soil with an occasional, stunted, mesquite bush—offered no shelter from the sun, and the heat was excessive. Company A started at noon with only a full canteen each. The next day, *coup de soleil* had prostrated two men and all were suffering from the lack of water; many were faint and exhausted, with some falling from their saddles. The second day, the captain decided to return to base, supposedly some 75 to 100 miles away. Marching in the midday heat, the men's mouths were so dry that they could not tell if they had anything in them. Their tongues were swollen; brown sugar would not dissolve in their mouths, and they could not swallow it.

> Vertigo and dimness of vision affected all; they had difficulty in speaking, voices weak and strange sounding. … [T]hey were also very feeble and had a tottering gait. Many were delirious.[78(p195)]

As their horses died, the men drank the blood. They also drank their own urine, sweetening it with sugar. They were oppressed with dyspnea and a feeling of suffocation, but they breathed as little as possible and through the nose, with closed lips

> covered with a whitish, dry froth. … Their fingers and palms looked shriveled and pale; some who had removed their boots suffered from swollen feet and legs.[78(p195)]

The third day, part of the unit reached base camp:

> both officers and men were almost helpless … and the … water did not greatly benefit any of them this day.[78(p196)]

A few men set out with extra canteens to backtrack and find stragglers and those who had been sent to find water. Fortunately, the next morning another unit with Indian scouts arrived at the base camp and helped in the rescue. The sufferers had an irresistible desire to drink, but their stomachs would not retain water; it was vomited up, as was food.[78]

Command and Control

As early as 1912 it had been suggested that even when water is readily available, troops working in the heat tend not to replace water as quickly as it is lost. In 1947, Adolph and his colleagues[79] termed this deficit "voluntary dehydration." The greatest deficits occur on the first active day in the heat, particularly during the first 12 hours. As shown by a study done in the United Kingdom in 1968,[80] the problem is universal in nature, with the same temporal issues: the 12-hour debts (as a percentage of initial body weight) on the first active day in the heat were 2.4% in Tripolitania, 2.6% in Swaziland, and 3.4% in Bahrain, but only 0.8% in Malaya. After 24 hours these deficits were 0.9% in Tripolitania, 1.7% in Swaziland, 3.4% in Bahrain, and 1.6% in Malaya. The deficits were almost completely abolished after 48 hours. Part of the problem may be the difficult logistical challenge of supplying adequate water to troops in the field: approximately 4 gallons per man per day in Kuwait[61]; the same amount was also needed in Singapore.[81]

Dehydration, expressed as the percentage of loss from initial, fully hydrated body weight, is a major contributor to problems during military operations in the heat. Beyond a level of about 2% dehydration, the rate of body temperature rise is accelerated with each additional percentage of dehydration, although the final temperature reached may not be very different.[82] Emphasis on "water discipline" (ie, training troops to perform in hot conditions with ever-decreasing ingestion of water) has proven to be a serious mistake. The United States,[83] the United Kingdom,[84] Israel,[85] and South Africa[86] have done independent but essentially equivalent studies of men working in the heat. Troop units, assigned to complete an approximately 10-mile march across hot, desert terrain, were split into three groups, based on their water intake:

- one third were allotted just one or two canteens for the mission;
- another third were given two canteens at the start, which would be refilled whenever requested during the march; and
- the remaining third were weighed on a scale before the march and during each rest break, and were required to ingest enough water at each break to return to their premarch body weight.

The results were the same in all these countries' studies: few who had only two canteens of water to drink were able to complete the march, most of those with ad libitum access to water failed to avoid dehydration and had difficulty completing the march, and those whose hydration was maintained at original levels by command control had minimal problems. The conclusion in all these studies was that thirst is an inadequate stimulus to maintain full hydration, and maintenance of normal body water levels is a major factor in reducing heat stress.

Note that the average soldier has only about 5 liters of blood, and that this circulatory system fluid must

1. transfer oxygen from the lungs to the working muscles, brain, and other vital organs;
2. transfer heat from the working muscles to the skin; and
3. at least initially, provide all the water used as sweat for evaporative cooling, at sustainable rates of 1 L/h, and short-term rates up to 3 L/h.

The need to provide adequate quantities of drinking water, and to reinforce its intake by making it palatable (slightly acidic) and cool (about 70°F), as well as by command control to ensure adequate intakes, must be a hallmark in prevention of heat illness. It is essential to solve the logistical problems of delivering 125 tons of water per 5,000 man-units per day, and to solve the problems of troops trying to ingest at least 1 L/h while wearing protective respirators. Dehydration by 5%, a shortfall of only 3.5 liters of water for the average 70-kg man, is considered a limit to mission effectiveness. Doctrine published as recently as 1942 in Field Manual 31-25, *Desert Operations*, stated:

> Restricted water consumption must become a habit. Training must condition troops to live on a limited water ration and must develop such self-discipline in the use of water as will assure the maintenance of combat efficiency on the limited water supply available.[87]

This concept of water discipline *does not work*. However, the doctrine in this field manual against drinking alcoholic beverages is still valid.

The foregoing is not to deny that thirst can be a major problem in the heat, but that thirst, in itself, is not necessarily an adequate stimulus to avoid dehydration. As the explorer Hedin wrote of his experience crossing a desert in 1899, "the first few days the tortures of thirst are so poignant that you are on the brink of losing your senses."[88(p228)] MacDougal[89] reported that one day's deprivation of water so disrupted men's mental balance that although suffering from thirst, these men forded waist-deep streams to continue on and die in the desert. Larrey, describing Napoleon's 1798 campaigns into Egypt and Syria, reported that

> [w]ithout food or water the army corps entered the dry deserts bordering Libya, and arrived only with the greatest difficulty on the fourth day of the march at the first place in Egypt which offered supplies. Never has an army undergone such great vicissitudes or such painful privations. Struck by the burning rays of the sun, marching always afoot on still more burning sand, … the most vigorous soldiers, consumed by thirst and overwhelmed by heat, succumbed under the weight of their arms.[64]

However, it is difficult to recognize other adverse effects of heat on Napoleon's military operation, which was considered a successful campaign.

CONCLUSIONS

Viewed from the numbers and nature of heat injury reported in the military medical literature, it appears that the major effect of heat on large-scale military operations is the need to supply such large quantities of potable water to troops engaged in active operations under hot conditions (up to 125 tons of water per day per 5,000 men)[61]; this may compete with delivery of other essential military supplies. Other effects of heat on individual units can prevent them from accomplishing their assigned missions. However, as suggested by Napoleon's campaigns in Egypt, effects of "heat stress" on large-scale operations are difficult to identify, particularly given the vastly improved capabilities of modern military communications and other command and control capabilities. Any such heat stress effects tend to be diffused and have limited impact during operations by larger than company-sized military units. Rotation of reserves or replacement of units seriously degraded by heat appear to allow large-scale military operations to continue with only barely detectable effects of heat.

When ample supplies of drinking water are available, the real impact of heat on military operations is on the effectiveness of unseasoned units (ie, units during their first 3–5 days in country) with limited manpower reserves, who are attempting to carry out missions that involve sustained, moderate-to-heavy levels of activity under operational conditions where such "agents of heat" are present as high temperature, high humidity, low air motion, heavy loads, protective clothing, or personnel protective items such as body armor, chemical–biological warfare masks, and so forth.

Many afteraction reports document the adverse impact of heat on military operations. The reports included in this chapter suggest these effects, as do books by military historians such as *The Soldier's Load and the Mobility of a Nation,* by S. L. A. Marshall.[28] However, Ogburn's *The Marauders*[90] (which reports on the World War II operation by American troops in the China–Burma–India theater, who were led by Merrill and cut off behind Japanese lines in Burma) indicates what well-led, motivated troops can accomplish despite heat, difficult terrain, and lack of resupply. This supports the World War II conclusions reported by Whayne on the extent to which leadership can overcome the adverse effects of heat on military operations, even under severe heat stress.

Because the effects of environmental heat are dramatically amplified by increasing activity, heat favors defensive over offensive operations. Any requirement for wearing body armor, chemical-protective ensembles, or both, must consider their effects in increasing heat stress. However, heat has usually had little medical or tactical significance on the overall outcome of military operations; the primary adverse effects of heat on military operations are at the small-unit level. Such effects can be avoided to a great extent by proper doctrine, training, and leadership. The Israeli Army policy that heat illness is a court martial offense—not for the heat casualty but for the unit leader—provides an insightful comment on the occurrence of heat illness during military operations.

Now that we have previewed heat illness—both as it affects military operations and in terms of the classic epidemiological triad (agent, disease, and host factors)—the stage is set for the problem to be considered in greater depth in the ensuing chapters.

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Chapter 1: ATTACHMENT

THE ORIGINS OF THE US ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE AND ITS RESEARCH ON EXTREME ENVIRONMENTS

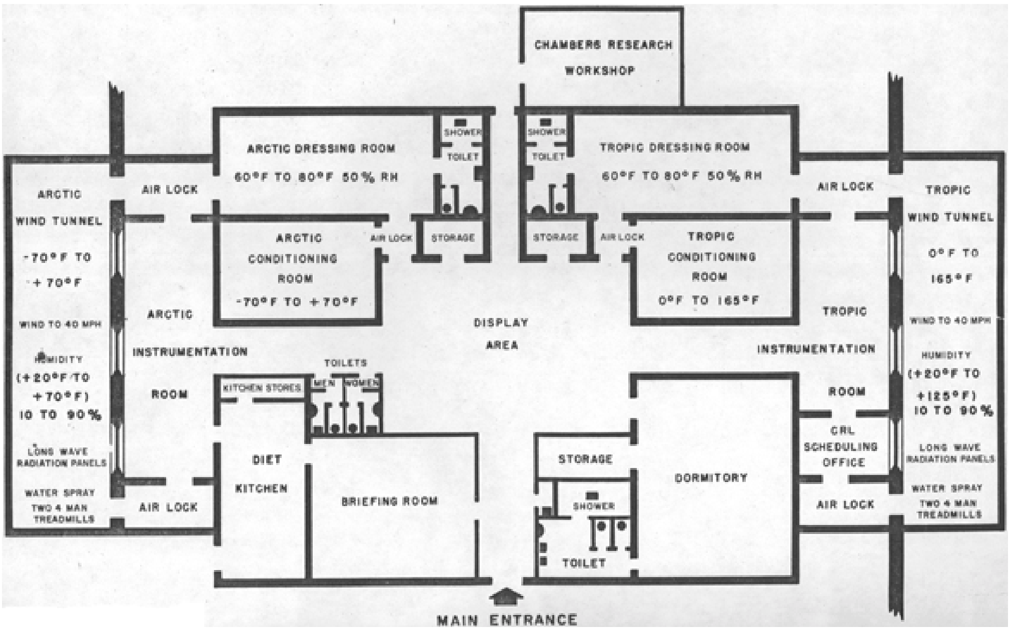
Until World War II there was little government interest or support in the United States for environmental research on the effects of heat, cold, or altitude. Then these effects became of critical government concern, with US military pilots flying high-altitude missions; tank crews fighting in the desert; infantry living and fighting in the jungle; the mountain division in Northern Italy; troops in winter in Alaska to repel Japanese attacks on the Aleutian Island chain; and naval crews sailing in tropical seas trying to work in confined gun turrets, boiler rooms, and the like. Fortunately, the Harvard Fatigue Laboratory had been set up as an industry-funded, nonprofit laboratory in 1927 to study fatigue and discomfort of workers, and ways to improve productivity. Conceived as part of Harvard Medical School, its first 3 years were spent establishing normal physiological values for healthy adult workmen. These data provided baselines for studies of the effects of environment on workers, but the subsequent "applied" work was relegated to a basement of the Harvard Business School, where some rooms were set aside for the laboratory. The Chairman of the Board of the Harvard Fatigue Laboratory, L. J. Henderson, was renowned for his studies on respiratory physiology; one focus of the laboratory was on Peruvian altitude studies. Another was on heat stress: in Panama in 1931; in sharecroppers in Mississippi in 1939; and throughout the construction of Boulder Dam in the Nevada desert. Researchers associated with the Harvard Fatigue Laboratory before World War II included such luminaries as Beane, Brouha, Belding, Darling, Dill (who published his monograph on "Life, Heat and Altitude" there), Folke, Forbes, Graybiel, Horvath, Johnson, Robinson, Talbott, Turrell, Sargent, and Scholander. Frank Consolazio, who later headed a Surgeon General nutrition group, started as a technician at the Harvard Fatigue Laboratory.

Attachment Fig. 1. Left to right: James Bogart, a technician in the Physiology Branch of the Military Ergonomics Division; the water "immersion" (nose only) manikin; Harwood (Woody) Belding, PhD, Professor at the University of Pittsburgh (Pennsylvania) School of Public Health, the inventor of these manikins; his manikin, Chauncy; Ralph F. Goldman, PhD, Founder and Director of the Military Ergonomics Division, who conceived of the cotton skin to make a "sweating" manikin, and also conceived of the need for a walking manikin to study the effects of the "pumping" of clothing by body motion; a "sweating" copper manikin; J. Robert Breckenridge, MS, head of the Biophysics Branch of the Military Ergonomics Division of the US Army Research Institute of Environmental Medicine (USARIEM), Natick, Mass. This photograph was taken in 1972, on the occasion of USARIEM's purchase of Belding's manikin, Chauncy; the other two manikins, which had been used at Wright Patterson Air Force Base, were on permanent loan from the US Air Force.

By 1942, the US military had set up a number of laboratories to deal with the problems of environmental extremes. Researchers from the Harvard Fatigue Laboratory, many of them in uniform, provided the cadre for these laboratories. The US Navy set up a laboratory at Pensacola, Florida, and the Army Air Corps set up the Aero-Medical Research Laboratory near Dayton, Ohio, at what became Wright-Patterson Air Base during the war. The Armored Medical Research Laboratory was established at Fort Knox, Kentucky, by the Combat Armored Divisions to study the specific problems of that combat arm, with Dr William Beane as its commander. There was no Medical Research and Development Command (until 1958), so medical and medical service corps officers were detailed to the Fort Knox laboratory. Doctors Ashe, Eichna, Horvath, Keats, and Shelley carried out classic studies on heat effects and acclimatization, perhaps stimulated by stories that German General Erwin Rommel, who was dominating tank warfare in North Africa, had done studies on tank crewmen in a climate chamber in Germany in the early 1930s.

The US Army Quartermaster General, recognizing the problems of food, personal equipment, clothing, and particularly cold weather protection (as a result of the Aleutian campaign in Alaska, where far more members of the US Army's 7th Division were injured by cold than by the enemy), established the Climatic Research Laboratory (CRL). Sited in Lawrence, Massachusetts, where Pacific Mills (a manufacturer of woolen goods) had a very large cold chamber capable of producing temperatures of –112°C, CRL's first commander was Colonel John Talbott; its first scientific director was Harwood Belding, PhD. The copper manikin that Belding developed in 1939 proved to be a key tool in studies of clothing insulation; it allowed precise measurement of clo, the unit of measurement for clothing insulation developed by A. P. Gagge,[1] and served as a prototype for similar manikins for the US Army Air Corps and the US

Attachment Fig. 2. From right to left, Mr Gerald Newcomb; R. F. Goldman, PhD; Captain John M. Witherspoon, Medical Corps, US Army, a physician assigned as medical monitor for this study; and eight test subjects wearing different rain wear, which varied in coverage, air permeability, and design. The test subject seated in the foreground at position 5 (arrow), wearing the full-coverage, impermeable, hooded rain parka, experienced the least heat stress while walking in this garment. This unanticipated, counterintuitive finding was one of the key factors leading to the development of the "pumping coefficient" for clothing and to the subsequent construction of a walking manikin. Photograph: US Army Natick Laboratories, Natick, Mass. Negative 66-6-15-218-2.



Attachment Fig. 3. Floor plan of the Climatic Research Laboratory, US Army Natick Laboratories, Natick, Massachusetts, which was occupied in 1954. Source: US Army Quartermaster Research and Development Command, Natick, Mass.

Attachment Fig. 4. Building T24 at Fort Churchill, Ontario, Canada, where scientists from the Quartermaster General's Environmental Protection Research Division (EPRD) at Natick, Massachusetts, measured heat loss during the night under arctic and subarctic conditions.[1] Among many other studies conducted at Fort Churchill was a joint nutrition study in 1956 between the EPRD and the US Army's Medical Nutrition Research Laboratory, Fitzsimons General Hospital, Denver, Colorado. (1) Goldman RF, Brebbia DR, Buskirk ER. *Heat Loss During the Night Under Subarctic Conditions.* Natick, Mass: Environmental Protection Research Division; March 1960. ERPD Technical Report EP-129. Photograph: US Army Natick Laboratories, Natick, Mass. Negative 4328-56.

Navy, as well as for sectional copper hands and feet, which were used in testing hand and footwear. Some 30 years later, when fitted with a "sweating" cotton skin by Goldman, such manikins (Attachment Figure 1) allowed Alan Woodcock's theoretical moisture permeability index (I_m) to be measured for complete clothing ensembles. (Woodcock, a Canadian, was chief of the Biophysics Division at CRL.) By the end of the 20th century, close to 100 manikins, some of which have the "walking" capability established by Goldman[2] as useful in analyzing human heat transfer, serve as fundamental tools to generate data for functional clothing design and modeling of human tolerance limits to heat and cold.

In 1951, CRL moved from Lawrence to a former Veteran's Hospital in Framingham, Massachusetts, pending completion of the US Army Quartermaster Research and Development Command's Natick Laboratories, the cornerstone of which had been laid in 1951. The Korean War maintained the Quartermaster's orientation to cold weather studies, and in late 1954, the group, now renamed the Quartermaster Research and Engineering Command, moved to Natick, Massachusetts. The climatic chamber facilities provided are shown in Attachment Figures 2 and 3. To supplement these superb research laboratory facilities, the group carried out numerous field studies in arctic, desert, and tropical climates, and, after 1968, at high terrestrial elevations. A number of studies were carried out on military operations under subarctic conditions at Fort Churchill on Hudson Bay in Ontario, Canada (Attachment Figure 4). Heat production, heat loss, and body composition changes in the cold were primary topics. A number of nutrition studies were also carried out at Fort Churchill in collaboration with the US Army Nutrition Laboratory based at Fitzsimons General Hospital, Denver, Colorado. However, the discovery of Russia's developments in chemical warfare refocused research on heat, particularly on the heat stress and performance limitations associated with wear of protective cloth-

Attachment Fig. 5. At Fort Lee, Virginia, in 1962, R. F. Goldman, PhD, and Mr Gerald Newcomb are seen with a test subject in one of the earlier studies on the effects of wearing nuclear–biological–chemical (NBC) clothing on military performance capability (see Table 1-2). Dr Howard Hembree of the Fort Lee test group is standing behind Dr Goldman; at far right, Mr Tom Dee of the Environmental Protection Research Division Field Test Division is seen talking with another subject. Photograph: US Army Natick Laboratories, Natick, Mass. Negative P-7876.

Attachment Fig. 6. (**a**) The US Army Research Institute of Environmental Medicine (USARIEM), Natick, Massachusetts. (**b**) Edward F. Adolph, PhD (right of center), Professor of Physiology, University of Rochester Medical School, Rochester, New York, the keynote speaker at the 17 October 1968 dedication of the new, 75,000 ft^2 USARIEM building. Others in this photograph are, from left to right, Brigadier General G. F. Gerace, Commanding Officer, US Army Quartermaster Research and Development Command's Natick Laboratories; David E. Bass, PhD, Technical Director, USARIEM; Major General J. Blumberg, Commanding Officer, US Army Medical Research and Development Command; [Dr Adolph]; Colonel James E. Hansen, Medical Corps, US Army, Commanding Officer, USARIEM; and Lieutenant General Austin W. Betts, Commanding General, US Army Research and Development Command. Photograph (b): Courtesy of American Physiological Society, Bethesda, Md.

a

b

Attachment Fig. 7. The additional energy cost required to march on soft sand, found to be a multiplier (terrain coefficient) of 2.1 times the energy cost at the same march rate on a treadmill or blacktop road, is being measured in this study.[1] The military volunteer subjects are shown wearing "Max Planck" gasometers. This 7-lb gas meter measures a timed volume and the temperature of respired air, and collects an aliquot sample (0.3% of each exhalation) in the rubber bag shown hanging from the gasometer. The difference between the oxygen content of ambient air (20.93%) and the residual oxygen content subsequently measured in the sampled expired air, multiplied by the gasometer's measured respiratory volume (L/min, corrected to standard temperature and atmospheric pressure), can be directly converted to kilocalories per minute using the factor of 4.85 kilocalories per liter of oxygen consumed. This photograph helps explain why the multiplier is so high, if one notes the amount of sand lifted with each step and recalls the finding (from an earlier study[2]) that the energy cost of 1 pound of footwear is equivalent to that of 5 pounds carried on the back. (1) Soule RG, Goldman RF. Terrain coefficients for energy cost prediction. *J Appl Physiol.* 1972;32:706–708. (2) Soule RG, Goldman RF. Energy cost of loads carried on the head, hands or feet. *J Appl Physiol.* 1969;27:687–690.

ing (Attachment Figure 5). The US Army Research Institute of Environmental Medicine (USARIEM) played a major role in studies on chemical–biological protective clothing from 1958 to 1980 (see Table 1-7 in Chapter 1, Introduction to Heat-Related Problems in Military Operations).

By the 1960s there were extensive reorganizations to eliminate duplication and combine functions. The Quartermaster General's Environmental Protection Research Division (EPRD) at Natick and The US Army Surgeon General's Armored Medical Research Laboratory (AMRL) at Fort Knox had been competing for the limited research and development funding available during the Cold War. A joint decision was made that The Surgeon General would take responsibility for environmental research and combine its Fort Knox AMRL with the Quartermaster's EPRD into a single organization, USARIEM, which was formally established in 1961. Colonel Don Howie, Medical Corps, US Army, of the Medical Research and Development Command, developed plans for a USARIEM building, to consist of some 75,000 ft^2. Although occupancy had taken place some months earlier, the formal dedication was held on 17 October 1968, with Edward F. Adolph, PhD, one of the world's leaders in heat stress studies in the desert during World War II, serving as the principal speaker (Attachment Figure 6). Former Senator Leverett Saltonstall of Massachusetts, a major supporter of Natick; General William C. Westmoreland; and other dignitaries also attended.

A few years later, to supplement specific Cold, Heat, Altitude, and Exercise Divisions, USARIEM set up a Military Ergonomics Division with a broad-based, five-faceted research program,[3] which is exemplified in Attachment Figure 7:

1. define the soldier's tolerance limits to work, cold, and heat;
2. identify (based on studies by the other divisions) the physiological basis for such limits;
3. assess extension of these limits by physiological or psychological means or both (conditioning, training, acclimatization, nutrition, motivation, etc);
4. assess tolerance extension by improved clothing or equipment, or by redesigning the mission (ie, add manpower, time, work/rest cycles, etc); and
5. predict small unit performance as a function of physical, physiological, psychological, and tactical factors.

This program has been quite useful in supplying design guidance to clothing and equipment developers; guidance for preventive medical officers on thermal and work problems; planning information for tactical and logistics personnel; training information to the combat forces; and recommendations to government and industry for regulation of exposures. While not providing all the answers, this program organized the available information, identified areas in which more research was needed, and helped set relative priorities for military research in the areas of heat, cold, and work.

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