Encapsulated Environment

Tom M. McLellan,[*1] Hein A. M. Daanen,[2,3] and Stephen S. Cheung[4]*

ABSTRACT

In many occupational settings, clothing must be worn to protect individuals from hazards in their work environment. However, personal protective clothing (PPC) restricts heat exchange with the environment due to high thermal resistance and low water vapor permeability. As a consequence, individuals who wear PPC often work in uncompensable heat stress conditions where body heat storage continues to rise and the risk of heat injury is greatly enhanced. Tolerance time while wearing PPC is influenced by three factors: (i) initial core temperature (T_c), affected by heat acclimation, precooling, hydration, aerobic fitness, circadian rhythm, and menstrual cycle; (ii) T_c tolerated at exhaustion, influenced by state of encapsulation, hydration, and aerobic fitness; and (iii) the rate of increase in T_c from beginning to end of the heat-stress exposure, which is dependent on the clothing characteristics, thermal environment, work rate, and individual factors like body composition and economy of movement. Methods to reduce heat strain in PPC include increasing clothing permeability for air, adjusting pacing strategy, including work/rest schedules, physical training, and cooling interventions, although the additional weight and bulk of some personal cooling systems offset their intended advantage. Individuals with low body fatness who perform regular aerobic exercise have tolerance times in PPC that exceed those of their sedentary counterparts by as much as 100% due to lower resting T_c, the higher T_c tolerated at exhaustion and a slower increase in T_c during exercise. However, questions remain about the importance of activity levels, exercise intensity, cold water ingestion, and plasma volume expansion for thermotolerance. Published 2013. *Compr Physiol* 3:1363-1391, 2013.

Introduction

Under most situations, humans control their body temperature within a narrow range seeking the aid of additional clothing to prevent excessive heat loss during exposure to the cold or the removal of clothing to assist with heat transfer during exposure to hot environments. However, there are many occupational settings, such as during firefighting, hazardous waste or explosive ordnance disposal, or in the military, where clothing must be worn to protect the individual from the hazards of their work environment. In addition, there are several sporting arenas, such as American football or auto racing, where protective clothing is worn to help prevent injury. The worker or athlete does not have the option to remove this personal protective clothing (PPC) and, as such, their ability to thermoregulate and continue to work or perform at a peak level can become compromised. In the context of the following discussion, PPC is distinct from personal protective equipment, which includes additional items carried or worn over the protective clothing to confer added protection such as body armor, air cylinders, hearing protectors, hard hats, or helmets. Respirators, however, are included as part of the encapsulating PPC terminology and this review begins with a brief discussion of the limitations involved with the use of respirators.

A detailed overview of the impact of PPC on thermoregulation and work performance then follows with an emphasis of these effects during exposure to hot environments. In addition, the effects of physical factors, such as ambient temperature and vapor pressure, clothing design, age, body composition, sex, menstrual cycle and circadian rhythm, and physiological interventions, such as heat acclimation, aerobic fitness, hydration, work and rest schedules, pacing, and cooling will be discussed.

Respiratory Limitations

The requirement for the use of PPC may also include the need to protect against air-borne hazards or contaminants. Respirators either contain a filtering device or provide purified air with a face mask connected to an external hose-line or self-contained breathing apparatus (SCBA). Regardless of the type of respirator that is required for protection, there is an increased inspiratory and expiratory breathing resistance as well as an increased dead space associated with their use (8, 19, 49, 64, 92, 106, 118, 135, 201). The increased breathing

*Correspondence to DrTom.McLellan@gmail.com
[1] Defence R&D Canada—Toronto, Toronto, Ontario, Canada
[2] TNO Behavioural and Societal Sciences, Soesterberg, The Netherlands
[3] MOVE Research Institute & Faculty of Human Movement Sciences, VU University, Amsterdam, The Netherlands
[4] Department of Kinesiology, Brock University, St. Catharines, Ontario, Canada

Published online, July 2013 (*comprehensivephysiology.com*)
DOI: 10.1002/cphy.c130002

resistance disproportionately augments the work of breathing as flow rates rise above those associated with moderate exercise or approximately 40 L·min^{-1} (19, 177). The additional dead space by itself is known to increase ventilation (8,92) but when combined with the additional work of breathing the use of a respirator often reduces total ventilation at higher metabolic rates (49,59,106,118). The resultant change in ventilation with increasing metabolic demand is highly dependent, however, and directly related to the individual's ventilatory sensitivity to hypercapnia (49).

The use of a respirator also decreases maximal ventilatory function (201), $\dot{V}O_{2\,max}$ (49, 59, 64, 146), and exercise tolerance (118, 135, 146, 254), with the largest decrements in work performance being noted in those individuals with the greatest rating of discomfort to an added respiratory load (91). To decrease inspiratory work and increase protection levels, blowers have been attached to the mask or filter so that positive pressure is generated. Most studies show that the effect of positive pressures of 5 to 10 mbar cause no significant change in various physiological parameters of ventilation and circulation; even strong blowers offer no physiological advantage during heavy exercise (56).

The use of a respirator works in concert with the other components of the PPC to confer protection against the hazards of the environment. However, the other components of the PPC, whether this represents body armor, a load-carriage system for the SCBA or the multilayered clothing layers of the protective garment, interact with the respirator to further impose limitations to breathing. Two studies of note have attempted to delineate the separate and combined effects of using either a respirator with a filter device (178) or SCBA (64) with the other components of the PPC on ventilatory function.

Muza et al. (178) proposed that a portion of the ventilatory impairment associated with the use of military PPC results from the restricted motion of the chest wall due to wearing of multiple clothing layers and use of additional load-carriage equipment and body armor. They observed that the chemical defense PPC and respirator decreased maximal voluntary ventilation 25% compared with the wearing of a battle dress uniform and that one-fifth of this decrease was due to the wearing of the PPC, body armor, and load-carriage equipment. Their calculation of elastance was increased 16% with the use of the PPC and respirator. During submaximal exercise at about 600 W, Muza et al. (178) also reported that the reductions in tidal volume and increase in breathing frequency while wearing the chemical defence uniform reflected the increase in chest wall elastance rather than increases in resistance with the use of the respirator. Thus, although the restriction to movement of the chest wall with the wearing of the PPC has less influence on the overall impairment to maximal ventilator function, its effects during submaximal exercise are more evident than the impairments associated with the use of the respirator.

Eves et al. (64) studied the impact on ventilation and $\dot{V}O_{2\,max}$ with the use of the SCBA regulator or the load-carriage assembly alone or when the regulator was used while the cylinder was carried. Compared with the control condition, which involved breathing through a low-resistance respiratory valve, the use of the SCBA regulator alone or when the SCBA was used and carried reduced $\dot{V}O_{2\,max}$ approximately 15%, due to reductions in maximum flow rates, tidal volume, and inspiratory time. Carrying the SCBA but breathing through a low-resistance respiratory valve also decreased $\dot{V}O_{2\,max}$ but this represented a smaller overall effect of 5%. The findings from this study also revealed that the negative effects with the use of the SCBA on maximal ventilatory function were greater for smaller individuals with a smaller absolute $\dot{V}O_{2\,max}$.

It is clear that the use of a respirator imposes additional and yet distinct limitations for personnel encapsulated with PPC. For firefighters and emergency response personnel that may have to perform very strenuous work requiring the use of SCBA, maximal efforts would be significantly reduced due to the use of the regulator (38,64). In contrast, during prolonged submaximal exercise the impact of the PPC clothing layers and load-carriage equipment on ventilatory function may have greater effects on work tolerance than the added resistance of breathing through a respirator (178).

Heat Balance

The heat balance equation below represents the relationship between avenues for heat loss and heat gain.

$$\dot{S} = \dot{M} - \dot{W}_{ex} \pm (\dot{C} + \dot{K} + \dot{R}) - \dot{E}_{sk} + \dot{E}_{co} - \dot{E}_{resp} \pm \dot{C}_{resp} \quad (1)$$

where the rate of heat storage ($\dot{S}$) can be positive and in a state of heat gain, negative, and in a state of heat loss, or zero indicating a state of thermal balance. The rate of heat production ($\dot{M}$) will always represent a source of heat gain and wet heat transfer through the evaporation of sweat at the skin surface ($\dot{E}_{sk}$) and through respiration ($\dot{E}_{resp}$) will always represent avenues of heat loss. Dry heat transfer through convection ($\dot{C}$), conduction ($\dot{K}$) and radiation ($\dot{R}$) can represent an avenue of heat loss or a source of heat gain depending on whether ambient, surface or radiant temperatures are less than or greater than skin temperature, respectively. Some of the total energy produced through metabolism might be transformed into external work ($\dot{W}_{ex}$) rather than heat, which would reduce $\dot{S}$ for any given $\dot{M}$. When clothing is worn, some heat, which is lost through the evaporation of sweat at the skin surface, can be liberated through the condensation of water vapor ($\dot{E}_{co}$) onto the outer clothing layers.

Factors affecting heat balance

There are four factors influencing the heat balance:

The local environment. High temperatures surrounding the human body make it more difficult to lose heat by convection and radiation. Wind washes away the relatively warm boundary air layer surrounding the skin leading to enhanced dry heat loss (when the skin has a lower temperature than ambient temperature) and evaporative cooling. High humidity values reduce the ability to evaporate sweat from the skin and thus moves the heat balance to the hyperthermic side. Precipitation wets the skin and garments; the high thermal capacity and conductivity of water may cause a rapid decrease in body temperatures (241). Altitude exposure leads to skin vasodilation due to the lower oxygen levels in the air and this may enhance heat loss (228).

Clothing. Clothing reduces heat loss; textile materials trap air that serves as an insulator. When the air pockets between clothing layers are exceeding a certain thickness, the air starts to move and this ventilation reduces total clothing insulation. Garments with a high water vapor resistance, such as rain protective garments, reduce the ability to evaporate sweat. This leads to a large reduction in heat loss during heavy exercise.

Work intensity. The metabolic input to the heat balance is strongly dependent on the work intensity, ranging from about 100 W in rest to over 1000 W during strenuous exercise. Note that work in actual occupational environments may not consist solely of exercise requiring movements such as the treadmill walking typical of laboratory studies. Instead, high metabolic requirements can also come from high levels of isometric work.

Individual factors. It is well defined that acclimatized subjects have much higher sweat rates than unacclimatized subjects so that body heat loss is enhanced (179, 261). Physical training may lead to physiological adaptations that are partly comparable to heat acclimation changes (105, 192). Also, body composition plays a role in the heat balance, for instance relatively fat people cool slower in the cold.

The factors affecting the heat balance are dealt with in more detail later, starting with clothing. These factors are all essential for thermal modeling of the human body. Accurate measurement of the factors can lead to validated empirical predictions of core temperatures during exercise even in PPC (74, 85). Also, the factors affecting the heat balance can serve as the starting point for countermeasures to reduce heat strain in protective equipment: local environment may be modified, clothing insulation, ventilation or vapor permeability adapted, exercise intensity adjusted, and finally acclimation or training may be initiated.

Impact of clothing

Clothing forms the interface between humans and their environment. When a thermal or water vapor gradient exists between the skin and the environment, clothing will decrease heat and moisture transfer. Clothing properties important for heat and moisture transfer are insulation, water vapor, and air permeability including closures and designed openings, skin coverage, layering, moisture absorption and condensation, fit, and radiation exchange. The clothing parameters interact with the environment (temperature, humidity, wind, and solar radiation) and human related parameters (sweat gland activity, body position, and body motion) (188).

Insulation

Insulation is a measure of *thermal resistance*, the capacity of a clothing layer system to prevent heat exchange via conduction and convection. In other words, it is a measure of resistance to heat flow. Note that the concept of *thermal conductivity*, though typically not commonly used in relation to textiles, is the inverse of thermal resistance or insulation.

For clothing, the primary insulation is provided by trapping air next to the body, with the body warming up that air layer and thus decreasing conductive and convective heat loss by reducing the thermal gradient between the body and environment. The ability to trap air is dependent upon the fabric thickness and density (151). For very high densities the conductivity of the fibers plays a role in thermal insulation. When the distance between textile layers exceeds the boundary layer dimensions, the air starts moving and thermal insulation no longer increases. The movement of trapped air thus depends on wind speed and movement of the individual and their limbs. Thermal insulation is generally expressed in one single measure for the entire body, but it is good to realize that thermal insulation differs for every part of the body dependent on the coverage and movement of the body part. In the cold, the extremities are colder than the torso and this means that identical insulative material on the torso and hands will have different effects on heat loss due to the different thermal gradients between these regions of the body and the environment. The cold hands in the cold environment will have reduced benefit of the insulative layer and greater heat loss, while the warm skin of the torso will cool more slowly.

As noted below, the presence of liquid sweat or water in clothing significantly decreases insulation due to the high *thermal conductivity* (i.e., low thermal resistance) of water compared to air. Therefore, a priority in much of clothing design is in rapidly moving sweat or water through the clothing layers to maintain insulation, although this may work against the goal of efficient evaporative heat dissipation.

The total insulation (I_T) of the PPC represents the resistance to dry heat transfer from the skin to the environment and is shown below in Eq. (2) as the sum of the intrinsic clothing insulation (I_{cl}), which is the resistance to heat transfer from the skin to the clothing surface, and the additional resistance at the clothing surface (I_a), which is normalized to the body surface area by accounting for the increased surface area of the clothed body (f_{cl}) (82, 83).

$$I_T = I_{cl} + I_a \cdot f_{cl}^{-1} \quad (2)$$

The dimensionless ratio of $I_a \cdot I_T^{-1}$ represents the extent that the clothing garment insulation impedes dry heat transfer from the skin surface to the environment and is defined as Burton's clothing permeation factor, F_{cl} (84, 183). A required clothing insulation (I_{req}) to preserve heat balance according to Eq. (1) is especially relevant when resting or working in cold environments (111).

Insulation is in reality manipulated by skin coverage, as much as by clothing thickness. Typically, the coverage increases from 50% for hot weather clothing to 98% for cold weather gear. Thickness is not uniform either. Typically the hands, which require greater dexterity, the head or those areas needing to flex are thinner clad than other parts.

Water vapor permeability

Water vapor permeability is a measure of the capacity for a material to transfer water vapor. The objective scale for permeability is a dimensionless value (i_m) ranging from 0 (completely impermeable) to 1 (completely permeable). In warm environments, this permeability measure is often of greater relevance to determination of the heat balance than the dry (radiation, conduction, and convection) heat loss pathways, due to its impact on the amount of evaporative heat loss that is possible. An example of a highly conductive but very low permeability material would be a sheet of plastic. In contrast, down is an example of a material with low conductivity but good water vapor permeability. The two measures of conductivity and permeability are generally not directly related.

In an analogous manner to F_{cl}, a clothing permeation factor that defines the extent that clothing reduces evaporative heat loss, F_{pcl}, is defined as the dimensionless ratio of the water vapor resistance of the boundary clothing air layer to the water vapor resistance of the complete clothing ensembles (98, 183).

Table 1 presents total thermal resistance and water vapor permeability coefficients for various military, industrial, and sport PPC.

Evaporative resistances differ from location to location on the body (250). During walking, limb speed had a much stronger effect on the moisture transport of the arms and legs than of the torso. These localized boundary air layer and clothing evaporative resistances are essential to be known to estimate thermal comfort in garments (250).

Air permeability

Insulation is strongly dependent on air motion. The typical sources of air motion are wind, activity and natural convection. Lotens and Havenith (143) combined these to an effective wind speed. Kerslake (127) showed how air layer insulation dropped with effective wind speed and Havenith et al. (97) how clothing insulation dropped, depending on the air permeability of the ensemble.

Table 1 Thermal Resistance, Where 1 Clo Represents 0.155 $m^2 \cdot °C \cdot W^{-1}$, and the Dimensionless Woodcock Water Vapor Permeability Coefficient for Different PPC Ensembles

PPC	Clo	i_m
Military duty uniform (157)	1.06	0.41
Military biological and chemical protective uniform (157)	1.90	0.27
Firefighting bunker clothing (217)	1.55	0.27
American football uniform (152)	1.47	0.36
Standalone chemical and biological uniform (157)	1.53	0.31
Aluminized two-piece overgarment (110)	2.0	0.15
Impermeable chemical protective suit (110)	1.9	0.06

Air permeability is defined as the ability of the fabric to support airflow through the fabric (convection) under small pressure gradients (81), allowing for ventilation. Havenith et al. (95) observed differences in thermal strain (heart rate and core- and skin temperature) in subjects exercising with textile versus membrane outer layers that were identical in insulation and water vapor permeability. The ensembles differed in air permeability, though.

The interaction between ventilation, humidity, and thermal comfort was investigated by Ueda et al. (247) with five shirts of similar cut but different cotton knits, on chest, back, and upper arm. Trials were performed at 30% and 45% $\dot{V}O_{2\,max}$ in a neutral ambient environment. They reported different rates of ventilation across the three measured sites, and an inverse relationship between fabric air permeability and microclimate moisture during light exercise and sweating. Despite similar physiological outcomes, thermal comfort was consistently higher in shirts with higher ventilation, suggesting that perceptual measures may be more sensitive than physiological ones and should be incorporated into overall clothing performance assessment.

Bernard et al. (12) studied chemical protective garments during treadmill exercise at a constant metabolic heat production rate of 160 $W \cdot m^{-2}$ in the heat (34°C, 50% RH) with nominal air movement, with dry bulb temperature progressively increasing 0.8°C every 5 min. The six prototype garments were similar in material but had different levels of porosity through incorporating different densities of 0.0024 mm holes. While evaporative resistance and passive diffusion of water vapor was an important metric, they reported that the convective permeability was a stronger predictor of the critical wet bulb globe temperature (WBGT) at the point of uncompensable heat stress.

Gonzalez et al. (81), using human experiments, tested clothing ensembles with roughly similar vapor permeability but a very wide span of air permeability (4 orders of magnitude) in addition to a control semi-clothed condition. Their data also supported that air permeability was strongly correlated to maximal sustainable workload at the point of uncompensable heat stress (UHS), and provided better prediction and correlation than water vapor resistance.

Multiple clothing layers

The characteristics of the clothing material together with the number of clothing layers that comprise the PPC determine heat exchange between the body and the environment. When unclothed, heat transfer can occur directly across the skin surface with the surrounding ambient air layer. In most situations of exercise with minimal or highly permeable clothing, the priority for clothing design is to maximize the rapid evaporation of secreted sweat and the movement of water vapor to the environment.

However, when multiple clothing layers are worn successive trapped air layers are formed, each with its own microenvironment through which heat transfer must occur before being dissipated to the external ambient environment (22, 109, 236). The volume of the air between skin and the outer protective garments can be 30 L or more for industrial protective clothing (53, 237). Several book chapters and reviews are available that explain the impact of clothing on wet and dry heat transfer (65, 77, 93, 195). In addition, the effects of air movement and the pumping effects of body motion also impact the transfer of heat through the clothing layers (12, 15, 95, 145, 182, 248), as does the wetting of the clothing layers with sweat (47, 119). The thermal and evaporative resistance to heat transfer through the PPC may be determined with an articulating mannequin over several wind speeds (83, 136, 152) but other factors such as posture and clothing fit will influence the resultant thermal and vapor resistance of the PPC (96, 97).

In general, multiple clothing layers encapsulate air pockets between the folds, rather than creating extended air layers. These pockets do not naturally exchange air with the environment and so-called chimney effects are largely absent. It takes body motion to force hot, moist air out, and suck fresh air in. Clothing design may enhance this process. The best design is one that is loose fit, thus creating large air pockets, reinforced by large openings. Often underclothing is stretch material, with smaller air pockets, and outer clothing is heavier non-stretch material. The consequence is that trapped air becomes concentrated under the outermost layer. Clothing design for improved ventilation should be focused on that item.

Clothing fit (absence of local obstructions) and tightness (loose or tight design) can influence its thermal performance and also thermal comfort through physiological or perceptual mechanisms, and clothing fit and, therefore, actual heat exchange will vary throughout the clothing (247, 249). The fit and tightness of the clothing determines the size of the microclimate volume and thus the amount of thermal resistance and ventilation. At the same time, clothing fit can influence thermal and overall user comfort through altering the amount of contact between the clothing and skin and through fluctuations in temperature.

Theoretically, thermal and water vapor resistance should progressively increase with an increasing air gap. However, as the air gap increases, natural convection through the clothing and forced convection from movement will also increase, such that the rate of increasing thermal insulation may plateau or even decrease. Increased forced convection from wind will also theoretically decrease the rate of rise in thermal and water vapor resistance with increasing air gap. Three-dimensional scanning technology has been used to accurately quantify the air gap and also size and location of skin contact with different clothing systems on a thermal manikin (200) and humans (53, 103).

To directly investigate the effect of clothing fit on thermal and water vapor resistance, Chen et al. (30) tested three fabrics with differing weight, stiffness, and air thermal resistance in five sizes (similar length but different chest girths) on a sweating manikin. All other clothing (base layers, pants, etc.) was kept constant, such that jacket sizes were the only variable. With no wind, larger garments resulted in up to 30% greater thermal insulation and 20% greater moisture vapor resistance compared to small sizes. However, wind had the effect of decreasing both thermal insulation and vapor resistance across all sizes. Thus, depending on the required function (e.g., activity level and ambient temperature), clothing sizing may be manipulated to favor heat gain or loss.

Effect of motion

PPC constitutes an additional weight that has to be transported and thus causes an increase in metabolism and consequently in heat production (2,76,232). However, more than half of the additional metabolic power can be attributed to other factors, such as increased friction of movement and hobbling effects of the clothing, rather than solely to the added weight of the PPC (58, 61, 196, 239).

As reproduced in Figure 1 below, Teitlebaum and Goldman (239) showed that wearing five layers of an Arctic protective clothing ensemble increased metabolic rate over and above that observed when subjects walked while carrying the same load (11.2 kg) in a weight belt. These authors reported a 16% difference in metabolic rate between the two load carriage conditions and attributed it to increased friction due to the interaction of the layers of clothing. The friction not only increases the effort, but also affects the movement economy. The magnitude of the "hobbling effect," described by Teitlebaum and Goldman (239), is likely heavily dependent on the characteristics of the clothing involved (e.g., weight, fabric, and thickness). However, these data suggest that on average, the effect would be to increase metabolic rate by approximately 3% per layer of clothing.

Similar findings were reported by Duggan (61), who examined the effect of various combinations of protective clothing ensembles (against chemical agent and cold weather)

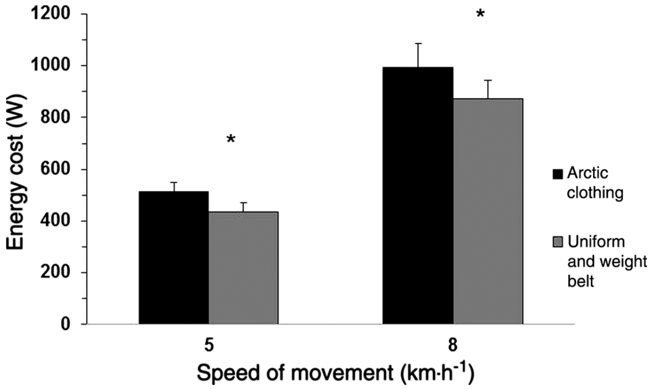

Figure 1 The energy cost of movement while wearing a multilayered Arctic clothing ensemble or carrying equivalent weight as a single-layer uniform with weighted belt. Adapted from Teitlebaum and Goldman (239).

on the energy cost of bench stepping. When corrected for the weight of the clothing, the $\dot{V}O_2$ was greater by an average of 9% in the four-layer ensemble compared to the single layer control condition, or approximately 3% per additional layer above the base condition. Therefore, when estimating the energy cost of work in protective clothing, it is important to consider both the weight and the number of layers in the ensemble.

Dorman and Havenith (58) also demonstrated that the increase in $\dot{M}$ through the use of PPC during stepping, walking, or throughout an obstacle course was attributed to more than just the additional weight of the clothing. Some of the multilayer PPC tested by Dorman and Havenith (58) increased $\dot{M}$ by 20% compared to the control condition despite only increasing the clothing weight by about 5 kg or 7% of body mass.

Clothing moisture effects

When wearing clothing, much of the sweat may become absorbed into the clothing, which will become wet. Wetting can affect both the thermal and protective characteristics of the clothing as well as influence the rate of heat transfer (47, 119). Chen et al. (31) used a sweating manikin to test the effects of light versus heavy perspiration on the inner layer of 12 different ensembles ranging from underwear through to full rainwear (Gore-Tex jackets and trousers). In the heavy perspiration mode, which was still much less in magnitude and more uniform than anticipated with the nonuniform and heavy sweating with exercise, the garment thermal insulation decreased 2% to 8% compared to light perspiration. Within this range, the thicker garments and ensembles generally accumulated more moisture and had greater decreases in insulation. These changes are important both during and especially postexercise, as the chilling observed with cessation of exercise may reflect decreased thermal insulation in addition to maintained evaporative heat loss from the accumulated sweat. However, the increased conduction is hard to tell apart from the continued cooling from sweat evaporation.

Moisture transfer is an important component of heat transfer in garments. Absorption of evaporated sweat in the garment generates heat at the location of absorption. At this point the temperature increases. Consequently the dry heat flow to the environment increases, while the wet heat flow is decreased. The amount of moisture that can be absorbed depends on the fiber type and is known as regain. Wool has a large regain, whereas nylon and polyester have small regain properties. The same thermal mechanism holds for condensation. Lotens and Pieters (144) showed that the surface temperature of impermeable clothing is warmer due to condensation and that even in impermeable clothing evaporation contributes considerably to heat loss. The liquid that is left at the inside of the outer clothing may cause undesired cooling when the work rate is reduced.

Maximal evaporative heat dissipation from the body occurs when secreted sweat is vaporized at the skin (179) thus extracting the heat of evaporation from the skin. If the evaporation happens away from the skin, the heat of evaporation is partly extracted from the environment thus decreasing the efficiency of evaporative heat loss (164). Havenith et al. (94) tested the impact of wetting different clothing layers within a variety of permeable and impermeable clothing ensembles on the latent heat of evaporation. Their manikin data clearly demonstrated that the heat from the manikin required to evaporate the water, assumed at 2.430 J.g^{-1} at 30°C, became significantly less when the site of evaporation was within the clothing layers. The actual heat requirement was dependent on both the distance of the site of evaporation from the skin and the number and nature of both the overlying and underlying layers.

A microclimate heat pipe effect can also be created within the clothing system where heat is transferred to the outer clothing layers through the condensation of water vapor, especially when the condensation is at the inside of the PPC. The liquid can wick back and be evaporated in a loop, thus transporting heat towards the PPE layer (101). The evaporative heat transfer process through the PPC clothing layers is shown below schematically in Figure 2.

Radiation exchange

Heat radiation exchange accounts for a substantial part of the heat balance in quiet air conditions. Radiation energy, emitted by the sun, industrial heat sources, or a heated environment consists of short wavelength radiation (order of 1 mu) and is absorbed at the clothing surface. Dark colors absorb more heat than light colors or reflective surfaces. Intense solar radiation on a dark surface can increase the temperature by more than 30°K. The heated surface emits radiation of a longer wavelength (order of 10 mu). In this range, the color is very different, but that is not visible through the human eye. Radiation may also penetrate to deeper clothing layers and bounce back and forth, depositing heat in various layers. Thus,

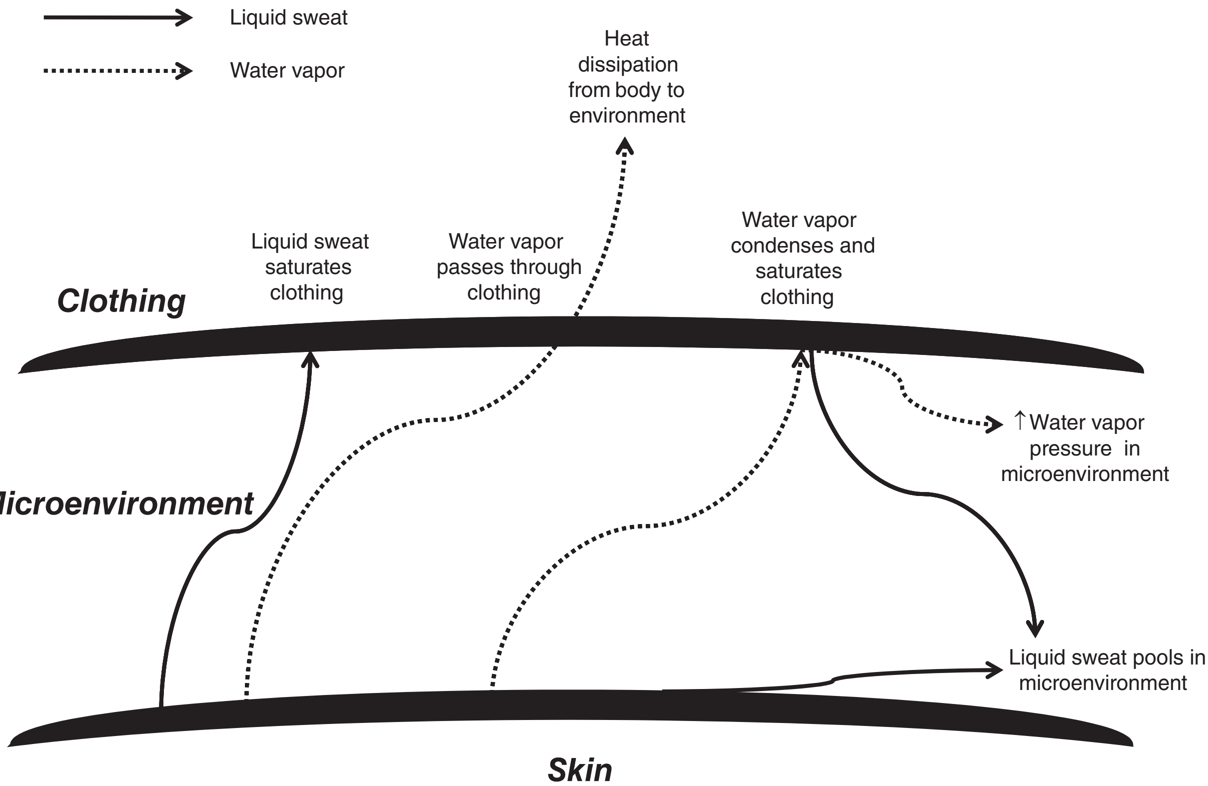

Figure 2 A schematic representation of sweat production and its vaporization through clothing together with sweat lost through dripping off the skin surface and condensation in the clothing layers. Reproduced, with permission, from Cheung (32).

radiation is interacting with the heat loss pathways of convection and evaporation. For fully emitting clothing surfaces the radiation exchange is about 5 $W \cdot m^{-2}$ for a 1°K temperature difference over the adjacent air layer, at room temperature. This number increases with increasing surface temperature. Whether the increased surface temperature is associated with increased skin temperature underneath depends on ventilation (223) and compensation by additional sweating (142).

Heat and Cold Indices

Several attempts have been made to include the physical environmental parameters (temperature, wind, relative humidity, and radiation) in one single index. The combinations are discussed below.

Temperature and wind

The combination of ambient temperature and wind speed is called wind chill. Wind chill is related to the risk of freezing of the exposed skin and to the decrease in manual dexterity (50). The wind chill index as an estimator of cold injury risk was revised in 2008 (116). In the heat, wind has a cooling effect by enhancing convective and evaporative heat loss.

Temperature and humidity

High humidity increases thermal stress in the heat and is not relevant for the cold. Leithead and Lind (134) demonstrated that all cases of fatal heatstroke in the US Army from 1942 to 1944 occurred above specific combinations of ambient temperature and relative humidity. There was a clear demarcation above which the casualties occurred. The combination of ambient temperature and relative humidity is called the heat index in the United States and the humidex in Canada.

Temperature, radiation, wind, and relative humidity

A more complex and well-known climatic index is the WBGT, which is a composite temperature used to estimate the effect of temperature, humidity, and solar radiation on humans. It is used by industrial hygienists, athletes, and the military to determine appropriate exposure levels to high temperatures. It is derived from the following equation:

$$\mathrm{WBGT} = 0.7T_w + 0.2T_g + 0.1T_d \qquad (3)$$

where, T_w is the natural wet-bulb temperature, as an indicator of humidity, T_g is the globe thermometer temperature, also known as a black globe thermometer to measure solar radiation and T_d is the dry-bulb temperature or the normal air temperature. Safe WBGT limits to reduce the risk of heat injury are dependent on metabolism and heat acclimatization status. The WBGT limits are based on standard clothing of 0.6 Clo only. However, clothing adjustment factors are available based on experiments that used a simple addition to the WBGT value (12).

A relatively new initiative is the Universal Thermal Climatic Index (UTCI). Thermal strain is estimated with a thermal model based on input of climatic parameters. For any combination of air temperature, wind, radiation, and humidity (stress), UTCI is defined as the isothermal air temperature of the reference condition that would elicit the same dynamic response (strain) of the physiological model (117).

Thermal and physiological strain indices

Thermal strain is the effect of the previously described thermal stressors on the human body. Important parameters to evaluate thermal strain are body core temperature, mean skin temperature, heart rate, and sweat loss. Based on core and mean skin temperatures, the body heat gain can be calculated. A body heat gain of over 10 $kJ \cdot kg^{-1}$ body weight is generally considered as an indicator for heat related problems (141).

During exercise in the heat, sweat loss is the main mechanism to lose heat. Core temperature increases more when individuals are hypohydrated as compared to euhydrated. Therefore, an international standard, ISO 7933, was based on the ratio between the amount of sweat that should be evaporated to stay in thermal equilibrium and the amount of sweat that can be evaporated maximally. This required sweat rate index standard was recently replaced with the Predictive Heat Strain Index developed by Malchaire et al. (147). This index is mainly used for industry.

Moran et al. (175) developed the physiological strain index (PSI) as an instanteous measure of physiological strain and have demonstrated its applicability to both sexes (174) and to various combinations of exercise and heat stress with differing levels of hydration (173). Sometimes thermal strain is combined with thermal stress indicators, to make an individual recommendation for performance limits (63).

Heat stress index

The Heat Stress Index (HSI) seems particularly useful to assess thermal strain in PPC. The HSI represents the ratio between the heat loss required to maintain a thermal steady-state (E_{req}) and the maximum evaporative potential from the body through the PPC to the environment (E_{max}). The HSI is applicable under all conditions regardless of the use of PPC and if the HSI is less than 1 then the environmental conditions together with $\dot{M}$ and the clothing worn will define compensable heat stress; a condition where core temperature (T_c) will increase and reach a steady-state proportional to $\dot{M}$, and $\dot{S}$ will be zero during the thermal steady state (83). In contrast, when the HSI exceeds 1 the combined environmental conditions, clothing worn and $\dot{M}$ define UHS (83), where $\dot{S}$ will continue to be positive and T_c will continue to rise to some critical level that will eventually lead to decreases in both physical and cognitive performance (11, 23, 46, 75, 78, 89, 90, 104, 171, 243) and an increased incidence of heat injury and illness (26, 27, 42, 199).

Equations which can be used to determine E_{req} and E_{max} when clothing is worn (85) are as follows:

$$E_{req} = (\dot{M} - \dot{W}_{ex}) + A_D \cdot (\bar{T}_{sk} - T_a) \cdot I_T^{-1} \quad (4)$$

where A_D is the Dubois surface area (m^2), I_T is the total thermal clothing insulation ($m^2 \cdot {}^\circ C \cdot W^{-1}$) assessed over three wind speeds, $\bar{T}_{sk}$ is mean skin temperature, and T_a is ambient temperature.

$$E_{max} = 16.5 \cdot i_m \cdot I_T^{-1} \cdot A_D \cdot (P_{sk} - \varphi_a \cdot P_a) \quad (5)$$

where 16.5 is the Lewis Relation (${}^\circ C \cdot kPa^{-1}$), i_m is the Woodcock water vapor permeability coefficient (dimensionless) determined with a heated and wetted articulated manikin, P_{sk} is the skin saturation vapor pressure, ϕ_a is the ambient relative humidity, and P_a is the ambient saturation vapor pressure.

Table 2 presents the E_{req}, E_{max}, and the HSI values for an individual wearing military nuclear, biological, and chemical PPC clothing while at rest or exercising in a warm and a hot environment. Due to the increased thermal resistance and decreased water vapor permeability of the ensemble, even very light exercise in a hot environment of 40°C can result in conditions of UHS and continued heat storage in the body (153, 162, 164). Indeed, the impairment of heat transfer while wearing military PPC in the heat has been reported to be so severe that body heat storage and an increase in core temperature could exist even under resting conditions (164). As stated earlier, UHS can exist in many other occupational settings where PPC must be worn such as with firefighters (38, 217, 229), hazmat workers and industrial PPC (6, 10, 57, 190, 197, 232, 246, 255), with the use of body armor for the military or riot control equipment for police and national security partners (20, 24, 39) and with American football (4, 152).

Clothing in the cold

Work in PPC in the cold may lead to cold- or heat-related problems depending on the insulation, water vapor and air permeability of the garments, exercise intensity, and environment. At ambient temperatures below −15°C in NBC-protective clothing, finger temperatures dropped below 15°C (206). Manual dexterity shows a strong decrement below this threshold in finger skin temperature (52). Due to the reduced dexterity, the risk for accidents may increase during work. Similarly, Cortili et al. (45) observed that work duration was decreased below 1 hour in ventilated NBC-protective garments in −20°C due to the cold at the extremities. At very low ambient temperatures (−20°C or lower) hypothermia may occur during light work or rest. The reduced core temperature further enhances extremity cooling since blood flow

Table 2 A Comparison of the HSI in Different Environments (153, 162–164) (Assuming Ambient Vapor Pressure of 1.1, 2.2, 3.7, 4.8, and 2.1 kPa at 40°C 15%, 30%, 50%, and 65% RH and 30° 50% RH, Respectively) at Metabolic Rates (W) Representing Very Light, Light, Moderate, and Heavy for Military Guidelines (170) (Assuming a Respiratory Exchange Ratio of 0.85) while Wearing a Nuclear, Biological, and Chemical Protective Ensemble [Thermal Resistance and Vapor Permeability Coefficient of 0.291 $m^2 \cdot °C \cdot W^{-1}$ and 0.33 (85), Respectively]. Skin Temperature in All Conditions Was Assumed to be Constant at 37.0°C and External Work Was Assumed to be Zero

		30°C, 50% RH		40°C, 15% RH		40°C, 30% RH		40°C, 50% RH		40°C, 65% RH	
Metabolic rate (W)		(W)	HSI	(W)	HSI	(W)	HSI	(W)	HSI	(W)	HSI
Very light	E_{req}	120	0.8	190	1.0	190	1.3	190	2.0	190	3.5
(170)	E_{max}	155		190		150		95		55	
Light	E_{req}	290	1.9	360	1.9	360	2.4	360	3.8	360	6.5
(340)	E_{max}	155		190		150		95		55	
Moderate	E_{req}	460	3.0	530	2.8	530	3.5	530	5.6	530	9.6
(500)	E_{max}	155		190		150		95		55	
Heavy	E_{req}	630	4.1	700	3.7	700	4.7	700	7.4	700	12.7
(675)	E_{max}	155		190		150		95		55	

NOTE. The evaporative heat loss required to maintain thermal steady state (E_{req} in W) was divided by the maximal evaporative heat loss possible in the environment (E_{max} in W) to obtain HSI. A HSI < 1.0 indicates a compensable heat stress, while a HSI > 1.0 indicates a positive rate of heat storage within the body and an uncompensable heat stress.

to the extremities is minimized in an attempt to counteract hypothermia.

Clothing ensembles in both occupational and recreational settings are designed to protect the wearer from the external environment. However, due to the bulk of the required clothing (e.g., gloves and thick parkas), this can lead to a decrement in functionality, both through decreases in gross and manual dexterity (205), but also through an increase in heat strain (37). Hyperthermia remains a risk even when exercising in cold weather while wearing clothing, as the combination of significant heat production along with high thermal insulation and sometimes low permeability may impair heat exchange and cause sustained heat storage. Rissanen and Rintamaki (207) demonstrated that core temperatures increased above 38.0°C during 60 min of heavy marching in −33°C ambient temperatures when wearing nuclear, biological, and chemical protective clothing, even while mean skin and finger temperatures fell below levels of comfort and tolerance at −15°C ambient temperature or lower. A summary of their findings is presented in Table 3.

While hyperthermia may exist during exercise, low water vapor permeability can challenge thermoregulation during subsequent passive cold exposure. Because of the thick and bulky clothing, sweat can drip off the skin and become trapped within the fabric, in turn decreasing clothing insulation and increasing conductive heat loss. Therefore, when exercising in the cold, thermal balance can swing between high rates of heat gain and loss depending on activity levels. Both modeling simulations (262) and laboratory testing (206) demonstrated that core temperature can approach or exceed 38.0°C during 60 min of exercise when wearing cold weather and/or chemical protective gear at −10°C or below, then decrease in excess of 1°C during subsequent rest of equal duration. In particular, mean skin temperature can drop to below 27°C during rest periods at −20 and −30°C (262), eliciting thermal discomfort and shivering.

Heat Tolerance

The definition of heat tolerance can vary among researchers with some defining the term as the highest core temperature that can be tolerated prior to exhaustion (131, 171, 215), whereas others define heat tolerance in terms of a limit for the increase in body heat storage (S) (252). With the former definition, heat tolerance is affected only by those factors that alter the core temperature tolerated at exhaustion, while with the latter definition, factors that influence both the initial and final core temperature, as well as the heat capacity of the body would affect heat tolerance. Here, we will focus on the latter definition and discuss those factors that influence body heat storage while wearing the PPC. Although the focus of discussion will be on military PPC, the findings are equally applicable to other occupational and sport settings that require the use of PPC.

Tolerance time (TT) in PPC is defined as the time to reach one of several end-point criteria during conditions that define UHS (see Table 1). The exact end-point criteria can vary due to ethical considerations or by experimental design, and may, therefore, differ from one laboratory to another or even within the same laboratory from one experiment to another. Typically, ethical constraints revolve around the allowable increase in core temperature and heart rate; this increase in rectal temperature (T_{re}), for example, can vary by at least 1°C

Table 3 Thermal Strain at Different Work Rates in Watts (W) at Various Ambient Temperatures (T_a) while Wearing Semi-permeable Nuclear, Biological, and Chemical Protective Clothing that Weighed 6 kg with an Estimated Thermal Insulation of 2 Clo

T_a (°C)	Rest (<170 W)	Light work (170-340 W)	Moderate work (340-510 W)	Heavy work (510-680 W)
25	Unlimited work time	Working time < 2 h Heat discomfort	Heat strain in 60 min Performance degradation	Heat strain < 60 min Performance degradation
20	Unlimited work time	Working time < 3 h	Heat strain in 60-120 min Heat discomfort	Heat strain in 60 min Performance degradation
15	Unlimited work time	Working time > 3 h	Risk of heat strain > 120 min Heat discomfort	Heat strain > 60 min Performance degradation
10	Unlimited work time	Working time > 3 h	Heat strain possible Heat discomfort	Heat strain > 60 min Performance degradation
0	Extremity cooling Cold discomfort	Unlimited working time Extremity cooling possible	Heat strain possible Extremity cooling possible	Risk of heat strain
−10	Extremity cooling Risk of whole body cooling	Cold discomfort Extremity cooling	Heat strain possible > 60 min	Heat strain possible > 60 min
−20	Whole body cooling	Risk of whole body cooling > 60 min	Heat strain possible Risk of extremity cooling	Heat strain possible > 60 min
−25	Whole body cooling < 30 min	Whole body cooling < 60 min Performance degradation	Risk of extremity cooling	Heat strain minimal

NOTE. Reproduced, with permission, from Rissanen (204).

with typical ceilings reported between 39.0°C and 40.0°C (14, 43, 131, 216, 220, 222). In addition, other factors such as nausea, ataxia, syncope, voluntary termination, or a maximum length of exposure may define TT. Because of these different end-point criteria, comparison of TT among studies or even within the same study before and after an experimental treatment must be approached with caution. TT can be influenced by the initial and final T_{re}, the heat capacity of the body ($C_{p,b}$), and the rate of heat storage ($\dot{S}$) as shown in the following equation;

$$TT = (T_{re,final} - T_{re,initial}) \cdot C_{p,b} \cdot \text{mass} \cdot (\dot{S} \cdot 60 \cdot A_D)^{-1} \quad (6)$$

where TT is expressed in minutes, $C_{p,b}$ is in J·kg^{-1}·°C^{-1}, and A_D represents the body surface area (m^2).

Figure 3 depicts the relationship between TT in military nuclear, biological, and chemical PPC and metabolic rate for different temperatures and vapor pressures. All of the depicted curves from various datasets (153, 162–164) are well defined by hyperbolic functions, which are shown below for the different environmental temperatures and vapor pressures;

$$TT(\text{min}) = 965 \cdot ((\dot{M} - 125) \cdot 60/1000)^{-1} \quad \text{for } 30°\text{C},\ 50\%\ \text{RH}(2.1\ \text{kPa}), \quad (7)$$

with the numerator representing heat storage in kJ and the denominator is heat production in watts converted to kJ per minute;

$$TT(\text{min}) = 1310 \cdot ((\dot{M} - 120) \cdot 60/1000)^{-1} \quad \text{for } 40°\text{C},\ 15\%\ \text{RH}(1.1\ \text{kPa}) \quad (8)$$

$$TT(\text{min}) = 1240 \cdot ((\dot{M} - 60) \cdot 60/1000)^{-1} \quad \text{for } 40°\text{C},\ 30\%\ \text{RH}(2.2\ \text{kPa}) \quad (9)$$

$$TT(\text{min}) = 1370 \cdot ((\dot{M} + 50) \cdot 60/1000)^{-1} \quad \text{for } 40°\text{C},\ 50\%\ \text{RH}(3.7\ \text{kPa}) \quad (10)$$

$$TT(\text{min}) = 1100 \cdot ((\dot{M} + 45) \cdot 60/1000)^{-1} \quad \text{for } 40°\text{C},\ 65\%\ \text{RH}(4.8\ \text{kPa}) \quad (11)$$

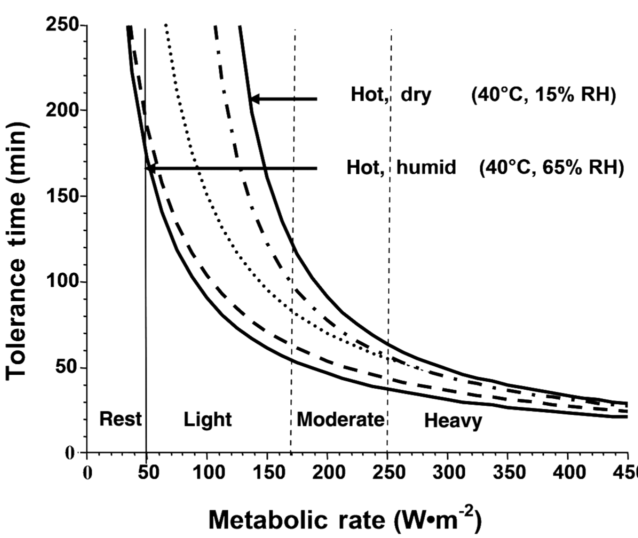

Figure 3 The relationship between tolerance time and metabolic rate when wearing Canadian Forces nuclear, biological, and chemical protective clothing in different environmental conditions. Solid and dotted lines represent data from various environmental conditions derived from McLellan (153) and McLellan et al. (162–164).

The vertical asymptote of these forcing functions defines the metabolic rate that delineates infinite TT and compensable heat stress at values below and finite TT and UHS at metabolic rates above this asymptote. These vertical asymptotes would occur at 125, 120, 60, −50, and −45 watts for Eqs. (7) to (11), respectively. Given that resting metabolic heat production approximates 100 watts (or 50 $W \cdot m^{-2}$ as shown in Fig. 3), it is apparent that when the ambient temperature is 40°C and vapor pressure exceeds about 2 kPa (or about 30% relative humidity) the conditions define UHS or continued heat storage even at rest.

The curves shown in Figure 3 also reveal that the ambient temperature and vapor pressure have far less impact on TT as $\dot{M}$ increases. This reflects the fact that it takes time for the sweat that is secreted at the skin surface to be evaporated and move through the various clothing layers as shown in Figure 2. Since the clothing restricts the kinetics of evaporative heat transfer for at least 30 to 45 min in these hot environments (164), and since dry heat transfer would represent a source of heat gain, the major determinant of heat storage is the metabolic rate, as shown in Eq. (1) above. Thus, at metabolic rates above approximately 500 W, the environmental temperature and relative humidity have very little influence on the rate of heat storage when this particular PPC is worn. In contrast, at lower rates of heat production the clothing barrier for evaporative heat transfer is eventually overcome and the resultant evaporative cooling (and TT) becomes proportional to the vapor pressure gradient between the PPC and the environment.

The series of curves shown in Figure 3 represent the influence of various environmental conditions when the same PPC is worn. However, the curves could also represent the influence of changing thermal characteristics, or $i_m \cdot I_T^{-1}$, of the PPC. For example, as the PPC becomes less permeable to water vapor transfer or thicker, due to additional clothing and air layers, the curve would shift to the left. In contrast, as the clothing material becomes thinner or more breathable the curve would shift to the right. With totally impermeable PPC, such as is required for hazmat workers in industrial or emergency response settings (6, 10, 197, 246, 255), the curve would be shifted far to the left. In fact, since there would be minimal heat lost due to evaporation at increased ambient temperatures (101), the shape of the curve may flatten and be represented principally as a straight line indicating that the metabolic rate would be the sole determinant of TT. Comparisons that have been made between military PPC, as depicted in Figure 3, and impermeable industrial PPC have shown that the rate of heat storage is approximately 30% faster when the impermeable clothing is worn while exercising at 215 $W \cdot m^{-2}$ and exposed to an ambient temperature of 30° and 50% relative humidity (203). However, given that ambient vapor pressure has a greater effect on TT at lower metabolic rates with military PPC, differences in rates of heat storage, and as a result differences in TT, between semi-permeable military and impermeable industrial PPC would be expected to be greater than 30% at lower metabolic rates. To date, this has not been verified experimentally.

While protective clothing is being continually improved and lightened, the requirement for adequate environmental protection is generally contradictory to the desire for adequate ventilation. For example, the requirement to meet National Fire Prevention Association standards for protective clothing has led to firefighting clothing ensembles that create greater heat stress for the individual than protective ensembles that were used before this standard was introduced in 1987 (148, 230).

In addition, the need to provide protection from fragmentation blast has necessitated the use of body armor that covers the torso, neck, arms, groin, and upper legs of soldiers. Although this armor confers additional protection for the soldier, it creates an additional barrier to heat loss from the body (24). Interestingly, however, current military PPC for biological and chemical protection has improved thermal characteristics compared to older PPC due to changing operational expectations within contaminated regions (62). The advantage of the improved porosity and reduced resistance to water vapor transfer is more evident at faster speeds of walking, due to the pumping effects in the clothing, during wind speeds below 1.5 $m \cdot s^{-1}$ but at higher wind speeds the additional pumping effects through movement become less important (95).

The importance of understanding the impact of these hyperbolic functions on explaining the relationship between metabolic rate and TT cannot be overstated. The convergence of these curves imply that researchers may conclude that intervention strategies designed to influence TT during UHS when PPC is worn are ineffective, when in reality differences might have been observed had a lower rate of heat production been chosen as the independent variable. This is indeed the case when the effects of rehydration (34), heat acclimation (2, 3, 28, 165) and vapor pressure (164, 171) were examined with military biological and chemical PPC. In addition, the lack of effect noted for states of hyperhydration with glycerol (131), comparisons between the luteal and follicular phases of the menstrual cycle (129), impact of endurance training (2), aerobic fitness (257), the WBGT index (244), and cooling vests (122) could have reflected the high metabolic rate chosen to evaluate the treatment effects. Different conclusions may have been reached had a lower rate of heat production been used during these studies. Similarly, using a lower rate of heat production as the independent variable may provide greater sensitivity when evaluating changes in material and clothing design of PPC (13, 157).

Initial core temperature

Several factors are known to influence core temperature prior to donning PPC and can, therefore, have a significant impact on total body heat storage and TT as described in Eq. (6).

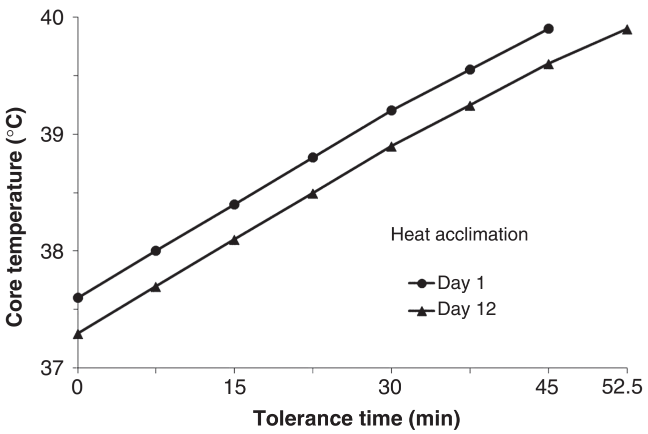

Figure 4 The effects of 12 days of heat acclimation to a hot and humid environment on tolerance time during cycling at a constant power output. Note that the increase in tolerance time following the heat acclimation is due to the decrease in resting core temperature. The figure is derived from data in Nielsen et al. (181).

Heat acclimation

Since the microenvironment within the PPC is hot and wet (164), the traditional benefits of increased evaporative cooling that accompany a period of heat acclimation (179) confer little advantage when encapsulated (2, 3, 28, 165). Instead, the benefits that follow a period of acclimation to a hot and wet environment are limited to the decrease observed in resting core temperature (3, 17, 33, 180, 181). For example, Nielsen et al. (181) examined the thermoregulatory and cardiovascular responses involved in a 12-day acclimation to a hot (35°C) and humid (87% RH) environment. Over the 12-day period, well-trained cyclists improved their cycle time to exhaustion by about 15%. Since both the rate of increase in core temperature during the exercise as well as the temperature tolerated at exhaustion (40°C) were unchanged from day 1 to 12, the 15% improvement was attributed entirely to the small but consistent decrease of 0.2°C in initial T_c, as depicted in Figure 4.

The degree of specificity required for heat adaptation in PPC remains equivocal. In a study comparing 15-day heat acclimation in different environmental conditions (warm-humid, hot-dry, and radiant) but at a similar wet bulb globe temperature of 33.4°C to 33.6°C, Griefahn et al. (88) reported equivalent time course of heat adaptation and also transferability across environments. Dawson (55) also contended that analogous wet-humid heat adaptation could be obtained by exercising in preferably low-permeable clothing. However, findings from studies conducted by Aoyagi et al. (2, 3) and McLellan and Aoyagi (158) revealed that acclimation to a hot-dry environment was less effective than acclimation to the hot-wet microenvironment created while wearing the PPC, as well as the importance of using a low rate of heat production to evaluate the changes in heat tolerance during UHS. In their study that compared hot-dry versus hot-wet heat acclimation (158), greater changes in exposure times were noted following acclimation to hot-wet conditions, which were created by wearing the PPC daily for 12 days. TTs increased 27% from 104 to 130 min as a result of the hot-wet heat acclimation program compared with the 11% increase from 109 to 120 min that followed the 12 days of hot-dry heat acclimation. These improvements were related not only to the lower T_{re} at rest but also to a slower rate of increase in T_{re} that presumably reflected a reduction in hidromeiosis with the hot-wet heat acclimation. Fox et al. (67) noted that sweat suppression was more evident during a heat-tolerance test in a hot-wet environment for individuals who had acclimated to hot-dry conditions compared with those subjects who had acclimated to the hot-wet test environment.

Follow-on work by Cheung and McLellan (33) revealed, however, that the benefits of acclimation to the hot-wet microenvironment within the PPC were minimal if fluid was provided throughout the heat-tolerance test. The previous studies from this same laboratory involving heat acclimation with PPC (2, 3, 158) had restricted fluid intake during the heat-stress exposures. Fluid replacement has been demonstrated to increase TT while exercising in the heat with PPC (34). As such, fluid replacement may have extended exercise-heat tolerance during the preacclimation heat stress exposure to near the maximum possible in the UHS conditions, thereby limiting the amount of improvement that could be observed with subsequent heat acclimation. If this is the case, it would underline the importance of fluid replacement during UHS regardless of fitness or acclimation status (see below). However, it should also be noted that ensuring adequate hydration is complicated with the use of a respirator and because of the added difficulty, individuals may choose to consume less fluid than is required. Also, the use of some respirators may not permit fluid intake and, as such, the provision of fluid would be restricted to recovery periods in noncontaminated areas when the respirator could be removed.

Regardless of the interactions between heat acclimation and hydration, it is important that sufficient time is allocated to recover from the heat strain during the acclimation process, so that the physiological adaptations can take place. If sufficient recovery is not allowed, the adaptations may be postponed to after the heat acclimation period (54), as depicted below in Figure 5. The lowering of resting core temperature is also observed after heavy exercise in temperate environments (224). Therefore, Kampmann et al. (121) postulate that it is the exercise *per se* that causes the change in resting core temperature and not the heat. They also showed that about one-third of the average lowering of core temperature at the end of exercise may be attributed to the lowering of resting core temperature values.

The acclimation effects gradually disappear when heat exposure is ended. This process, called deacclimation was supposed to take twice as long as acclimation (192) but it was recently shown that some aspects of heat acclimation, such as the reduction in body core temperature and rate of perceived exertion, may be maintained for 26 days (253). Figure 6 shows that the drop in resting core temperature that was acquired during acclimation, still exists during reacclimation 26 days

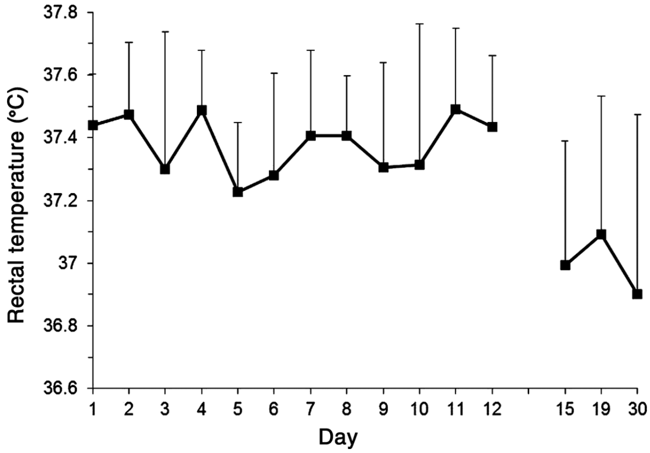

Figure 5 Rectal temperature in the morning during 12 days of heat acclimation (HA) with minimal recovery and 3, 7, and 18 days later. Please note that the reduction in core temperature is not seen during, but after HA. Reproduced, with permission, from Daanen et al. (54).

later. This means that people working in protective equipment still have benefits from acclimation even if it was acquired a month before.

Hypohydration

Studies have also revealed that fluid loss approximating 2% to 2.5% of body mass during exercise in the afternoon will increase resting T_c the next morning if fluid replacement is restricted (33, 34). The increase in T_c approximates 0.2°C and can lead to decreases in TT and total heat storage of 15% to 20% during light exercise while encapsulated (33,34). Importantly, these same studies demonstrated that a state of hypohydration largely counteracted any benefits to TT derived from heat acclimation during UHS. Larger increases in resting T_c are evident following fluid losses during exercise that approach 5% of body mass that result in even larger decrements in TT during an UHS exercise and heat-stress exposure the next morning (215). These data clearly reveal the importance of proper rehydration to help ensure optimal performance if daily or repeated exposure using PPC is required.

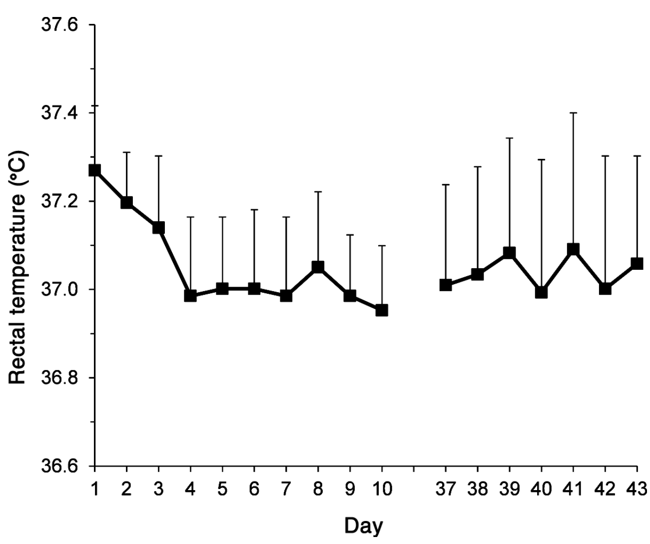

Figure 6 Rectal temperature after 60 min exercise during heat acclimation for 10 days followed by reacclimation 26 days later for 7 days. Note that even after 26 days the core temperature is the same as the end of the initial heat acclimation period. Reproduced, with permission, from Weller et al. (253).

Menstrual cycle

The postovulatory luteal phase of the menstrual cycle is associated with an increase in resting T_c of approximately 0.3°C (107, 113, 128). Kolka and Stephenson (129) examined the influence of different phases of the menstrual cycle during UHS and while T_{re} remained significantly higher in the mid-luteal phase compared with the early-follicular phase, TT was similar in both phases (60 min and 55 min, for the early-follicular and mid-luteal phases, respectively). However, $\dot{M}$ exceeded 200 $W{\cdot}m^{-2}$, which may have reduced the likelihood of detecting changes in TT, as explained earlier (see Fig. 3). Interestingly, Kolka and Stephenson (129) also reported that the T_{re} tolerated at exhaustion was higher during the mid-luteal (38.6°C) versus the early-follicular (38.4°C) phase such that the change in T_{re} or total heat storage was similar during the various phases of the cycle under these UHS conditions. In contrast, during an intermittent work and rest protocol that reduced the average $\dot{M}$ to 110 $W{\cdot}m^{-2}$, TTs were significantly reduced 14% during the mid-luteal phase to 107 min from the 128 min observed during the early-follicular phase of testing (240). Also, the final T_{re} was unchanged at 38.8°C during the phases of the cycle but the change in T_{re} from beginning to end of the heat-stress exposure and the resultant change in body heat storage were significantly reduced during the mid-luteal phase (240). This is but one example of where it is unclear whether physiological states that are associated with shifts in the control of resting T_c also proportionally impact the T_c tolerated at exhaustion. In other words, it is unclear whether the body regulates heat storage (252) or the attainment of a maximal T_c that remains relatively constant despite alterations in effector control (79, 80).

Aerobic fitness

Although it is not commonly reported, a higher aerobic fitness is associated with a reduction in resting T_c (33, 105); this decrease of approximately 0.2°C is independent of the state of hydration or heat acclimation and can increase TT when PPC is worn (33). However, the mechanism responsible for this lowering of resting T_c with increased aerobic fitness has not been clearly established.

Circadian rhythm

The normal circadian rhythm leads to oscillations in resting T_c that can vary by 0.5°C from early morning to mid-afternoon (130), which, in theory, should reduce TT when wearing PPC in the afternoon. However, it has been observed that trials conducted in the early afternoon were associated with an increased rectal temperature tolerated at exhaustion that offset the circadian influence on resting rectal temperature, and thus, maintained TTs similar to trials conducted in the morning (161). Given that other effector responses, such as the temperature threshold for the onset of sweating and skin vasodilation, occur at higher temperatures in the afternoon compared with the morning (234), it is possible that the T_c tolerated at exhaustion is also regulated at a higher temperature in the afternoon. More recently, Hobson et al. (108) concluded that exercise capacity in the heat was greater in the morning than the afternoon due to this circadian effect on resting T_c. However, their exercise test involved cycling in the heat at 65% VO_{2max} with TTs that approximated 45 min. At exhaustion HR was close to maximal values which may have limited the attainment of a true maximal T_c due to the heat stress conditions. It was noteworthy that some of their participants ended their trials with T_c values below 38.0°C, suggesting that a true thermal tolerance was not achieved. Nevertheless, this is another example where discrepant findings do not clearly reveal whether it is body heat storage (252) or the attainment of a maximal core temperature (80) that defines the upper limits to tolerance to UHS.

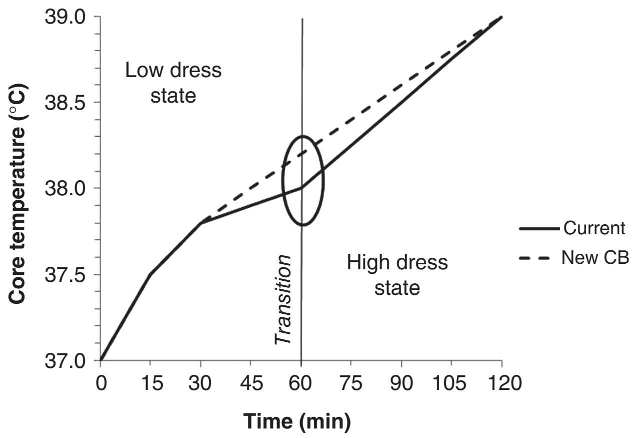

Figure 7 The change in core temperature while wearing either the current personal protective ensemble consisting of the combat uniform and overgarment concept or new stand-alone chemical and biological (CB) uniforms. During the low dress state minimal protection is required and only the combat uniform is worn. However, during the high dress state full encapsulation and maximum protection is required, necessitating the use of the overgarment. The use of the new CB uniforms does not require an overgarment since the CB protection is already included within the clothing material. Notice after 60 min at the beginning of the transition from the low to high dress state core temperature is higher for the new CB uniform.

Dress states and transition

Although the PPC is designed to protect the individual from the hazards of their work environment, there are situations where some of the PPC may be worn as a stand-alone duty uniform even if the threat of exposure to environmental hazards is low. This is certainly the case for new generation chemical and biological protective garments in-use by the military (1, 62), since the traditional concept of wearing a protective garment over the duty uniform adds additional thermal strain due to the added uniform layer (155). However, if the thermal resistance and water vapor permeability of the new chemical and biological PPC when worn as a stand-alone garment is higher than the in-service duty uniform, then T_c will be increased during periods of compensable heat stress compared with the use of the traditional uniform. As a result, the soldier will be at a disadvantage as they transition to a state of encapsulation and UHS since their T_c will be elevated. This disadvantage can offset the intended advantage of these standalone uniforms on rates of heat storage during encapsulation such that TT would be no different than the use of the traditional overgarment concept (157). This is shown schematically in Figure 7. It is important, therefore, that evaluations and comparisons of new and old PPC clothing designs consider the context of the intended operational use of these garments. Since the soldier could be in a low dressed state for extended periods prior to transitioning to full encapsulation, evaluations that are conducted only while in high dressed states can provide misleading biases about the benefits of new clothing designs. In fact, recent efforts in new CB standalone uniforms have focused on the incorporation of zippered vents into the torso, arms and legs to reduce thermal strain during periods of extended wear in a low dressed state, such that TT after transitioning to high dressed states, with the closing of the zippers, is increased compared with the use of the traditional battle dress uniform and overgarment concept (62, 157, 159).

Precooling

Studies have shown the advantage of lowering T_c through exposure to the cold before exercise (132) or the ingestion of cold water or an ice-slurry prior to and during exercise in a hot environment (133, 208, 226, 227). These latter studies clearly revealed the heat-sink effect of the ingested fluid. Mathematical calculations show that approximately 136 kJ of heat is required to raise the temperature of 1 L of refrigerated (4°C) water to 37°C, assuming a heat capacity for water of 4.12 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$. For a 70 kg individual this transfer of heat to 1 L of ingested fluid would lower resting T_c about 0.6°C. Indeed, Lee et al. (133) reported that preexercise T_c was reduced 0.5°C following the ingestion of 900 mL of 4°C water over a 30-min period before the start of a cycling test to exhaustion in a warm, humid environment. With the continued ingestion of a smaller 100 mL bolus of cold fluid every 10 min during exercise, TTs were significantly increased 12 min, or 23%, from the control condition of 52 min. Although the heat-sink effect of the cold water or ice-slurry ingestion has not been unequivocally demonstrated with the use of PPC, there is no reason not to expect that reductions in T_c with cold water ingestion prior to encapsulation would increase TT during subsequent UHS. In addition, the bolus of fluid ingested will help ensure a state of euhydration at the beginning of UHS, which is more critical for optimizing exposure times when PPC is worn than rehydrating after exercise has begun (also see the discussion below) (34).

Final core temperature

Hypohydration

Sawka et al. (215) were the first to study the effects of hypohydration on tolerance to UHS. Following exercise that reduced body mass by 5%, fluid intake was restricted until the exercise and heat stress exposure the following morning. They reported that the T_c tolerated at exhaustion decreased from 39.1°C to 38.7°C and that a higher percentage of participants terminated their exposure while hypohydrated due to exhaustion at any given T_c. For example, 50% of the participants terminated the euhydrated trial at a T_c of 38.9°C whereas this value decreased to 38.4°C following the loss of fluid from the previous day's exercise and subsequent fluid restriction overnight. Consistent with the effects of hypohydration on resting T_c described above, Sawka et al. (215) also showed that the effects of 5% hypohydration were even greater when plotted against the change in T_c from rest rather than just the absolute value of T_c. In other words, 50% of participants terminated the euhydrated trial after a change in T_c from rest of 2.2°C whereas this value decreased to an increase on only 1.3°C while hypohydrated. Thus beginning UHS exposure in a hypohydrated state will not only elevate resting T_c (33, 34, 215) but when the loss of fluid approaches 5% of body mass the T_c at exhaustion and exercise time will also be reduced (215).

State of encapsulation

Montain et al. (171) revealed that the T_c tolerated at exhaustion was significantly reduced about 0.3°C when participants were fully encapsulated, which included breathing through a respirator and covering the head with a hood. The authors suggested that the covering of the face and head led to a reduced heat tolerance, as reflected by higher mean skin temperatures, and/or greater subjective discomfort with the use of the mask and breathing through the respirator. As reviewed by Cheung et al. (38), the use of the SCBA as part of the PPC for firefighters and hazmat workers would be expected to reduce maximal work performance. Others have also reported an increased thermal and cardiovascular strain with the covering of the head with a helmet (24) or mask and hood (25) but neither of these studies were designed to test the effects of these additional protective items on thermotolerance. Interestingly, earlier work by McLellan et al. (162) reported lower T_c and higher HR at exhaustion when full rather than partial PPC was worn while performing heavy exercise at 30°C and 50% relative humidity. These data are in contrast to the effects of full encapsulation reported by Montain et al. (170) and suggest that cardiovascular rather than thermal strain may limit tolerance under certain exercise and heat-stress conditions.

Aerobic fitness

Havenith and van Middendorp (102) reported that inter-individual variations in aerobic fitness and anthropometric measures could account for a significant portion of the variance in heat storage not explained by differences in metabolic rate and environmental conditions. In either temperate, hot-dry (21, 225), or hot-wet environments (100), $\dot{V}O_{2\,max}$ was significantly and inversely correlated with core temperature and heart rate. Although there is a wealth of information that supports the benefits of an increased aerobic fitness for reducing the thermal and cardiovascular strain during exercise in environmental conditions that promote evaporative heat loss [for review see Armstrong and Pandolf (5)], it is not as clear whether aerobic fitness influences tolerance to UHS. Certainly differences in $\dot{V}O_{2\,max}$ alone are not a good predictor of differences in T_c tolerated at exhaustion during UHS (172, 198, 214, 215), indicating that the amount and type of regular physical activity may be more critical for improving heat tolerance (7, 105, 214). A series of studies using a cross-sectional design, however, has repeatedly verified the importance of aerobic fitness for increasing the T_c tolerated at exhaustion while wearing PPC (33, 216, 220). In these studies both $\dot{V}O_{2\,max}$ and habitual levels of regular activity were used to classify groups as either endurance-trained or sedentary. It is also important to note that as our understanding of those factors that influenced tolerance to UHS increased over the course of these studies, so did our ethical ceilings for the T_c used to withdraw participants from the heat-stress exposure. Table 4 below shows that as the ethical ceilings increased from 39.3°C (33) to 39.5°C (216) and finally to 40.0°C (220) so did the T_c tolerated at exhaustion for those participants classified as endurance-trained. However, and equally important, the T_c tolerated at exhaustion did not increase for those classified as sedentary.

As mentioned above, others have indicated that aerobic fitness does not influence the T_c tolerated at exhaustion during UHS (172, 198, 214). One potential problem with experimental designs that do not involve the use of PPC relates to the rate of heat production required to create UHS. For example, Périard et al. (198) compared T_c tolerated between trained ($\dot{V}O_{2\,max}$ of 66 ml·kg^{-1}·min^{-1}) and untrained ($\dot{V}O_{2\,max}$ of 53 ml·kg^{-1}·min^{-1}) during exercise at 60% and 75% $\dot{V}O_{2\,max}$ at 40°C and 50% relative humidity. At these high rates of heat production exercise trials lasted approximately 60 min at 60% and 30 min at 75% $\dot{V}O_{2\,max}$ and exhaustion was associated with near maximal levels of cardiovascular strain. Final T_c was not different between groups although the authors did report that for four of the eight trained participants the exercise trial at 60% $\dot{V}O_{2\,max}$ was terminated when the ethical limit of 39.5°C for T_c was attained. In contrast, at lower rates of heat production, representing only 25% to 30% $\dot{V}O_{2\,max}$ while wearing PPC, exhaustion occurs without reaching maximal heart rates (33, 220). For example, Selkirk et al. (220) reported that heart rates at exhaustion were similar between endurance-trained and untrained participants reaching approximately

Table 4 Aerobic Fitness ($\dot{V}O_{2\,max}$) and Core Temperature (T_c) Tolerated at Exhaustion while Wearing Encapsulating Clothing and Exercising at 40°C and 30% Relative Humidity for Participants Engaged in Regular Aerobic Training more than Three Times Per Week (Endurance Trained) or Not Engaged in Regular Aerobic Training (Sedentary)

	Endurance Trained		Sedentary	
T_c Ethical Ceiling	$\dot{V}O_{2\,max}$ (ml·kg^{-1}·min^{-1})	T_c (°C)	$\dot{V}O_{2\,max}$ (ml·kg^{-1}·min^{-1})	T_c (°C)
39.3°C (33)	60 (3) (n = 8)	39.2 (0.2)*†	46 (3) (n = 7)	38.7 (0.3)
39.5°C (216)	55 (5) (n = 12)	39.4 (0.2)*†	44 (4) (n = 12)	38.7 (0.5)
40.0°C (221)	62 (6) (n = 12)	39.7 (0.3)*†	42 (3) (n = 11)	39.0 (0.3)
All studies	(n = 32)	39.4 (0.3)*	(n = 30)	38.8 (0.4)

NOTE. Values are mean (SD). * indicates significant difference between endurance trained and sedentary whereas † indicates a significant difference between other endurance trained T_c values at exhaustion.

80% of maximal values. Only 2 of the 38 participants in these combined studies (33, 220) ended their heat-stress exposure after reaching the ethical ceiling of 95% of maximal heart rate. Thus, under these conditions of UHS where rates of T_c increase approximated 1°C·h^{-1}, differences in TT between endurance-trained and untrained primarily reflect the differences in T_c tolerated. In addition, others have also demonstrated differences in the T_{re} tolerated during passive heating, where it was reported that only 4 of 11 (36%) inactive participants could tolerate increases in T_{re} to 39.0°C, whereas 22 of 26 (85%) regularly active or endurance trained participants could endure this increase in thermal strain (176). At higher rates of heat storage exceeding 2°C·h^{-1} it is evident that limits to cardiovascular strain may be reached sooner than limits of thermal strain, thereby leading to conditions where T_c tolerated at exhaustion is not different between endurance-trained and untrained participants (198). This is further demonstrated from earlier data by Cheung and McLellan (34), which compared tolerance during UHS at heavy and light metabolic rates. Shown below in Figure 8 is the

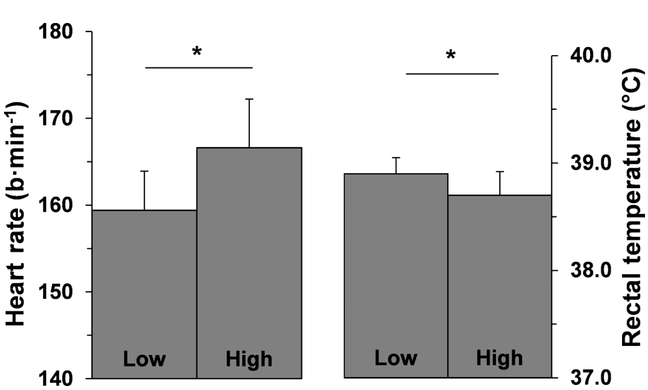

Figure 8 Heart rate and rectal temperature tolerated at exhaustion during low exercise intensity of 165 W·m^2 with a tolerance time of 105 min versus high exercise intensity of 260 W·m^2 and tolerance time of 60 min. The asterisk indicates a significant difference between the low and high exercise intensities.

impact of rates of heat production on limits of cardiovascular and thermal strain tolerated while wearing PPC. During heavy exercise equivalent to 260 W·m^2 and TT of 60 min the heart rate and T_{re} tolerated at exhaustion were significantly higher and lower, respectively, from values observed during lighter exercise at 165 W·m^2 that led to TT of 105 min. It is conceivable that even higher heart rates and lower T_{re} values at exhaustion may have been observed had the exercise intensity been even higher and TT reduced. However, Montain et al. (171) reported higher heart rates but similar T_{re} levels at exhaustion in full PPC during heavy exercise at 300 W·m^{-2} lasting 45 min compared with moderate exercise at 210 W·m^{-2} that lasted 65 min. It should be apparent that additional research is required to help clarify the discrepant findings revealed for the T_{re} tolerated at exhaustion between endurance-trained and untrained in PPC (33, 216, 220) versus UHS conditions that have not involved the wearing of PPC (172, 198).

There are pronounced physiological adaptations that accompany regular aerobic exercise that can account for the higher thermotolerance of endurance-trained versus untrained individuals. The expanded plasma volume for the endurance-trained confers greater protection from gut endotoxin leakage as thermal strain rises above 38.0°C during UHS (210, 220). Furthermore, cellular adaptations related to the expression of heat stress proteins, coupled with improved anti-inflammatory cytokine profiles at temperatures above 39°C, reduce the impact of increasing thermal strain and help to maintain gastrointestinal barrier integrity (220, 221). In addition, since a given absolute level of thermal strain represents a lower relative strain for the endurance-trained, due to their ability to tolerate higher T_{re} values, key neuroendocrine stress cascades are also significantly reduced (259, 260). Prolactin concentrations, a known marker of fatigue, were lower in endurance trained individuals for a given level of thermal strain, yet similar at exhaustion despite higher T_c tolerated for the endurance-trained compared to untrained individuals (260). Indeed, the change in prolactin in the peripheral circulation during exercise and heat stress appears to be highly dependent on thermal strain (258).

It is noteworthy that nearly half of the endurance-trained individuals reached the ethical limit of 40.0°C (220, 260), yet verbally indicated that they would have been able to continue exercising if permitted, whereas all untrained individuals succumbed to volitional fatigue at a lower T_c. Subsequently, therefore, it is indeed the highly motivated endurance athletes which are more susceptible to the manifestation of exertional heat illness in these harsh environmental conditions with high rectal temperatures. Untrained individuals, who are under significant cardiovascular and thermoregulatory strain, will fatigue and voluntarily terminate exercise at a lower T_c (198), thus lowering their risk of excessive temperature elevations, yet at the same time, may be at risk for developing early signs/symptoms of exertional heat illness at much lower temperature thresholds (220).

Beyond physiological adaptations, high aerobic fitness may provide a perceptual attenuation of thermal discomfort that increases final core temperature tolerated, and thus exercise capacity in UHS. In a cross-sectional study of untrained and trained males and females ($\dot{V}O_{2\,max}$ of 43.6 and 59.0 mL·min^{-1}·kg^{-1}, respectively) exercising in PPC at an identical workload of 3.5 km·h^{-1} in a hot (40°C, 30% RH) environment, the level of physiological strain, modeled as a function of heart rate and rectal temperature, were similar across groups (242).

The perceptual strain, equivalently modeled from ratings of perceived effort and thermal comfort, closely matched physiological strain for the untrained group throughout exercise. However, for the trained group, a mismatch was observed throughout exercise, with the perceptual strain significantly underestimating their own physiological strain throughout exercise and much lower than that of the untrained group (242). Interestingly, when the maximum T_c used to calculate the PSI was increased from 39.5°C to 40.1°C the perceptual and physiological strain were matched for the trained group.

Morrison et al. (176) also used a cross-sectional design with three distinct fitness groups (highly trained: 71.2; moderately trained: 57.2; lower-fit: 49.6 mL·min^{-1}·kg^{-1}) in assessing neuromuscular functioning with passive hyperthermia. Interestingly, only 4/11 lower-fit participants voluntarily tolerated passive heating to 39.0°C, compared with 11/13 for each of the highly and moderately fit groups. These different limits of tolerance are depicted below in Figure 9. In each case, the reason for termination was voluntary choice by the subject, rather than any physiological guideline being reached. This also indirectly suggests that perceived thermal discomfort is attenuated as a consequence of aerobic training and can contribute to the higher tolerated core temperatures in fit individuals.

If the T_c tolerated is increased for the endurance-trained, the question naturally follows whether the T_c tolerated at exhaustion will be increased for sedentary participants that undergo an aerobic training program. The effectiveness of these programs for improving heat tolerance would appear

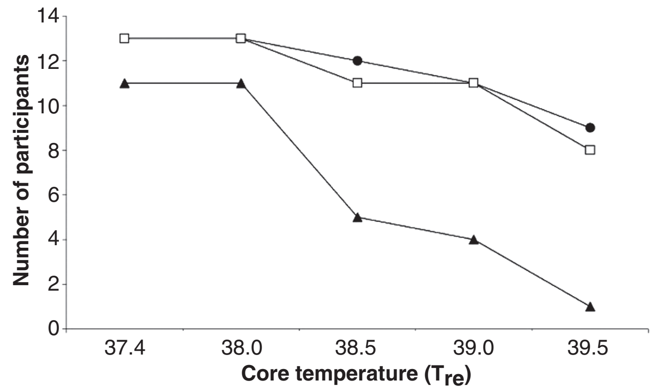

Figure 9 Sample size of participants from each training status throughout a passive heating protocol. The highly fit (circles), moderately fit (squares), and lower fit (triangles) groups began with similar sample sizes, although the majority of the lower fit participants were unable to complete the protocol. Reproduced, with permission, from Morrison et al. (176).

to be dependent on many variables, including the intensity, duration and frequency of training. Metabolic hyperthermia is the major stimulus for thermoregulatory adaptations (68) and the degree and duration of T_c rise induced by training may be the critical determinant for the degree of heat adaptation. A greater sweating response and heat tolerance was noted following land-based, compared to water-based, training on a group of previously untrained subjects, with the disparity being attributed to the higher level of metabolic hyperthermia and sweating rates during land-based exercise (7). Interestingly, however, the training-induced rise in T_c on a daily basis is not essential for the observed adaptations in aerobic capacity (263).

Few studies have compared the heat tolerance response of unfit subjects during UHS before and after a controlled endurance training program designed to improve aerobic fitness. We have examined this response with the use of two different training models. Our first attempt used the more classical endurance training model that involved typical progressions in intensity from 60% to 80% $\dot{V}O_{2\,max}$, frequency from 3 to 4 days·week^{-1} and duration from 30 to 45 min·session^{-1} over an 8 week period (2). This training program increased $\dot{V}O_{2\,max}$ approximately 15% from 40 to 46 mL·min^{-1}·kg^{-1} and produced significant decreases in heart rate and T_{re} responses during 2 h of compensable heat stress exposure at 40°C and 30% relative humidity. In addition, control subjects showed no change in $\dot{V}O_{2\,max}$ over the 8-week period and no change in their thermoregulatory or cardiovascular response during the 2 h of compensable heat stress. However, the endurance training program offered no benefit to the subjects during UHS which involved the encapsulating PPC. TTs remained unchanged at 50 min during heavy exercise at 550 watts and T_{re} and heart rate responses also were unaffected by the training program. Interestingly, sweat rates were elevated after the training but evaporative heat loss was unchanged when the PPC was worn indicating that the characteristics of the clothing determine the amount of evaporative heat loss to the environment.

Next, a short-term aerobic training model, which had been reported to induce rapid cardiovascular and thermoregulatory changes during submaximal exercise (87), was examined (35). The 12 days of training for 1 h·d^{-1} at 65% $\dot{V}O_{2\,max}$ led to significant decreases in the rise in T_{re} and heart rate at the end of the 1 h of walking in a thermoneutral environment and small but significant increases in $\dot{V}O_{2\,max}$ of 5%. During the UHS condition with PPC there were no changes in the heart rate or T_{re} responses during exercise at 380 watts and TT approximated 90 min regardless of the state of training (35).

The ability of short-term aerobic training of sedentary or moderately fit individuals to replicate the decreased physiological strain and elevated exercise-heat tolerance observed with endurance-trained individuals is of direct occupational interest. In many occupational settings, workers may be required to work in hot environments with minimal preparation time to significantly increase aerobic fitness or facilities to perform heat acclimation with PPC. In these environments, short-term aerobic training is not an adequate substitute for a high level of aerobic fitness resulting from habitual exercise and training (36). Following 2 weeks of aerobic training, cardiovascular and thermal strains during UHS were similar in individuals of moderate fitness compared with those of high fitness. However, the range of core temperature that could be tolerated during the heat exposure remained significantly lower in moderately fit individuals, as did TT and the final T_c tolerated prior to the onset of voluntary exhaustion.

Based on the findings from these studies (2, 35, 36) aerobic training programs lasting from 2 to 8 weeks offer little benefit to work performance in the heat for previously unfit subjects when PPC is worn. Yet, the cross-sectional analyses presented above (33, 216, 220) support the importance of aerobic fitness to improve work performance when a very hot and humid microenvironment is created with the use of PPC. It is conceivable, therefore, that tolerance for less fit individuals is related more to the strain on the cardiovascular system in its attempt to dissipate body heat and maintain arterial blood pressure, whereas the increase in body heat content may be the greater limiting factor for more fit subjects. In addition, differences in body fatness between fitness groups (216), protection from gut endotoxin leakage and heat stress protein response (220, 221), as well as the reduction in neuroendocrine stress cascades (259, 260) that occur following months or years of regular aerobic training may all be involved in explaining the differences in thermotolerance between endurance-trained and sedentary individuals during UHS created with exercise while wearing PPC.

Laboratory versus field studies

There has been one comprehensive comparative evaluation of the thermotolerance to UHS during intermittent and continuous exercise in a desert environment while wearing encapsulating military biological and chemical PPC (214). The findings revealed that T_c tolerated at exhaustion was increased about 0.8°C for soldiers stationed and working daily in the summer desert heat of Arizona compared with a dataset compiled from many years of testing in controlled laboratory conditions. Since the participants in the field or laboratory datasets had comparable fitness levels, the authors suggested that the greater heat acclimatization for those living and working in the desert environment compared with the short-term heat acclimation programs employed during laboratory studies may have accounted for these differences (214). It is also interesting that the differences in thermotolerance between field and laboratory studies is comparable to the differences in T_c tolerated between endurance-trained and sedentary participants discussed above (see Table 2). These similarities may further support the view that $\dot{V}O_{2\,max}$ values alone are not a good predictor of the T_c that can be tolerated (215) and that, in addition, regular activity patterns are also important.

Blood volume expansion

Approximately one-half of the difference in the exercise stroke volume between trained and untrained subjects can be attributed to their differences in blood volume (112). Thus, some of the differences in the cardiovascular strain during exercise in the heat between trained and untrained subjects could reflect their differences in central blood volume. It is also noteworthy that plasma volume expansion has been shown to have no effect on the core temperature response for the endurance trained during exercise in a warm environment (168, 251) or for the moderately trained during exercise in the heat (213) whereas plasma volume expansion in untrained subjects has been successful in lowering the core temperature during submaximal exercise in a warm (187) but not a cool environment (86, 209). It is important to note that only two of these studies involved exposure to UHS (213, 251) and that only the study by Sawka et al. (213) that utilized a randomized treatment order included end-point criteria of a high rectal temperature or heart rate to assess TT. Sawka et al. (213) reported a nonsignificant increase in TT of 16% or 10 min following plasma volume expansion with 7 subjects. They also reported, however, that whereas only 1 subject was able to complete 90 min of exercise in the control trial and five subjects terminated the session due to exhaustion, three subjects completed the exercise following plasma volume expansion, and only two subjects terminated their trial due to exhaustion. Thus, with a larger sample size of untrained subjects, it is possible that increasing plasma volume may allow a higher core temperature to be tolerated before exhaustion occurs. Nevertheless, these studies have not been done but certainly the differences in blood volume between endurance trained and untrained (220) could account for some of the difference in T_c tolerated at exhaustion.

Fluid ingestion

Independent of any effects of fluid ingestion on rates of heat storage during UHS (see below), there is some evidence to support the benefit of fluid ingestion for increasing the T_c tolerated at exhaustion. During an intermittent work and rest protocol during UHS with firefighting PPC, Selkirk et al. (219) reported higher T_c at exhaustion when fluid was provided throughout the heat-stress exposure compared with no fluid ingestion. Interestingly, all participants ended their trial during the rest period when fluid was restricted, whereas all participants ended their trials while walking if sufficient fluid was provided. Thus, when fluid is restricted cardiovascular stability is compromised such that exhaustion occurs at a lower T_c during weight-bearing activity. Whether similar effects would be observed during weight-supported exercise, such as cycling, has not been reported.

Rate of heat storage

Environmental influences

As shown in Eq. (1), the rate of heat storage is determined by the relationship between avenues for heat loss and heat gain. If the ambient temperature exceeds skin temperature then dry heat exchange represents a source of heat gain and avenues for heat loss will be dependent on the vapor pressure gradient established through the PPC clothing layers and the ambient environment (22) and respiratory heat loss (138). The kinetics of evaporative heat loss are largely established by the characteristics of the clothing (47). High rates of activity while wearing PPC, however, may result in situations where the rates of heat storage and heat tolerance are governed primarily by the rate of heat production and not by environmental conditions, as was shown earlier in Figure 3. In these situations, variations in ambient water vapor pressure, which help to establish the gradient for evaporative heat loss [see Eq. (5)], may have little impact on heat tolerance (153, 164).

Body composition

At a given rate of heat production per unit of tissue mass, the change in temperature of that mass will be dependent on its heat capacity. Typically, the heat capacity of the body's tissue is estimated at 3.47 $kJ{\cdot}kg^{-1}{\cdot}°C^{-1}$. However, since the heat capacity of adipose tissue is approximately one-half of lean tissue (72), individuals with a higher body fatness should have a faster rise in T_c for any given rate of heat production during UHS. Indeed, McLellan (156) reported that T_c increased more rapidly for women who stored less heat per unit of mass compared with their male counterparts while performing intermittent exercise in the heat with PPC. Differences in heat storage between the sexes disappeared when they were matched for body fatness (156), implying that differences in heat tolerance between men and women, in general, is not a sex-related issue but rather one of body composition. Interestingly, this cross-sectional comparison between the sexes also revealed that those individuals that tolerated the highest T_{re} at exhaustion had a lower body fatness and higher $\dot{V}O_{2\,max}$ regardless of sex compared with individuals that could not tolerate high T_{re} values (156).

Given that other cross-sectional comparisons between endurance-trained and untrained males contrasted lean and aerobically fit participants against unfit individuals with a higher body fatness, a study was conducted that attempted to extract the importance of fitness and fatness on tolerance to UHS (216). This study involved testing over 50 volunteers to match 24 for both high and low levels of aerobic fitness and body fatness. The findings revealed that a high aerobic fitness, regardless of body fatness, was associated with higher T_{re} tolerated at exhaustion, as discussed previously. In addition, the comparisons also showed that a lower rather than a higher body fatness led to a slower rate of increase in T_{re} (1.3°C·h^{-1} vs. 1.6°C·h^{-1}, respectively) and longer TTs (116 vs. 82 min, respectively) for those individuals matched with a high aerobic fitness. However, rather surprisingly, the comparisons did not reveal an advantage for the leaner individuals who were matched with a low aerobic fitness (216). As discussed below, subsequent analyses also highlighted the importance of movement economy when the PPC is worn during treadmill exercise.

Individuals with a high surface to volume ratio benefit from this since both dry and wet heat loss can take place over a relatively larger surface area. It is not surprising that the surface-to-volume ratio of people originating from around the equator is more than 10% higher than those from polar regions (137). The superior running performance of black athletes in the heat as compared to Caucasians with similar running performance in thermoneutral circumstances (149) can be explained by their body composition (150). The reduced weight and corresponding larger relative body surface area of African runners are held responsible for the performance differences in the heat. When wearing PPC, the described benefits may not apply since the surface area of the garments may become more important than that of the human skin.

The aging process, *per se*, is known to reduce heat-induced vasodilation (125), which, in theory, should increase $\dot{S}$ for any given $\dot{M}$. The aging process is also associated typically with a more sedentary lifestyle and an increase in body fatness, which would both reduce TT while wearing PPC. However, when older and younger individuals are matched for body fatness, surface area-to-mass ratio and aerobic fitness there is little impact of age on the thermoregulatory response to heat stress (124, 191, 193, 231) and a similar conclusion would be expected with the use of PPC. Regression analyses also revealed that age had no influence on T_{re} or $\dot{S}$ during heat stress, which were closely related to $\dot{V}O_{2\,max}$ (99). Yet these earlier cross-sectional comparisons fail to account for the decrease in $\dot{V}O_{2\,max}$ with age that occurs regardless of activity level (256), implying that older and younger comparisons between groups matched for $\dot{V}O_{2\,max}$ may actually be comparing more active older and less active younger participants. Studies to date have not considered activity patterns as an independent factor for comparing the exercise heat-stress response for older and younger individuals and it is not known whether older, less active individuals could be at greater risk of heat injury while wearing PPC than their younger counterparts. Confounding these comparisons in an occupational setting requiring the use of PPC would also be the fact that work experience on job-related specific tasks may improve the efficiency of performing those tasks, such that $\dot{M}$ may actually be reduced for the older more experienced worker.

Gross movement economy

As shown in Eq. (1), $\dot{S}$ represents the balance between sources of heat gain and avenues of heat loss. When comparisons are made between groups of individuals often $\dot{S}$ is assumed to be similar when the same PPC is worn during exercise while exposed to a hot environment. However, if movement economy is different between groups then $\dot{M}$ and $\dot{S}$ will also be different. As a result, the influence of various physiological differences between groups on tolerance to UHS could be misinterpreted. For example, in the study previously discussed, the influence of differences in body fatness on tolerance to UHS was not observed for individuals who were matched for a low aerobic fitness (216). Closer analyses revealed, however, that the participants with the higher body fatness had an improved movement economy at the slow speed of walking at 3.5 km·h^{-1}. Others have also shown that individuals with higher body fatness have improved economy of movement at slower speeds of walking (29, 48). As shown in Table 5, this improved movement economy reduced $\dot{S}$ for this group such that their rate of increase in T_{re} and TT was similar to the group with the same aerobic fitness but lower body fatness.

As was discussed earlier (see Fig. 1), the wearing of PPC typically increases the energy cost of movement beyond what would be due to the added weight of the ensemble (58,61,239). Yet even while wearing the same PPC there is considerable individual variation in the decrease in movement economy associated with walking or stepping exercise (58). Indeed, compared with wearing track pants and a sweat shirt, there was no significant increase in the oxygen cost of performing an obstacle course while wearing biological and chemical PPC, although mean values were increased 17% (58). Nevertheless, typically the hobbling effect of the clothing decreases movement economy (58, 61, 239), which further increases the heat production associated with wearing the PPC, and this additional penalty needs to be considered when rates of heat production are estimated for various activities or occupational tasks, especially since occupational guidelines are defined in terms of the absolute metabolic rate.

Work/rest schedules

The curves shown in Figure 3 can also be used to help explain whether implementing work and rest schedules while wearing this protective clothing is the correct strategy (154). For example, the vertical asymptote for the desert condition (40°C and 15% relative humidity) occurs at a metabolic rate of 100 W·m^{-2}. At metabolic rates greater than this value there will be continued heat storage since the conditions represent UHS, whereas at metabolic rates below this asymptotic value cooling will occur since these conditions represent compensable heat stress. The reader should note that the metabolic heat production at rest is about 50 W·m^{-2}. If the soldier was performing a reconnaissance patrol moving at a slow speed the rate of heat production might approximate 175 W·m^{-2}. After 30 min of patrol, T_c might increase from 37.0°C to 38.0°C in the UHS conditions. If this were then followed by 15 min of rest, which would now represent compensable heat stress, core temperature might decrease to 37.5°C. The next 30 min of patrol would increase core temperature to 38.5°C followed again by another rest period which would lower core temperature again. A final 30-min patrol might then increase core temperature to 39.0°C where the soldier might begin to experience symptoms of exertional heat illness. Thus, in contrast to the 60 min of continuous work that would lead to core temperatures around 39.0°C, 90 min of total work are performed with this work and rest schedule. Therefore, in these dry desert conditions, implementing work and rest schedules is the correct strategy for increasing the total work output.

However, the metabolic rate that defines the vertical asymptote for the hot and humid environment (40°C and 65% relative humidity) occurs at a nonphysiological value of 10 W·m^{-2} implying that even under resting conditions there will be continued body heat storage. Thus, during rest periods

Table 5 Rates of Heat Storage ($\dot{S}$) Determined from Partitional Calorimetry, Changes in Rectal Temperature (ΔT_{re}), T_{re} Tolerated at Exhaustion and TT during Uncompensable Heat Stress while Wearing Protective Clothing for Groups Matched for Aerobic Fitness and Body Fatness

Group	$\dot{S}$ (W·kg^{-1})	Rate of ΔT_{re} (°C·h^{-1})	T_{re} tolerated (°C)	TT (min)
High fitness/low fatness	3.27	1.27	39.5‡	116‡
High fitness/high fatness	3.41	1.55†	39.2§	82†
Low fitness/low fatness	3.52	1.20	38.6	70
Low fitness/high fatness	2.87*	1.23	38.8	74

NOTE. * indicates significantly different from the other groups; † indicates significantly different from high fitness/low fatness; ‡ indicates significantly different from low fitness/low fatness; and § indicates significantly different from low fitness/high fatness.

the soldier's core temperature will continue to increase and the next work bout will begin at an even higher core temperature than at the beginning of the previous rest period. As a result, less total work will be performed before symptoms of exertional heat illness are seen. In these very hot and humid environments, therefore, implementing work and rest schedules may not be the most prudent strategy if the objective is to move to a safer area where the protective clothing can be removed and the soldier can then cool more effectively. This has also been alluded to by an earlier publication by Kamon et al. (120) that reported a progressive rise in T_c during repeated work and rest schedules in a hot humid environment that also subsequently necessitated increased rest periods in a cool environment to return T_c to baseline levels.

Models can also be used to develop effective guidance for supervisors to predict continuous work times and provide work and rest schedules that could be adopted to help manage the heat strain of wearing protective clothing. If the models have been validated with human data in laboratory trials (74, 85), then there is greater confidence in their use for predicting heat strain responses in other PPC, environmental conditions, and rates of heat production. Work and rest schedules have been developed for the military and first responder community using predictive models validated initially from human laboratory testing (154, 217). However, it is important to remember that the individual variation in thermotolerance is quite large due to the influence of factors discussed. As a result, although these models can accurately predict the mean responses during exposure to various environmental conditions with different types of PPC, the variation about this mean response can be substantial.

Pacing strategies

The work pace during prolonged work in the heat is continuously regulated to prevent changes in physiological systems that may be limiting or detrimental to performance. The initial pace is rather independent of ambient temperature. After several minutes, however, the pace starts to drop (233, 238, 245). The metabolic heat production is reduced to compensate for the increase in body heat storage that results from the hampered heat loss. Therefore, it may be beneficial to start at a slower pace in the heat to reduce the initial speed of heat storage and thus override the tendency to slow down the metabolic rate later. Also precooling has been shown to reduce the "dip" in performance during exercise in the heat (60). In general, when people have the freedom to choose their own pacing rate during work in the heat, the risk for heat injuries is much less than when a fixed tempo is enforced on the worker (166).

Cooling

As previously discussed, precooling has been shown to effectively reduce heat strain in work. Cooling during work has the benefit that the produced heat can be (partly) compensated for immediately. For personnel working in conditions with power

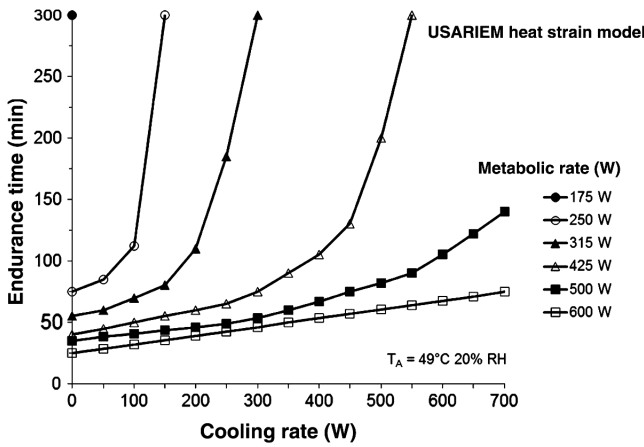

Figure 10 The theoretical effect of cooling on tolerance time in protective equipment based on modeling studies. Reproduced, with permission, from Pandolf et al. (194).

supplies available, like in transport systems, cooling during work may be appropriate. However, for personnel that have to move around in the work environment, personal cooling is a challenge since the cooling system has to be carried or a link to the cooling system has to be made.

Less cooling power is required to stay in thermal equilibrium during rest than during heavy exercise. Figure 10 shows the results of modeling studies regarding the relation between rate of cooling and endurance time at different metabolic rates (194). Cooling extraction rates of about 100 W have almost no impact on TT during heavy exercise (metabolism 600 W), but leads to increased performance during light work (metabolism 250 W). Therefore, the application of cooling systems should always be considered in relation to the task that is performed.

One avenue of engineering and research has been in designing control systems for automatic control of cooling within protective clothing, basing the control algorithm on a variety of possible physiological feedback factors (66). Ideally, such systems are able to achieve optimal control and cooling while minimizing energy use and therefore power and weight requirements. Many physiological indicators have been experimented with such control systems, including skin temperature, heart rate, carbon dioxide production, sweat rate, metabolic rate, and core temperature; in some cases, a combination of a rapid responding (e.g., skin temperature) and a slower responding (e.g., metabolic rate) indicator has been employed to achieve both rapid and sustained response control (66). Alternately, control utilizing carbon dioxide production as an index of metabolic heat production, along with mean body temperature (calculated from ear canal and mean skin temperatures) as an index of thermal comfort, has been successfully tested (189).

A simpler system may be possible from only skin temperature feedback. Stephenson et al. (235) reported that a pulsed cooling algorithm, with cooling being activated at a Tsk $>34.5°C$ and deactivated when Tsk $< 33.5°C$, was as effective in cooling as time-based pulsed cooling (2 min on, 2 min off) or constant cooling, yet reduced power consumption by 46% compared with constant cooling. Regardless of the control system, it appears important to avoid prolonged cooling of the body that can lead to skin vasoconstriction and thermogenesis. Both physiological responses are undesired since they counteract cooling efficiency. For example, it is recommended to stop cooling when skin temperature drops below values of 33°C (40), as this value can be considered as the threshold below which vasoconstriction starts to increase.

In general, one can distinguish between four main cooling methods: liquid cooling systems, air cooling systems, phase change materials (PCMs) and external extremity cooling.

Liquid cooling systems Liquid cooled systems have the advantage that considerable amounts of body heat can be removed effectively, but a power supply, pump, and heat exchanger are imperative. In a manikin study, Frim et al. (69) showed that a decreased inlet temperature and increased tubing length causes an almost linear increase in heat loss. The heat removal becomes essentially independent of flow rate at higher flows. The maximum heat removal is about 170 W under optimal conditions. Generally, water is taken as the cooling fluid. It has the advantage that leakages do not cause severe problems. However, other cooling fluids like glycol are known to have higher heat capacity and may thus be more effective in removing heat. At this moment, it is generally accepted that the disadvantages in terms of bulk and mass outweigh the benefits for dismounted soldiers and fire fighters wearing PPC. However, liquid cooling systems could be a viable option to reduce T_c during rehabilitation or rest periods when the PPC can be removed (43).

Air cooling systems The simplest version of air cooling is using ventilation only. In this case, ambient air is blown in the air space between the skin and the inner clothing layer. Reffeltrath (202) introduced 32°C ambient air in the immersion suit of a pilot and observed an increase in evaporation efficiency from 57% to 90%. The core temperature increase during the flight task was 0.5°C in 2 h as opposed to 1.0°C in 2 h without ventilation cooling. The extra evaporative cooling energy matched the reduced body heat gain during forced ventilation. Barwood et al. (9) used ventilated vests in extreme hot dry conditions (45°C/10% RH) during military tasks and observed reduced thermal strain and increased exercise performance without causing skin irritation and discomfort.

In contaminated environments, ambient air can only be used for ventilation of the air layer in the suit after filtering. Due to the high ventilation rates (typically several hundred liters per minute) adequate filtering is often impossible. If the air in the volume between skin and protective garment is pumped around without any (filtered) air from the outside, the evaporated sweat will be more evenly distributed. However, the air layer will become saturated in a few minutes during exercise, thus offering little advantage to the wearer.

For the dismounted soldier, systems are available that ventilate the air layer created by spacer materials under the ballistic vest. As ambient temperature and vapor pressure increase the effectiveness of these systems will decrease (41). Evaluation of these systems generally shows that the small benefit due to increased evaporation efficiency is outweighed by the increased weight and mass of the system. The cooling efficiency increases when the air is cooled or dried prior to entering the suit. Air can be cooled through several methods, such as adiabatic expansion and the use of a vortex pipe. However, these methods are rarely used in human cooling systems despite their potential.

Phase change materials Most materials absorb heat when they change from a solid to a liquid state. Ice vests are an example. Wearing an the ice vest has been shown to increase exercise time in biological and chemical protective clothing in a hot wet environment from 104 to 116 minutes while esophageal temperature was 0.3°C lower in the end (126). More recently, PCM based on paraffin are incorporated in clothing systems to function as a thermal buffer. However, large quantities of PCMs are generally necessary to observe noticeable effects. Gao et al. (71) compared two PCM vests with different melting points during work in extreme heat, but found no reduction in core temperature. Probably, the vests made it more difficult to evaporate the produced sweat so that the net effect was not positive.

Extremity cooling Early work by Livingstone et al. (139, 140) and House et al. (115) and House (114) revealed that the arteriovenous anastomoses (AVA), located in the palms of the hands and finger tips and soles of the feet and toes, are very effective when immersed in cold water for transferring heat from T_c. These AVA open up when the local tissue temperature in the extremities decrease below a certain threshold, a process called cold-induced vasodilation (51). Indeed, House et al. (115) and House (114) showed that the rate of cooling from the immersed hands and forearms is dependent on the thermal gradient between T_c and the water bath, such that greater rates of cooling are evident when the hands were immersed in 10°C versus 20°C or 30°C water. Another important observation from this work was that cooling continued until T_c returned to resting levels, implying that the regulation of the AVA was controlled centrally under conditions of heat strain rather than locally by the temperature of the surrounding skin temperature. These observations suggest, therefore, that the AVA would remain a very effective mechanism for transferring heat from T_c even if the hands were immersed in very cold ice water.

The use of hand and forearm immersion to assist with the management of heat strain for firefighters has been demonstrated by Selkirk et al. (218), as shown in Figure 11. Fire services may require their personnel to go to a rehabilitation station after using one or two cylinders of air. During this rehabilitation period, most of the firefighting PPC is removed and the 15 to 20 min of rest can be used to actively cool the firefighter. Selkirk et al. (218) revealed that TT was increased 65% when the hands and forearms were immersed in cool

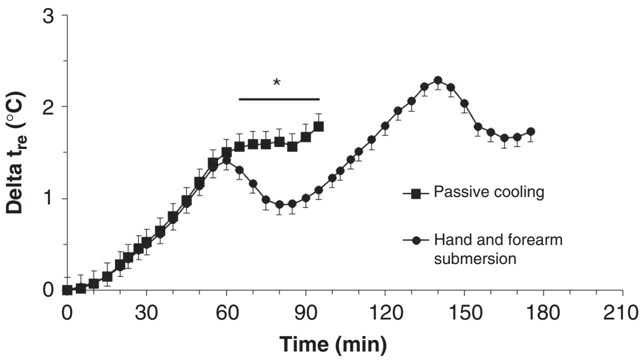

Figure 11 The effects of hand and forearm submersion in 18°C water for 20 min on the increase in rectal temperature (expressed as delta T_{re}) following 50 min of exercise at 35°C while wearing full firefighting PPC. The asterisk indicates a significant difference between the hand and forearm immersion trial compared with the condition that involved passive cooling when some of the firefighting PPC was removed during the 20-min rest periods. Tolerance time was increased significantly from 108 ± 14 min with passive cooling to 179 ± 50 min with hand and forearm submersion. Adapted from Selkirk et al. (218).

water of 18°C, which was the in-line hose temperature available to the fire service. Selkirk's study also demonstrated that 70% of the total cooling occurred during the first 10 min of immersion when the thermal gradient between T_c and the water bath was the greatest. Thus, very short cooling periods may still promote effective cooling to lower T_c prior to the start of the next work period. Immersion in colder water will promote even greater heat loss, especially if the forearms are also immersed to maintain the reduced temperature of the blood returning from the hands to the core (73, 139).

Giesbrecht et al. (73) demonstrated that cooling was more effective during rest periods following exposure to UHS with PPC when hands were immersed in 10°C rather than 20°C water, similar to the earlier findings by House et al. (115), and that hand and forearm immersion in either water bath temperature was more effective than immersion of only the hands. In addition, the earlier work by House (114) showed that immersion of both the hands and feet in 10°C water produced faster rates of cooling during the initial 10 min of immersion compared with the immersion of either the hands or feet alone.

Hydration

In a compensable heat stress environment, fluid replacement has been demonstrated to have a major influence on cardiovascular and thermal responses during set-workload exercise. An important study performed by Montain and Coyle (169) compared responses to ~65% $\dot{V}O_{2\,max}$ cycling in a warm environment (33°C, 50% RH) in fit cyclists while receiving fluid replacement ranging from 0% to 80% sweat loss. They reported a progressive attenuation in heart rate and core temperature responses with increasing levels of fluid replacement during exercise, and this study contributed to the emphasis on maintaining hydration status as close to euhydration as possible emphasized by the American College of Sports Medicine in the mid-1990s (44). In the past decade, a counterargument has arisen that fluid replacement on an ad libitum basis, centered around training individuals to drink according to thirst, has gained importance (184, 186). This proposal comes from anecdotal evidence of minimal fluid consumption by elite marathoners even in the heat, and also reports that elite runners can, without drinking during workouts, maintain training intensity and close to full euhydration over a heavy training period based solely on ad libitum dietary intake (70). Also, the lack of realistic airflow in many laboratory studies has been argued as artificially magnifying the impact of fluid replacement during exercise (211). In the current 2007 updated position stand (212), the overall hydration consensus has shifted slightly toward maintaining dehydration at less than 2% body weight during exercise, and to plan for fluid ingestion across a range of 400 to 800 mL.h^{-1} depending on individual (e.g., mass and acclimation status) and situational (environment and exercise intensity) factors.

In situations of UHS and wearing PPC, where airflow is typically minimal due to the presence of clothing, hydration status may be much more critical to maintaining homeostasis and performance. As discussed earlier, hydration status plays an important role in determining TT in PPC through a slight elevation in initial core temperature, thus decreasing the total thermal window available for exercise. Whenever possible, individuals should begin exercise in a euhydrated state, as fluid replacement alone cannot overcome the thermal disadvantage stemming from a state of hypohydration.

Cheung and McLellan (34) reported that TT during continuous exercise in PPC when euhydrated and given fluid replacement (200-250 mL each 15 min) was significantly higher (107 min) than when either euhydrated with no fluid replacement (93 min) or when hypohydrated by 2% to 2.5% body weight but with fluid replacement (87 min). Thus, both a state of euhydration and fluid ingestion are critical components for maximizing exercise capacity in PPC. Note that with sweat rates of 1.2 to 1.3 kg·h^{-1} during light exercise, some level of dehydration is unavoidable even with the fluid ingestion conditions. However, with mean body weights of ~75 kg in this study, overall body weight loss would equate to <1%. Note that fluid ingested does not necessarily correlate with changes in plasma volume due to the time delay between ingestion and intestinal absorption. As also discussed previously, high rates of metabolic heat production may dampen the efficacy of fluid replacement, with similar TTs of 53 to 59 min across the three conditions in that same study when exercise intensity was rated above 500 W heat production (34).

The benefit of fluid replacement during exercise in PPC has been proposed to be by increasing the heat-storage capacity of the body, rather than any changes in the rate of heat storage itself (160). However, apart from understanding that fluid replacement with exercise in PPC is critical (34), the optimal fluid replacement rate is relatively unknown and has been the focus of very few studies compared to compensable heat stress environments. Selkirk et al. (219) performed a dose-response study comparing physiological responses to graded levels of rehydration during intermittent 50-min bouts of treadmill exercise at 4.5 km·h^{-1}, 0% grade protocol with PPC in the heat. Fluid replacement occurred during the 30-min recovery breaks, and ranged from 0%, 37%, 63%, and 78% of sweating rate. Both total TT and work TTs were significantly enhanced with 78 and 63% fluid replacement compared to no rehydration, with total TT also improved with 37% rehydration. Body mass loss with 63%, 37%, and 0% fluid replacement were 1.24%, 1.52%, and 2.16%, respectively.

Gastric emptying and intestinal absorption is finite at approximately 0.8 to 1.2 L·h^{-1}, and higher rates of fluid ingestion may be counterproductive by leading to a sensation of bloating, potential nausea, risk of hyponatremia, and increased urination. In addition, the actual rate of fluid replacement may need to be adjusted depending on the type of PPC, state of encapsulation, metabolic heat production, and environmental conditions to avoid net gain in body weight (16). Thus, combined with Cheung and McLellan (34), this suggests that full maintenance of baseline body weight is not required to significantly improve TTs. Rather, moderate fluid replacement to maintain body weight loss at levels <1.5% to 2.0% might form a starting basis for occupational guidelines.

Beyond these general volume guidelines, many questions remain concerning optimizing fluid replacement strategies in PPC, as the few existing studies largely utilize plain water at near body temperature. Some important outstanding questions with no existing evidence-based data include:

- Precooling using cold water or ice slurries can decrease initial core temperature (133, 226), and cooler fluid temperatures during exercise increases voluntary fluid consumption by ~50% (18). Therefore, what are the effects of cold water in TT with PPC?
- Given the time delay for fluid entry into the body upon ingestion, and the greater rates of gastric emptying with stomach volume (167, 185), is an initial large volume of fluid preferable over an even drinking protocol?
- Intravenous infusion during recovery breaks restored plasma volume more rapidly than oral rehydration but did not decrease physiological strain nor increased TT during subsequent exercise in a compensable heat tolerance test (123). Whether this lack of difference is consistent with PPC and intermittent exercise remains unknown.

Conclusion

Although PPC is essential to ensure the safety of personnel when they are required to work in hazardous environments, the clothing restricts the exchange of heat with the environment, often creating conditions of UHS. As a result, heat storage continues until individual limits of tolerance are reached or the severity of the UHS conditions is reduced through the removal of the PPC and/or by lowering the rate of heat production. Exposure limits in the encapsulated environment are influenced by factors that affect resting T_c, the T_c tolerated at exhaustion and the rate of increase in T_c from the beginning to end of the heat-stress exposure. A summary schematic of the way that several of these factors might influence tolerance while wearing PPC in UHS conditions is depicted in Figure 12.

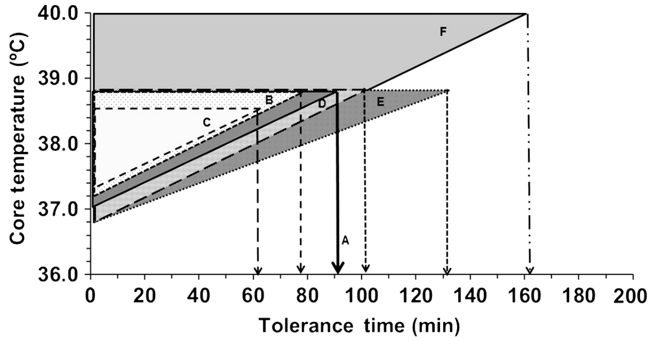

Figure 12 A schematic representation of the tolerance time during uncompensable heat stress for a sedentary untrained individual (A) and the influence of raising the initial resting core temperature due to circadian rhythm, menstrual phase or minor (B) or severe (C) hypohydration, lowering resting core temperature through heat acclimation or precooling strategies (D) and a decrease in body fatness, an increase in gross movement efficiency or providing cooling during encapsulation (E). Also depicted is the improvement in heat tolerance for an endurance trained individual (F) who can tolerate much higher core temperatures at exhaustion. The values depicted on the *x*-axis represent mean changes that would be expected from the average response observed during light exercise. Individual effects could be much greater or less.

Throughout this review, several topics were identified where additional research was needed to clarify the role of various factors in defining the limits to tolerance while in an encapsulated environment. Such research topics might include:

- The interaction between the intensity of exercise and cardiovascular strain in reducing the T_c tolerated for trained and untrained participants.
- The role of activity levels, rather than $\dot{V}O_{2\,max}$, in determining limits of thermal strain tolerated during UHS.
- The effects of cold water ingestion and/or the ingestion of a preexposure bolus of fluid on tolerance while encapsulated.
- The role of plasma volume in establishing limits of thermotolerance for untrained individuals.
- The importance of fluid replacement for maintaining orthostatic tolerance during weight-bearing activity while encapsulated.

- The role of work-related experience on efficiency of conducting occupational tasks.

Acknowledgements

The authors would like to acknowledge the effort of the many volunteers that endured the discomfort of exercising in the heat while wearing various protective clothing ensembles. T. M. McLellan would like to also acknowledge the technical assistance provided at DRDC Toronto by Mrs. I. Smith and D. Kerrigan-Brown and Mr. J. Pope and R. Limmer. The research contributions of Drs. Y. Aoyagi, G. A. Selkirk, and H. E. Wright, have also been invaluable. S. S. Cheung was supported by a Canada Research Chair.

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