

# United States Army Research Institute of Environmental Medicine: Warfighter research focusing on the past 25 years

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## United States Army Research Institute of Environmental Medicine: Warfighter research focusing on the past 25 years

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**Pandolf KB, Francesconi R, Sawka MN, Cymerman A, Hoyt RW, Young AJ, Zambraski EJ.** United States Army Research Institute of Environmental Medicine: Warfighter research focusing on the past 25 years. *Adv Physiol Educ* 35: 353–360, 2011; doi:10.1152/advan.00049.2011.—The United States Army Research Institute of Environmental Medicine (USARIEM) celebrated its 50th anniversary on July 1, 2011. This article reviews its history, evolution, and transition of its research programs as well as its scientific and military accomplishments, emphasizing the past 25 yr. During the 1990s, USARIEM published a series of pocket guides providing guidance for sustaining Warfighter health and performance in Southwest Asia, Somalia, the former Republic of Yugoslavia, Rwanda, and Haiti. Issues identified during Operation Desert Storm elicited research that improved nutritional guidelines for protracted desert operations; safer use of nuclear, chemical, and biological protective clothing; equipment, development, and fielding of efficient microclimate cooling systems; and effective evaluation of pharmaceuticals to protect soldiers from chemical and biological threats. During the first decade of the 21st century, USARIEM and the Department of the Army published official medical/performance doctrines for operations in the heat and cold and at high altitude. The current Global War on Terrorism focused research to improve doctrines for hot, cold, and high-altitude operations, reduce musculoskeletal training injuries, provide improved field nutrition, more efficient planning for operational water requirements, and improve both military clothing and materiel. This article also describes the critically important interactions and communications between USARIEM and deployed units and the benefits to Warfighters from this association. This report presents USARIEM's unique and world-class facilities, organizational changes, scientific and support personnel, and major research accomplishments, including the publication of 2,200 scientific papers over the past 25 yr.

biomedical modeling; environmental physiology; military clothing; military nutrition; military performance

THE VALUE of any military medical research laboratory is measured by its contributions to the health, safety, performance, and well-being of its customers. For the United States (U.S.) Army Research Institute of Environmental Medicine (USARIEM), the individual soldier, other Warfighters, and integrated units have been its customers and foci of research attention. In 1986, an article (5) was published chronicling the history, organizational changes, and research accomplishments of USARIEM during its first quarter century. Also, a book was published to commemorate the Institute's 25th anniversary, with current information on performance and physiological and

medical responses to heat, cold, high altitude, diving, and poor air quality (9). Thus, while the detrimental effects of environmental extremes on the health and performance of soldiers dominated early USARIEM research (5), more recent thrusts have encompassed the full scope of operational factors affecting contemporary combat and training missions (6). This article provides an updated account of the accomplishments, unique facilities, and organizational changes at USARIEM over the past 25 yr as well as how the programs have broadened to address emerging threats and requirements.

For example, in the mid-1980s, when the U.S. Army Military Nutrition Laboratory in Denver, CO, and later San Francisco, CA, was decommissioned, its mission was transferred to USARIEM. This was a logical consequence since USARIEM has been colocated since the mid-1960s at the Natick Soldier Research, Development, and Engineering Center (NSRDEC), the chief developer of field rations for the U.S. Army. The synergism between USARIEM and NSRDEC was exemplified in the 1980s, when USARIEM scientists executed an extensive field study with the 25th Infantry Division. It assessed the nutritional adequacy of long-term consumption of newly developed field rations by NSRDEC. This study is cited also as a representative example of multiple field studies that bring USARIEM scientists on site to identify, investigate, and improve or resolve environmental and operational issues with potentially adverse effects on U.S. Warfighters.

As Army requirements emerged and the Institute's mission evolved, particularly in the 1990s, new areas of research included gender studies, electrolyte requirements and replacement, new protective ensembles, epidemiology, and the constantly expanding range of operational stressors. Despite the contingencies of asymmetric warfare, the original challenges to military performance, health, safety, and efficiency persisted in the 21st century. Summer temperatures of 49°C (120°F) in Iraq, mountainous and cold weather operations in Afghanistan, protracted foot patrols, body armor, heavy loads, sustained operations, musculoskeletal injuries, thermal acclimatization, field-feeding adequacy, sleep deprivation, chemical/biological protective ensembles, and gender-specific issues remain of primary interest to the U.S. Army.

Occasionally, USARIEM research has been rapidly refocused to address critical Army problems. For example, in 1991, during Ranger training, a pneumonia outbreak forced cancellation of the class; in 1997, high rates of hyponatremia were reported during Army and Marine basic training; and, in 2002, an unusual rash of heat stroke cases was observed. USARIEM made recommendations on nutritional intake, guidelines on electrolyte and fluid replacement and better diagnosis of hyponatremia, and course schedule reorganization and work-rest cycles, respectively, to resolve these issues.

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In the past 25 yr, USARIEM has assumed an ever-increasing responsibility to communicate, both in briefings and written documents, recommendations to attenuate the impact of environmental and operational stressors on Army health, safety, and performance. A few representative examples are bulletins for acclimatization to high-altitude and mountain sickness management, the control and management of heat stress and injury, water and electrolyte requirements and work-rest cycles while wearing protective ensembles in the heat, and prevention and management of cold-weather injuries (1, 2, 4). USARIEM has also published two volumes of *Textbooks of Military Medicine* (7, 8). While the latter are written for medical officers, physician assistants, and nurses, most contain practical information for company commanders and the Warfighter. Likewise, USARIEM scientists are often called upon to deliver briefings to units about to deploy or train in harsh environments. Audiences have ranged from the Flight Surgeons' Course (Ft. Rucker, AL) to countless Army, Marine, National Guard, and Reserve units about to train in the Mojave Desert (Ft. Irwin and 29 Palms, CA).

Thus, USARIEM scientists remain committed to a relevant research program that continues to address the requirements and contingencies that our Warfighters face, irrespective of where in the world they may be called upon to deploy. As training and operational issues are identified and reported, research programs can and will be immediately refocused to address and resolve the problems. Research results will continue to be communicated rapidly to field units so that our soldiers continue to be the most effective, healthiest, and safest fighting force in the world.

#### *Organizational Changes at USARIEM During the Past 25 Years*

USARIEM has had three major organizational changes over the past 25 yr. These three organization changes were the result of Institute mission adjustments to better address the emerging problems faced by our modern Army and its Warfighters. In 1986, the Institute had seven research divisions, each with a defined research mission. These were the Altitude Research Division, Cold Research Division, Exercise Physiology Division, Health and Performance Division, Heat Research Division, Military Ergonomics Division, and Military Nutrition Division. In 1991, USARIEM was reorganized into a three research directorate/nine research division structure. These were the Environmental Physiology and Medicine Directorate, with Altitude Physiology and Medicine, Biophysics and Biomedical Modeling, and Thermal Physiology and Medicine Divisions; the Experimental Pathophysiology Directorate, with Comparative Physiology as well as Cellular Physiology and Pathology Divisions; and the Occupational Health and Performance Directorate, with Military Nutrition, Military Performance and Neuroscience, Occupational Medicine, and Occupational Physiology Divisions. In 1996, the Institute again reorganized into a five research division structure: the Biophysics and Biomedical Modeling Division, Environmental Pathophysiology Division, Military Nutrition and Biochemistry Division, Military Performance Division, and Thermal and Mountain Medicine Division. In 1997, the Environmental Pathophysiology Division was disbanded with its research mission mostly assimilated into the Thermal and Mountain

Medicine Division. Finally, in 2000, the Military Nutrition and Biochemistry Division became the Military Nutrition Division. From 2000 to the present, USARIEM has maintained its four research division structure.

Each of the four research divisions at USARIEM has a defined research mission. However, the research divisions routinely collaborate on research efforts, and this interdisciplinary approach is vital to their success. The research mission of the Biophysics and Biomedical Modeling Division is to develop biomedical models and networked physiological sensor systems to enable Warfighters to predict strain and counter health threats from physical challenges, protective ensembles, nonagent chemical exposure, and extreme environments. The Military Nutrition Division conducts research on nutritional issues affecting the health and fitness of Warfighters while supporting the Surgeon General's responsibilities as the Department of Defense Executive Agent for nutrition through evaluating rations and examining the interactions between nutrition, performance, and the environment. The focus of the Military Performance Division is to execute research to enhance performance (behavioral, cognitive, physical, and psychomotor) of military tasks and/or prevent performance decrements from physical overload, nutritional deprivation, environmental and occupational stresses, and musculoskeletal injuries. Finally, the Thermal and Mountain Medicine Division conducts research to sustain and enhance performance (cognitive and physical) and minimize medical problems associated with military operations under heat, cold, and high-terrestrial altitude conditions. In addition, these divisions provide significant research support to the developers of military clothing, equipment, food, and pharmaceuticals.

#### *Institute Facilities and Personnel*

USARIEM is housed in a 7,061 sq m (76,000 sq ft) building (see Fig. 1) located at the Natick Soldier Systems Center (NSSC) in Natick, MA, a short distance west of Boston. The Institute offers a myriad of unique facilities and is in close proximity for collaboration with many of the finest universities, colleges, and medical research centers in the world.

USARIEM has environmental and biophysical evaluation chambers of various sizes that control temperature [−10 to 50°C (14 to 122°F)], relative humidity, and wind speed, which are used for human research. Three biophysical chambers contain articulated, movable, and static manikins or other models of the hands and feet with sensors for testing thermal and other vapor resistance values of clothing. The Institute also has Association for Assessment and Accreditation of Laboratory Animal Care-accredited animal care facilities, animal surgical facilities, and environmentally controlled animal laboratories as well as extensive molecular and biochemistry laboratories.

The Institute also uses the NSSC's two recently renovated Doriot Climatic Chambers [18.3 m long × 4.6 m wide × 3.4 m high (60 ft long × 15 ft wide × 11 ft high)], each equipped with wind generation capability. The Doriot Climatic Chambers are among the largest and most sophisticated environmental chambers in the world. These chambers, one each for cold and hot conditions, are capable of simulating nearly any arctic, desert, or tropic environment our Warfighters might encounter in the world. Both chambers have two five-person treadmills,



Fig. 1. The United States Army Research Institute of Environmental Medicine.

and this facility can accommodate and house 25 soldier volunteers.

USARIEM has hypobaric (altitude) chambers consisting of a large [ $6.3 \times 3.0$  m ( $20.6 \times 9.7$  ft)] and small [ $3.7 \times 2.7$  m ( $12 \times 9$  ft)] chamber connected by an airlock. These chambers with updated control panels can simulate and control pressure [sea level to 9,000 m (29,350 ft)], temperature [ $-32$  to  $43^\circ\text{C}$  ( $-26$  to  $110^\circ\text{F}$ )], and relative humidity. Also, the Institute has an off-site laboratory known as the USARIEM Maher Memorial Altitude Facility, which is on the summit of Pikes Peak in Colorado. This 195 sq m (2,100 sq ft) facility at an altitude of 4,300 m (14,100 ft) has two laboratory rooms, a medical aid room, and a dormitory that can accommodate 16 research volunteers.

The Institute houses a water immersion laboratory, which can maintain cold and hot water temperatures ranging from 5 to  $50^\circ\text{C}$  ( $41$  to  $122^\circ\text{F}$ ) in a 10,000-gallon (37,854 liter) concrete tank. This tank is 3.0 m long  $\times$  3.0 m wide  $\times$  4.3 m deep (10 ft long  $\times$  10 ft wide  $\times$  14 ft deep) and is used for human testing using one underwater treadmill or two cycle ergometers.

USARIEM conducts diverse nutritional research studies using a state-of-the-art metabolic kitchen also located in the Doriot Climatic Chambers at the NSSC. The metabolic kitchen is 21.2 sq m (228 sq ft) and is equipped with a freezer, refrigerator, heating, and bulk storage capabilities.

USARIEM shares with NSRDEC a relatively new Center for Military Biomechanics Research, a fully equipped 464.5 sq m (5,000 sq ft) biomechanics laboratory that includes a 12-camera Qualysis infrared video motion analysis system as well as a unique patented dual-force platform treadmill that measures  $x$ ,  $y$ , and  $z$  forces and torques for individual foot impact while walking. There are also six portable Myomonitor electromyographic systems to measure muscle-nerve activity.

USARIEM has three human performance laboratories (one newly constructed), each 40.9 sq m (440 sq ft), and a new bone health/body composition laboratory [73.6 sq m (792 sq ft)]. These laboratories have the most advanced contemporary tech-

nology including ergometers, peripheral quantitative computed tomography, dual X-ray absorptiometry, and tibial ultrasound.

There is a new Warfighter Cognitive Performance Laboratory and an Advanced Psychology Laboratory. The cognitive performance laboratory is a 74.3 sq m (800 sq ft) facility and has the EST 2000, which is a weapon engagement simulator that can mimic the operational characteristics of 25 different weapons. Marksmanship scenarios are created and tested for effects of workload, simulated sustained operations, fragmented and inadequate sleep, physiological or metabolic disruption, fatigue, and therapeutic strategies. The psychology laboratory is a 46.5 sq m (500 sq ft) facility that can accommodate 24 test volunteers for computerized assessment of cognitive and behavioral performance.

USARIEM's total workforce has remained fairly stable over the past 25 yr. The Institute currently has about 200 staff including 100 civilian employees, 60 military personnel, and 40 contractors. The total workforce has not changed by more than  $\pm 10\%$  over this 25-yr period. Of these 200 individuals,  $\sim 50$  have doctoral degrees (JD, PhD, or MD). Over the past 25 yr, the Institute has had 10 Commanders at the rank of Colonel.

Many USARIEM soldiers have deployed in support of contingency operations, i.e., the Gulf War, Operation Desert Storm, Operation Iraqi Freedom, Operation Enduring Freedom, and Operation New Dawn. In the past 5 yr, USARIEM has had numerous soldiers (including active duty soldiers as well as civilian staff serving in their National Guard or Army Reserve roles) deploy: 15 in support of Operation Enduring Freedom, 11 in support of Operation Iraqi Freedom, and one in support of Operation New Dawn. These soldiers have deployed to theatres in support of research teams, research investigations, Reserve units, National Guard units, and/or as a Professional Filler System Officer in active Army units. Deploying soldiers/soldier scientists adds relevance and an important first-hand perspective to USARIEM's research focus and mission.

For more detailed information on USARIEM, go to: <http://www.usariem.army.mil>.

*Institute Research Accomplishments During the Past 25 Years*

1986–1990. Due to the perceived imminent threat of chemical/biological warfare, Institute research focused on chemical/biological protective clothing (CB-PC) during this time period. Many thermal manikin and biomedical modeling studies were conducted to quantify the insulation, water vapor permeability, and thermal burden imposed by protective clothing and equipment. Studies evaluated the biophysical effects of newly developed CB-PC ensembles in hot and cold environments with varying types and levels of physical exertion. A chemical threat agent-protective patient wrap was developed and evaluated to protect casualties during evacuation.

The biophysical characteristics of newly developed handwear, footwear, underwear, sleep systems, and various uniforms were compared with standard issue items. This evaluation process helped ensure that new clothing and individual equipment items improved on the original and led to the establishment of standard test routines. In 1988, the Institute purchased a new thermal hand model, the first of many upgrades to its biophysical models.

Highlights of this period included the development and refinement of multiple biomedical prediction models. A human cold water immersion thermoregulatory model was developed that predicted metabolic rate and deep body temperature. A microclimate cooling model was created and integrated to a desktop computer format that could predict required rest times and heat storage rate effectiveness for air-cooled vests. Mathematical simulations were incorporated into models to enable estimation of blood flow to muscle, visceral areas, and skin as well as changes in stroke volume, heart rate, and cardiac output. Multiple laboratory and field studies provided data for USARIEM model validation and verification.

A series of hypobaric chamber studies examined several medications to treat or prevent acute mountain sickness (AMS). These led to a field study in Bolivia at an altitude of 3,660 m (12,000 ft) that validated the effectiveness of acetazolamide as a prophylaxis to AMS. Energy expenditure studies on Marines during cold weather training at high altitude demonstrated that they were active 18 h/day with mean daily energy expenditures of 4,800 kcal/day. USARIEM scientists led a study called Operation Everest II, which simulated a 40-day climb of Mount Everest within USARIEM hypobaric chambers and resulted in over 40 scientific publications.

The threat of chemical/biological warfare also resulted in many animal and human studies of the physiological impact of pharmacological and clothing equipment protective measures. Atropine, physostigmine, and pyridostigmine bromide were examined for their impact on thermoregulation and physical performance in hot and cold environments. Wearing CB-PC markedly increased heat strain and reduced performance during mounted and dismounted military activities. Numerous microclimate cooling technologies (liquid, conditioned, and ambient air) were evaluated and refined to reduce the heat stress burden of CB-PC.

Multiple studies were conducted to determine the fluid and electrolyte needs for extended operations in desert environments. These focused on fluid palatability, drinking behavior, voluntary dehydration, and bioavailability of various fluids for rehydration. Other important studies examined the effects of

age, sex, and ethnicity on thermoregulation and the ability to perform in hot or cold environments.

Military nutrition research focused on evaluating the nutritional adequacy of combat rations for sustaining soldiers during operational conditions. In 1985, soldiers subsisting on the Army's newest individual combat ration, the Meal Ready-To-Eat (MRE), were found to consume insufficient energy and experienced modest weight loss during protracted field exercises. Although strength and endurance were not affected, the Office of the Surgeon General established policy limiting subsistence on MREs to 10 consecutive days. In the late 1980s, ration consumption, changes in body weight, adiposity, blood nutrient levels, and daily energy expenditure rates were assessed in groups of soldiers subsisting on new, improved versions of MREs and other rations during field exercises in different environments. Those studies routinely showed that ration improvements increased consumption rates and mitigated weight loss.

During this period, several significant studies were completed evaluating physical performance and cognitive function in various settings. Using validated psychological assessment tools, cognitive function was assessed in studies comprising cold weather training at high altitude as part of Operation Everest II, heavy exercise including load carriage, and with heat exposure while wearing CB-PC gear. These stressors clearly elicited significant decrements in cognitive function. Later, studies of cognitive function and vigilance were expanded to include marksmanship when USARIEM acquired the "Weaponer M16 Rifle Simulator," a remarkable tool for assessing shooting accuracy and response time data acquisition.

Important studies of musculoskeletal injuries during basic training were conducted at Ft. Jackson, SC. The correlation of total running mileage and musculoskeletal injuries was documented. Other risk factors for injury included female sex, lack of prior physical activity, low aerobic fitness, smoking, excessive and/or very little joint flexibility, and prior injury. To improve fitness, power, and strength, several physical training studies were conducted. Successful studies demonstrated means to increase a soldier's load carriage capabilities.

A new method of estimating body fat was developed, validated against underwater weighing, and incorporated into Army Regulation 600-9. Using this technique, studies on West Point cadets demonstrated that their body fat percentages remained relatively constant over a 10-yr period, with men having 12% and women having 26.5% body fat. In 1990, a dual X-ray absorptiometer device was obtained to assess bone mineral density as well as muscle and adipose tissue. The dual X-ray absorptiometer device replaced underwater weighing and became an extensively used and invaluable research tool over the ensuing years.

1991–2000. The Institute coordinated the development and implementation of three compact, lightweight, ambulatory, microprocessor-based monitors: a core temperature monitor that uses an Federal Drug Administration-certified, ingestible, radiotelemetry pill; a canteen volume monitor that measures soldier fluid intake; and a pedometer that uses body mass and foot ground contact times to estimate the metabolic cost of walking and running. Data collected using these devices were applied to validate and verify algorithms and provide more complex and accurate predictive models.

Multiple algorithms were developed, refined, and incorporated into various USARIEM models. For example, an algorithm that predicted the degree of dehydration while wearing chemical-protective clothing was integrated into USARIEM thermoregulatory models. A mathematical algorithm capable of predicting the effects of cold-induced vasodilation was combined with a lumped-parameter model of the human fingertip. A cold-shivering algorithm was developed and integrated into an interactive, computer-based thermoregulatory model.

To better support the Army's materiel developers, the Institute formulated and refined a biophysical model to predict the impact of microclimate cooling over a wide range of operational scenarios and also completed thermal manikin evaluations of the biophysical characteristics of load carriage equipment and modular body armor. Working with the National Aeronautics and Space Administration, Institute modelers estimated the heat strain associated with the shuttle launch entry suit and the cooling needed from National Aeronautics and Space Administration's liquid cooling system. The model predicted that wearing the burdensome and insulated shuttle launch entry suit while performing the physically demanding tasks associated with emergency egress would require supplemental cooling to avoid significant heat strain.

Five studies conducted with collaborators from the University of Colorado Health Sciences Center and Stanford University examined women's adaptive responses to high altitude. These studies determined that their responses, susceptibility to AMS, and performance capabilities were comparable with those of men. Also emphasized were approaches for the effective induction and retention of altitude acclimatization to sustain military performance and reduce AMS.

In February of 1995, four Army Ranger students died from hypothermia while training in Florida swamps. A series of field and laboratory studies was designed to develop corrective actions. These investigations demonstrated that prior physical exertion induced "thermoregulatory fatigue," which increases the risk of hypothermia. USARIEM developed cold exposure safety guidelines for soldiers performing physical exertion in cold water and made accommodations for "thermoregulatory fatigue." Another series of studies demonstrated that insulative-cold acclimatization could be induced in soldiers, and the benefits and stimuli needed for induction were delineated.

In July of 1997, Ft. Benning had an outbreak of symptomatic hyponatremia with one death. USARIEM identified excessive water consumption as the primary cause, and the misdiagnosis as dehydration with inappropriate treatment. A series of laboratory and field studies at Ft. Benning resulted in safer fluid replacement guidelines and work-rest cycles for hot weather training.

Collaborative studies with Harvard Medical School used magnetic resonance spectroscopy to complement skeletal muscle biopsy and biochemical analysis techniques. These studies quantified the impact of heat acclimatization, physical training (skeletal muscle temperature), and hydration on changes in skeletal muscle metabolism. Other studies with the Naval Blood Laboratory examined the beneficial role of blood volume expansion on thermoregulation and exercise performance in hot and high-altitude environments.

Throughout the 1990s, studies continued on the acceptance and consumption rates of newly developed rations. In 1991,

soldiers subsisting on the newest version (XII) of the MRE during a 30-day field exercise manifested <3.5% weight loss with no nutritional deficiencies, mood disorders, or performance degradation. These findings led to revision of Office of the Surgeon General policy, extending allowable use of the MRE to 21 consecutive days, a policy still in effect today.

Additional military nutrition issues were also investigated in the mid-1990s. Observational studies assessed dietary intake, nutritional status, and nutritional knowledge of soldier populations at various garrisons, training bases, and military schools. These studies showed that soldiers generally exceeded national guidelines for fat and cholesterol intake, that nutrition knowledge among soldiers was generally poor, and that many soldiers regularly consumed countless dietary supplements, observations of continued concern, even today.

Also in 1991, investigations on nutritional requirements of Special Operations Forces (SOF) soldiers began. Army Ranger School students were initially observed to lose 10–15% body weight and large amounts of body fat during the 9-wk school, attributable to a 1,500 kcal/day energy deficiency from high energy expenditure and restricted rations. Impaired endocrine and immune function and increased infection rates were also documented. Later, small increases in daily energy intake were shown to mitigate weight loss but not normalize immune function of these students. Compromised immune function persisted even in a 1997 study of SOF soldiers consuming a nutritionally inadequate diet during a 21-day course of equivalent intensity as Ranger School. However, providing those soldiers a commercial food product containing supplemental energy, structured lipids, and micronutrients normalized immune function, an observation confirmed in a subsequent study of Ranger School students. Subsequently, changes in the feeding of Ranger School students were adopted to increase food consumption. In 1997, the 75th Ranger Regiment requested an assessment of nutritional requirements of Rangers training in garrison. As anticipated, higher energy requirements were documented for Rangers than for conventional trainees. This prompted the Army to increase the basic daily food allowance for the 75th Ranger Regiment with concomitant increased funding. In 2000, a similar assessment of 10th Special Forces Group (Airborne) resulted in a similar increase for all SOF personnel.

During this period, several studies confirmed the ability of caffeine administration to improve performance associated with vigilance and marksmanship target detection as well as friend-foe target identification. Also, the Total Army Injury and Health Outcomes Database (TAIHOD) was established. This extensive database initially contained 15 million records including all Army personnel, hospital, disability, fatality, and lost-time reports for 1980–1984. The TAIHOD has expanded to become one of the Army's most powerful epidemiological research tools.

The high incidence of stress fractures in both men and women during basic training required investigation. While women manifested a greater incidence of stress fractures, this difference was mainly due to their lower aerobic fitness, an independent risk factor for stress fractures. Stress fracture incidence in men and women of similar fitness levels were comparable. A 24-wk, 5-day/wk comprehensive physical training program was administered to a group of women. While significant physiological, psychological, and performance ben-

efits were documented, this rigorous program elicited one or more musculoskeletal injuries in 50% of these volunteers.

**2001–2010.** The Institute used thermoregulatory modeling to estimate the personal cooling requirements for occupants of high-mobility multipurpose wheeled vehicles during exposure to desert conditions. This analysis documented the need for supplemental cooling within the vehicle, and thus the Tank and Automotive Research Development and Engineering Center retrofitted certain high-mobility multipurpose wheeled vehicles to provide personal cooling for occupants.

To help ensure the safety of soldiers performing chemical/biological defense missions, the Institute transitioned the USARIEM heat strain decision aid (HSDA) computer program to the Joint Warning and Reporting Network Acquisition program. The Joint Warning and Reporting Network Acquisition program is a computer-based application that networks nuclear, biological, and chemical sensors directly with joint and service command and control systems. The HSDA is an empirical model that incorporates a set of predictive equations for soldiers working in a wide range of environmental conditions while wearing various military uniforms. The HSDA model provides guidance for the safe duration of a single bout of continuous work, optimal work-rest cycles, and suggested water consumption for prolonged physical activity under various weather conditions.

The Institute also developed a probability of survival decision aid (PSDA) in collaboration with the U.S. Coast Guard Research and Development Center. The PSDA calculates the survival probability of a victim in the water or floating in an emergency craft as a function of time and environmental variables. The PSDA has become a formal module within the U.S. Coast Guard's Search and Rescue Optimal Planning System and its search planning software.

In 2004, a Warfighter Physiological Status Monitoring product development team was created to focus on the development, validation, and field testing of wearable ambulatory monitoring systems that assessed individual Warfighter physiological status in all environments. This physiological status monitor includes vital sign and thermal work strain monitoring and is scheduled for integration into the Army's futuristic wearable computer system designed to improve battlefield awareness.

Recently, the Institute has worked with the U.S. Marine Corps, Program Manager-Marine Expeditionary Rifle Squad, an organization within the Marine Corps Systems Command to assess thermal work strain experienced by Marines during mounted and dismounted rifle squad operations in Iraq and Afghanistan. These studies have quantified the physiological demands on Warfighters in theater and have guided improvements in U.S. Marine Corps equipment and doctrine.

This decade was also highlighted by transitioning biomedical science into Army medical/performance doctrine for operations at environmental extremes. USARIEM wrote three Technical Bulletins based on published "best practices," which were then published by Headquarters, Department of the Army, on heat, cold, and high altitude.

A series of studies focused on acclimatization to high altitude and the benefits of intermittent hypoxic preconditioning. Multiple research studies continued to define and refine the impact of nutritional supplements on physical and cognitive performance at environmental extremes. During this decade,

molecular biology techniques were more fully integrated into the environmental medicine research programs. Gene expression studies were conducted in association with hyperthermia, hypothermia, and hypoxia. A gene expression study on Marine Corps recruit heat stroke patients (Parris Island Marine Corps Depot) demonstrated that prior viral infection was a common characteristic. Gene knockout mouse models were extensively used to study the pathophysiology of heat stroke, and other studies delineated the role of cytokines in mediating the systemic inflammatory response associated with organ damage.

Body armor became standard military issue during contingency operations in Iraq and Afghanistan. Consequently, studies were conducted to evaluate the impact of body armor on physiological responses and aerobic performance at environmental extremes. USARIEM evaluated several interventions to alleviate the heat strain associated with body armor. USARIEM and NSRDEC demonstrated that manipulating skin temperature within an "optimum" zone could abate cardiovascular and heat strain while reducing electrical power requirements (~40%) for microclimate cooling. This novel approach was awarded a U.S. Patent and provides for future development of lighter-weight microclimate cooling for dismounted soldiers.

In 2001, nutritional supplementation studies using small laboratory animals showed that adverse behavioral effects of operational stress were mitigated by increasing dietary levels of neurobiologically active amino acids and, from 2003–2007, that variations in dietary minerals underconsumed by soldiers decreased hepatic and skeletal muscle protein synthesis, bone strength, intestinal health, and immune function. These studies also indicated that operationally comparable variations in dietary minerals could modulate cell signaling pathways that regulate protein synthesis, with potential health and performance impacts. These basic studies led to investigations of macronutrient modulation of molecular signals regulating muscle protein synthesis in humans experiencing operational stress conditions so as to identify beneficial food fortification or dietary supplementation strategies for soldiers. Similarly, investigations started in 2005 confirmed that many women entering the Army have deficient iron status, which declines further during basic training. Consequently, providing supplemental iron capsules or iron-fortified food products to female soldiers exhibiting iron deficiency anemia ameliorated those declines and improved both cognitive and physical performance.

Research on new combat rations continued from 2006–2009, with a focus on a compact, lightweight individual ration, the First Strike, designed for SOF, light infantry, and other dismounted combatants during logistically austere missions of <10 days. Early prototypes used MRE components, but in smaller amounts that provided only 2,500 kcal/day, raising health and performance concerns. Between 2006 and 2010, modeling and laboratory studies in collaboration with the NSRDEC Combat Feeding Directorate investigated optimal nutrient content, packaging, and menus to fit First Strike's size specification and encourage on-the-move snacking. Field studies demonstrated that the "optimized" First Strike ration enhanced energy, carbohydrate, and caffeine consumption as well as self-paced work and cognitive function compared with MREs. Collectively, these findings demonstrated the suitability of the First Strike ration for operational use by selected personnel operating under logistically austere conditions.

An expansion of the database in the TAIHOD continued. A series of >60 publications on topics pertaining to musculoskeletal injuries, anthrax vaccinations, alcohol use, domestic abuse, brain injury, posttraumatic stress disorder, suicide, and the efficacy of parachute ankle braces were published. A landmark TAIHOD study determined that, between 1981 and 2005, the number of U.S. Army medical disability discharges increased sevenfold, with 80% of the discharges because of musculoskeletal injuries.

The evaluation of prospective physical training programs designed to improve fitness and reduce injuries was undertaken. The Army's new Physical Readiness Training program was evaluated and shown to be effective for both performance enhancements and beneficial physiological adaptations.

A series of collaborative studies began with the Israeli Defense Force on factors associated with stress fractures during military training. This research was highlighted in a special supplemental volume of *Medicine and Science in Sports and Exercise* titled "Gender Factors Contributing to Performance and Musculoskeletal Injury in Military Recruits" (10).

Several studies were completed detailing the effects of deployment to Iraq and Afghanistan on aerobic capacity, physical performance, and body composition. Despite the concerns about soldiers being physically compromised by deployment, the actual changes seen were not significant. However, an unexpected finding was that several months immediately after their return from deployment and resumption of physical training, their injury rates increased 15–45% compared with that of a "nondeployed" control group.

The first study to include pre- and postdeployment neuropsychological assessments of U.S. Army soldiers in Iraq was conducted in collaboration with the Boston Veterans Affairs Hospital. Deployment affected soldier performance decrements on tasks involving sustained attention, verbal learning, and visuospatial memory, whereas simple reaction time was improved.

Research in the area of muscle physiology and injury has characterized molecular events responsible for important postinjury remodeling and repair. It was documented that pretreatment with an adenosine A<sub>3</sub> receptor agonist is an intervention that may minimize skeletal muscle damage. IGF-I was found to be a valid biomarker of operational stress experienced by soldiers. Clearly, these molecular approaches demonstrate significant potential in advancing our knowledge of environmental and operational medicine.

#### *Information Products, Partnerships, and Collaborations*

Over its 50-yr history, the scientists at USARIEM have published ~3,000 scientific papers. While these papers include research articles, book chapters, scientific proceedings, and technical reports, the vast majority appear in the peer-reviewed scientific literature. During the past 25 yr, the Institute has published ~2,200 of these 3,000 scientific papers.

During the 1990s, USARIEM published a series of seven pocket guides. The first was critically important as it provided guidance for Operation Desert Storm and was titled "Sustaining Health and Performance in the Desert: Pocket Guide to Environmental Medicine for Operations in Southwest Asia." This guide was so well received that six others were written for small unit leaders concerning soldier health and performance in

Southwest Asia, Somalia, the Former Republic of Yugoslavia, Rwanda, and Haiti and one involving nutritional guidance for military field operations in temperate and extreme environments.

During the first decade of the 21st century, USARIEM transitioned the results of its biomedical science into Army medical/performance doctrine for operations at environmental extremes. Based on the best practices, as recommended by USARIEM scientists, the Department of the Army published updated official doctrines referred to as Technical Bulletins on heat stress and casualty management (65 pages) in 2003 (4), prevention and treatment of cold weather injuries (86 pages) in 2005 (2), altitude acclimatization and casualty management (120 pages) in 2010 (1), and prevention and treatment of musculoskeletal injuries in 2011 (3).

USARIEM scientists are members of many professional organizations and societies. However, the American College of Sports Medicine (ACSM) and the American Physiological Society (APS) are probably the two most prominent in terms of membership and involvement. USARIEM has published nearly 350 papers and >100 papers in APS and ACSM journals or books, respectively. The Institute has a formal agreement with ACSM as the current and immediate past Editors-in-Chief (2000 to present) of ACSM's flagship journal have been USARIEM staff members. USARIEM scientists serve on numerous APS or ACSM committees, on book/journal Editorial Boards, and as book/journal Associate Editors/Editors.

During the first decade of the 21st century, USARIEM had nearly 60 formal partnerships/collaborations with academia, hospitals and medical centers, industry, and foreign governments. Harvard University, the John Hopkins University, Massachusetts Institute of Technology, and Wellesley College are a few of the 30 major partnerships/collaborations with academia. Brigham and Women's Hospital, Massachusetts General Hospital, Pennington Biomedical Research Center at Louisiana State University, and the University of Colorado Health Science Center represent the hospitals and medical centers with formal agreements. Fisher Scientific, Gillette, GalaxoSmithKline, and Millipore are several of the 25 industrial partnerships/collaborations. The Defense Research and Development Canada, Israeli Defense Forces, North Atlantic Treaty Organization (consisting of 28 member countries), the United Kingdom Institute of Naval Medicine, and The Technical Cooperation Program (Australia, Canada, New Zealand, the United Kingdom, and the U.S.) represent some of the Institute's foreign government collaborations. These many partnerships/collaborations with academia, industry, or other governments were primarily driven by mutual research interests where each party made a unique contribution and have resulted in numerous joint scientific publications.

From 2000 to 2010, USARIEM had nine active U.S. Patents. Representative patents include the following: "Method for Interpreting Forces and Torques Exerted by Left and Right Foot on Dual Plate Treadmill," "Personal Water and Additive Apparatus," "Body Thermoregulation Using Skin Temperature Feedback," "Gear Type Drink-O-Meter to Measure Fluid Consumption," and "Methods to Protect Skeletal Muscle Against Injury."

In conclusion, as USARIEM celebrates its 50th anniversary, the Institute's scientists and staff, past and present, can feel proud of both their prolific scientific productivity and their successful efforts to enhance, protect, and sustain our country's Warfighters both stateside and abroad. As noted 25 yr ago (5),

the Institute's future remains bright primarily because of the excellence of its current administrative support, technical, and research staff and their collective willingness to do all that is necessary to identify, investigate, and resolve issues that affect the safety, health, and effectiveness of our Warfighters.

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**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the author(s).

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