Chapter 7
Behavioral and Technological Adaptation

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Abstract Maintaining a euhydrated state is critical for normal biochemical and physiological function. Hydration is normally a dynamic process of the constant loss of water from the body (insensible as well as dynamic water loss from sweating) being replaced through drinking, eating, and the metabolism of food. Significant water loss from sweating during exercise must be replaced to avoid heat and other related injuries. Monitoring of physiological processes has occurred from ancient times but has become sophisticated in the last 100 years. Wearable wireless monitoring has been developed allowing the wearer to determine their physiological status under a variety of conditions (exercise, environmental). Monitoring may help avoid injury that may occur when physiological limits are exceeded (e.g., heat stroke). In addition to physiological monitoring, wearable cooling technologies have been developed which limit the effects of environment on the physiological burden of the environment reducing the risk of heat injury to workers.

Introduction

Behavioral and technological adaptations play critical roles in reducing thermal strain during physical activity in extreme heat. For example, modifying drinking and hydration behaviors to maintain a euhydrated state is critical for normal biochemical and physiological function. This chapter aims to provide an overview of

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fluid and thermoregulatory regulation in humans and methods that are commonly utilized among the physically active population to protect or augment physiological capacity to optimize physical performance in the heat.

Hydration

Body Water

The human body is composed of approximately 60% water depending on age, fitness, and degree of acclimatization [1]. Body water contains dissolved solutes (electrolytes, proteins, etc.) necessary for cellular function and provides the aqueous medium in which all biochemical and physiological processes occur [2]. There is a dynamic turnover of body water due to several processes that can result in water gain or loss from the body. Water loss through behavioral or physiological mechanisms (not trauma) can be due to a voluntary or involuntary reduction in water intake, insensible water loss across the skin and respiratory tracts, sweating during hyperthermia or high work rates, diarrhea, and vomiting. Replacement of body water usually occurs through the ingestion of water, food-containing water, and water produced through metabolic processes [3]. In a curious coincidence, the amount of water produced solely from metabolism equals the loss of water through respiratory evaporative processes [1, 4]. However, water production from metabolism alone is not generally enough to replace the water lost through other physiological processes (sweat, urination, respiration). Thus, additional water must be consumed by drinking and eating in order to maintain a relatively euhydrated state [3, 5]. Human daily consumption of water varies greatly and can range from approximately 2.5 L to between 5 and 10 L of water per day depending on activity levels and the thermal environment [3]. For example, it is common to lose as much as 6–8 L of sweat during intense or prolonged exercise in hot and humid environments [6]. Thus, the consumption of water increases (or should) with increased physical activity to replace water loss due to sweating. However, this level of water loss through sweating is difficult to replace on a short-term basis and can result in as much as a 3% deficit in body water by weight over time even with a high level of water intake. Under most circumstances, the balance between average water loss and gain is such that the average human euhydrated state usually remains stable over an extended period of time due to several mechanisms including hormonal control of renal fluid conservation [2, 7].

Electrolyte/Carbohydrate Regulation and Control of Hydration

Plasma electrolyte concentrations (primarily sodium, potassium, and chlorine) are under renal control through several hormonal pathways, including the renin-angiotensin-aldosterone system (RAAS) as well as antidiuretic hormone (ADH) [7]. The synthesis and release of those hormones occur through changes in plasma

volume and plasma concentration of sodium chloride. ADH secreted from the pituitary gland, which has direct neural connections with the hypothalamus, may also receive neural input from other sources. The function of ADH is to reduce water loss by the kidney, but it has no effect on the water loss through sweat glands. Body water, including plasma volume in the vascular compartment, is also regulated by the RAAS. Changes in fluid volume or electrolyte (sodium) concentration will activate the RAAS to conserve fluids and electrolytes at the level of the kidney and sweat glands through the action of aldosterone [8]. The control of fluid (especially plasma) volume is also important in the maintenance of blood pressure and organ perfusion. Another product of the RAAS is angiotensin II, a powerful vasoconstrictor that helps maintain blood pressure and overall cardiovascular function in the presence of significant fluid loss from the vascular compartment, as well as a significant stimulator of the release of aldosterone from the adrenal glands [7].

Hydration is essential for life regardless of activity level. As thirst is not a reliable indicator of hydration status, it is important to follow guidelines for rehydration during normal activity, during exercise, and during exposure to hot and/or humid environments. A general guideline for those exercising in the heat for 1–2 h is to drink plain, cool water (containing no electrolytes). To avert heat injury, it may be necessary to consume sufficient quantities of water containing electrolytes including sodium [Na^+] to prevent dehydration, hyponatremia, and cardiovascular stress [3]. Generally, a 1.0 kg decrease in body weight represents a 1.0 L decrease in body water (mostly plasma volume as well as extracellular compartments) that should be replaced through the consumption of fluids. Unfortunately, vomiting, which can occur during heat injury, may result in between 1.5 and 5.0 L of fluid loss, thus further dehydrating the individual. However, a victim of heat injury who has been vomiting may not be able to consume fluids by mouth. Rehydration may have to occur through an intravenous (i.v.) route. [9, 10].

It should be noted that fluid replacement during prolonged sweating by consuming large quantities of plain water may result in a condition known as hyponatremia [3]. Hyponatremia is generally the result of a poor fluid-replacement strategy before, during, and after prolonged exercise. Plasma sodium (Na^+) concentrations are regulated to remain between 135 and 145 $mmol \cdot L^{-1}$ under normal physiologic conditions because of its importance in cellular volume and function. Thus, hyponatremia (low plasma sodium) is defined as a Na^+ concentration < 135 $mmol \cdot L^{-1}$ (mild) and severe hyponatremia as a plasma Na^+ concentration of 120 $mmol \cdot L^{-1}$. Hyponatremia, aggravated by significant loss of Na^+ from prolonged sweating, may become a potentially life-threatening condition [11].

Outside of the patient population, hyponatremia usually occurs in high-endurance athletes participating in marathons, ultramarathons, and Ironman triathlons, but it can also occur in persons working for long periods of time in hot environments [12]. The incidence of hyponatremia in high-endurance athletes ranges from 13% to 18%. Symptoms of hyponatremia can range from none to minimal (~70% of cases) to severe, including encephalopathy, respiratory distress, and death [10]. During these events or work periods, hyponatremia develops when the athlete or worker consumes too much plain water in an attempt to rehydrate after copious sweating. The excess water results in a dilution of plasma Na^+, which, in turn, causes an

osmotic disequilibrium that can lead to cerebral edema and pulmonary edema. These conditions have proven fatal in a small number of patients [12].

Risk factors for the development of hyponatremia are exercise durations of greater than 4 h, gender (females are more likely to develop hyponatremia), low body mass, excessive consumption of water (>1.5 $L \cdot h^{-1}$), pre-exercise hydration, consumption of nonsteroidal anti-inflammatory medications (although not all studies have shown this), and extreme environmental temperature [12]. Consumption of large quantities of plain water is highly correlated with the development of hyponatremia [13]; the majority of athletes or workers in hot environments become at least mildly hyponatremic. However, not all those with hyponatremia become symptomatic [12]. Therefore, the presence of mild hyponatremia may not be harmful. Nevertheless, hyponatremia can have devastating consequences, such as death, for the individual [12]. Prevention of this condition involves appropriate use of fluid-replacement strategies including the consumption of balanced electrolyte/carbohydrate "sports drinks" such as those discussed previously [10]. However, consumption of large quantities of water alone may be enough to cause hyponatremia. A condition known as primary or psychogenic polydipsia, a medical condition in which the patient consumes large quantities of water (>3 $L \cdot d^{-1}$), may result in hyponatremia, coma, and seizures [14, 15].

The issue of hyponatremia aside, there is a popular notion that sodium loss from sweating is significant and must be replaced on a regular basis after the commencement of exercise. Notwithstanding this belief, actual sodium loss is limited because much of the sodium reaching the sweat glands is returned to the plasma through active transport mechanisms [3]. Therefore, sweat is hypotonic to the plasma, and only insignificant amounts of sodium are lost in the first hour or two of exercise [16]. However, during prolonged sweating lasting several hours, significant amounts of sodium may be lost, and it is advisable to consume a sports drink that contains balanced electrolytes to replace those lost during sweating, as long as the concentration of electrolytes and carbohydrates does not exceed 8% by volume. Exceeding the 8% limit will slow absorption of fluids from the gastrointestinal (GI) tract [1]. The situation is complicated by the fact that the water absorption from the duodeno-jejunal section of the gastrointestinal (GI) tract is somewhat rate limited (~ 8.1 $ml \cdot h^{-1} \cdot cm^{-1}$). The rate of water absorption in the gut does *no*t seem to be influenced by intensity of exercise or sweat rate [17]. Thus, depending on circumstances, the intake of plain water could exceed the capacity for the GI tract to absorb it. The addition of carbohydrate/electrolyte to the water can increase the fluid absorption to ~12.0 $ml \cdot h^{-1} \cdot cm^{-1}$ [17].

Electrolyte and carbohydrate sports drinks should be as palatable as possible and cool but not cold (~15 °C). Small quantity taken at frequent intervals, i.e., about 830–1180 mL (28–40 oz.) every 15–20 min, is a more effective regimen for practical fluid replacement than the intake of large amounts of fluids per hour [3]. Communal drinking containers may not work as well as individual bottles since

individuals are seldom aware of just how much sweat they produce or how much water is needed to replace that lost in the sweat (~1 $L \cdot h^{-1}$ is a common rate of water loss). Consuming individual bottles of replacement fluids provides a visual indication of the volume of fluid intake (replacement).

Therefore, in an environment with a high heat index coupled with copious sweating, it would seem prudent to provide the subjects with carbohydrate/sodium containing drinks to assure that sufficient water is absorbed by the GI tract to replace that lost due to sweating. Finally, severe sweating for a period of hours can induce a phenomenon known as sweat gland fatigue, which may ultimately contribute to the reduction the ability to regulate core body temperature [1, 3].

Physiological Consequences of Dehydration and a Poor Hydration Strategy

From a practical standpoint, it has been suggested that there is an inverse relationship between body core temperature (T_{core}) and a decrease in body water beyond 3% [18]; however, recent studies have challenged this assertion [19]. In fact, during some athletic events, athletes may voluntarily hyperhydrate (consume extra fluids) prior to heavy or prolonged exercise which may improve performance and be protective against thermal stress. In principle, the increased fluid would allow for increased heat loss from sweat evaporation and provide a buffer against hypohydration [18]. However, poor hydration habits among nonprofessional athletes (e.g., casual joggers, high school athletes), heat exposure during outside work, and those exposed to heat in occupational settings can lead to heat-related illness and injury [20].

Dehydration can occur due to substantial sweating followed by a failure to rehydrate during exposure to a hot environment, with or without high humidity. Rates of water loss from sweating may reach as much as 1.0 $L \cdot h^{-1}$ for moderate exercise in the heat up to a maximum of 3.7 $L \cdot h^{-1}$ and, if this fluid is not replaced, may have serious physiological consequences [21]. The initial decrease in plasma volume can lead to an increased plasma osmolality, which can cause muscle cramps [4]. As dehydration worsens, the result may be a compromise in cardiovascular function since the water lost through sweating may result in a general decrease in plasma volume. The decreased plasma volume further leads to a reduction in stroke volume resulting in an increased heart rate and myocardial oxygen demand, which may, in the susceptible individual, trigger ischemic events in those with underlying coronary artery disease [22, 23]. The reduced plasma volume also leads to a reduction in cutaneous blood flow in order to redirect blood to more central regions (presumably to maintain cardiovascular stability). Consequently, the reduction in blood flow leads to a reduction in heat loss through the skin. The reduction in heat loss from the skin may contribute in a significant way to heat injury and heat stroke [24].

Origin and Control of Core Body Temperature

The existence of internal body heat is the result of the metabolic conversion of substrate – primarily carbohydrates, fats, and to a lesser extent proteins – into energy in the form of adenosine triphosphate (ATP) (the so-called energy currency of the body). ATP is central to the energy driven process of the body. Energy in the form of ATP is used by muscle in the performance work [25]. Although the metabolic production of ATP may occur in the absence of oxygen (anaerobic metabolism), the vast majority of ATP is produced in the presence of oxygen (aerobic metabolism) [25]. The process is not efficient (<25%), and, after a portion of the energy is consumed in supporting various physiological and biochemical processes, the remaining energy (>75%) is converted into heat [20]. For example, at rest the average aerobic metabolic energy production is about 4.2 $kJ \cdot kg^{-1} \cdot h^{-1}$ (or 1.0 $kcal \cdot kg^{-1} \cdot h^{-1}$). Therefore, a 75 kg man would generate about 315 $kJ \cdot h^{-1}$ (75 $kcal \cdot h^{-1}$) of metabolic energy. An increase above the basal level of activity will result in an increase in the metabolic energy production and, thus, an increase in core body temperature. Should the O_2 consumption during exercise increase to ~500 $ml \cdot min^{-1}$, this would result in the production of 656 $kJ \cdot h^{-1}$ (156 $kcal \cdot h^{-1}$) of energy. Should only ~25% of this energy be used for physiological and biochemical processes and the remaining 75% be released as heat, then ~492 $kJ \cdot h^{-1}$ (123 $kcal \cdot h^{-1}$) of core body heat must be exchanged with the external environment in a balanced manner such that the core body temperature remains more or less constant.

Body core temperature (T_{core}) is controlled to within a narrow range because nearly all physiological and biochemical mechanisms operate within this optimal temperature [4]. T_{core} is maintained primarily through a balance between metabolic heat production and the transfer of heat to the environment through four biophysical/physiological mechanisms, namely, conduction, convection, radiation, and sweat evaporation. In thermoneutral environments, radiation, convection, and, to a lesser extent, conduction, are the primary mechanisms involved in heat transfer from the body to the external environment [1]. In hot environments, or during physical exercise (as core body temperature increases ~ 0.5 °C above baseline), sweat evaporation becomes the most important mechanism for heat transfer to the environment [1]. The contribution of each of these physical and physiological mechanisms involved in human thermoregulation can be described using the basic heat balance equation, as follows:

$$S = (M - W) \pm C \pm R \pm K - E$$

where S = change in body heat content (changes in T_{core}); (M-W) = total metabolism minus external work performed; C = convective heat exchange; R = radiative heat exchange; K = conductive heat exchange; and E = evaporative heat loss. By determining the values of each of these factors, one can establish the flow of heat from the body to the environment and further determine if there will be an increase (or

decrease) in T_{core}. Note that the term W represents the amount of metabolic energy used to perform work. The energy used to perform external work (W) is subtracted from the total amount of energy produced since mechanical work does not create heat [1]. In addition, nonphysiological (behavioral) strategies (leave the area, don or doff clothes, etc.) are also used in human thermoregulation [1].

During strenuous exercise or during exposure to hot environments, sweating followed by evaporative heat loss is the primary means of transferring heat in humans from the body to the environment. For every liter of water that evaporates, 2436 kJ (580 kcal) is extracted from the body and transferred to the environment [3]. The enormous capacity for heat loss through sweat evaporation is more than adequate to dissipate metabolic heat generated by a subject both at rest (~315 kJ·h^{-1} for a 75 kg man) and at high levels of activity. For example, mean sweat rate in endurance athletes during exercise ranges from 1.5 to 2.0 L·h^{-1} [26]. This magnitude of sweat loss, which translates into an evaporative heat loss capacity of 3654–4872 kJ (~11.6–15.5 times the amount of heat produced at rest), easily transfers sufficient heat to the environment to prevent or minimize increases in T_{core}. An ambient wet-bulb temperature (to account for humidity) of 35 °C can result in a body fluid loss at rest (80 kcal·h^{-1}) of 0.8–1.0 L·h^{-1} through sweating. This fluid loss would be correspondingly greater with activity and in those individuals acclimatized to hot environments [1].

Human beings have 2–5 million eccrine (sweat) glands asymmetrically distributed over the body not all of which are active [4]. The physiological process of acclimatization involves, in part, recruitment and activation of previously dormant sweat glands in order to increase the sweat rate and, potentially at least, heat transfer to the environment [27, 28]. Acclimatization also involves triggering of the sweating response at a lower T_{core} and at an earlier point during the exposure to heat or exercise [29]. In addition to dehydration from sweating, significant water loss from the respiratory tract at rest can be as great as ~350 mL·d^{-1} under mild conditions of heat and humidity. Respiratory water loss will also contribute to the overall dehydration of an individual exposed to heat or during exercise [3]. Therefore, physiological acclimatization to heat will result in a greater loss of body water in any particular hot environment compared with no acclimatization.

Although a generally extremely effective means of heat transfer, heat loss through the vaporization of sweat can be defeated in environments with high humidity [3]. The evaporation of sweat is inhibited, and heat transfer to the environment is reduced, if not completely blocked, in humid environments where the atmosphere is saturated with water. For example, when the *heat index* (a combination of heat and humidity as described in tables produced by National Oceanic and Atmospheric Administration [NOAA]) is greater than 35 °C and is largely due to high humidity, the evaporative heat loss is virtually nonexistent. Thus, even if an individual is exercising in an ambient "dry" temperature within a comfortable range (e.g., 21–23 °C), the high humidity (>90% relative humidity [RH]) can still inhibit sweat evaporation and could result in an "apparent temperature" or heat index high enough to create heat stress that is potentially great enough to result in heat injury. Indeed, it has been

reported that several football player deaths occurred when the absolute temperature was below 23 °C but the RH was >95% [3]. However, this situation may have been aggravated by the football player's protective gear blocking the normal routes of heat exchange with the environment.

Work to Rest Ratio

The control of heat stress is not limited to the physiological mechanisms discussed previously. There are several other means of controlling heat stress, which do not rely on biophysical or physiological mechanisms. Some of these means are in a category usually known as "administrative" controls according to OSHA-NIOSH. These controls usually involve limiting exposure to heat using work/rest cycles, which allow the individual to exit the hot area for a time. When the individual moves away from the source of heat, the physiological processes of heat transfer to the (presumably) cooler environment can occur. In addition to the removal from heat, the individual may be allowed to physically rest, thus reducing the metabolic heat production that is added to the environmental heat source. In addition, the individual may be able to rehydrate in order to avoid the effects of dehydration discusses previously. Depending on the severity of the heat exposure, administrative controls can be adjusted to allow for a greater percent of rest per work as part of limiting the exposure to the heat.

Other work/rest cycles may take the form of timing the work during a cooler part of the day or evening to limit the exposure to heat. Work/rest may also take the form of putting additional workers on the job in order to reduce the workload for any given individual (thus reducing the amount of metabolically generated heat) [30]. In addition to these strategies, workers should be provided with an area that is cool in order to obtain respite from the heat. The individual must be provided with plenty of opportunity to drink fluids (even require workers to drink a specified amount of fluid per hour to maintain proper hydration). The administrative policy must also allow for self-paced work (i.e., workers can reduce work intensity or rest when they feel the need).

Finally, an administrative policy may use the Thermal Work Limit guide to define the maximum sustainable work (metabolic) rate that a well-hydrated and acclimatized individual can maintain in a particular thermal environment [30]. This may involve some monitoring of T_{core} and sweat rates to assure that the T_{core} does not exceed 38 °C ("industrial" and "hyperthermia") and the fluid loss from sweating does not exceed 1.2 kg·h^{-1}. In a hot environment, the thermal work limit may only be maintained with appropriate work/rest cycles and adequate hydration. However, monitoring of T_{core} and hydration in the field can be a challenge. Strictly speaking, it would require a designated person (supervisor, industrial hygienist, etc.) to periodically measure the workers T_{core} and body weight (to determine fluid loss from sweating) and this may be logistically challenging in the field.

Cooling Strategies and Devices

Several strategies for mitigating the effects of heat stress, including those involving the physiological response to heat (physiological heat strain), and the biophysical and physiological mechanisms for removing heat from the body have been discussed. Non-physiological administrative strategies to reduce heat exposure through work/rest cycles, as well as fluid-replacement strategies, have also been described previously. The following discussion will focus on the strategies for limiting the physiological response to heat exposure through the application of cooling devices that prevent increased T_{core} during exposure to environmental and internally generated heat.

Numerous studies have addressed a multiplicity of cooling garments, ice vests, and phase change materials used to keep the wearer cool. Each of these strategies has its advantages and disadvantages. The most effective cooling systems appear to be Spandex™ body suits impregnated with flexible plastic tubing in contact with the skin and through which fluid is continuously circulated thus allowing heat to be removed away from the wearer through convection (Fig. 7.1) [31, 32]. The temperature and flow rate of the fluid may be controlled with a water bath and pump system such that the rate of heat transfer may be adjusted to the heat output of the person wearing the system. The advantage of this system is that the rate of heat transfer can be controlled [31, 32].

From a physiological standpoint, optimal heat transfer occurs during exposure to an *optimal* temperature not a *maximal* temperature. The reason for this involves the physiology of heat transfer from the skin to the environment. Under normal circumstances, heat moves from the core regions of the body to the skin (shell) for heat transfer by both mass transfer and through the circulation of warm blood from central regions to the skin via the cutaneous circulation [4]. The redistribution of blood to the cutaneous circulation involves complex cardiovascular adjustments including a vasodilation of cutaneous blood vessels near the surface of the skin. The greater the mobilization of warm blood to the skin, the greater the heat transfer. However, the magnitude of the vasodilation of the cutaneous blood vessel is influenced by cold receptors in the skin. Should the skin become cold enough, the cutaneous vasculature will constrict thus limiting blood flow to the skin. This reduction in blood flow reduces the opportunity for heat transfer to the environment thus conserving

Fig. 7.1 Liquid cooling garment. (NPPTL/NIOSH photo archive)

body heat in a cold environment [1]. Therefore, should the circulating water temperature in the cooling garment be too low, the wearer will experience a cutaneous vasoconstriction, which will actually reduce the heat transfer from the skin to the circulating water tubing [31, 32]. Fortunately, studies have shown that a water temperature of 18 °C is an optimal temperature for maximal heat transfer, since that water temperature does not induce cutaneous vasoconstriction [31]. However, in certain therapeutic settings, there is a desire to induce body temperature to below normal (hypothermia: T_{core} ~ 32–34 °C) using a water-cooled system or a convective spray cooling strategy [33, 34]. However, these strategies are for special medical applications and are not performed outside of a modern clinic.

The cooling garment described above has some significant disadvantages for use in the field. First of all, the garment is tethered to a water bath and temperature controller that is too bulky to be taken into the field [31, 32, 35]. Secondly, the garment cooling system requires a power source to operate the water circulating bath and temperature controller. This is also not practical for field use at this time. Currently, these types of liquid cooling systems are used either for research purposes or in specialized settings such as military aircraft [36, 37].

As of this writing, cooling systems used occupationally are essentially a fabric vest with a series of pockets into which are inserted plastic bags containing ice or some kind of phase change material. The advantage of using a cooling vest employing ice or phase change material packs is that they allow complete mobility by not being connected to a motorized circulating water bath. However, the disadvantages are that the ice melts or the phase change material warms such that no cooling is provided and there are no means to control the temperature against the skin. Other significant issues include imposing too cold a temperature against the skin resulting in vasoconstriction of the cutaneous vasculature and a reduction of the flow of warm blood to the periphery limiting the potential for heat exchange. Finally, the melting of ice or warming of the phase change material occurring within 30–45 min limits the cooling advantage to heat exposures of less than an hour, thus requiring that the ice pack/phase change material must be frequently replaced and refrigeration must be available to store ice/phase change materials for use which requires electricity.

Some cooling systems rely on a vapor compression system for cooling that can be used in conjunction with a self-contained breathing apparatus (SCBA). This application has, thus far, been tested in our lab at the National Personal Protective Technology Laboratory, NIOSH/CDC, in conjunction with the SCBAs with HAZMAT suits [38]. A wearable vapor compression cooling system has also been developed by Aspen Systems, Inc. This system is belt worn and can force compressed cool air into a garment capable of providing 120–300 W of cooling to the wearer. The advantage is portability, but the disadvantage is limited battery life (2 h) and weight.

A novel approach to personal cooling is being investigated using anisotropic materials constructed of carbon nanotubes. This material allows transfer of heat in only one direction (e.g., body heat is permitted to cross the material, but environmental heat is prevented from crossing the material in the opposite direction) [39]. Clearly, these new materials may revolutionize the construction of protective

garments which will provide passive cooling and solve many of the difficulties described in previous paragraphs in this section.

Physiological Monitoring Systems

Physiological monitoring has been performed in one form or another for more than 2500 years. The ancient Indian physician, Sage Kanada (~600 BCE), was the first to describe the pulse and relate the pulse to various physiological and pathological states [40]. Body temperature (i.e., fever) and its relationship to illness were noted by the ancient physicians Hippocrates (fifth century BCE) and Galen (second century CE) [41], but the ability to measure body temperature had to wait until the invention of the first crude mouth thermometer by Santorio in 1625 [42]. Arterial blood pressure was first measured in a horse by the English clergyman Stephen Hales [43], but the auscultative technique using a stethoscope and cuff sphygmomanometer was not developed until the nineteenth century. The first noninvasive sphygmomanometer was invented by von Basch ~1881 but was not introduced into clinical medicine until the development of modern auscultative techniques by Riva-Rocci in 1896 [44]. The electrical activity of the heart was first measured by Marey [45], but the first "electrocardiogram" (ECG) was recorded by Waller [46]. Finally, the "modern" ECG was recorded by Einthoven [47], who was also the first to recognize its clinical significance.

The twentieth century witnessed the rapid expansion of technologies allowing for the measurement of physiological variables with ever-increasing accuracy and rapidity. As human physiological research moved from the laboratory to the field, the ability to measure physiological variables without being "tethered" to the laboratory became increasingly important. This necessity fostered the development of several types of "remote" or wireless physiological monitoring systems that eventually became commercially available. Metabolic measurements (breath by breath analysis of O_2 consumption and CO_2 production) using a wearable "metabolic cart" became possible with the development of devices like the COSMED™ devices (e.g., K4b2) beginning in 1980. A wearable heart rate monitor that included a chest strap and a wristwatch-type receiver (Polar™ Heart Watch) was first introduced in 1982. NASA, in collaboration with the Johns Hopkins University, developed an ingestible "core" temperature pill for use by astronauts [48]. The technology has since been commercialized under the name of the CorTemp (HQ Inc.). A similar technology is commercially available under the Minimitter™ brand. In-helmet temperature monitors have also been developed and compared favorably to core body temperatures measured by rectal thermistors [49]. An attempt to measure several physiological variables simultaneously has also been developed by Zephyr™ Technology, Inc. (Fig. 7.2) [50]. Founded in 2003, this system utilizes a chest strap with sensors that monitor heart rate, heart rate variability, respiration, skin temperature, activity level, and 3D axis accelerometry. The sensor vest known as the LifeShirt® had the capability of monitoring heart and respiratory rate, tidal volume,

Fig. 7.2 Zephyr Technology™ Bioharness. (Photo courtesy of Zephyr™ Performance Systems with permission)

ECG, and skin temperatures [51]. Although the LifeShirt is no longer available, the technology provided a platform for physiological monitoring that became a model for other technologies. Recently, a synchronous wearable wireless body sensor network has been developed using novel textile technologies, which may prove invaluable when worn by emergency first responders [52]. In fact, these technologies continue to undergo development with the aim of adding more monitored variables, providing the most accurate measurements of those variables, and increasing the robustness for use in the field under a variety of environmental conditions.

These technologies are used by both athletes and patients in hospital settings, but interest has been shown in several occupational categories (e.g., firefighters, first responders) and the military in continual monitoring of physiological variables for safety reasons [50, 51]. Therefore, any device used for physiological monitoring must not only provide accurate measurements of the physiological variables but must be extremely robust to allow use in harsh environment.

In addition, the device itself must have a limited impact on the physiological burden of the wearer [53]. In sum, it seems safe to say that the rapid development of wearable physiological monitoring systems for use by athletes, first responders, and military personnel will continue. Advances in technology are expected to include a greater array of measurable physiological variables, smaller less ergonomically burdensome devices, and increased robustness thus allowing the use of wearable physiological monitors under the most harsh of environmental conditions.

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