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RESEARCH AND TECHNOLOGY
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RTO MEETING PROCEEDINGS **MP-HFM-086**

Maintaining Hydration: Issues, Guidelines, and Delivery

(Le maintien de l'hydratation : enjeux,
principes directeurs et logistique)

Papers presented at the RTO Human Factors and Medicine Panel (HFM) Specialists' Meeting held in Boston, United States, 10-11 December 2003.

This Meeting was organized back to back with a USARIEM and the American College of Sports Medicine (ACSM) Specialists' Meeting on "Hydration and Physical Activity" from 8-9 December 2003.

Papers published in Annex to RTO-MP-HFM-086.

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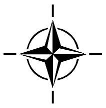

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The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

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AVT	Applied Vehicle Technology Panel
HFM	Human Factors and Medicine Panel
IST	Information Systems Technology Panel
NMSG	NATO Modelling and Simulation Group
SAS	Studies, Analysis and Simulation Panel
SCI	Systems Concepts and Integration Panel
SET	Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

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Maintaining Hydration: Issues, Guidelines, and Delivery

(RTO-MP-HFM-086)

Executive Summary

Maintaining body hydration at normal or euhydrated levels is essential to optimize both physical and cognitive performance. Inadequate fluid replacement and a state of dehydration or hypohydration can lead to an increased risk of heat injury. The challenge for the soldier to maintain a euhydrated state is exacerbated when rates of fluid loss are increased such as during exposure to hot environments that can include prolonged periods of work carrying equipment and ammunition and wearing body armour and other forms of protective clothing. The logistics of providing the fluid is of critical importance since the soldier is already expected to carry heavy loads and every kilogram (or litre of fluid) added to the soldier's pack increases their physiological cost of moving over the terrain. In addition, there is the need for the medical support teams to be prepared to deal with an increased incidence of heat injury, including heat stroke, and the rare cases of hyponatremia that may occur with overhydration.

On 10-11 December 2003, scientists, engineers, medical officers and other military representatives from NATO and Partners for Peace countries met in Boston, Massachusetts, U.S.A. for a Human Factors and Medicine Panel (HFM) Specialist's meeting on "Maintaining Hydration: Issues, Guidelines and Delivery". The purpose of the HFM Specialist's meeting was to bring together experts from the military and defence science community that could examine the physiological and logistical costs associated with maintaining hydration during recent deployments to the hot climatic regions of the Middle East and mountainous terrains of Afghanistan. There were two keynote addresses and 18 scientific and technical papers presented over the two days. There were 39 registrants from 7 countries with papers given by scientists and medical officers from the Netherlands, United Kingdom and United States. The program was divided into 4 sessions entitled *"Hydration Issues and Problems"*, *"Current Military Fluid Guidelines, Requirements and Planning"*, *"Water Logistics and Delivery System"* and *"Medical Issues with Fluid/Electrolyte Imbalances"*.

The US, UK and NE forces experienced significant heat injury cases and problems with maintaining operational tempo during recent deployments to Afghanistan and Iraq. The logistics of providing water to assist with the management of the heat stress was an enormous issue. There is a need to provide more precise estimates of fluid requirements to lessen the loads that the soldier might have to carry and reduce the costs associated with water transport and re-supply. There is the need to continue to validate and improve prediction models for estimating fluid requirements in the operational theatre. There is also a need to improve the ability of the soldier to have access to water on the move as well as improve the delivery and resupply mechanisms. The ability to generate water from other sources such as engine exhausts and purify natural sources of water while on the move is critical for the soldiers of the future to be able to meet the requirements of the Objective Force of self-sustainment for 3-7 days. New methods and technologies to assess the soldier's hydration status in the field were also presented and discussed with the aim of preparing the soldier of the future to better meet the challenges of maintaining operational requirements during exposure to such extreme environmental temperatures.

The discussions clearly documented the heat stress problems facing the military during deployments to countries with extreme environmental conditions. The most significant challenge that remains for the military is to provide sufficient water supply for the fast advancing strike force that may be expected to continue their operations without re-supply for up to 7 days. The soldier cannot be burdened by the need to carry all of their water requirements. New technologies that provide a source of water supply while the soldier is on the move are critical for sustaining operations for the Objective Force warrior and soldier of the future.

Le maintien de l’hydratation : enjeux, principes directeurs et logistique

(RTO-MP-HFM-086)

Synthèse

Le maintien de l’hydratation du corps à des niveaux normaux ou euhydratés est indispensable à l’optimisation des performances physiques et cognitives. L’insuffisance du remplacement liquidien, associée à un état de déshydratation ou d’hypohydratation peut accroître le risque de malaise causé par la chaleur. La difficulté qu’éprouve le combattant à maintenir un état d’euhydratation est exacerbée lorsque les pertes de fluides organiques augmentent, comme par exemple lors de l’exposition de celui-ci à des environnements chauds, associée au port de matériel et de munitions pendant des périodes prolongées, vêtu d’un gilet pare-balles, ainsi qu’éventuellement d’un autre type de vêtement de protection. La logistique de l’alimentation en liquide est d’une importance décisive puisque le combattant porte déjà des charges importantes et que chaque kilogramme (ou litre de liquide) ajouté à son équipement a pour effet d’accroître le coût physiologique de son avance. En outre, les équipes de soutien sanitaire doivent faire face à un nombre croissant de cas de malaises causés par la chaleur, y compris les coups de chaleur, ainsi que les rares cas d’hyponatrémie qui peuvent accompagner l’hyperhydratation.

Les 10 et 11 décembre 2003, des scientifiques, des ingénieurs, des médecins militaires, ainsi que d’autres représentants militaires de l’OTAN et des pays du PPP se sont réunis à Boston, dans le Massachusetts (Etats-Unis), dans le cadre d’une réunion de spécialistes organisée par la Commission sur les facteurs humains et la médecine (HFM) de la RTO, sur le thème « Maintien de l’hydratation : boissons, quantités et ingestion ». Cette réunion de spécialistes HFM avait pour objectif de rassembler des scientifiques civils et militaires du domaine de la défense pour étudier les coûts physiologiques et logistiques associés au maintien de l’hydratation lors de déploiements récents dans des régions climatiques chaudes du Moyen-Orient, ainsi que dans des zones montagneuses de l’Afghanistan. Deux discours d’ouverture et 18 communications scientifiques et techniques ont été présentés pendant les deux jours. La réunion a permis de réunir 39 représentants de 7 pays, des présentations ayant été données par des scientifiques et des médecins militaires des Pays-Bas, du Royaume-Uni et des Etats-Unis. Le programme a été organisé en 4 sessions intitulées « L’hydratation : problèmes et défis », « Directives, besoins et prévisions militaires dans le domaine de l’alimentation en liquide du combattant », « La logistique et les systèmes d’ingestion de l’eau », et « Questions médicales concernant les déséquilibres liquide/électrolyte ».

Les forces armées US, UK et NE ont connu de nombreux cas de malaises causés par la chaleur, ainsi que des difficultés de maintien de la cadence opérationnelle voulue lors de récents déploiements en Afghanistan et en Iraq. La logistique de l’alimentation en eau pour lutter contre les effets du stress thermique est très complexe. Des estimations plus précises concernant les besoins en liquide seraient nécessaires, afin de réduire les charges supportées par le combattant et de réduire les coûts associés au transport et au réapprovisionnement en eau. Il faut poursuivre le travail de validation et d’amélioration des modèles de prévision pour l’estimation des besoins en liquide sur le théâtre d’opérations. Il est également nécessaire de faciliter l’accès à l’eau pour le combattant en mouvement, ainsi que d'améliorer les mécanismes d'ingestion et de réapprovisionnement. Pour le combattant de demain, il est indispensable de pouvoir produire de l’eau à partir d’autres sources, telles que les échappements des moteurs, et de pouvoir purifier des sources naturelles d’eau localisées au cours d’un déploiement, afin d’atteindre l’objectif d’une autonomie de 3 à 7 jours. De nouvelles méthodes et technologies d’évaluation de l’hydratation du combattant en campagne ont également été présentées et discutées en vue de mieux préparer le combattant de demain à relever les défis du maintien de ses capacités opérationnelles lors de son exposition à des températures ambiantes si extrêmes.

Les discussions ont permis de bien cerner les problèmes auxquels sont confrontés les militaires lors de leur déploiement dans des pays où les conditions d’environnement sont extrêmes. En conclusion, il est à noter que le défi le plus appréciable pour les militaires reste l’alimentation en eau en quantité suffisante d’une force d’intervention qui avance rapidement et qui doit poursuivre ses opérations sans réapprovisionnement pour une période pouvant aller jusqu’à 7 jours. Il n'est pas concevable d'obliger le combattant à transporter l’intégralité de ses besoins en eau. La mise au point de nouvelles technologies d’alimentation en eau pour le combattant en mouvement est indispensable au soutien des opérations du "guerrier de la force objective" et du combattant de demain.

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† Paper not available at the time of publishing.

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Technical Evaluation Report

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INTRODUCTION

On 10-11 December 2003, scientists, engineers, medical officers and other military representatives from NATO and Partners for Peace countries met in Boston, Massachusetts, U.S.A. for a Human Factors and Medicine Panel (HFM) Specialist's meeting on "Maintaining Hydration: Issues, Guidelines and Delivery". This meeting followed a scientific meeting on December 8 and 9 organized by the United States Army Research Institute of Environmental Medicine (USARIEM) and the American College of Sports Medicine that dealt with "Hydration and Physical Activity". Summaries of the presentations made during this meeting are included in Appendix A.

The purpose of the HFM Specialist's meeting was to bring together experts from the military and defence science community that could examine the physiological and logistical costs associated with maintaining hydration during recent deployments to the hot climatic regions of the Middle East and mountainous terrains of Afghanistan. There were two keynote addresses and 18 scientific and technical papers presented over the two days. There were 39 registrants from 7 countries with papers given by scientists and medical officers from the Netherlands, United Kingdom and United States.

THEME / OVERVIEW

Maintaining body hydration at normal or euhydrated levels is essential to optimize both physical and cognitive performance. Inadequate fluid replacement and a state of dehydration or hypohydration can lead to an increased risk of heat injury. The challenge for the soldier to maintain a euhydrated state is exacerbated when rates of fluid loss are increased such as during exposure to hot environments that can include prolonged periods of work carrying equipment and ammunition and wearing body armour and other forms of protective clothing. The logistics of providing the fluid is of critical importance since the soldier is already expected to carry heavy loads and every kilogram (or litre of fluid) added to the soldier's pack increases their physiological cost of moving over the terrain. In addition, there is the need for the medical support teams to be prepared to deal with an increased incidence of heat injury, including heat stroke, and the rare cases of hyponatremia that may occur with overhydration. This Specialist's meeting was designed to bring together experts from the military and defence science communities that could discuss hydration issues and concerns from recent deployments to the Middle East and Afghanistan.

SPECIALISTS MEETING PROGRAM

The overall program was chaired by Dr. Mike Sawka from USARIEM with invited chairs for each of the other sessions. Colonel Carel Banse from the NATO Research and Technology Agency in Paris represented the HFM panel executive at the meeting. Other members of the Program Committee included Dr. Scott Montain from USARIEM (US), Dr. Tom McLellan from DRDC Toronto (CA), Mr. Roger Masadi from NATICK (US), Mr. Rene Nevola from QinetiQ (UK) and Captain Maarten Hoejenbos from the Ministry of Defence (NE). Dr. McLellan also served as the technical evaluator for the meeting. The Specialist's meeting began with a welcome by Dr. Sawka and an overview of the NATO RTO and HFM panel by Colonel Banse. LTCOL B. Freund, the Deputy Commander at USARIEM, provided an overview of the research program at USARIEM together with the need to study hydration management for the military.

One keynote speaker was positioned at the start of each day. Dr. H. Daanen (NE) presented recent hydration challenges for the Dutch Army deployed to Iraq as well as some current research programs at TNO. Colonel R. DeFraites discussed force health protection issues related to hydration management with recent US deployments with special reference to Operation Iraqi Freedom.

The program was divided into 4 sessions. Sessions I, entitled *"Hydration Issues and Problems"*, was chaired by Dr. Mike Sawka. In addition to the first keynote address, this session contained 5 presentations. Session II was entitled *"Current Military Fluid Guidelines, Requirements and Planning"* and was chaired by Dr. McLellan. This session contained 4 presentations. Session III that began the second day included the keynote address by COL DeFraites and 4 additional presentations. This session was entitled *"Water Logistics and Delivery System"* and was chaired by Mr. Masadi. The final session was chaired by Dr. Montain and was entitled *"Medical Issues With Fluid/Electrolyte Imbalances"*. This session contained 5 presentations. Dr. McLellan was then asked to provide a summary of the technical evaluation of the meeting and closing remarks were then given by Dr. Sawka to complete the program.

TECHNICAL EVALUATION

Key Note Addresses

Dr. Hein Daanen presented the first keynote address entitled, *"Thermal Sweating Experiences in the Netherlands Armed Forces"*. In his talk, he focused on the problems of heat injury experienced by the Dutch Army during their recent deployment to Iraq. In an attempt to reduce the risk of heat injury in the operational theatre, Dutch soldiers were first sent to Kuwait for 7 days of heat acclimation. Soldiers were provided with 7.5 L of cool water per day and the use of a 1.5 L delivery system that was carried and provided easy access to a continuous supply of water. The number of heat injury cases was approximately 2-fold greater during the heat acclimation phase in Kuwait than during the operational phase in Iraq attesting to the benefits of heat acclimation and adequate fluid supply during exposure to hot environments.

Dr. Daanen then discussed some recent findings from studies that had been conducted at TNO. He discussed the use of the THYDN model developed by Dr. Lotens for predicting heat strain in various climatic conditions and work rates while wearing different clothing ensembles. He also stated that the model had been validated with the findings from laboratory human trials. Recent findings were also presented that revealed a significant reduction in core temperature and an improvement in cognitive performance for aircrew wearing an air-cooling vest during exposure to hot environments. Dr. Daanen emphasized that the vest is effective only when an individual is sweating, however, one should not believe that the use of the vest would induce greater whole-body fluid loss. In fact, due to the increased evaporative efficiency with the air-cooling system, sweat rates are actually reduced compared with the no-cooling condition.

Dr. Daanen concluded by presenting findings from a study that examined the benefits of pre-cooling on subsequent physiological strain during exposure to the heat. A water-perfused suit was used to cool the whole body or only the legs or torso. During subsequent cycling exercise whole-body pre-cooling significantly reduced the core temperature for over 40 minutes. Since rates of heat storage during the exercise trials appeared similar with the different cooling strategies, the advantage to the cyclist appeared to occur from the lowering of core temperature at the beginning of the heat exposure.

COLONEL R. DeFraites from the U.S. Army Office of the Surgeon General presented the second keynote address entitled, *"Force Health Protection Issues Related to Water Management, Hydration with Recent Deployments and Army Transformation (Operation Iraqi Freedom and Beyond)"*. He began his talk by providing an overview of the threat assessment for Iraq that included the temperature extremes and the problems of providing a purified water supply for their troops. He then reported epidemiological data that revealed the incidence of heat injury cases in the U.S. Army that required hospitalization was about 3 cases/1000/yr over the past 10 years. In addition, a 6-fold greater incidence rate was documented for heat injury cases treated on an outpatient basis. During Operation Iraqi Freedom there were 6 heat-related fatalities and 65 additional heat injury cases that required evacuation. Of these, 30 were diagnosed as heat stroke and 24 as heat exhaustion. Thus, heat injury continues to be a problem during the early stages of deployment to countries with hot environments.

The second portion of COLONEL DeFraites' talk focused on the logistical concerns of ensuring an adequate supply of potable water was available. During the early stages of Operation Iraqi Freedom bottled water was supplied to the troops. However, even after purified sources of water became available, troops preferred the issue of bottled water. Total costs for this requirement approached $60 M US of which $18 M US was lost during the transport of the water. One-third of all transportation costs during Operation Iraqi Freedom was attributed to the supply of water to the troops. It was emphasized that future deployments must instill the confidence within the soldier of the purity of the treated water to help reduce the enormous cost associated with the issue and transportation of bottled water. COLONEL DeFraites also spoke to other programs within the U.S. Army that are researching new ways to harvest a clean water supply from engine exhausts or condensing ambient water vapour. He concluded his presentation by stating that these current programs are critical if the stated requirements for self-sustainment of 3-7 days for the Objective Force are to be achieved.

Hydration Issues and Problems

Soldiers are expected to carry heavy loads to ensure that their missions are completed successfully. Every kilogram added to their load increases the physiological burden to the soldier. It is not surprising, therefore, that soldiers are keen to keep their loads to a minimum wherever possible. A very interesting account of the problems that faced the U.S. soldiers during their recent deployment to Afghanistan was the first paper in this session presented by Mr. Fred Dupont. Although Army doctrine defines certain loads that are permissible to meet certain operational requirements, Mr. Dupont explained that the soldiers were exceeding these recommended loads by 30-40%. In some instances, soldiers were carrying in excess of their body weight and this was in the mountainous terrain at altitudes approaching 10,000 ft. During these missions that lasted between 1-3 days, soldiers were carrying their own supplies of water that in some instances represented 9-10 kg or over 30% of their fighting load. Mr. Dupont emphasized that there is a critical need for the soldier to have the confidence in the re-supply chain to enable them to lighten their load. Issues related to the purification of water sources while on the move, the generation of a water supply from other sources such as engine exhaust and the provision of cooling to the soldier were discussed as potential areas of research that would assist the soldier in meeting their operational objectives.

Mr. René Nevola who discussed data from a collective training exercise in the UK presented the second paper in this session. The study focused on the operational readiness and effectiveness of aircrew over a 60-hour period and whether guidelines to provide up to 12 litres of water per day were appropriate. For this study hydration status was monitored before and after the exercise and included such measures as total body water using doubly-labeled water, plasma volume determination with hematocrit and hemoglobin measures, urine specific gravity and colour, and body mass. Other measures of physiological strain included heart rate and body temperature recordings. Environmental conditions throughout the training exercise would be considered to be representative of a temperate climate with wet bulb globe temperature (WBGT) reading reaching about 20ºC during the afternoon. The findings revealed that only 4 of the 14 subjects had a decrease in plasma volume indicating insufficient hydration practices. These subjects were also those that were required to don protective clothing more often than the other subjects in the study. In general, therefore, providing *ad libitum* water supply up to 12 litres per day was sufficient to maintain hydration during a simulated operational environment.

Major Persson presented the next paper in this session. His talk focused on the advantages of a liquid-cooling vest for aircrew flying rotary wing aircraft. Major Persson explained that the local environment within the helicopter can sometimes be 5ºC greater than the WBGT of the ambient conditions because of the greenhouse effect of the aircraft. In addition, with an NBC threat aircrew are required to wear protective undergarments that create an additional thermal burden. His data revealed that the microclimate cooling reduced the heat strain associated with being in MOPP 4 and allowed the successful completion of simulated 2-hour sorties in environmental conditions of almost 38.0ºC with 50% relative humidity. Subjects presented with a mild 1.6% state of dehydration over a 3-hour period that was considered to be manageable. Flight performance scores were affected more by the encumbrance of wearing protective clothing than by the heat stress of their trials. Thus providing cooling to aircrew would be one way to manage the heat stress of operating in hot environments and reducing hydration requirements because of the reductions in body temperature afforded with the use of the cooling.

The fourth paper in this session also dealt with hydration and heat stress concerns of aircrew working in hot environments and was presented by Dr. K. Bradley. The talk focused on the UK Harrier GR Mark 7 aircraft. Environmental conditions in Iraq exceeded any WBGT values associated with available guidelines for the management of heat strain. Also the use of thermal models did not produce very sensitive estimates of work tolerance. Thus, Dr. Bradley reported on a laboratory study that simulated conditions for pilots in Iraq that included exposures to 50ºC dry bulb and 58ºC globe temperatures during a simulated 45-min stand-by and 60-min flight exercise that involved about 200 W of heat production by the pilots. Once the flight exercise period began the temperatures were reduced to 30ºC to simulate the presence of air conditioning in the cockpit during flight. Core temperatures increased to values approaching 38.5ºC during the stand-by period. In addition, dehydration rates were close to 3% by the end of the 60-min flight period indicating the need to monitor rehydration practices closely for pilots that may be expected to perform multiple sorties throughout the day.

The last paper in this session was presented by LCOL Bricknell who discussed heat stress issues for the UK forces deployed this past summer to Iraq. Available guidelines would have suggested that all work be ceased with the WBGT levels that were being recorded in Iraq during the summer months. LCOL Bricknell also presented a video of a UK field medical officer commenting on the heat stress problems that were experienced by the UK soldiers. Their initial findings suggested that a 7-day pre-deployment heat acclimation program was not sufficient to deal with the heat stress exposure for such extreme environments. It was also suggested that a major issue was ensuring that soldiers also ate sufficient meals to replace the electrolytes lost through sweating. To try to manage the problem of heat stress, the UK implemented procedures that banned all non-essential activity between 1000 and 1600 hours, implemented a buddy system, provided an area with convective fan cooling, and encouraged soldiers to drink as much as possible and eat regular meals. LCOL Bricknell reported that the UK experienced 849 heat injury cases, of which 766 were admitted to hospital and 166 subsequently airlifted back to the UK for additional treatment. The majority of the cases (55%) occurred during the pre-deployment heat acclimation period. In addition, it was reported that a fairly high incidence of hyponatremia was evident with apparently 6% of the cases being attributed to a lack of electrolyte replacement (rather than overdrinking). It was suggested that it would be worthwhile to look at those factors that are associated with heat intolerance that might help identify those soldiers that should not be deployed to these hot environments.

Clearly, both the US and UK forces have experienced significant heat injury cases and problems with maintaining operational tempo during exposure to these hot environments. The logistics of providing water to assist with the management of the heat stress is an enormous issue. If resupply and delivery of potable water cannot be guaranteed, the soldier will be expected to carry even greater loads into the operational theatre that will increase their rates of heat production and rates of fluid loss.

Current Military Fluid Guidelines, Requirements and Planning

It was evident from the first session that there is a need to provide more precise estimates of fluid requirements to lessen the loads that the soldier might have to carry and reduce the costs associated with water transport and re-supply. Dr. M. Kolka presented the first paper in this second session and it dealt with revising the U.S. Army fluid replacement guidelines for training in hot environments. Dr. Kolka presented figures that showed that heat illness cases in the U.S. Army were approximately 30 cases per 100,000 soldier-years. However, during the first Iraq war these figures doubled. In addition, there had been reports of a few cases of hyponatremia and associated fatalities each year during training periods in the summer months. It was implied that the current fluid replacement guidelines could have led to situations of over hydration during exposure to certain environments for certain soldiers. As a result of these latter cases, the current fluid replacement guidelines were re-evaluated using computer predictions and laboratory trials. The major changes to the guidelines involved classifying workrates as low, medium and high and limiting the fluid replacement schedules to no more than 1.5 litres per hour and no more than 12 litres pre day. The success of these new guidelines was then documented during the summer training periods of 1997 and 1998. When the new guidelines were used only 1% of trainees had plasma sodium levels below 135 versus 8% when the old guidelines were used. Provisions were also made for the wearing of protective clothing and for factors such as body size and gender that would be expected to impact on the required consumption rates.

The second paper of this session was given by Mr. René Nevola and dealt with hydration issues during a 194-km desert march. The objective of this study was to test whether the provision of 12 litres of water per day would be sufficient to meet hydration requirements for this type of operation. Computer modeling predicted that participants would require 50 litres of water over a 60-hour period. Data were collected on five subjects that participated in 6 days of heat acclimation in Qatar prior to beginning the march. During the march, body mass was recorded every 6 hours and impedance was used to assess total body water at the beginning and end of the trial. In addition, heart rates, core temperature (using a radiopill), water and food intake and urine output were measured. Four of the five subjects completed the march with the one subject suffering a physical trauma and being forced to stop the exercise. For the others, the march was completed in 78 hours and 35 litres of water was consumed on average for each participant. Thus, although the water consumption was approximately 30% of the predicted requirement, the total duration of the march was increased about 30% compared with the model predictions. Only small changes in body mass were recorded and impedance indicated no change in total body water, therefore, indicating the appropriateness of the volumes of water consumed. On average, participants slept for only 4 of the total 78 hours thus incurring a substantial energy and fluid intake requirement to complete the exercise. The findings thus indicated that a ceiling of about 12 litres per day would be sufficient to manage even the most severe hydration requirement.

Captain Carter presented the next paper in this session and he addressed the use of prediction models for validating warfighter fluid requirements. Presently, the U.S. Army is using 2 models to predict the heat strain of the soldier. The USARIEM heat strain model tends to over-predict hydration requirements since it attempts to match predicted rates of sweat loss based on Emax calculations with fluid requirements. Over-predictions by 25% can lead to a substantial increase in cost and burden to the soldier or to logistical support units trying to maintain fluid supplies for the troops. The second model, SCENARIO, includes input for states of dehydration and heat acclimation and predicts required rest periods and extent of heat stress casualties associated with the rate of work being performed while wearing various clothing configurations. In its present form, the model is limited to workrates below 475 W and for work durations less than 2 hours. In addition, the application of the model to environmental temperature extremes is quite limited at this time. Studies are being planned to address and improve the usability of these models in operational environments.

The final paper in this session was presented by Ms C. O'Brien and dealt with the impact of hypohydration on temperature regulation in the cold. Exposure to the cold also exacerbates water balance concerns for the soldier. Wearing bulky clothing can lead to increased rates of sweating while performing heavier work and there is increased water loss through respiration because of the cold, dry ambient conditions. Exposure to the cold also blunts thirst and the cold-induced diuresis promotes greater fluid loss. Ms. O'Brien presented data from 2 studies. The first study examined the impact of hypertonic hypohydration (as occurs with sweating during exercise) or isotonic hypovolemic hypohydration (as occurs with the cold-induced diuresis) on temperature regulation during cold air exposure to 7ºC. Total heat debt was similar with all trials although the vasoconstrictor response was somewhat attenuated during the hypertonic hypohydration trial. The second study examined whether a state of hypohydration impacted on the potential risk of cold injury. Compared with a euhydrated state, a condition of hypertonic hypohydration was not associated with any effects on skin or finger temperatures. Although performance data were not included in this study, the findings suggest that finger dexterity and motor performance would not be affected by the state of hydration during cold exposure.

This session revealed the need to continue to validate and improve prediction models for estimating fluid requirements in the operational theatre. At this point, a maximum rehydration schedule of 12 litres per day seem advisable with adjustments made on an individual case depending of the size of the soldier, their state of heat acclimation and their expected rate of heat production and clothing configuration for the particular set of environmental conditions.

Water Logistics and Delivery Systems

This session dealt with current and new technologies that were being developed to address the issue of water delivery for the soldier. From the previous presentations, it was clear that there is a need to improve the ability of the soldier to have access to water on the move as well as improve the delivery and resupply mechanisms.

Mr. Pentheny presented the first paper in this session and he focused on current systems in use by the U.S. Army to provide fluid for the soldier on the move. Traditionally the soldier was expected to carry 2 litres of fluid or the equivalent of 2 standard-issue canteens. Presently, a 3-litre (100 ounce) hydration bag has been provided to allow the soldier greater access to fluid as required in hot environments. Soldiers also consume carbohydrate and electrolyte drinks that place greater demands on the cleaning of canteens or hydration bags. These specialty drinks can more easily promote bacterial growth. It was also stressed that a single larger volume container may reduce the total physiological burden of carrying the additional fluid since a greater percentage of the total carried weight would represent the weight of the fluid rather than the weight of the container.

Mr. Cullen then presented an overview of the use of the Camelbak® technology for various military environments. The system provides a 3-litre reservoir to meet hydration needs on demand. The technology also does not affect tactical awareness since it is a hands-free delivery system. Mr. Cullen presented findings from the use of his product during trials in East Timor that indicated an improved usefulness of the Camelbak® technology as well as studies that showed the effectiveness of the technology while wearing NBC protective clothing. The company has also introduced anti-microbial technology into their systems to assist the soldier in using carbohydrate and electrolyte drinks if so desired. The systems are easy to use and ergonomic in their integration with the current load-carriage systems of the soldier.

The third paper of this session was presented by Dr. J. Dusenbury. His talk focused on current and future technologies for land-based water purification and distribution programs within the U.S. Army. Presently, the U.S. military relies on the reverse osmosis water purification unit (ROWPU) that was developed in the early 1980's to provide water for their soldiers. There is both a 600 gal/hour and 3000 gal/h ROWPU currently in service. The smaller units are positioned more forward in the column of the advancing force whereas the larger unit is positioned at the rear to provide additional supplies for vehicles, laundry and to meet hospital requirements. The ROWPU has also been adapted, if necessary, to be used in an NBC environment. Current new technologies that are in the development stage include a smaller 125 gal/hour ROWPU that can be transported on the back of an armoured vehicle in the forward lines. Also, to assist the Objective Force in achieving their expectation of 3-7 days of self-sustainment, the U.S. Army has invested in a program focused on recovering purified water from engine exhausts. Currently, the process is about 50-60% efficient. Thus, to deliver the minimum requirement of approximately 6.5 litres of water/soldier/day, fuel consumption would have to approximate 11-13 litres/soldier/day. Presently, there is not a consensus agreement as to whether this technology would deliver all of the water requirements. The other technology being considered is the recovery of water from air. However, presently this is a very inefficient process requiring in excess of 630 W/hour to recover 1 litre of water. Current research programs are examining the efficiency of hydrophilic carbon-activated surfaces that should reduce the energy requirements of the process.

The last paper in this session was presented by Dr. A. Senecal. His talk focused on the use of the process of forward osmosis to generate water to hydrate rations. Presently, the meal ready to eat (MRE) requires about 4 litres of water to rehydrate the beverages and food in the ration pack. Once rehydrated the total weight of the MRE is approximately 4 kg. The light ration packs also require about 4 litres to rehydrate but their total weight is less once rehydrated (at about 2.5 kg). The objective of this program is to develop a process that rehydrates rations from non-potable water using forward osmosis. Presently, the process is approximately 99% effective in removing or filtering particle matter. However, it is a slow process. Thus, it would be effective to be done while the soldier is on the move or when there is sufficient time during rest periods. To speed the rate of rehydration, research is examining the influence of osmolality, electrolyte and acid content of the hydration pouch used in the forward osmosis process.

The papers presented in this session have documented that technologies exist today or will exist in the near future to help meet the water requirements of the soldier. One issue that continues to be apparent is the increased physiological cost that would be expected to carry the water requirements for the most forward soldiers in the advancing force. The ability to generate water from other sources such as engine exhausts and purify natural sources of water while on the move is critical for the soldiers of the future to be able to meet the requirements of the Objective Force of self-sustainment for 3-7 days.

Medical Issues with Fluid/Electrolyte Imbalances

The last session dealt with recent medical issues that were present during Operation Iraqi Freedom, the impact of dehydration on cognitive function and then showcased some new technologies that might be used to assess hydration status in the field.

Major S. Kaushik recounted her experiences as a medical officer for the U.S. Army during Operation Iraqi Freedom. She provided medical support for approximately 3,600 soldiers during their advance to Ba'qubah north of Baghdad. Initially, soldiers were rationed with 2-3 1.5-litre bottles of water per day. Eventually, some of this rationed supply was used for hygiene and dental care. WBGT exceeded 50ºC in the afternoon, which heated the bottled water if it was sitting in the sun. Ice was purchased initially to cool the water supply but local merchants became unwilling to sell to the American troops soon after terrorists targeted their stores. Even after ROWPU units were set-up and functioning, troops preferred bottled water indicating that their confidence was low in the purity of the processed water form the ROWPU. This is a major command issue. Soldiers need to be convinced that the water produced from the ROWPU is safe.

Major Kaushik then discussed the number of heat injury cases that were treated. During the early summer months of May and June, prior to establishing re-supply lines, 20-25 cases/month were treated. The number of treated cases fell in July but then increased again once the operational tempo increased in August and September. There were not sufficient opportunities for soldiers to hydrate and cool down during this period of increased operational tempo.

Dr. K. Bradley presented the next paper in this session. She presented data from 3 studies that focused on the impact of dehydration on cognitive performance of aircrew. Cognitive performance was assessed using a battery of tests that measured attention, memory, simple reaction time and higher-order decision making processes using a multi-task battery that simulated cockpit activities for pilots. In the first study, exposure to a WBGT environment in excess of 35ºC did not impact on cognitive performance despite a rise of approximately 1.0ºC in deep body temperature. In the second study, dehydration of 1%, 3% and 5% were induced by fluid restriction and exercise prior to performing the cognitive testing. Performance during the multi-task battery was impaired at dehydration levels greater than 3%. However, core temperature was also significantly different during these trials so it was unclear whether it was the rise in core temperature or the state of dehydration that impaired cognitive function. Thus, a third study was conducted to try to answer this question. Subjects completed 4 trials that induced either a state of euhydration or dehydration using the diuretic frusemide on day 1 with cognitive testing being performed on day 2. The use of frusemide without fluid replacement induced a 3.5% decrease in body mass. Despite the magnitude of this decrease, cognitive performance was unaffected compared with the euhydrated state or with the initial dehydrated state that also involved subsequent fluid replacement. Thus, the impairment in cognitive performance observed in the earlier studies had to be attributed to the rise in deep body temperature rather than to the state of dehydration.

The last 3 papers in this session presented new methods to assess hydration status in the field. Dr. R. Hoyt presented the use of heart rate interval scaling to detect a change in hydration. Current statistical methods used to assess the heart rate variability distribution were unable to detect changes with an exercise-induced state of dehydration. However, at rest, there was a much wider distribution of the heart rate interval scale with dehydration, indicating that the method may be of some use to detect cases of soldier dehydration at rest.

Dr. S. Siconolfi next presented research that examined whether a change in the ratio of interstitial to extracellular fluid volume could be used to indicate the extent of exercise-induced dehydration. Twenty-eight men and women were studied before and after 1 hour of exercise in the warm environments of Texas. The 2% decrease in body mass over the hour provided a gross estimate of the extent of body water losses. Plasma volume, determined by measuring hematocrit and hemoglobin, decreased 4.2%. The ratio of interstitial fluid to extracellular fluid volume was determined using bioimpedance. The ratio decreased 3.2% following the one-hour of exercise. Dr. Siconolfi concluded that the use of bioimpedance to determine this ratio could be an effective non-invasive method to assess changes in hydration status in the field.

Dr. D. Moran presented the last paper in this session that also represented the last paper for the meeting. His presentation described a new method that used radio frequency to assess hydration status. He described an approach that used radio frequencies below 1 GHz to represent ionic absorbance and frequencies above 1.5 GHz to represent water absorbance. The ratio of low to high frequency absorbance should be proportional to plasma osmolality and thus give an indication of the state of hydration. In the first study, 13 subjects were heat stressed during exercise in a hot environment at 40.0ºC with or without fluid restriction. The rise in body temperature and decrease in body mass were significantly greater during the trial with fluid restriction. During the second study, 10 men and 10 women performed up to 3 hours of treadmill exercise in a warm environment at 30.0ºC with or without fluid restriction. Greater differences in the rise in core temperature and decrease in body mass were evident in this study when fluid was either available *ad libitum* or was restricted. Predicted changes in total body mass losses using the radio frequency methodology correlated with actual weight changes with r^2 values in excess of 0.9. Dr. Moran stated that additional studies are needed to continue to validate the method using doubly labeled water, different populations and testing circadian factors that could influence the interpretation of the findings. The eventual aim is to develop a device about the size of a wristwatch that could measure radio frequency across the wrist to assess the soldier's state of hydration.

It was clear from this session that there continues to be cases of heat injury during military operations that are exacerbated by the extreme environmental temperatures, the inadequacy of water supply during the early stages of forward advance and the expectation to be able to maintain an operational tempo regardless of environmental conditions. It was also clear that cognitive performance is impacted by heat stress that can have serious consequences on the decision-making process of the soldier. Finally, some new promising research was presented that discussed methods to improve the assessment of soldier hydration in the field. These new methods and technologies could be part of the soldier of the future that includes sensor technology to assess their physiological status.

SUMMARY

This HFM Specialists meeting has provided the opportunity for the exchange of information and an open forum for dialogue among scientists and military representatives of NATO and PfP countries. The discussions clearly documented the heat stress problems facing the military during deployments to countries with extreme environmental conditions. Despite attempts to heat-acclimate soldiers prior to performing operational duties, there continues to be many cases of heat stroke and heat exhaustion. Thus, there is a need for basic research to study the physiological processes that lead to protection for some and yet fail to protect others during repeated heat stress exposure. It was also clearly presented that the logistics of providing water supply is a major concern and cost. The reliance of the soldier during Operation Iraqi Freedom on bottled water, even when other purified sources became available, created an enormous logistical burden and transportation cost. Clearly, this is a leadership issue where commanders must be able to convince their soldiers of the purity of the water generated by the ROWPUs. The most significant challenge that remains for the military is to provide sufficient water supply for the fast advancing strike force that may be expected to continue their operations without re-supply for up to 7 days. The soldier cannot be burdened by the need to carry all of their water requirements. New technologies that provide a source of water supply while the soldier is on the move are critical for sustaining operations for the Objective Force warrior and soldier of the future.

Appendix A

Summaries of the Presentations from the American College of Sports Medicine Roundtable Scientific Meeting on *"Hydration and Physical Activity"*

INTRODUCTION

On December 8 and 9 2003, the American College of Sports Medicine convened a panel of experts to discuss current issues regarding hydration for physical activity. The purpose of this roundtable discussion was to bring together a panel of experts on hydration and physical activity with the aim to review the scientific literature, perform evidence-based analyses and to discuss controversial issues. The ultimate goal of the meeting will be to develop a consensus statement regarding hydration before, during and after vigorous physical activity. The roundtable discussion was also meant to serve as a precursor for revising the current ACSM position stand on fluid replacement. The meeting was co-chaired by Dr. Mike Sawka from USARIEM, Dr. Larry Kenney from Pennsylvania State University and Dr. Robert Murray from the Gatorade Sport Sciences Institute. The meeting consisted of 14 presentations. The presentations were organized into 3 areas; fluid and electrolyte requirements, hydration effects on performance and hydration effects on health. A scientific writing team was formed to provide consensus statements for each of these 3 areas. Dr. Priscilla Clarkson will be responsible for preparing the information on fluid and electrolyte requirements, Dr. Doug Casa for hydration effects on performance and Dr. Bill Roberts for hydration effects on health.

Key summary points from these presentations are included on the following pages.

Assessing Hydration Status: Laboratory and Field

Samuel N. Cheuvront, Ph.D.
United States Army Institute of Environmental Medicine, Natick, MA

Key Points:

- There is presently no scientific consensus for 1) how to best assess athlete hydration status, 2) what criteria to use as acceptable outcome measurements, or 3) when to best apply available assessment methods (laboratory or field).

- Hydration assessment techniques include the measurement of 1) total body water by isotope dilution or bioelectrical impedance analysis, 2) plasma markers such as osmolality, sodium, or fluid regulatory hormones, 3) urine markers, such as osmolality, specific gravity, or color, 4) changes in body mass, and 5) other variables, such as salivary flow or gross, physical signs and symptoms of clinical hypohydration.

- Bioelectrical impedance analysis, plasma markers other than osmolality, salivary flow and gross physical signs and symptoms of hypohydration are inappropriate hydration assessment methods for athletes and the conditions common to athletics.

- In most athletic arenas, the use of first morning body mass measurements in combination with some measure of first morning urine concentration allows ample sensitivity (low false negative) for detecting daily deviations from euhydration. The methods are simple, inexpensive, accurately dichotomize euhydration from hypohydration, and can therefore be used as a sole source of assessment in the field or as a morning "check" for laboratory work.

- When more precision of acute hydration changes is desired, plasma osmolality, isotope dilution, and body mass changes provide for the accurate gradations in measurement often required in the laboratory.

Water and Electrolyte Requirements: Effects of Exercise and Environment

Ron J. Maughan, Ph.D.
Loughborough University, Leicestershire, LE11 3TU, England

Key points:

- Water is the largest single component of the human body and has a remarkably high turnover rate; in the sedentary individual living in a temperate climate, about 5% of total body water is typically lost and replaced on a daily basis.

- Thermal and exercise stresses increase water loss because of the need for sweating to control body temperature, and sweat losses can reach 2-3 1/h. There is a large inter-individual variability in both sweating rate and sweat composition.

- When prolonged exercise is performed in a hot environment, 20-40% of total body water can be turned over in a single day. In spite of this, the body water content is tightly regulated.

- Sweat contains a variety of solutes, and solute losses, especially loss of sodium, can be high. Salt (sodium chloride) losses vary greatly between individuals, even in the same exercise and climatic conditions, but may reach close to 20 g per day for athletes training twice daily in hot conditions. Losses of other electrolytes are generally small relative to whole body stores and are unlikely to have functional consequences when food intake is adequate to meet energy expenditure.

Diet Effects on Water Requirements

Stella L. Volpe, Ph.D.
University of Massachusetts, Amherst, MA

Key Points:

- Fluid intake can be consumed by both food and beverages.
- Caffeine does contribute to fluid intake of individuals who are not caffeine naive.
- Alcohol is a beverage that cannot be considered to contribute to fluid needs.
- Proteins and carbohydrates may increase water requirements, but research provides equivocal results.
- Increased salt intake may increase water, but research provides equivocal results.

Fluid and Electrolyte Requirements
Replacements Strategies After Physical Activity

Susan Shirreffs, Ph.D
School of Sport & Exercise Sciences, Loughborough University, Loughborough, LE 11 3TU, UK

Key points:

- The primary factors influencing the post-exercise rehydration process are the volume and composition of the fluid consumed.

- The volume consumed will be influenced by many factors, including the palatability of the drink and its effects on the thirst mechanism. Despite this, however, with a conscious effort some people can still drink large quantities of an unpalatable drink when they are not thirsty.

- Post-exercise rehydration can only be achieved if a fluid volume greater than the sweat volume lost is consumed.

- Replacement of the sodium lost in sweat is a pre-requisite for retention of drinks consumed after exercise. There is no strong conclusive evidence for the necessary inclusion of any other electrolytes.

- Plain water is not an effective post-exercise rehydration drink UNLESS sodium is ingested at the same time via solid food.

Hydration and Mental Function: Lab Studies

J. Mark Davis, Ph.D.
University of South Carolina, Columbia, South Carolina.

Key points:

- How you THINK, FEEL and REACT is likely to be important components in your ability to perform optimally, but it is often overlooked in the scientific community. Consequently the scientific evidence is limited and largely theoretical as this time, especially as related to sport performance.

- Heat stress/hypohydration can deteriorate mental function with as little as 2% body weight loss and it increases in proportion with the level of hypohydration.

- Various mental tasks are differentially affected by heat stress/hypohydration with decreased attention/vigilance and tiredness occurring first followed by complex mental function (multi-tasking), then psychomotor performance, simple mental tasks, all of which can occur prior to serious deterioration of physiological function. The increase in core body temperature associated with these impairments is well within the range that occurs with heat stress and hypohydration during exercise.

- Fluid replacement can improve mental function during activities ranging from low level occupational work to heavy exercise.

- The addition of carbohydrate to the replacement fluid can further enhance the benefits on mental function.

- Caffeine can also be effective if added to a fluid replacement beverage, but large individual differences and increased risk of side effects are a possible concern.

- These benefits can be important for optimal performance of all kinds of activity from low level industrial work to heavy exercise training and competition, especially in circumstances where vigilance, concentration, decision making, and rapid reaction to changing environments is more critical (e.g., team sports and strenuous military and industrial labor).

Hydration Effects on Performance: Sports Performance Studies

Clyde Williams, Ph.D.
Loughborough University, Loughborough, UK

Key Points:

- Endurance capacity during prolonged running is greater when fluid is consumed than when fluid is withheld.

- Endurance running capacity during prolonged intermittent exercise is greater when a carbohydrate-electrolyte solution, rather than flavoured water, is ingested throughout exercise.

- Soccer-related skill (ball dribbling) is better maintained after prolonged intermittent running when water, rather than no water, is ingested throughout exercise.

- Soccer-related skills (passing and goal shooting) decrease during prolonged intermittent exercise but the decrease tends to be less when a carbohydrate-electrolyte sports drink, rather than water, is ingested throughout exercise.

- Endurance running capacity during prolonged intermittent exercise in the heat (30ºC) appears to be greater when flavoured water is ingested than when a 6.5% carbohydrate-electrolyte sports drink is ingested during exercise.

- The rise in body temperature appears to be greater during prolonged intermittent exercise in the heat (~30°C) when a 6.5% carbohydrate-electrolyte solution is ingested than when flavoured water is ingested during exercise.

Hydration and Occupational Work Performance

Tom M. McLellan, Ph.D
DRDC Toronto, Toronto, ON, CANADA

Key Points:

- Guidelines established by ACGIH and ISO are in place to assist employers in the management of heat stress in the workplace. These guidelines are intended to limit the rise in core temperature to 38.0°C throughout the workday and include the availability of fluid for employees.

- Recently revised guidelines for hot weather military training have been shown to be effective in the management of heat stress while minimizing the risk of overhydration and hyponatremia. These guidelines were developed to allow core temperature to rise to 38.5°C.

- For individuals involved with wearing protective clothing in support of emergency response situations, the use of guidelines that restrict the rise in core temperature may not be applicable. In these situations, workers that begin their task in a hypohydrated state will have elevated resting core temperatures and reduced core temperatures at exhaustion. A state of hypohydration will reduce the employee's heat storage capacity and capability when the protective clothing is worn.

- When work is begun in a euhydrated condition while wearing protective clothing in hot environments and fluid is provided during the work phase or during intermittent rest periods, the core temperature that can be tolerated at exhaustion is increased. As a result, total heat storage capacity is increased.

- Both the volume and temperature of the ingested fluid can influence the heat storage capacity when protective clothing is worn. Since the characteristics of the clothing have a major impact on the rate of heat storage once work is initiated, providing cool water or a carbohydrate and electrolyte beverage can increase heat storage through a heat-sink effect.

Laboratory Studies on Physical Performance and Fluid Ingestion

Edward F. Coyle, Ph.D.
The Human Performance Laboratory. Department of Kinesiology and Health Education
The University of Texas at Austin, Austin, TX 78712

Key Points:

- The amount of fluid that people are advised to ingest during exercise is based upon its effectiveness in attenuating both fatigue as well as illness due to hyperthermia, dehydration or hyperhydration.

- When possible, fluid should be ingested at rates that most closely match sweating rate.

- When that is not possible or practical or sufficiently ergogenic, some athletes might tolerate body water losses amounting to 2% of body weight without significant risk to physical well-being or performance when the environment is cold (e.g.; 5-10 ºC) or temperate (e.g., 21-22 ºC).

- However when exercising in a hot environment (i.e., > 30 ºC), dehydration by 2% of body weight impairs absolute power production and predisposes individuals to heat injury.

- Fluid should not be ingested at rates in excess of sweating rate and thus body water and weight should not increase during exercise.

- People will benefit the most by better tailoring their individual needs for fluid to the specific challenges of their sport especially considering the environment's impact on sweating and heat stress.

Fluid and Electrolyte Requirements: Requirements for Specific Athletic Events

Louise M. Burke, Ph.D.
Australian Institute of Sport, Canberra, Australia

Key Points:

- Prescriptive guidelines for hydration practices are not meaningful across or even within sports, due to the considerable variability in the sweat losses of athletes, and the sports-specific differences in the factors that influence fluid intake during exercise.

- The athlete needs to have tools to monitor their sweat losses in a particular situation and to periodically undertake such measurements in training or competition to assess fluid needs and how well their current hydration practices address these needs. Observations of hydration practices across a variety of sports suggest that many athletes could increase their fluid intake during exercise to better match, but not exceed, their rates of sweat loss.

- A variety of different factors influence the fluid intake practices of athletes, including access to fluid, opportunities to drink, awareness of sweat losses, gastrointestinal comfort, the palatability of the drink, and the culture within a sport. To improve sub-optimal fluid intakes, the athlete should examine the specific factors that limit fluid intake in their sport or situation. Creative solutions can often be found to overcome or reduce the impact of these limitations, but these are specific to the event and the athlete.

- The opportunities to drink within a sport should be identified and targeted. Access to adequate supplies of fluid should be organized to match the opportunities to drink.

- Experimentation and practice may help the athlete to learn the skills and to develop a greater gastrointestinal tolerance for fluid intake during exercise.

- The provision of palatable drinks is important in encouraging fluid intake. As well as enhancing the flavor characteristics, the addition of carbohydrate and electrolytes to exercise fluids can address specific nutritional needs of various sports

Dehydration and Extertional Heat Illness Cramping in Sports; Heat Bombs in Football

E. Randy Eichner, M.D.
University of Oklahoma Health Sciences Center, Oklahoma City, OK

Key Points:

- Not all cramps are alike, but salty sweating is key in whole-body heat cramps.
- Historical evidence indicts sodium depletion in heat cramps.
- Research on athletes indicts sodium depletion in heat cramps.
- Football players who cramp lose more fluid and twice the sodium in sweat as teammates who do not cramp.
- Heat cramps have three roots: muscle fatigue, dehydration, and sodium depletion.
- Athletes who cramp need more salt. The solution for heat cramps is saline.
- Linemen can heat up fast in pre-season conditioning in moderate climates in T-shirt and shorts.

Exertional Heat Stroke

Bill Roberts, M.D.
University of Minnesota Medical School, Minneapolis, MN

Key Points:

Clinical observations and suggestions from road racing, football, and soccer tournaments.

- Prompt recognition and rapid onsite ice water immersion or ice packing cooling - good outcome even with very high rectal temps.
  - Limiting degree-minutes above 104-106°F to 30-60 degree-minutes seems to improve outcome.
  - Delayed recognition resulting in >60-120 degree-minutes - death, especially if rectal temp > 108°F.
  - >60 minutes above 108 °F has bad prognosis (>120 degree- minutes).
  - Prognosis is good for those who wake up rapidly during treatment.
  - Release from medical area is reasonable when the athlete is clinically stable and has a normal temperature if the athlete was treated and cooled immediately.
  - Transfer to emergency facility is prudent for athletes not responding to treatment or who have any complicating factors or who are football players with large volume fluid losses.

- Wearing full or partial pads before acclimatization increases risk.
  - Helmet on rule negates simple heat loss measure.

- Fluid replacement during activity maintains vascular heat transport system and fluid supply for sweating
  - There is a functional fluid restriction when water breaks are short and water source is to far from immediate practice area.

- Monitoring the heat stress is a critical reduction strategy.
  - Minimal if any practice modifications were used for high heat stress conditions when football players died.

- Players should be monitored for hydration and well being.
  - Inter-practice monitoring is not done or is not supervised.
  - The player is not a good judge of well being.
  - Other players and coaches did not notice or report changes.
  - Rest in air-conditioned spaces improves cooling between games and practices.
  - Hyperventilation is primal cooling not a behavioral problem.
  - Vomiting is a bad sign and practice should stop for the day and maybe the next day.
  - Teams should institute a buddy system.

- EHS is generally an early season practice issue.
    - It is rare for a physician to be on site.
    - Reduction strategies must include ATC and coach education for early EHS recognition and on-site first aid.

- There must be an emergency response protocol for each practice site.
    - A cooling protocol should be set up in advance and equipped.
    - There was no onsite emergency plan or evaluation/treatment protocol.

Exertional Hyponatremia

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Key Points:

- The hyponatremia associated with prolonged exercise arises primarily from fluid overload, but under replacement of sodium losses contributes to the sodium dilution.

- The reduction of extracellular solute leads to movement of water into the intracellular space. If the resulting cellular swelling is of sufficient magnitude, symptoms of central nervous system dysfunction will occur.

- Competitive and recreational athletes as well as occupational workers performing prolonged work should be taught that persistent excessive fluid intake can be harmful and fluid intake should not exceed sweat losses.

- During prolonged exercise lasting in excess of 3-4 hours, snacks or fluids containing sodium chloride should be ingested to offset the loss of salt in sweat. The latter recommendation is especially prudent for individuals who know that they lose excessive amounts of salt in their sweat.

Issues with Active Special Populations

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Key Points:

- At any given level of hypohydration, children undergo a greater heat strain than young adults. Even 1% hypohydration can induce a decrease in aerobic deficiency in children.

- Consumption of flavored beverages with 18 mEq/L NaC1 and 6% carbohydrate enhances children's *ad libitum* drinking and prevents voluntary dehydration during exercise in the heat.

- Elderly people are particularly prone to dehydration, even when physically inactive. This reflects phsyiological (a reduced ability to concentrate urine) and behavioral (reduced thirst sensation and sensitivity to flavors) deficiencies.

- Patients with cystic fibrosis who exercise in the heat undergo excessive involuntary dehydration. This reflects their diminished voluntary drinking, most probably due to a diminished osmotic thirst drive. Giving these patients a beverage with a high NaC1 concentration induces an enhanced thirst drive.

- Patients who lose large volumes of urine (e.g., in diabetes mellitus) are at excessive risk of dehydration.

Fluid Replacement: Comparison and Critique of Published Position Statements

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Key Points:

- Nine Position Statements are reviewed.

a. ACSM Position Stand: Exercise and Fluid Replacement. Med Sci Sports Exerc 28(1): i-vii, 1996

b. ACSM Position Stand: Weight Loss in Wrestlers. Med Sci Sports Exerc 28(2): ix-xii, 1996 #

c. ACSM Position Stand: Heat and Cold Illnesses During Distance Running. Med Sci Sports Exerc 28(12) i-x, 1996 #

d. National Athletic Trainers' Association Position Statement: Fluid Replacement for Athletes. J Athletic Training 35(2): 212-224, 2000

e. ACSM, American Dietetic Association, Dietitians of Canada Joint Position Statement: Nutrition and Athletic Performance. Med Sci Sports Exerc 32(12): 2130-2145, 2000 #

f. International Marathon Medical Directors Association Advisory Statement: Guidelines for Fluid Replacement During Marathon Running. IAAF Technical Quarterly 17(1): 7-11, 2002

g. National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses. J Athletic Training 37(3): 329-343, 2002 #

h. USA Track & Field Advisory: Proper Hydration for Distance Running - Identifying Individual Fluid Needs. Posted on web site (www.usatf.org), April, 2003

i. Inter-Association Task Force Consensus Statement: Exertional Heat Illnesses. NATA News, pg. 24-29, June 2003 #

- Although the focus of these five Position Statements is not fluid replacement specifically, all contain information regarding fluid replacement.

- Comparison of the topics relevant to fluid replacement are identified for each Position Statement above.
    - ➢ The topic "excessive drinking/exertional hyponatremia" appears in six of these documents (items a, c, f, g, h and i above), including the current 1996 ACSM Position Stand.

- Critique: recommended changes to the current 1996 ACSM Position Stand (above) are presented.

- Critique: other topics are presented for possible inclusion in the revised 2004 ACSM Position Stand.

Thermal Sweating – Experiences in the Netherlands Armed Forces

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ABSTRACT

The Netherlands Armed Forces (NAF) were tasked to defend the German plaines and Scandinavia within the NATO doctrine until the end of the Cold War. Now, the NAF are present in peace keeping and peace enforcing operations all over the world, such as Iraq, Afghanistan, Liberia and Eritrea. Clothing, equipment, logistics and training of the troops had to be adapted to the extreme climatic circumstances. A 7-day acclimatisation period in Kuwait was built in before deploying in Iraq. During this period heat related illness was observed, but this hardly occurred afterwards in Iraq. In Iraq blisters and diarrhoea were most common, affecting about half the troops. Water intake was strictly enforced and the use of water backpacks (Camelbaks) enabled water consumption at any moment. During operations some meteorologists and physicians used a Tactical Decision Aid for Thermal Exposure to estimate the heat strain on the human body and to take the appropriate measures. This model, developed by TNO, proved to be valuable, but needs improvement to become widely accepted. We feel that the currently employed Wet Bulb Globe Temperature is not a good indicator since clothing, acclimatisation status and exercise level are often not included in the analysis. One of the measures to alleviate heat strain is the use of cooling vests. In the TNO defence research labs practical cooling methods for the helicopter pilot and soldier in the field are under investigation. An air vest enhances evaporative cooling and improves thermal comfort. However, this cooling method is dependent on sweat loss and regular drinking is necessary to maintain the fluid balance. It is shown that pre-cooling, e.g. in the vehicle that transports the soldiers to the location of operation, effectively reduces sweat during operation, while it does not deteriorate gross efficiency.

1.0 EXPERIENCES OF THE NETHERLANDS ARMED FORCES IN IRAQ

1.1 Change in operational tasks

Between the end of the World War II and the end of the Cold War, the Netherlands Army was tasked to defend the German plains and the Marines and Air Force were tasked to defend the North Flank (Scandinavia). Now, the Netherlands Armed Forces are active in peace keeping tasks and peace enforcing tasks over a much wider area (Table 1).

The Netherlands Armed Forces (NAF) are trained and equipped to operate in cold areas. The new areas of deployment are scattered over the world and often in warm, humid or hot, dry areas. It is a challenge for the NAF to change the equipment and training to operate effectively in these new areas of deployment. This paper describes the efforts undertaken to alleviate heat stress in Iraq. First, the preparation for the deployment in Iraq is described as well as the experiences and medical consequences of work in the heat. Thereafter, three research projects are described aiming at alleviating heat stress: a tool to estimate the heat strain and the effect of heat strain reducing measures, a cooling device during operation and a project to determine the advantages of cooling prior to operation.

Paper presented at the RTO HFM Specialists' Meeting on "Maintaining Hydration: Issues, Guidelines, and Delivery", held in Boston, United States, 10-11 December 2003, and published in RTO-MP-HFM-086.

Table 1: Main deployments of the Netherlands Armed Forces in the last 15 years

Mission	*Year*	*Country*	*Total*	*Main Unit*
UNTAG	1989-1990	Namibia	89	Military Police
UNTAC	1992-1993	Cambodia	2609	Marine Battalion
UNAMIR	1993-1994	Rwanda	39	Transport Platoon
UNAVEM	1991-1997	Angola	265	EOD / Engineers
UNTSO	Current	Israel	593	Observers
UNMEE	2000-2001	Eritrea, Ethiopia	1345	Marine Battalion, Air Force (CH47D)
ISAF	Current	Afghanistan	1734	Infantry Battalion
OEF	2002-2003	Qatar, Kyrgyz	1181	Air Force (F16, KDC-10)
UNPROFOR / SFOR	Current	Bosnia	20000	Mechanized Battalion
SFIR	Current	Iraq	2000	Marine Battalion, Air Force (CH47D)
UNMIL	Current	Liberia	250	Navy Hospital ship Hr.Ms. “Rotterdam”

1.2 Preparation for Iraq

In the summer of 2003 the NAF were tasked to operate in the South of Iraq in a hot dry climate. In preparation for this task a seven day acclimatisation period in Kuwait was imposed prior to deployment in Iraq. Exercise during the first two days was limited to 15 minutes of walking without equipment at 4.5 km/hour. During the last day the exercise intensity was raised to 60 minutes walking at 6 km/hour with equipment (combat suit, Kevlar helmet, bullet proof vest (13 kg), Camelbak (1.5 litre), combat vest (4 kg)) (Figure 1). The intention of the acclimatisation period was to decrease the thermal strain of the soldiers during the operation in Iraq.

Figure 1: A Dutch Mariner on patrol

During the acclimatisation period the air-conditioning in the hotels was turned off and the soldiers were encouraged to drink at least 5 bottles of water of 1.5 litres a day. Each soldier received a Camelbak of 1.5 litres in order to have water available at all times.

1.3 Experiences in Iraq

To avoid dehydration, water was abundantly available in many locations and the soldiers were encouraged to replace their lost sweat by drinking sufficient amounts of water. No salt was added, salt tablets were available when necessary. When predefined thresholds in the Wet Bulb Globe Temperature (WBGT) were surpassed, a warning was given to the soldiers to adapt their work intensity. In general, an attempt was made to avoid work during the hottest hours of the day.

The Marine Battalion was deployed in the southern province Al-Muthanna. The main activities were the escort of convoys, base security and patrolling. The patrolling was the most demanding task and the average duration was 4 hours twice a day. The CH47-D Chinook detachment was stationed at Tallil airbase and tasked with the insertion of marine patrols and medevacs. Average sortie duration was 5 hours and temperatures in the cockpit could rise to 68°C.

At the end of a day, the soldiers felt more fatigued than during operations in moderate climates. The hot temperatures during the night led to sleep deprivation. After two months in Iraq the tents were replaced by air-conditioned containers and heat induced sleep deprivation did no longer occur. The tendency to drink was reduced due to the warm sandy winds and continuous attention was necessary to prevent dehydration.

A suspicious device was observed during a specific operation, in which chemicals could be contained. Therefore, a soldier donned an impermeable chemical protective suit to investigate the device. During the task, the soldier had no cooling and it was extremely difficult to accomplish the task.

1.4 EPINATO Morbidity Surveillance

During the acclimatisation period and during the operation in Iraq, the contacts of the soldiers with the medical staff were registered using the EPINATO morbidity surveillance system. Table 2 shows the results for three main categories: digestive system (category 11), dermatological problems (category 13) and heat (and cold) injuries (category 24). In total 80 RNLAF and 800 RNLMC soldiers were monitored.

Table 2: EPINATO morbidity surveillance results

	Kuwait (July 2003)	*Iraq (Aug-Sept 2003)*	*Man-days lost to light duty, all duties or bedded down*
Digestive system	4	369	148
Dermatological problems	109	378	3
Heat / cold injuries	33	17	16

The digestive system complaints were mainly related to diarrhoea. The dermatological problems were mainly blisters of the feet. There was not sufficient time to get accustomed to the new desert boots, and this may have caused the relative large number of blisters. The number of heat injuries was rather low in Iraq as compared to the acclimatisation period, even though the temperature in Iraq was only slightly reduced. We believe that the acclimatisation contributed to this relatively low number of heat injuries. Even though the blisters did not result in many lost man days, there was an impact on soldier operation due to the fact that they had to visit a medic and be treated.

2.0 OPERATIONAL RESEARCH REGARDING THE FLUID BALANCE

Three research projects aiming to reduce heat strain are shortly described below.

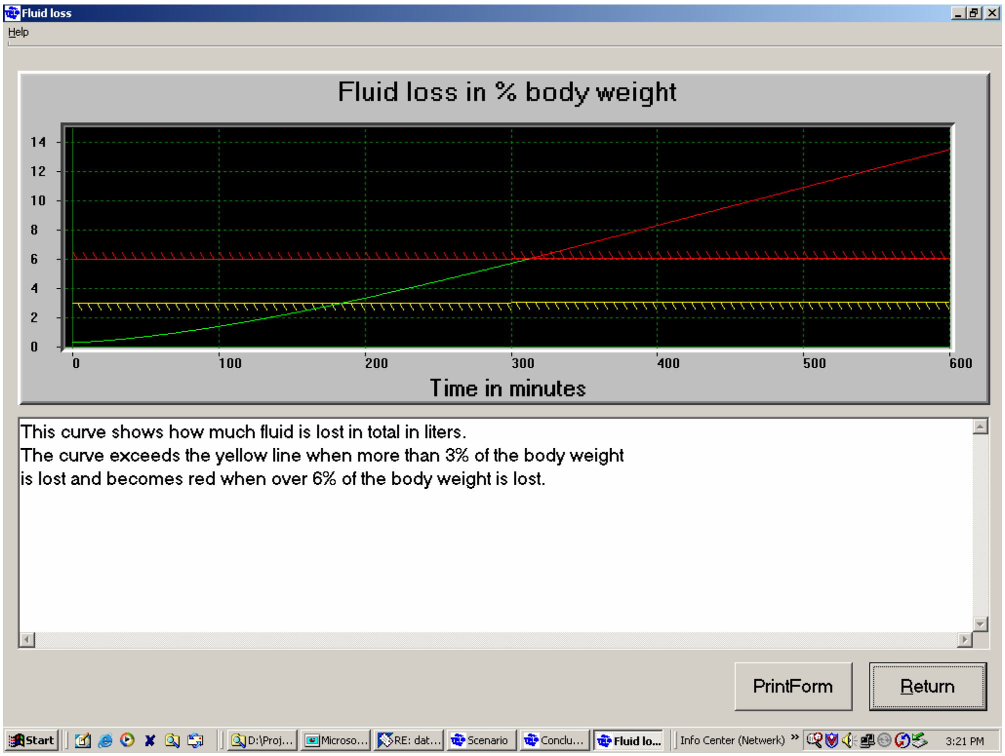
2.1 A Tactical Decision Aid on Thermal Exposure

The meteorologists and medical specialists of the Netherlands Armed Forces expressed a need for a tool that would predict the thermal strain and sweat loss during operation. For this purpose a Tactical Decision Aid (TDA) on Thermal Exposure was developed based on the models of Lotens (1993).

The following inputs have to be given:

- scenario
- climate (temperature, humidity, wind speed, radiation, precipitation)
- clothing (insulation and water vapour permeability - the military clothing ensembles can be pre-selected)
- work intensity (several military tasks were measured and their metabolic equivalents are preselectable in the program)
- individual characteristics like body weight, stature and acclimatisation status.

An example of output is given in Figure 2 for fluid loss.



This curve shows how much fluid is lost in total in liters.
The curve exceeds the yellow line when more than 3% of the body weight
is lost and becomes red when over 6% of the body weight is lost.

Figure 2 - Example output of the TDA on Thermal Exposure for fluid loss

The program has been validated by several studies (e.g. Den Hartog, 2003). It has been evaluated by selected meteorological and medical military officers and the feedback will be used to improve the interface and functionality of the program.

2.2 Cooling during operation

Several cooling systems have been developed for cooling during military operation, mainly based on liquid or air cooling. The Royal Netherlands Air Force was interested in systems to reduce heat stress of helicopter pilots. TNO Human Factors developed an air-cooling vest in co-operation with the Defence Logistics Organisation in the UK and Heathcoat (UK). Ambient air is blown in the lightweight vest that is worn under the aircrew's normal apparel.

Figure 3 - Set up of the experiment to evaluate cooling using an air vest

Six helicopter pilots flew in a flight simulator, which was placed in a climatic chamber. All six subjects flew the simulator in four different conditions; one neutral condition (15ºC Air temperature, 29ºC black globe temperature, 50% RH), and three warm conditions (35ºC Air temperature, 49ºC black globe temperature, 50% RH). During all conditions sunlight was simulated using two radiation sources. In two of the warm conditions ambient air was blown over the skin of the torso and the frontal part of the upper leg. The two conditions with air-cooling vest were different in respect to the type of blower, which was used to supply the vest with an air flow. The cooling effect depends on enhancing sweat evaporation from the skin. Simultaneously, air was blown through the HGU-65P helmet for additional cooling. The body temperature, task performance and subjective rating were determined to evaluate the efficacy of the cooling vest.

The heat strain which helicopter pilots experience during their task was significantly reduced using the air-cooling vest during this experiment and comfort was improved. The flow of ambient air over the body led to an increased evaporation of sweat and thereby cooled the body (Table 3). The performance in the heat was worse than in thermoneutral conditions during and after a double task (flying and a memory task). Wearing the vest led to an increase in comfort but not in performance.

It was concluded that the performance and the comfort of the pilots in warm environments can be increased by wearing the air-cooling vest.

Table 3 - Fluid balance using an air vest

	15ºC no blower		*35ºC no blower*		*35ºC with blower*	
	Mean	SD	Mean	SD	Mean	SD
Weight loss subject (gram)	184	85	645	188	585	91
Weight gain clothing (gram)	-29	35	279	147	56	38
Evaporated sweat (gram)	213	83	367	57	529	72
Sweat efficiency	1.16	0.22	0.57	0.09	0.90	0.06
Average cooling power (W)	72	28	124	20	179	25

2.3 Cooling prior to operation

Often, cooling during operation is not possible, but cooling prior to the operation is a possibility for instance by cooling the inside of a personnel carrier. A research project was performed to investigate to what extend pre-cooling reduced the sweat loss during operation (Van Es et al., 2003). The study was performed in eight male well-trained subjects, aged 18-29 years. Subjects performed 40 minutes of 60% VO_2-max cycling exercise in a 30°C, 70% relative humidity climatic chamber. They were semi-nude during cycling. In condition CC the subjects were previously cooled for 45 minutes. In condition N, no pre-cooling was given. In conditions WC and CW the lower and upper body were cooled respectively. The uncooled body part was warmed in such a way that the core temperature did not differ from that in condition N. Cooling and warming the body was done using a cooling- and heating suit in which cold (5°C) or warm (35°C) water flowed. Core temperature (in the intestines), skin temperature and body weight were determined. In condition N the evaporative heat loss (398 ± 77W) was significantly larger than in CC (209 ± 58W), WC (305 ± 67W) and CW (284 ± 68W). Evaporative heat loss was significantly smaller in CC than the other three. The heat storage in condition CC (442 ± 125W) was significant larger than in N (221 ± 65W), WC (303 ± 45W) and CW (296 ± 58W). It was concluded that the increased capacity for heat storage after precooling reduced the necessity for sweating.

Acknowledgements

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Hydration and the Modern Warrior's Load

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The increased lethality of forces employed as a combined arms, joint, or multinational team has positively impacted the Soldier's ability to do more with the same basic load, which increases the force effectiveness without adding significantly to the Soldier's load. However, the close fight – operations on urban and complex terrain – is still ammunition intensive, and with an emphasis on carrying more ammunition something else in the soldier's load must be sacrificed. Indeed, throughout history, the most challenging aspect of protracted conflicts, especially in urban and complex terrain, is how to support the Soldier with ammunition, food, and water. Soldiers can survive for extended periods with little or no food, and they can use supplements to meet their physical needs for even greater periods. Water is the one item that the Soldier must have to remain combat effective and there are no alternatives. While a Soldier can last several days without nutrition, in many environments the Soldier can only last hours before experiencing debilitating and life threatening effects of dehydration.

The modern battlefield has significantly impacted our ability to address this challenge and made it more difficult to meet the Soldier's needs. The battlefield of today realizes distributed forces, at times over hundreds of miles, and a paradigm shift from linear battles to noncontiguous operations that focuses on forced and early entry operations, as well as direct actions against key terrain and critical nodes. The challenge has often landed on the shoulders of the Soldier – literally. Soldier loads are rapidly becoming unmanageable, and a significant contributor to this problem is the Soldier's need for water. The Army must address the issue of Soldier load in combat and every area must be examined, to include Soldier hydration.

The Army, specifically the Center for Army Lessons Learned (CALL), at the request of MG Doesburg, Commanding General, RDECOM, recently took a dramatic step in identifying Soldier load issues in combat. This task was accomplish by training, deploying, and embedding a seven-man team with the 1st Brigade, 82nd Airborne Division (Task Force Devil, CTF82), during combat operations in support of operation Enduring Freedom III,

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Afghanistan. The members of the Soldier load study team, dubbed "Devil CAAT" for Devil Combined Arms Assessment Team, spent several months preparing and qualifying for this study effort, and two months in Afghanistan participating in 15 combat operations, while carrying the same loads as the Soldiers they studied. During the deployment period, in excess of 750 Soldiers were weighed and their equipment inventoried and recorded. Additionally, every aspect of combat resupply was examined, to include embedding a Devil CAAT member within the Combat Trains, to better identify resupply operations under combat conditions, and identify the impact on Soldier load.

Hydration is a serious issue in Afghanistan. Most of Afghanistan has a sub arctic mountain climate with dry and cold winters, except for the lowlands, which have arid and semiarid climates. It is common for summer temperature in the lowlands to reach 120 degrees Fahrenheit and mountainous regions to experience freezing temperatures. Approximately one-half of the country is over 6,600 feet in elevation, which places a greater demand on Soldier hydration requirements. Additionally, Afghanistan has very few lakes or rivers, so large sources of water are very scarce, which means subterranean water sources must be located, and wells dug.

During the Soviet occupation (1979-1989), many of the water sources were intentionally contaminated, in an attempt to force those living in rural areas into urban areas so the Russian's could better control and monitor their activities. Today, US Army water purification specialists in Afghanistan are still finding several contaminants that current purification technologies do not address. In light of this discovery, Army Leadership has elected to use bottled water for consumption, which comes in 0.5, 1.0, and 1.5 liter plastic bottles. Some water is purified and utilized for bathing and laundry purposes only. This approach places a significant demand on resupply operations, but is necessary to ensure the health and welfare of the Soldier.

The Soldier in Afghanistan carried 170 ounces of water in their on-the-move hydration systems, and an additional 64 ounces in their canteens. This basic load of 234 ounces of water or ~7 quarts, is expected to last the Soldier for 24-48 hours, based on activity. However, normal resupply operations are required once every 24 hours to ensure Soldiers are always prepared. As temperatures climb, the Soldiers will begin carrying even more water to compensate for the loss of body fluids. Medical personnel are constantly reminding Soldiers to increase their intake of Salt to compensate for this increase in fluid loss.

During larger operations – company and battalion – the battalion will move a support element (Combat Trains) to the area of operations. At least once per day, a small element of Soldiers must travel cross-country to resupply forces operating in multiple locations. There is tremendous risk associated with these resupply operations, as they are a prime target for ambush and the potential for mine strikes. However, rotary-wing aircraft are not always available and are high value targets, as well. These operations normally last throughout the evening and are manpower intensive.

While bottled water is necessary to support current operations, there are several challenges associated with this approach. First, several of the producers use less durable plastic containers, which results in the bottles breaking during vehicle and Soldier transport. Second, delivery is manpower intensive and adds to the risk that Soldiers performing resupply operations face. Third, some of the larger bottles are awkward for Soldiers to carry and take up a large amount of storage space. Fourth, it takes a large amount of vehicle space to transport enough water to support a battalion, utilizing current packaging. Fifth, the water is periodically inspected for quality. However, there are occasions when poor quality water is delivered to the Soldier as it is impossible to inspect every bottle individually. Sixth, there is a tremendous expense associated with supplying the force with bottled water.

The final issue is Soldier load. Soldiers cannot be expected to carry weights often in excess of 100 pounds or greater than 50% of their body weight. These weights have a negative impact on Soldier endurance, situational awareness, and the ability to respond quickly and accurately to a threat. A significant portion of this weight is attributed to the water that they are forced to carry. The Army must examine alternatives for supplying the Soldier with water, in all environments, and across the full spectrum of operations. New techniques of water testing and rapid field purification, water packaging, and water delivery are just a few areas worth investigation.

The Soldier needs water to fight and survive. The weight of water will not decrease in the future and the quantities required by our Soldiers will not decrease either. We must investigate alternative approaches to dealing with Soldier Hydration and supply, so we can get the weight off the shoulders of the Soldiers. After all, they have enough burdens to bear.

Hydration Status of Royal Air Force Personnel Conducting Simulated War-Fighting Tasks during a Collective Training Exercise in the UK

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ABSTRACT

The Royal Air Force (RAF) conducted a large-scale, 60-hour, Collective Training (CT) Exercise in the UK, to assess their operational readiness. CT tasks simulated the role of RAF Combined Incident Teams (CIT) at War-time operational tempo, under high levels of field stress [1]. The supply of potable water during CT was a high priority in order to reduce the risks of dehydration, which might degrade performance and present a danger to health. This study monitored the effectiveness with which the CITs conducted their War-time tasks, and their hydration status. Methods: Fourteen subjects, 12 men and 2 women (mean (1 SD) age 25.5 (6.4) years; body mass (BM) 78.1 (10.9) kg; body fat (bioimpedance) 19.1 (8.4) %; estimated $\dot{V}O_2max$ *(multistage fitness test) 47.8 (4.5)* $ml.min^{-1}.kg^{-1}$*) from the RAF consented to participate in the Ethics Committee approved study. Observers continuously monitored subjects throughout the CIT work shifts (day: 07:00 to 19:00 hours (9 subjects); night: 19:00 to 07:00 hours (5 subjects)). Performance during 38 tasks was assessed by RAF subject matter experts (SME) on an ordinal scale of 10 (optimal) to 0 (poor). Environmental heat stress during CT ranged from 6.5 to 20.4* ^oC *WBGT (mean (1 SD) 11.9 (2.3)* ^oC*). The RAF provided 12* $l.man^{-1}day^{-1}$ *potable water in accordance with military guidelines for temperate conditions [2]. The Maastricht protocol [3] for using doubly labelled water (DLW, incorporating deuterium dilution) was administered to measure energy expenditure. Blood samples were taken immediately pre- and post-CT to calculate changes in plasma volume (PV) [4]. Urine samples were collected daily (07:00 hours) and immediately after CT. Data recorded included body mass (BM) (daily); heart rate (every 15s); total body water (TBW) by deuterium dilution (pre- and post-CT); daily urine colour (Cu [5]) and specific gravity (SGu); and activity at the ankle and wrist (every 2s). Results: All tasks were completed effectively (SME rating 8.2 (0.6)). 59 (17) % of CT involved physical activity, most of which (89 (1) %) demanded* $< 50\%$ *heart rate reserve. Pre- and post-CT TBW (39.9 (0.7) litres and 38.7 (0.7) litres respectively), Cu and SGu were unchanged (*$p>0.05$ *ANOVA). Only 4 subjects (all from the day-shift) lost BM, 1.7 (0.5) kg. Compared with pre-CT values they lost 2.2 (1.0) % TBW and 3.2 (1.8) % PV, (t-test,* $p<0.05$*), and had a SGu > 1.015. Their energy expenditure (13.1 (1.3) MJ) did not differ from the remaining 10 subjects (12.3 (1.4) MJ) (t-test,* $p>0.05$*). They spent about 10 hours of the CT wearing complete nuclear, biological and chemical individual protective equipment (NBC IPE) which was longer than other day-shift subjects. Conclusions: All tasks were conducted to a high level of operational effectiveness. Pre-CT hydration status was adequately maintained in most subjects. The greatest risk of dehydration was to those wearing NBC IPE.*

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1.0 INTRODUCTION

1.1 Background

The Royal Air Force (RAF) have identified the need to develop operationally-related physical fitness standards with which to assess the readiness of their personnel for deployment. As part of the project to develop these standards the opportunity arose in September 2002 to conduct a comprehensive analysis of the physical demands to which RAF personnel were exposed. A training exercise had been planned to evaluate the operational effectiveness with which personnel who were considered to be 'fit for deployment' were able to conduct simulated War-fighting tasks at an austere base in the UK. This Collective Training (CT) Exercise (known as 'EX OPEVAL' [Exercise OPerational EVALuation]) at RAF St. Mawgan (Cornwall, UK), 05-29 September 2002, involved 1400 RAF personnel, sixteen fighter aircraft and engineering support from the Army. The military objective was to evaluate the effectiveness with which the War-time standard operating procedures (SOPs) and logistics could be demonstrated within the 'blanket' of a peace-time Exercise. The effective supply of potable water to personnel was one important factor encompassed within this evaluation process.

1.2 Military operations

Since the end of the Cold War British troops have been deployed in diverse environments to conduct a wide range of roles. Military operations are no longer limited to those extremely cold, wet conditions experienced during the Falklands conflict (1982). During the last 10 years deployed personnel have been required to maintain high levels of operational effectiveness to combat a relatively new threat in the predominantly hot climates of Kuwait, Iraq, Oman, and Sierra Leone. The rapid changes in environmental conditions experienced during the low-to-high-altitude operations in Afghanistan, have posed a further threat to the well-being of British troops, since the terrorist activities observed on September 11 2001. However, irrespective of the nature and location of the deployment, military operations and training exercises have always been recognised to be very physically demanding (with personnel expending energy at a rate of 11.3 [lowest] to 45.9 [highest] $MJ.day^{-1}$ [6]). The ability to meet the nutritional requirements of troops during military operations can determine the successful outcome of their mission and indeed the success of the entire campaign. Water is critical for survival, and will influence the effectiveness with which a military force can operate. There is a need to identify how much water is required by troops in order to allay the onset of performance-degrading dehydration and the risk of heat illness.

1.2 Heat illness

Heat casualties do not occur exclusively as a result of military operations during the Summer months, or from duty in hot climates. Casualties in the United Kingdom have been known to occur as early as March (Wyke Regis 1997) and as late as December (Brecon 1993) with a mean incidence of 100 cases of heat injury each year. In recent years (1993-97) there have been more than 516 reported cases of heat illness and several fatalities in the UK. The majority of these cases could have been prevented if the Commanders responsible (at all levels) had displayed a greater awareness of the risks, and managed the threat appropriately. The last six months of 2000 saw a further 50 cases of heat illness that required hospital treatment and which may have been prevented [7]. Commanders have a duty to assess the risks of heat illness arising from military operations and to ensure that these risks are minimised as far as practicable.

1.3 Dehydration

Dehydration will expose personnel to an increased risk of suffering heat illness. Poor management of water intake may result in ineffective military performance and to loss of life. All personnel will demonstrate a degree of dehydration during the course of their operational duty. As a consequence, their physical performance will continue to deteriorate as they progressively lose vital body fluids, and become increasingly more dehydrated [2]. Dehydration will result from operational duty in all environments where military personnel are commonly deployed (in the cold, at sea, and at high and low altitudes).

1.4 Meeting the need for potable water

The provision of potable water is essential during all prolonged and sustained military operations. The task of meeting this requirement for water in the field, both at times of peace and at War, is the responsibility of military logistics (UK Defence Catering Group (part of the Defence Logistics Organisation)). The cost of providing potable water to personnel in-theatre is enormous. It is, therefore, important to establish the true nature and scale of the requirement in order to manage available resources with the greatest efficiency. The most recent guidelines issued by the UK Ministry of Defence [7] describe a regime for military personnel to consume water at a minimum rate of 0.25 l.hour^{-1} (low intensity work conducted under conditions of 20°C Wet Bulb Globe Temperature [WBGT]), to a maximum of 2.0 l.hour^{-1} (for very high intensity work conducted under conditions of 25°C WBGT). Previous guidelines (UK Defence Council Instruction, Joint Service 59 dated 1996) had suggested an allowance of 12 litres of water per person per day under such conditions. It is well established that the requirement for consuming water is greatest at times when insensible water loss is at a peak (in response to a greater workload, an increased exposure to heat, or both) [2]. During Operation Telic (Kuwait and Iraq, 2003) the Defence Catering Group delivered 1,176,000 litres of water (within 784,000 bottles) to 28,000 British military personnel each week (6 litres of water per person per day) [8]. However, military guidelines recommend that personnel should aim to consume water at a rate of 1.0 l.hour^{-1} when working at low intensities under such hot environmental conditions (*ie* approximately 8 litres of water per person per day during an 8-hour shift, or 12 litres of water per person per day for a 12 hour shift).

1.5 Study objective

The aim of this study was to identify the extent to which the water provided by military logistics met the intake requirements for the RAF's combined incident teams (CIT) whilst they conducted their War-time operational role during a 60-hour CT Exercise in the UK.

2.0 METHODS

2.1 Collective Training Exercise

CT is a generic name for military exercises that are designed to provide the necessary setting for an operational scenario within which personnel can gain experience performing their military role at operational tempo. CT facilitates the assessment of personnel, equipment, operating procedures and military tactics within a single exercise conducted during 'peace-time'. This study followed the progress of subjects who participated in an RAF CT. The Exercise was designed to simulate true-to-life conditions for an operational deployment to an austere environment. Personnel were instructed to be on stand-by from 05 September 2002 until 05 October 2002. No advanced warning had been given to the subjects, concerning the start or end of the Exercise.

A War-fighting phase (midnight 22 September 2002 to midday 25 September 2002) was conducted within the Exercise to place personnel under 'operational stress'. A series of 'tasks' were implemented throughout this period, without warning, and which demanded the use of the comprehensive range of RAF tasks and military skills at operational tempo. During this period the personnel involved in the Exercise were on 24-hour standby. The host airfield was divided into 8 sectors (figure 1) within which the Combined Incident Teams (CIT) operated. Each sector was served by one of four CITs. Twelve-hour shifts were implemented (day shift: 07:00-19:00 hours; night shift: 19:00-07:00 hours) throughout each sector.

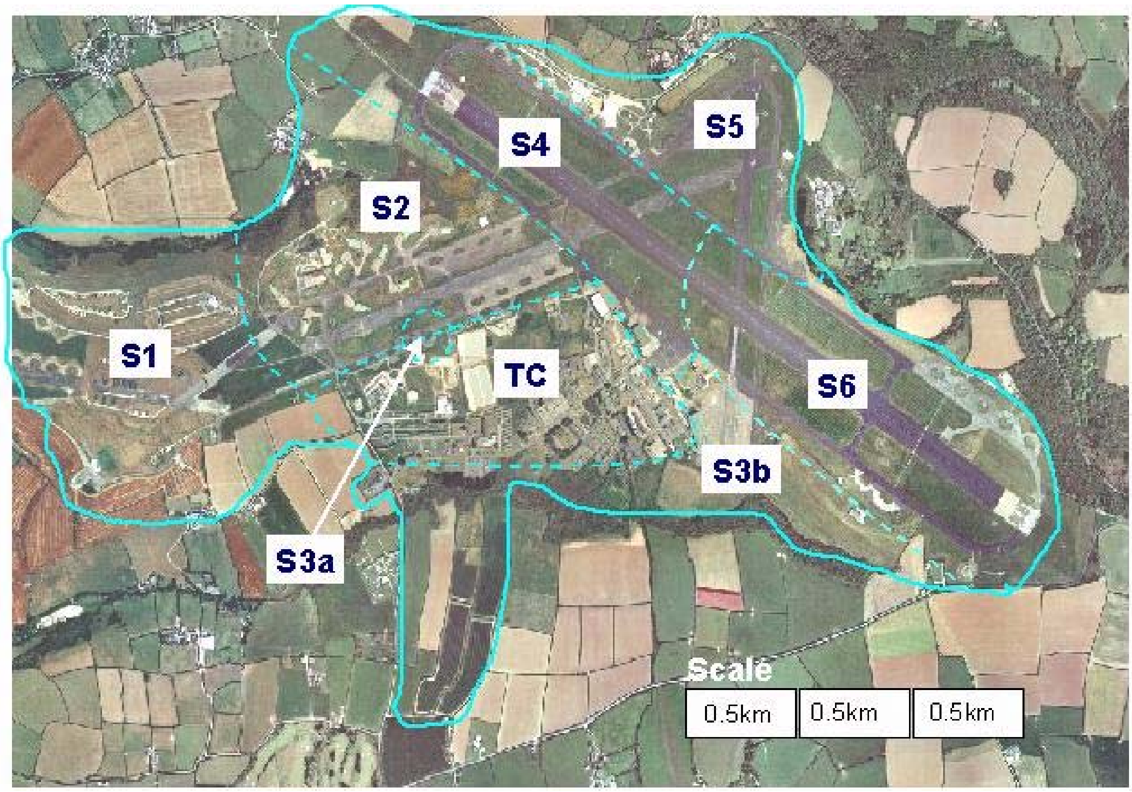

Figure 1: The airfield at RAF St. Mawgan which hosted the collective training exercise was divided into 8 sectors (S1, S2, S3a, S3b, S4, S5, S6 and TC [Tent City])

2.2 Subjects

Personnel assigned to CIT duties are eligible for deployed operations and may be taken from any trade or specialisation represented within the general RAF population. The role of the CITs is to conduct effectively and efficiently those operational tasks which are 'core' to the generic RAF role, as-and-when they are required. Such personnel are well-practised in the correct SOPs with which to complete effectively all of the core operational tasks of the RAF [1]. Therefore, CITs were best placed to demonstrate the correct procedures for all the necessary tasks at operational tempo.

Fourteen volunteers (12 men and 2 women, see Table 1) from the RAF CITs provided their written consent to participate in this QinetiQ Centre for Human Sciences Ethics Committee approved study (from a total number of 48 CIT personnel who were present at CT). All personnel involved with CT reported for duty at TC (the technical domestic site referred to as 'Tent City', see Figure 1) on 12 September 2002. A Training phase was conducted over the period 13-22 September 2002 during which all personnel at CT received lessons from the Directing Staff (DS) with specific instruction in military field craft, the common core skills and basic military SOPs. Assessments were conducted by the DS to confirm that personnel were capable of demonstrating the correct procedures associated with the core operational role and to conduct them with the required level of competence. During this period, the subjects were working to a 12 hour day shift (07:00-19:00 hours) at operational tempo during the War-fighting phase. Five subjects worked on the night shift, whilst the remaining 9 conducted their shift during the day. When subjects had completed a shift, they moved to TC where tented accommodation had been provided for them to rest and recover in readiness for their next shift. Subjects were most accessible to the team of five scientific staff at this stage (for the purpose of administering the scientific procedures) and during the 30-minute period which immediately preceded their next shift. Eight subjects were assigned to sectors S5 and S6, one subject conducted her duty at sector S1 and the remaining five subjects were required to operate at TC.

Table 1: Subject characteristics (data are reported as mean (1 standard deviation))

Measurement	unit	Men (n=12)		Women (n=2)	
Age	*years*	26.6	(6.2)	19.0	(0.0)
Body Mass (BM)	*kg*	79.6	(11.1)	69.0	(0.4)
Height	*cm*	178.6	(8.9)	170.4	(5.7)
Time in service	*years*	7.0	(6.5)	1.8	(0.4)
Body fat	*%*	19.1	(8.4)	26.1	(2.7)
Aerobic power	$ml.min^{-1}.kg^{-1}$ *[BM]*	48.9	(3.9)	42.7	(4.5)

2.3 Assessing the hydration status of military personnel

2.3.1 Water budget

A daily water allowance of 12 litres of potable water per person was provided by the RAF each day during the War-fighting phase of CT. Limited access to the subjects during the War-fighting phase of CT, prevented an accurate assessment of the quantity of water that was consumed. A number of procedures were possible, and they are described in the following paragraphs (the time that these procedures were implemented during the study is illustrated in Figure 2):

2.3.2 Total body water (deuterium dilution)

Before consuming a dose (‘D’) of deuterium oxide (^2H_2O) subjects provided two urine samples for the purpose of accounting for background levels of ^2H and ^{18}O isotopes: (a) 15 hours pre-dose (*ie* D-15hr); and (b) 1.5 hours pre-dose (*ie* D-1.5hr). The subjects’ body mass was measured immediately following the passing of each void. At 10:00hr on 13 September 2002, in a rested state, at least four hours after eating a normal breakfast and before conducting physical exercise, each subject consumed a calculated, combined dose (injectate) of ^2H_2O ($0.05g.kg^{-1}$[body mass] [3]) and $H_2{}^{18}O$ [1] ($0.15g.kg^{-1}$[body mass] [9]) (hereafter referred to as doubly-labelled water [DLW]). The mass of the vessel containing the DLW had been weighed prior to decanting the dose. The vessel was weighed once again post-ingestion (dose) and additionally, before and after consumption of a 100ml sample of tap water (consumed as a ‘chaser’). This additional liquid was used to ensure that as much as possible of the isotope had been flushed from the vessel containing the DLW and ingested by the subject (such a dose was found to provide the necessary excess enrichment of isotopes [9]). A 2ml sample of both the injectate and tap water were taken for analysis. Following a five-hour equilibration period [2] subjects provided a post-dose urine sample. Urine samples were collected in suitably sized flasks from which they could be decanted into 20ml sterile universal containers (Sterilin Ltd., UK), and kept frozen at -20°C prior to their transportation (packed in insulated dry ice containers) to the laboratories at Iso-Analytical Ltd (UK) for isotope ratio mass spectrometry. Total body water was assessed for each subject, by use of the initial dilution space measurement (plateau method [10]) for *individual* mean estimates (*ie* not population-grouped data). An estimate of relative body composition (*ie* body fat (%)) was calculated by applying the value for TBW to a standard regression equation [3].

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[1] Analysis certificate for the isotope content of ^{18}O was 11.01% and for deuterium it was 99.9%.

[2] The Maastricht protocol [3] recommends a 10-hr equilibration period. However, subjects could not confirm their movements for the next day. An evening urine sample (5 hours post injectate dose) was therefore used to ensure subject compliance.

[3] Equation: Body fat (%) = (TBW(%))*(-1.344) +87.5 (r^2=0.87) [1].

2.3.2 Distribution of body fluid (bioimpedance)

Dual frequency bioimpedance (z) analysis (5kHz and 200kHz frequencies) was performed with tetrapolar distal limb, surface electrodes on each subject using a Dualscan 2005 system (Bodystat®, Douglas, Isle of Man). Extra-cellular fluid (ECF) was assumed to be detected using the 5kHz frequency (equation 1) [11], whilst intra-cellular fluid (ICF) was calculated as follows (equation 3):

Equation 1: ECF (litres) = $[(0.178458 \times \text{height}^2)/\text{impedance (5kHz)}] + (0.06895 \times \text{weight}) + 3.794$

Equation 2: TBW (litres) = $[(0.24517 \times \text{height}^2)/\text{impedance (200kHz)}] + (0.18782 \times \text{weight}) + 8.197$ (although this equation has been justified, the values of TBW that were obtained by the deuterium dilution method were used)

Equation 3: ICF (litres) = TBW (litres) – ECF (litres)

These tests were conducted consecutively, before exercise, at least 2 hours after breakfast, and once the bladder had been emptied. Data were obtained for the subject's height, weight, and age prior to this test. Measurements of bioimpedance were taken pre- and post- CT.

2.3.3 The change in Plasma Volume (PV) [Post-CT / Pre-CT]

Two 20ml blood samples were taken before and after CT by venepuncture from the brachial vein on the right arm. A qualified phlebotomist conducted the pre-CT blood samples (08:15 hours) and the post-CT samples were obtained by RAF nurses at the 'field' medical centre (12:15 hours). Whole-blood samples were collected and stored in K3E (15% 0.054ml) BD Vacutainer™ tubes. One sample was used to analyse (at the on-site field laboratory):

- Haematocrit (Hct) was determined by microcentrifugation on duplicate whole blood samples with no correction for trapped plasma.
- Haemoglobin (Hb) content was assessed by means of photometry using microcurvettes of whole (venous) blood (Hemacue Ltd., model B-haemoglobin photometer, Ängelholm, Sweden).

Changes in plasma volume were calculated by comparing the pre- and post- CT ratios of Hb and Hct, as described by Dill and Costill 1974 [4].

2.3.4 Specific gravity of urine (SGu)

The specific gravity of each urine sample was assessed by means of a hand-held refractometer (Portable Refractometer model DIGIT 012, ref. 8100.0120, CETI Ltd., Belgium).

2.3.5 Urine pH

All of the urine samples were decanted into 20ml sterile, universal vessels (Sterilin Ltd., UK) from the larger containers that had been used to collect each void. The remaining residue (discarded urine) was tested for; pH, glucose; ketones; specific gravity; blood; proteins; nitrites; and leucocytes using specialised reagent strips designed for urinalysis (GP Multistix®, Bayer Ltd, France).

2.3.6 Urine colour (Cu)

The colour of each urine sample was rated using the 1-8 scale proposed by Armstrong *et al* 1994 [5].

2.4 Isotopic analyses

The interpretation of isotope clearance data to estimate TBW and energy expenditure was conducted using a computer program that had been made available by the UK NERC [4] Scientific Services [12]. Multiple sample analyses were conducted using each void obtained during CT (including the final void which was obtained at the end of the Exercise, referred to as 'ENDEX'). Assumptions made during the analysis have been summarised as follows [10]:

- The conversion of CO_2 to energy expenditure could be reflected by a food quotient (FQ) of 0.85;
- Population parameters were based upon a sample of 100 reporting a population dilution space ratio of 1.036;
- Interpretation errors could be effectively assessed using the iterative and jack-knife procedures described by Speakman [10];
- The ratio of hourly turnover of ^{18}O and ^{2}H (ko/kh) was accepted for values >1.0;
- Calculations assumed that all of the DLW isotope occurred as water and that the density of water remained constant at 1.0 $g.ml^{-1}$;
- The normal physiological range for the dilution space ratio was accepted as 1.0000-1.0552.

Based upon these assumptions, subsequent calculations of energy expenditure (expressed as $kJ.day^{-1}$) were conducted using the Coward *et al* 1985a [9], two-pool method, using individual dilution space ratios.

2.5 Gastrointestinal temperature (Tgi)

Several subjects during the War-fighting phase of CT, ingested a CorTemp© CT2000 temperature sensitive pill (referred to as a 'radio pill') approximately 30 minutes prior to the start of their 12-hour shift and following an initial 'test' to check that the pill was functioning correctly. Transmissions from the radio pill were detected and interpreted using a CT2000 data logger system (HQ Inc., Palmetto, USA), reporting temperature (assumed to reflect deep-body temperature) data every 1 minute, as the radio pill passed along the gastrointestinal tract. These data were downloaded to a computer (using an RS232 to COM1 link) for subsequent analysis at the end of each shift.

2.6 Environmental heat stress

WBGT [5] was measured at 1-hour intervals throughout CT and logged using an Edale Instruments Ltd (Cambridge, UK) model PTH-1 data recorder.

2.7 Operational effectiveness

Directing Staff (DS) were present throughout CT and they rated the effectiveness with which each task was conducted by the subjects (during the War-fighting phase), on a scale from 0 (poor performance) to 10 (optimal performance). The DS were the appointed subject matter experts (SMEs) with the necessary experience to assess the military performance of the subjects during CT.

2.8 Physical activity

Two Actiwatch® -AW4 systems (Cambridge Neurotechnology Ltd., UK) were placed on each subject: (1) on the lateral aspect of the subject's right wrist; and (2) lateral aspect of the right ankle. These accelerometry-based systems were set to record movement throughout CT, over 2s epochs. Data were

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[4] Natural Environmental Research Council (NERC).

[5] WBGT °C = 0.7[wet bulb temperature] +0.2[150mm globe temperature] +0.1[air temperature]

expressed in counts.min^{-1} and they described the number of movements recorded in the vertical (z) axis at the wrist and ankle. This enabled the degree of upper and lower body physical activity to be estimated. Periods of sustained inactivity were assumed to describe bouts of 'sleep'. Each subject wore a Polar® Vantage NV that was set to sample data at 15-second intervals throughout the War-fighting phase. During pre-CT baseline data collection period, values for resting heart rate were obtained as well as maximum heart rate (during a 20-m multistage fitness test which was performed in a gymnasium by each subject until volitional exhaustion). When considered in combination with the Actiwatch® -AW4 activity monitors, it was possible to use the heart rate data to assess the relative cardiovascular strain of the RAF tasks using the heart rate reserve method described by Karvonen (this is described in detail in [1]).

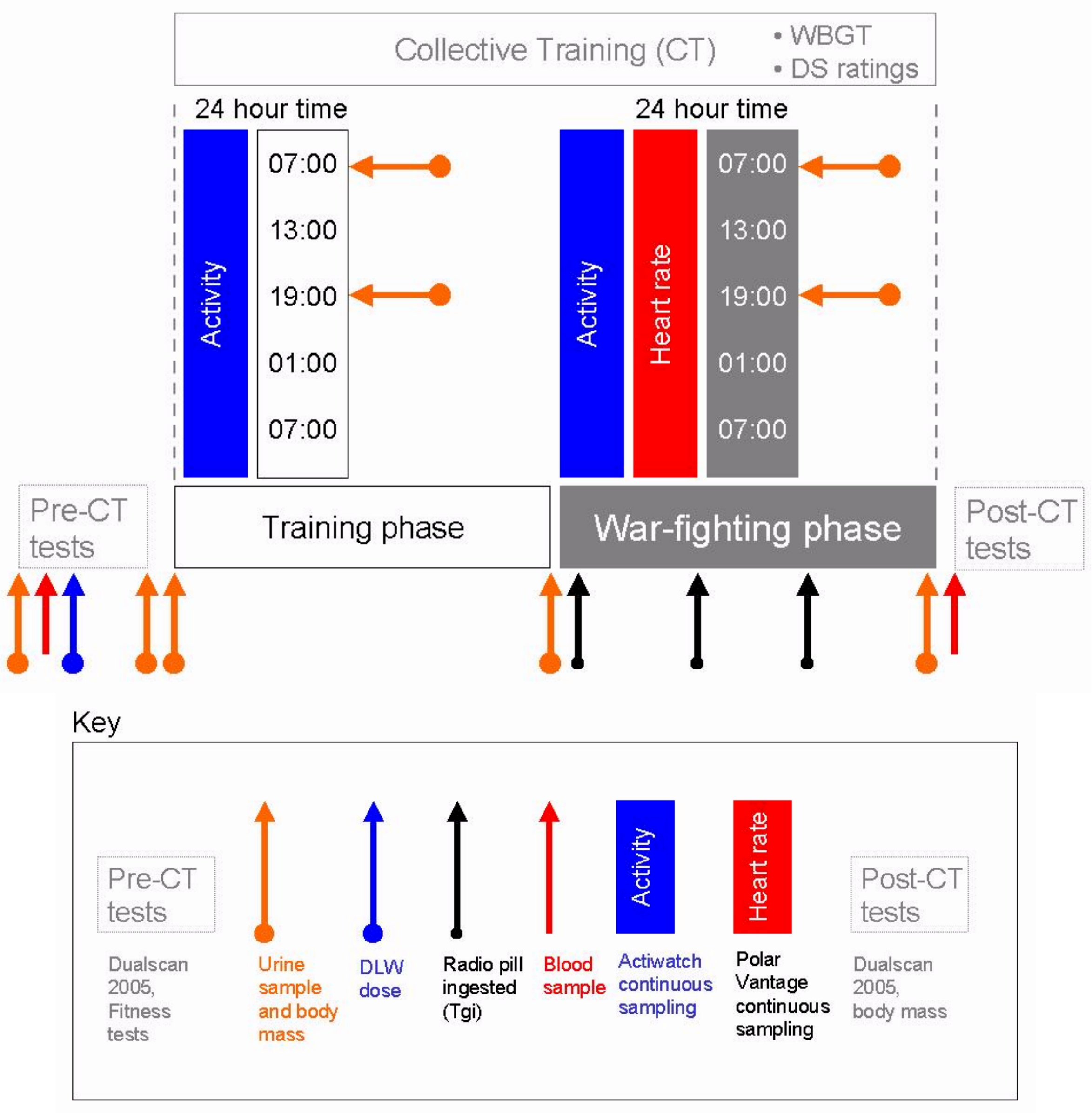

Figure 2: The schedule of protocols administered and of samples and measurements recorded

2.9 Statistical methods

The Statistical Package for the Social Sciences (SPSS version 8.0, SPSS Inc., Chicago, USA) was used to perform the data analyses. A one way repeated measures ANOVA was used to assess changes (post CT – pre CT) in TBW, PV (%), Cu, and SGu. The students paired t-test was performed to compare the differences between subjects who worked night versus day shifts. Statistical significance was accepted at the alpha = 0.05 level. All data are reported as mean (1 standard deviation).

3.0 RESULTS

The War-fighting phase was completed in 60 hours, with the subjects dressed in assault order (placing an additional 25 kg load to their body mass) throughout this period. All 38 tasks (approximately 12 per day) that were conducted during this War-fighting phase were completed to the required RAF standards and at the correct tempo to be considered 'operationally effective' (SME rating 8.2 (0.6)).

It was found that 59 (17) % of CT involved physical activity (as detected by the activity monitors worn at the wrist and ankle of each subject). The majority (89 (1) %) of this period of physical activity incurred a relatively low heart rate (see table 3), and hence the total cardiovascular strain of CT was considered to be low (*ie* subjects conducted their work at a mean heart rate which occupied less than 50% of their maximum heart rate reserve). The mean WBGT was 11.5 ^{o}C, ranging from a peak mid-day value of 20.4 ^{o}C to a night-time low of 6.5 ^{o}C). The alert status was 'high' during the study and subjects were frequently required to dress themselves in full Nuclear, Biological and Chemical Individual Protective Equipment (NBC IPE), which included a respirator.

The 12 litre allowance of potable water was available to subjects throughout the study. However, it was not possible to record the quantity of water that was consumed by the subjects. The difference in pre- and post-CT TBW (39.9 (0.7) litres and 38.7 (0.7) litres respectively), Cu and SGu were not statistically significant (p>0.05 ANOVA, see Table 2). The mean energy expenditure for the 14 subjects was 12.5 (1.3) MJ.day^{-1} (equivalent to 47.3 (6.1) kcal.kg^{-1} (FFM).day^{-1}).

Table 2: Comparison of the mean (1 SD) data for all 14 subjects, *pre* and *post* CT

		Pre CT	Post CT
Body mass	*kg*	78.1 (10.9)	76.9 (10.6)
Fat free mass	*kg*	63.2 (8.8)	n/a
Total body water (TBW)	*litres*	39.9 (0.7) [6]	38.7 (0.7)
Intra-cellular fluid (ICF)	*litres*	20.8 (3.1)	n/a
Extra-cellular fluid (ECF)	*litres*	18.3 (2.0)	n/a
Urine colour chart rating	*1-8*	3.5 (0.8)	3.7 (0.8)
Urine specific gravity	*unit*	1.016 (0.004)	1.020 (0.004)
Urine pH	*unit*	5.9 (0.4)	6.2 (0.7)
Change in plasma volume	*%*	n/a	0.7 [2.9]

** p<0.05*

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[6] Deuterium dilution was used to calculate Total Body Water (TBW) in men, and Dualscan 2005 data were used to report TBW for the women. These data account for 50.9% of total body mass in men and 45.1% of total body mass in women. All ICF, and ECF data were obtained using Dualscan 2005.

Only 4 subjects (subjects 2, 7, 9 and 12, who were all from the day-shift at sector 5, see Table 3) lost BM (1.7 (0.5) kg). Compared with pre-CT values these 4 subjects lost 2.2 (1.0) % TBW (0.9 (0.4) litres) and their PV was reduced by 3.2 (1.8) %, ($p<0.05$), and had a SGu > 1.015. Their energy expenditure (13.1 (1.3) MJ) did not differ from the remaining 10 subjects (12.3 SD 1.4 MJ) ($p>0.05$). However, they were observed to spend approximately 10 hours of CT wearing complete NBC IPE, which was longer than other subjects.

Despite administering the radio pill to the subjects, too few data were available to assess the effect of CT on Tgi for the purpose of statistical analysis. However, Tgi data were available for 2 subjects during CT. The peak value that was observed for these 2 subjects was 39.5°C. This value was recorded for subject 4 during the initial 10 hours of CT and at a time when he was required to provide a rapid response to a number of tasks at the beginning of his shift. Peak data (Tgi) recorded for these 2 subjects at a time when the alert status was high and NBC IPE was worn did not exceed 38°C. These subjects were least physically active on such occasions

4.0 DISCUSSION

The purpose of this study was to see whether the plan adopted by the UK military to supply water to troops at a time of War (in this case it was a training exercise intended to simulate a War-fighting scenario) was sufficient to meet each individual's requirement for water, and hence reduce the incidence of dehydration, and the threat of heat illness that has often been associated with it. At first sight it would appear that when CITs operating on an RAF airfield under the threat of War, conducted their duties with the desired level of effectiveness, they were able to fulfil their role without losing a significant proportion of their body water.

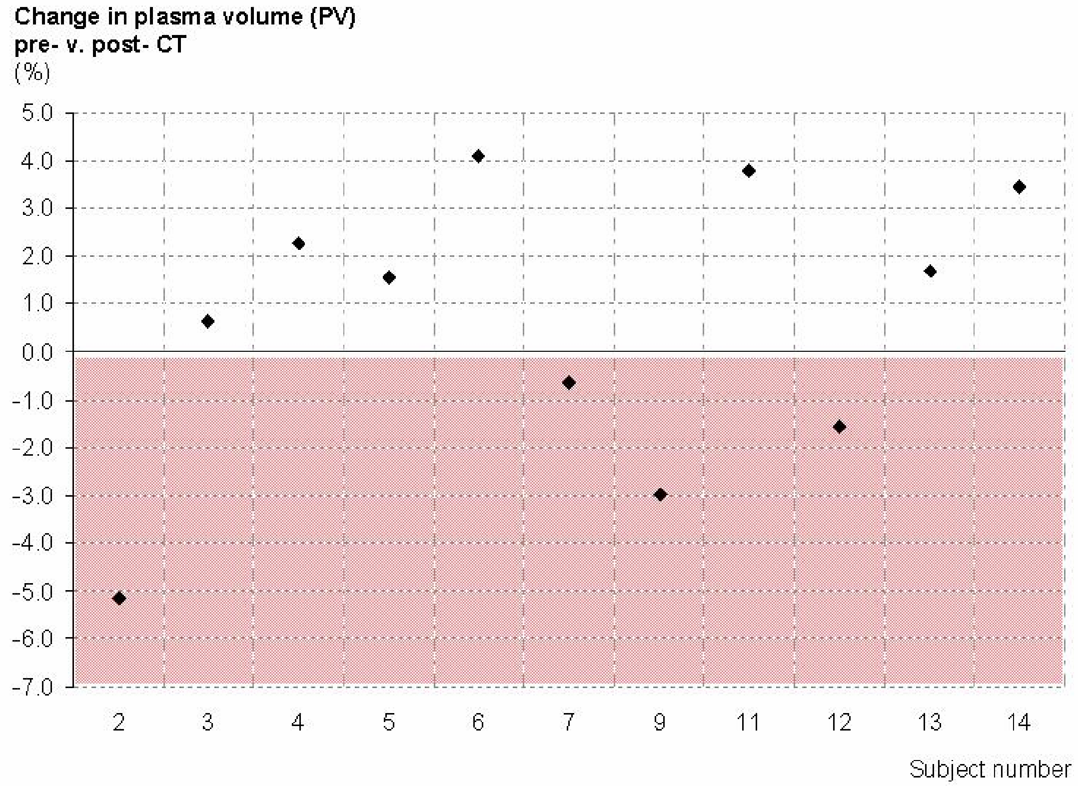

Figure 3: The change (%) in plasma volume post CT - pre CT for each subject

However, closer scrutiny of these data does not support such a statement for each individual subject. The availability of only 14 volunteers in this study limits the ability of the analysis to identify any significant differences between the varying conditions to which subjects were exposed during the study (*ie* subjects operated at different sectors within the airfield, and conducted different tasks, and some wore NBC IPE for a greater period of time than others *etc*).

Armstrong *et al* 1994 [5] proposed that a urine colour within the range 1-3 on their chart could be representative of an individual who was *'well hydrated'*, (hyperhydrated or euhydrated) whereas a value greater than 3 (*ie* 4-8 on the urine colour chart) signified a state of dehydration, the extent to which could be indicated by the numeric value of the colour rating. Subjects for whom there was a mean urine colour greater than 3, were also seen to report a mean loss in their TBW. However, when considered as a single group, the change in TBW was not significant.

SGu has also been reported to be indicative of an individual's hydration status (or level of fluid balance). Armstrong *et al* 1994 [5] identified a linear relationship between SGu and its perceived colour rating. A urine colour of 4 to 8 would be seen to have a SGu greater than 1.015. They suggested that there would be a high degree of confidence that the body was hypohydrated (*ie* dehydrated) when a subsequent void of urine was found to have a SGu equivalent to 1.029 or greater. If the lower value (SGu 1.015) is taken as the reference range above which subjects could be considered to be dehydrated, then 11 of the 12 subjects who had a Cu greater than 3 would have been classified as 'dehydrated' at some stage during CT. Despite each of the subjects having a negative change (*ie* reduction) in plasma volume (Figure 3), a SGu > 1.015, and a urine colour rated > 3 (Table 3), there was no consistent value observed for urine pH (which ranged from 6.5 to 7.5 post-CT).

Figure 4: A subject is seen drinking part of his daily water ration during CT

There was no significant change in PV (as defined by the ratio of Hb:Hct, [4]) for the subjects as a group (0.7 (2.9) % post-CT when compared with pre-CT values). However, when these data were observed at an individual level it was found that a number of subjects who had conducted their shifts at airfield sector 5 (*eg* subjects 2, 9 and 12) tended to suffer the greater losses in BM, TBW ($p>0.05$) and relative change in PV ($p<0.05$, see Table 3 and Figure 3) (BM*:* 1.4, 2.2, 1.4 kg loss; TBW: 0.6, 1.4, 0.7 litre loss; PV: 5.1, 2.9. 1.6 % loss from pre-CT values respectively). Two of these subjects (subjects 9 and 12) were found to have among the highest daily energy expenditure during CT (Figure 5). This was in contrast to those subjects who conducted their CIT tasks at sector TC. Too few data were available to determine the between-sector differences BM, TBW, and PV.

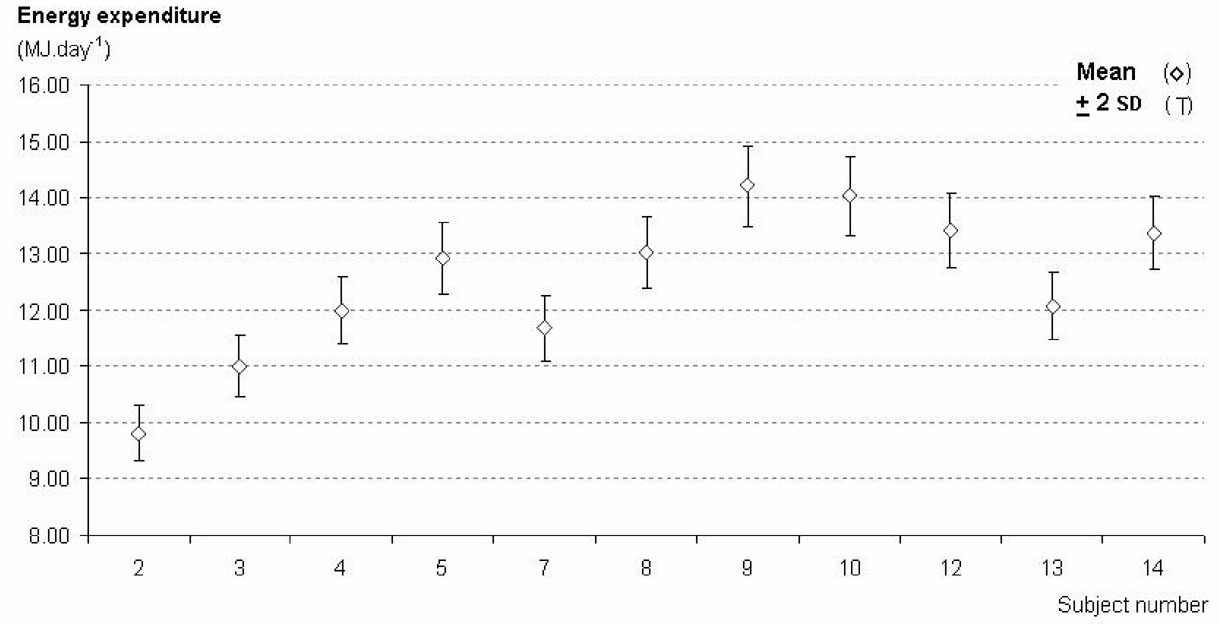

Figure 5: Daily energy expenditure for each subject during the War-fighting phase of CT (mean (2 SD))

During the planned de-brief, conducted immediately following the post-CT tests at ENDEX, subjects reported that due to the alert status during CT, they were often required to wear full NBC IPE and subsequently they had to drink water in accordance with RAF SOPs whilst wearing a respirator (Figure 4). Due to differences in the nature of the incidents that were staged at each sector of the airfield, some subjects were required to wear NBC IPE for a substantially longer period than subjects at other sectors.

Some subjects (those who had little operational experience in-theatre) had chosen not to consume their operational rations during CT, in preference to waiting until ENDEX to consume a freshly cooked meal. Such action may explain the inconsistencies that were observed in the change of BM during CT. The daily provision of 12 litres of potable water per person during the War-fighting phase of a 60-hour collective training Exercise in the UK was sufficient to avoid significant levels of dehydration (as determined by a loss in TBW, BM, or PV) throughout the CIT subjects as a group.

Table 3: Pre and post CT data for subjects who conducted the day shift at sector 5, compared with the same variables for the remaining subjects

Difference (post CT) – (pre CT)		**Sector 5 subjects (day shift) n = 4**	**Remaining subjects n = 10**	
Body mass (BM)	*kg*	-1.7 (0.5)	-1.2 (1.2)	
Total body water (TBW)	*litres*	-0.9 (0.4)	- 0.6 (0.6)	
Urine colour chart rating	*1-8*	-0.2 (1.1)	0.5 (0.7)	
Urine specific gravity (SGu)	*unit*	0.0006 (0.006)	0.005 (0.004)	
Urine pH	*unit*	1.3 (0.3)	0.1 (0.6)	
Change in plasma volume (PV)	*%*	-3.2 (1.8)	2.5 (1.3)	*
Energy expenditure during the War-fighting phase	$\mathit{MJ.day}^{-1}$	13.1 (1.3)	12.3 (1.4)	
Heart rate reserve (HRR) during the War-fighting phase	*% maximum HRR*	22.6 (2.3)	18.2 (2.6)	
Operational effectiveness	*1[poor] - 10 [optimal]*	8.4 (0.4)	8.1 (0.5)	

*Data are presented as mean (1 standard deviation) *p<0.05*

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Laboratory and Initial Operational Testing of a Microclimate Cooling Vest in Army Rotary Wing Aircraft

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INTRODUCTION:

The use of chemical protective clothing and equipment in helicopters presents several unique challenges for thermoregulation. While Thornton, Brown and Higgenbottom (1984), demonstrated that flying is not a physically demanding process (100-200 Watts), the maintenance of situational awareness and operation of controls is paramount for safe flight. In hot environments, flight performance has been adversely affected by the combination of heat and chemical protective clothing (Reardon et al., 1996). However, even in cold environments, the encumbrance of the chemical protective equipment has resulted in substantial decrements of performance. A previous environmentally controlled helicopter simulator study at the U.S. Army Aeromedical Research Laboratory (USAARL) showed that most crashes occurred with pilots wearing protective equipment while in a cool environment, mostly due to restriction of visual fields from the protective mask (Thornton et al., 1992). In addition to the mental workload of flying, the prolonged confinement of the cockpit on long missions exacerbates the distractions from chemical protective ensembles. Improperly fitting equipment and pressure spots can distract a pilot from his/her flight duties and compromise safety. Furthermore, the inability to urinate while on long missions while in chemical protection has caused aircrew to withhold fluid intake in an effort to minimize the need for urination. This voluntary dehydration before and during flights compounds further fluid losses from chemical protective clothing and gear.

The design of the cockpit provides several barriers that not only increase the heat load, but also make performance in chemical protective gear especially challenging. The large canopies create a greenhouse effect as incoming solar radiation is trapped. In standard non-combat flight profiles, this added heat load is dissipated as the aircraft ascends and is ventilated through open doors and windows. However, in a tactical chemical environment, the aircraft will have to be closed and fly at low altitudes, reducing the cooling effect of increased altitude. This greenhouse heating has raised the cockpit Wet Bulb Globe Temperature (WBGT) as much as 5° Celsius above outside WBGT in the Army's main utility aircraft, the UH-60 Black Hawk (Thornton and Guardiani, 1992). Furthermore, the use of chemical protective equipment in addition to survival gear adds substantial bulk to the aviator and may influence his/her ability to control the aircraft. This added bulk might limit the pilot's range of motion and preclude the safe operation of the aircraft.

The current U.S. Army aviator Chemical and Biological (CB) protective clothing ensemble consists of the standard Aircrew Battle Dress Uniform (ABDU) along with the Battle Dress Overgarment (BDO). The BDO is worn over the ABDU to protect against chemical warfare threats. An aviation life support equipment

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(ALSE) vest and laminated ballistic protection plates are worn over the BDO. When worn together, these components create a bulky ensemble that significantly encumbers the aviator and impairs thermoregulation and heat dissipation. A primary objective of Program Manager, Aircrew Integrated Systems (PM ACIS) and the Air Warrior (AW) program, is to develop new-generation aviator ensembles that will allow aircrew to operate in a combat environment while wearing CB mission oriented protective posture (MOPP4) ensembles while in a hot environment (up to 125° F). The key thermoregulating component of the new AW ensemble has been a water-cooled Microclimate Cooling Vest (MCV) worn underneath the uniform and survival equipment.

In order to adequately test the thermoregulatory effects of the cooling vest and the flight performance of the encumbered aviator, both environmentally controlled lab testing and operational testing in aircraft were performed. Initial data from the simulator studies also were used to establish the risk management environmental cut-off thresholds for operational testing. Even though the cooling vest performed well in the simulator testing at 90° Fahrenheit WBGT, operational testing showed MOPP4 equipment size and bulkiness still present additional obstacles to overcome in the development of the chemical protective ensemble. The initial laboratory test will be presented first, followed by operational testing results.

MATERIALS AND METHODS:

The basic combat uniform and equipment configuration worn by pilots on tactical missions consists of the aircrew uniform, flyer's gloves, flight helmet, pistol with holster, survival vest, radio, knife and soft body armor with ballistic plate. The AW Combat Configuration retained all of these components but added chemical protection in the form of a chemical protective undergarment, chemical protective mask, rubber boots and gloves. The AW configuration also added the microclimate cooling system, which consisted of the stationary cooling unit located on the floor of the aircraft and the wearable MCV. The cooling unit was either turned on or off based on the phase of the experiment.

Initial lab testing was conducted at the USAARL, Fort Rucker, Alabama, from 3-12 December 2001. Utilizing the laboratory's environmentally controlled UH-60 helicopter simulator, the Air Warrior ensemble was tested in both cool (70°F) and hot (100°F) conditions. The flight instruments and controls in the UH-60 simulator are directly linked to a real-time data acquisition system. This 128 channel, automated data acquisition system captures aviator input and aircraft response measurements at a 30-Hertz (Hz) sampling rate. The system allows continuous recording of cockpit instruments such as airspeed, altitude, roll, pitch, and slip. In addition to flight performance, other measured parameters included cockpit WBGT, body core temperature, skin temperature, heart rate, fluid balance, mood, and workload.

The MCV was worn next to the aviator's skin and covered the front and back of the torso. The MCV consists of approximately 110-130 feet of commercially available 3/32"ID/5/32" OD plasticized PVC tubing laminated between two layers of cotton fabric. The tubing is divided into six parallel circuits, reducing the pressure drop and temperature gradient across the garment and minimizing the likelihood of a complete loss of cooling if a tube becomes kinked or blocked. Each circuit covers a specific region of the body: front upper torso, front lower torso, back upper torso, back lower torso. The amount of tubing in each circuit is approximately evenly divided and is arranged in a horizontal pattern.

During laboratory evaluation phase, the volunteer pilots donned one of three chemical protective ensemble configurations: basic combat, normal (BC-N) environment; Air Warrior, normal (AW-N) environment; and

Air Warrior, hot (AW-H) environment. The first was a MOPP0 configuration, that is, no mask and no chemical-biological garment, whereas the other two were MOPP4 ensemble with a protective mask and undergarment. Both MOPP4 configurations added the MCV; however, only the hot condition had the cooling unit functioning. This resulted in the hot configuration being the most encumbering.

The eight volunteer UH-60 pilot test subjects were paired into four crews with each crew participating in the three test conditions in a repeated measures, counterbalanced design. The test condition designators included CS for cool-standard meaning 70°F and MOPP0 basic combat ensemble without the MCV, CM for cool-MOPP consisting of 70°F and the provided MOPP4 Air Warrior ensemble with the MCV but not actually turned on, and HM for hot-MOPP consisting of 100°F and the provided MOPP4 Air Warrior ensemble with the MCV vest turned on in the simulator. The test sessions consisted of an initial 20-minute block of simulated preflight activities involving ambulation at 3 miles per hour at zero grade on a treadmill in an environmental chamber at the prescribed temperature and 20% relative humidity. Then the crews walked to the USAARL UH-60 simulator set at the same temperature but 50% humidity as well as overhead heat lamps resulting in a 90°F WBGT composite heat stress measure. They flew two 2-hour sorties with an intervening simulated hot refuel break as an opportunity to urinate and adjust ensemble components to relieve hot spots. Measurements and questionnaires responses were obtained in standardized fashion per the governing protocol.

RESULTS:

Core Temperature and Heart Rate

Mean test subject core temperature as a function of test condition and minutes into the test sessions are provided in Figure 1. These show a rapid increase in core temperature during the simulated preflight treadmill walk in the environmental chamber followed by a progressive decline after entering the simulator. Initial core temperature rise was greatest for the hot-MOPP4 (HM) condition, followed by the cool-MOPP4 (CM) condition and the least for the cool-MOPP0 or cool-standard (CS) condition. The peak mean core temperature did not exceed 99.8°F and, likewise, did not drop below 98°F for any of the test conditions. Mean core temperature in the HM condition was about 0.4°F higher than CM and about 0.6°F higher than CS. But again, the absolute increase was quite modest compared to the approved upper limit on a core temperature of 102.5°F. The three core temperature profiles indicate initial body heat accumulation with subsequent passive or active dissipation. The later, of course, is associated with MCV use in the HM condition.

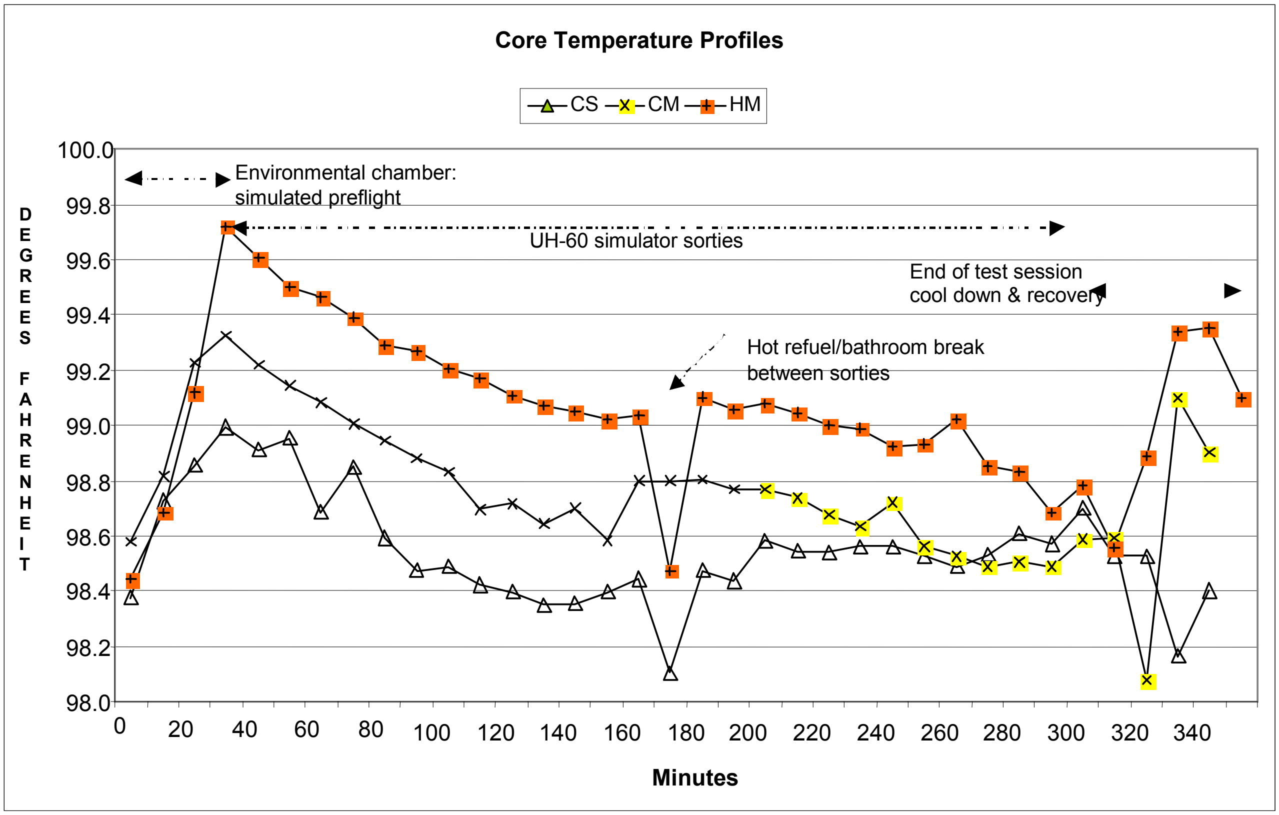

Figure 1: Core temperature responses.

The corresponding heart rate profiles for the three different test sessions are included in Figure 2. This shows a rapid spike in heart rate during the treadmill simulated preflight segment in the environmental chamber with a rapid decrease after test subjects settled into the simulator and a subsequent continuing heart rate decrease during the simulated sorties. As with core temperature, the mean heart rate for the HM condition in the simulator remained higher than for the CM condition by about 5 beats per minute. Although heart rate for the CM condition in the simulator was initially somewhat greater than for the CS condition, this difference converged after about two hours. Maximum mean heart rate response during the simulated preflight treadmill walk was about 115 beats per minute for both the MOPP4 configurations, but less than 100 for the MOPP0 configuration. The heart rate profiles are consistent with heavier workload associated during the simulated preflight treadmill walk due to the extra weight of the MOPP4 ensemble in HM and CM configurations and the effects of encumbrance and heat stress in the simulator for the CM and HM conditions.

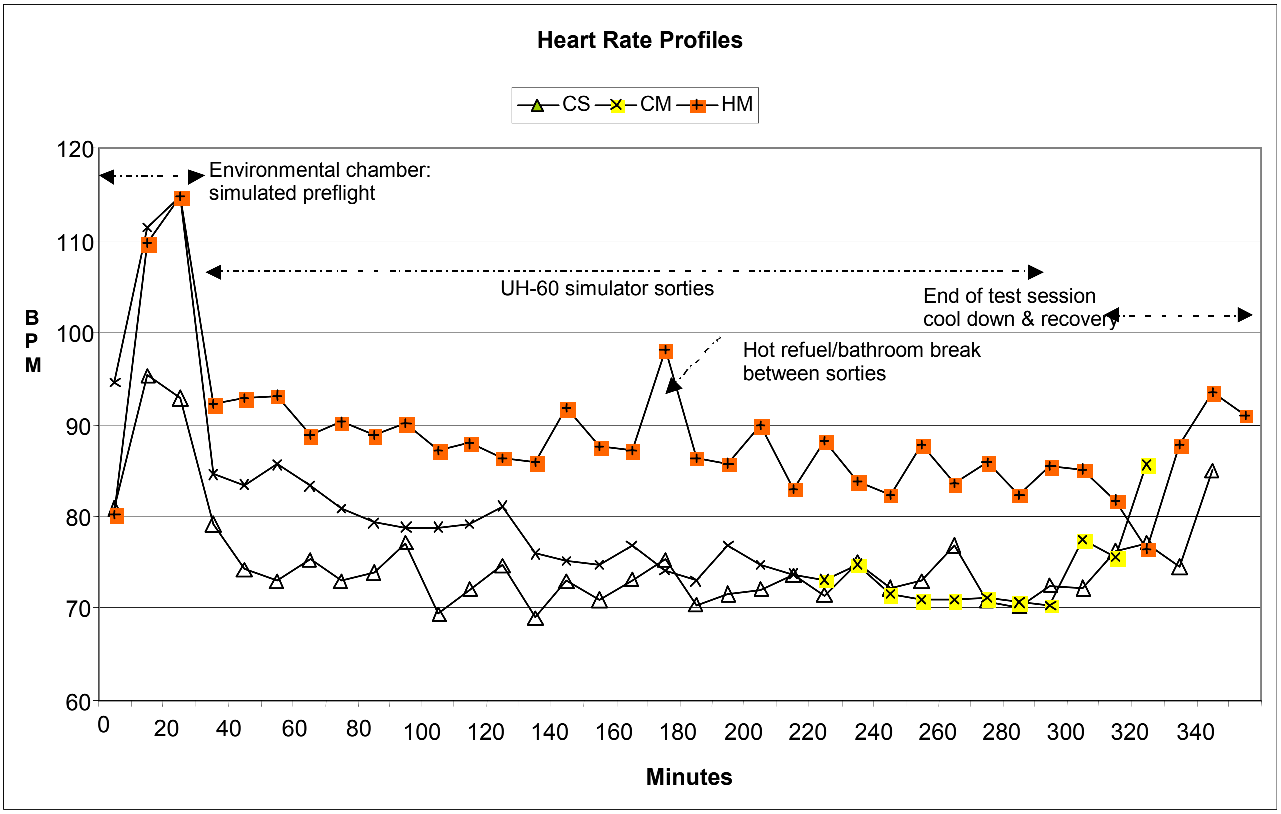

Figure 2: Heart rate response profiles.

Dehydration and Sweat Rates

The next results summarize the findings for test subject fluid and hydration status for the three test conditions. Figure 3 shows that mean percent dehydration was greatest for the HM condition despite use of the cooling vest. This is not entirely unexpected since the vest covered only the thorax, thereby allowing the remainder of surfaces to be directly stimulated to sweat from the local effects on the skin of the hot environmental temperature and relatively high humidity. The fluid deficit rate for the HM condition was approximately 300 cc per hour, which is a manageable compensable rate even when fluid intake is restricted to the protective mask drinking tube. As a reminder, in this study, fluid intake was self-regulated by the test subjects.

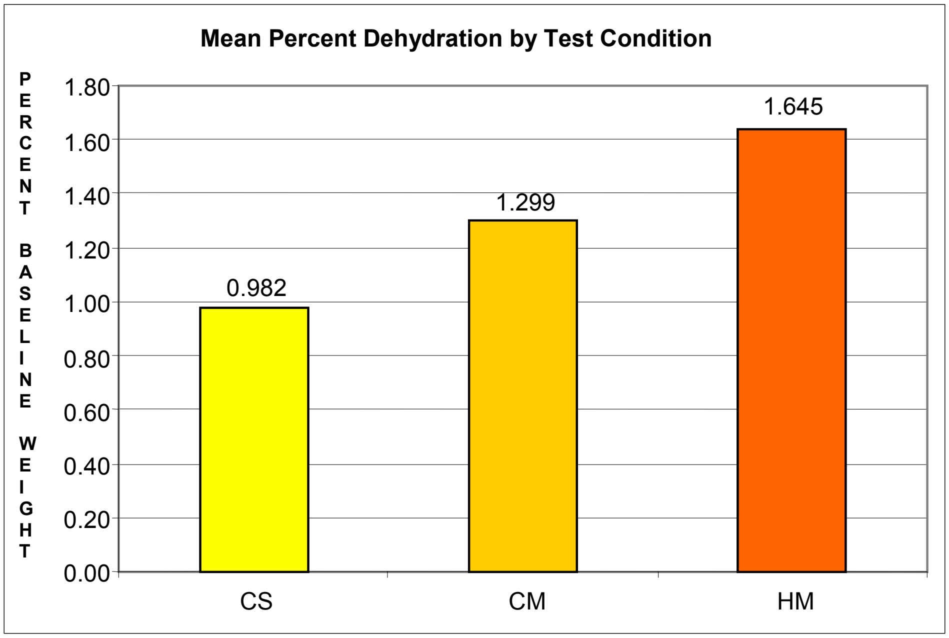

Figure 3: Percent dehydration.

The actual measured total sweat losses for each test condition are indicated in Figure 4. It is apparent that the MOPP4 ensemble alone was associated with a near doubling of the sweat loss compared to the MOPP0 ensemble in the 70°F or “cool” temperature condition. However, when averaged over the approximately 5.5 hour duration of the test sessions, the hourly sweat rates are on the order of 300 cc for the HM condition and less for the other conditions. This compares to maximum possible sweat rates of several liters per hour and maximum water absorption rates of imbibed water of 15-20 cc/minute or 0.9 –1.2 liters per hour, again indicating that incurred heat stress was well within the physiological compensable range for all test conditions including HM.

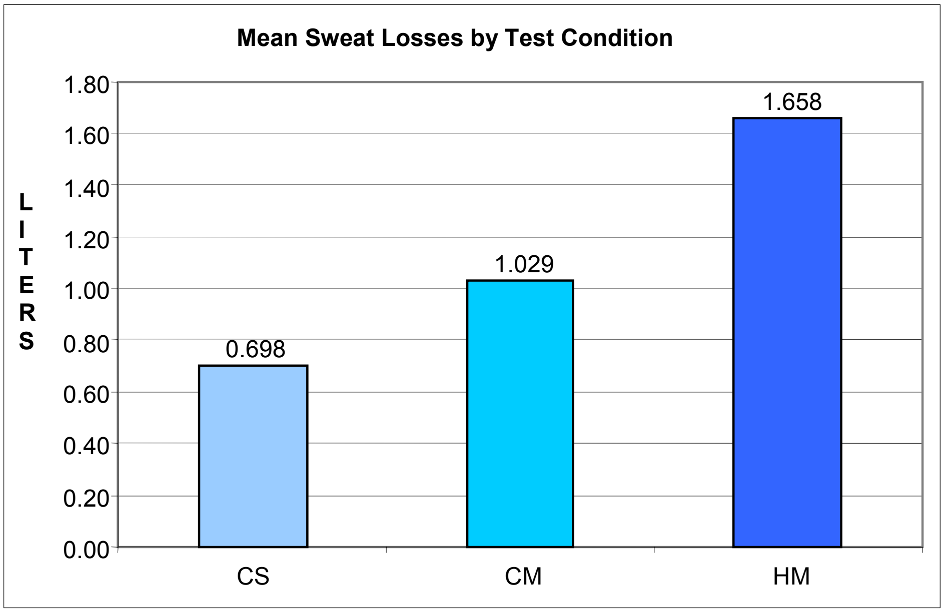

Figure 4: Sweat losses.

Flight Performance Scores

Effects of the different test conditions on a composite measure of flight performance are indicated in Figure 5, which shows a modest decrement due to MOPP4 when comparing CM versus baseline CS configurations. The incremental effect of HM is also depicted and is quite small. Factors associated with the MOPP4 configuration that could have affected flight performance in this manner include the general encumbrance and reduced agility for flight control adjustments, fatigue due to weight and encumbrance, difficulty maintaining preferred hand and arm position with respect to the cyclic, and impaired fields of view and visual cues due to the protective mask.

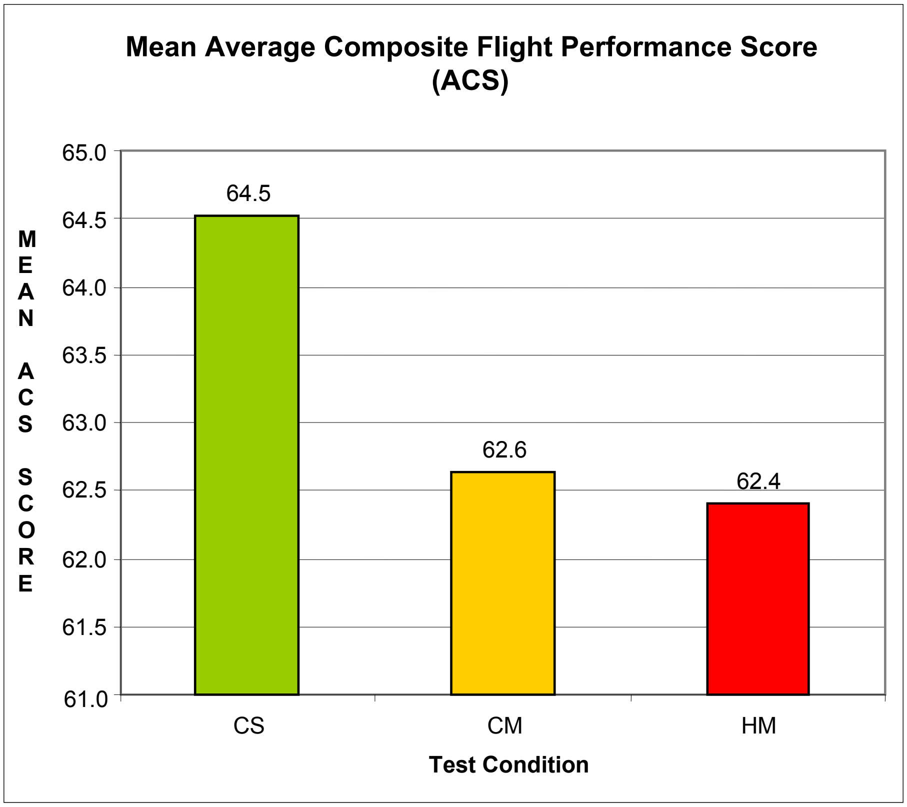

Figure 5: Flight performance scores.

OPERATIONAL TESTING METHODS:

The Air Warrior ensemble was field tested in four different Army helicopters from 15 July to 25 November 2002. The OH-58D Kiowa Warrior, the UH-60L Black Hawk and AH-64D Apache helicopters were tested at Fort Hood, Texas, while the CH-47 Chinook helicopter was tested in Alaska. A total of 76 crewmembers participated as subjects in the operational phase of the testing. These operational tests were used to assess crewmembers' ability to perform assigned aviation duties during the day and night while wearing the chemical protective ensemble. The flights consisted of multiship flights with at least half of the crew in each aircraft flying in full MOPP gear for 5.3 hours. Following each flight, crewmembers rated their ability to fly in the MOPP gear and compared the new system to the current MOPP equipment. Crewmembers rated equipment as acceptable or unacceptable. Aircraft temperature and relative humidity were recorded at 5-minute intervals to insure cockpit conditions did not exceed 90° F WBGT.

Due to risk management concerns, the 90°F WBGT setting of the simulator studies at USAARL served as the environmental cut-off limit for the operational studies. Although the cooling vest performed admirably under these conditions, no further helicopter simulator data were available for WBGTs greater than this value. No dual pilot MOPP4 data were collected on any actual aircraft. There were no waivers requested for dual-pilot, MOPP4 flights based on risk mitigation decisions by the test unit's chain of command. Consequently, flight events were completed with only half of the crew in MOPP4 gear. The impact of this limitation is that there was no full-crew, MOPP4 gear data collected to address this key performance parameter.

OPERATIONAL TEST RESULTS:

None of the flights or ground events were cancelled or terminated because of excessive temperature in the aircraft or WBGT. None of the aircrew terminated a flight or reduced the MOPP level based solely on temperature although some reductions were from nausea or general discomfort. Test crewmembers stated the MCV was exceptionally beneficial, improved their alertness and mission performance, and reduced overall stress and fatigue. These subjective evaluations by aircrew were consistent with mood findings in the previous laboratory testing. Since the AW system does not provide a method for removal of human waste, liquid or solid, aircrews had to be reminded of the risk of voluntary dehydration.

CONCLUSIONS:

The results from this USAARL UH-60 simulator heat stress study (test and evaluation) indicate that the MCU cooling vest system as installed and worn in the UH-60 simulator was effective in progressively reducing initially elevated core temperature and heart rate in a hot humid condition. The MCU vest was generally given high ratings for cooling effectiveness and did not elicit significant hot-spot ratings indicating a good level of comfort or tolerance. Perhaps the most significant results were that the MCU vest did not prevent sweating and a mild degree of dehydration compared to the cooler condition and, likewise, did not entirely suppress somewhat elevated heat stress and overall stress ratings in the hot encumbered condition. Additionally, average composite flight performance scores were reduced primarily by the encumbrance of the MOPP4 ensemble, but only minimally by the heat stress itself. These results indicate that the MCU vest system is effective in reducing an elevated core temperature and heart rate in heat-stressed UH-60 aviators wearing a MOPP4 ensemble encumbered with ballistic protection and additional survival gear, keeping them close on several key physiological measures to that experienced in the minimal stress condition (CS). Operational testing demonstrated the compatibility with most aircraft systems and the acceptance by crewmembers. However, the ensemble still presents some of the same visibility and bulk limitation posed by the current chemical protective ensemble.

DISCLAIMER: The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute an official Department of the Army endorsement or approval of the use of such commercial items.

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Hydration Requirements for Aircrew Operating in Very Hot Conditions

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ABSTRACT

This Study was undertaken to examine the heat strain and dehydration in aircrew operating in very high ambient temperatures. Rectal temperature, mean skin temperature, heart rate and total water loss were measured during laboratory simulations of a single, complete sortie (Dress, Rest, in-aircraft Stand-by and Flight phases). Each subject undertook 2 Trials: cool Dress and Rest and warm Dress and Rest. In both Trials, Stand-by and Flight were in very hot conditions. During Flight subjects exercised with a leg ergometer to raise metabolic rate to 107 $W{\cdot}m^{-2}$ *to simulate the physical activity of flying a combat sortie. Heat strain variables were measured at 1-minute intervals. Total water loss was measured over Rest, Stand-by and Flight, from which % dehydration was calculated. Rectal temperature rose throughout Stand-by and Flight in both cool and warm conditions, but approached equilibrium values at the end of Flight of 38.1 (1 SD = 0.3) ℃ (cool), and 38.3 (0.2) ℃ (warm). Absolute values of dehydration after warm Dress and Rest ranged from 1.4 to 3.2% of body mass. If this sample is representative of the fast-jet aircrew population, about 35% of these 1-hour sorties will result in dehydration of 2.5%, and about 10% in dehydration of 3.0%.*

1.0 INTRODUCTION

Maintaining optimal aircrew performance in very high ambient temperatures requires an understanding of the heat strain and hydration implications of pre-flight activities and in-aircraft stand-by, followed by single or multiple sorties. As part of experimental work related to such questions, we measured heat strain during laboratory simulations of hot-weather operations in a single-seat, fast-jet aircraft. The objective of the work described in this paper was to quantify the risk from dehydration to safe and effective mission performance.

2.0 METHODS

2.1 Overview

8 subjects, wearing Royal Air Force (RAF), fast-jet, Aircrew Equipment Assemblies (AEA) took part in 2 Trials. In the first, pre-flight dressing (up to 60 minutes) and simulated briefing (sitting at rest for 30 minutes) took place in cool conditions; in the second, these activities took place in warm conditions. After the rest phase, subjects simulated the in-aircraft, ground stand-by (45 minutes) and flight (60 minutes) phases of a sortie in very hot conditions. During Flight, subjects exercised continuously with a leg ergometer. Throughout Rest, Stand-by and Flight, heat strain and total water losses were measured. The risk of reaching various degrees of whole-body dehydration was calculated from the water loss data.

Paper presented at the RTO HFM Specialists' Meeting on "Maintaining Hydration: Issues, Guidelines, and Delivery", held in Boston, United States, 10-11 December 2003, and published in RTO-MP-HFM-086.

2.2 Subjects

After receiving written and verbal briefings on the purpose of the Study, its risks and risk management, 8 male subjects gave written consent to participate in the Study, which was approved by the local ethics committee. Subjects were within the anthropometric restrictions for aircrew flying a fast-jet aircraft in service with the RAF (Table 1).

Table 1

Physical characteristics of the 8 male subjects used in this Study

	Age (years)	**Height** (m)	**Body Mass** (kg)	**Body Mass Index** (kg m^{-2})	**Body Surface Area** (m^{2})
Mean	26.9	1.79	82.73	25.98	2.01
(1 SD) [1]	(1.8)	(0.05)	(10.79)	(3.79)	(0.12)

[1] Standard Deviation

2.3 Thermal environment

The thermal environments in the 4 phases of each Trial (Table 2) were selected to represent meteorological and fast-jet cockpit conditions measured in previous Studies.

Table 2

Thermal environment in the 2 Trials in the Study

Dress and Rest	*Cool*	*Warm*
Dry-bulb temperature	20ºC	30ºC
Black-globe (50 mm) temperature	20ºC	30ºC
Relative humidity	25%	38%
Air speed	0.5 m s^{-1}	0.5 m s^{-1}
Stand-by		
Dry-bulb temperature	50ºC	50ºC
Black-globe (50 mm) temperature	58ºC	58ºC
Relative humidity	13%	13%
Air speed	0.8 m s^{-1}	0.8 m s^{-1}
Flight		
Dry-bulb temperature	30ºC	30ºC
Black-globe (50 mm) temperature	38ºC	38ºC
Relative humidity	38%	38%
Air speed	0.8 m s^{-1}	0.8 m s^{-1}

Water vapour pressure in all 4 phases was constant (16.3 mbar)

Figure 1 shows the conditions achieved. The transition between Stand-by and Flight was slower than would occur in flight owing to limitations of the thermal laboratory plant. The heat stress on the subjects was therefore a little greater than might be the case during operations.

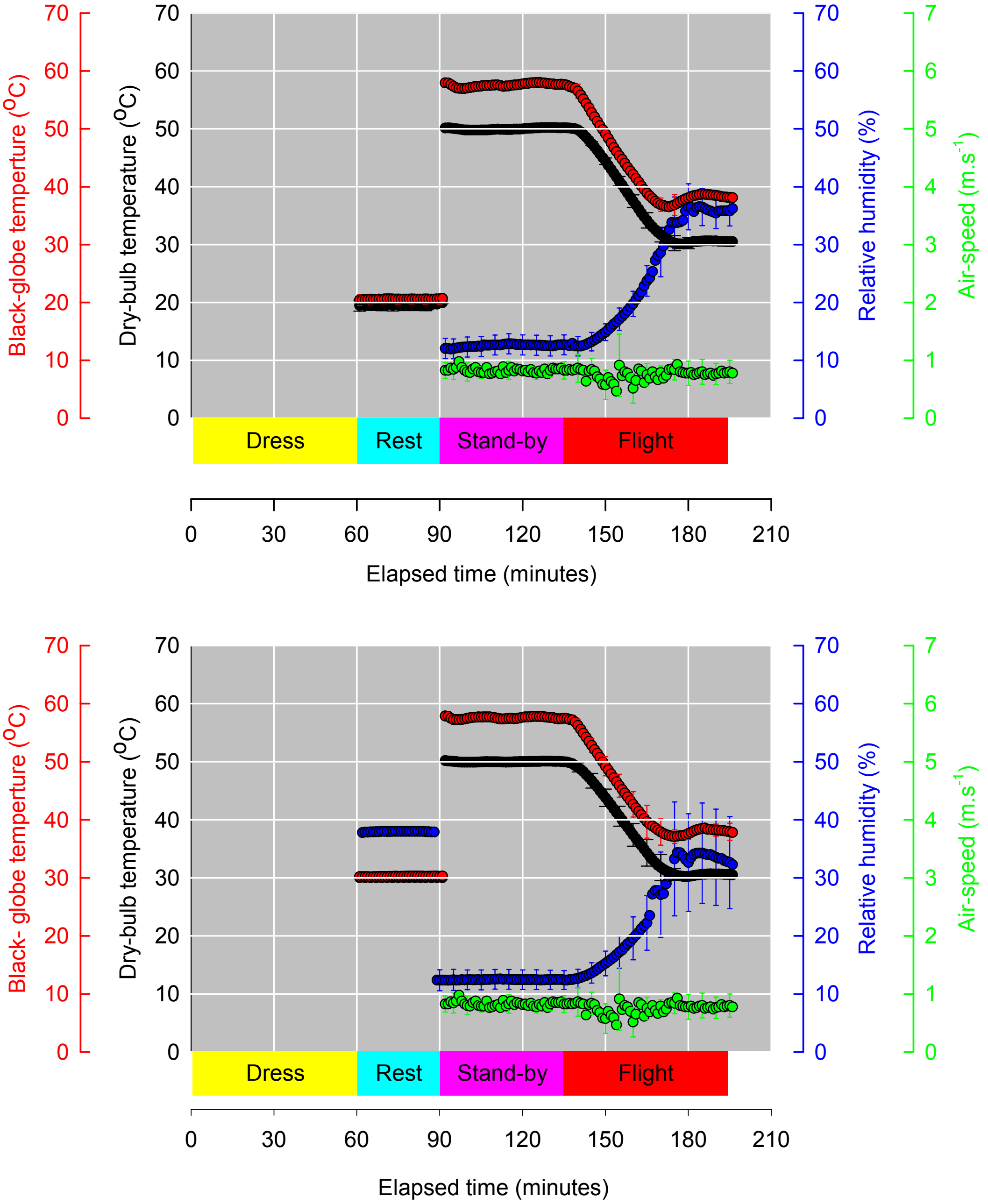

Figure 1

Thermal environment in cool Dress and Rest (upper panel) and warm Dress and Rest (lower panel)

Mean data (8 subjects) are shown at 1-minute intervals. For clarity, error bars (1 SD) are shown at 5-minute intervals. Where error bars are not visible, they are smaller than the symbols used to plot the data points.

2.4 Procedures

The main activities that took place in each Trial are listed below. On reporting to the laboratory the subject:

- Emptied his bladder and consumed 300 ml water;
- Undressed and inserted a rectal thermistor;
- Had nude body mass measured;
- Was instrumented with 4 skin thermistors and ECG electrodes;
- Donned the AEA;
- Had clothed body mass measured;
- Sat at rest in a cool (or a warm) laboratory for 30 minutes (Rest);
- Entered the hot chamber, strapped into an ejection seat, sat at rest for 45 minutes (Stand-by);
- Exercised for 60 minutes (Flight);
- Returned to the subject preparation area and was weighed clothed;
- Doffed AEA, removed instrumentation, towelled down and had nude body mass measured;
- Was kept under supervision until oral temperature was decreasing and was within 0.5°C of the pre-exposure value.

2.5 Aircrew Equipment Assemblies

The RAF fast-jet, Summer AEA worn during the 2 Trials in the Study comprised:

- Aircrew shirt Mk 2
- Long underpants
- Aircrew coverall Mk 15
- Anti-G trousers Mk 4
- Survival waistcoat
- Life preserver Mk 30L
- Terry-loop socks
- Aircrew boots 1965 Pattern
- Leg restraint garters
- Aircrew gloves, sweat resistant
- Flight helmet Mk 10B
- Oxygen mask Type P or Q

The intrinsic thermal insulation of this AEA is 0.9 clo; its Woodcock moisture permeability index is 0.4; it weighs 14.0 kg.

2.6 Exercise

During Flight subjects exercised with a leg ergometer to raise metabolic rate to 107 (1 SD 11) $W \cdot m^{-2}$ (oxygen uptake rate 0.64 (0.07) $litres \cdot min^{-1}$) to simulate the physical activity of flying a combat sortie. The ergometer was a weight attached to a horizontal pivot. Subjects pushed with their feet on a bar attached to the pivot, thus raising the weight once every 2 seconds. The required rate was indicated by a metronome tone. Subjects were continuously monitored to ensure that they maintained the required exercise rate.

2.7 Measurements

Measurements of rectal temperature (thermistor), mean skin temperature (thermistor) and heart rate (ECG electrodes) were made at 1-minute intervals during Rest, Stand-by and Flight. At 1-minute intervals, dry-bulb temperature, 50 mm black-globe temperature, relative humidity and air speed were measured at a height of 1.25 m above the floor (sitting chest height), 1 m in front of the subjects.

2.8 Drinking and dehydration

Subjects drank 300 ml of water during Dress; *ad libitum* during Rest; but water was not allowed during Stand-by and Flight. The change in nude body mass over Rest, Stand-by and Flight, corrected for water intake and any urine voided, but not for metabolic mass loss, was taken to indicate total water loss, from which whole-body dehydration was calculated.

3.0 RESULTS

3.1 Heat strain

Heat strain is shown in Figures 2 to 4. Rectal temperature rose continuously throughout Stand-by, to 37.3 (0.2)°C after cool Dress and Rest, but to 37.5 (0.2)°C after warm. During Flight the rate of rise of rectal temperature gradually decreased, until towards the end of Flight it reached near equilibrium values of 38.1 (0.3)°C (cool), and 38.3 (0.2)°C (warm). The small, but consistent, difference in heat strain would translate into a shorter safe ground Stand-by following warm Dress and Rest compared with cool Dress and Rest.

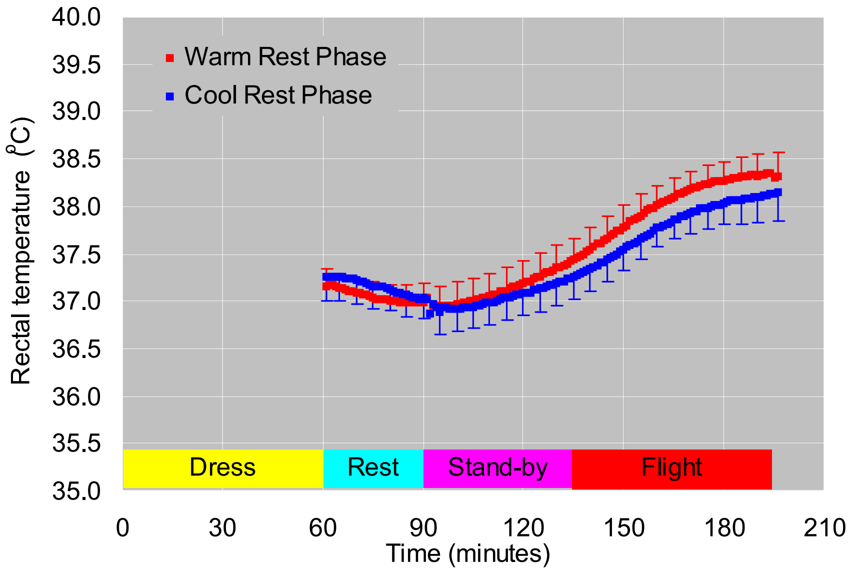

Figure 2

Rectal temperature in subjects who dressed and rested in cool or in warm conditions before Stand-by and Flight

Mean data (8 subjects) are shown at 1-minute intervals.
For clarity, error bars (1 SD) are shown at 5-minute intervals.

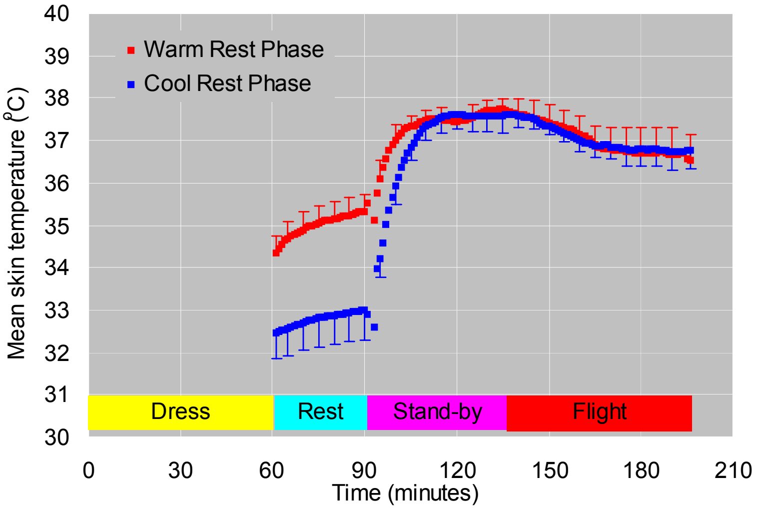

Figure 3

Mean skin temperature in subjects who dressed and rested in cool or in warm conditions before Stand-by and Flight

Mean data (8 subjects) are shown at 1-minute intervals.
For clarity, error bars (1 SD) are shown at 5-minute intervals.

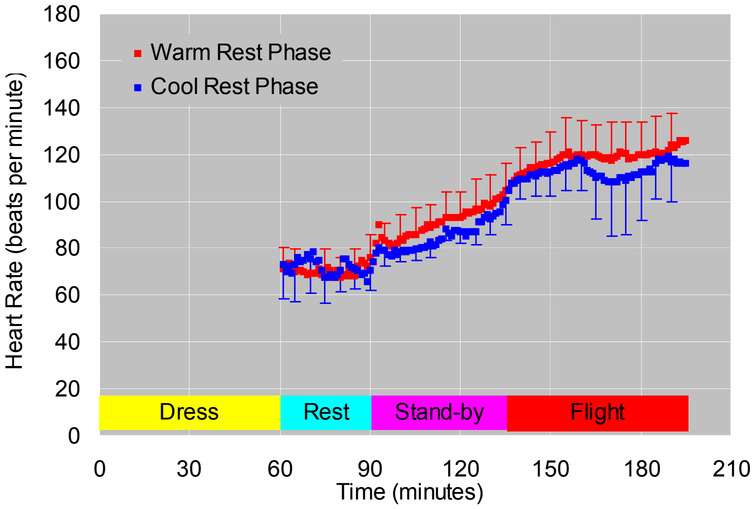

Figure 4

Heart rate in subjects who dressed and rested in cool or in warm conditions before Stand-by and Flight

Mean data (8 subjects) are shown at 1-minute intervals.
For clarity, error bars (1 SD) are shown at 5-minute intervals.

3.2 Water loss and dehydration

Figure 5 shows the total water loss and dehydration, which were 28% higher after warm Dress and Rest compared with cool ($p<0.01$, Student's t test). Absolute values of dehydration after warm Dress and Rest ranged from 1.4 to 3.2% of body mass.

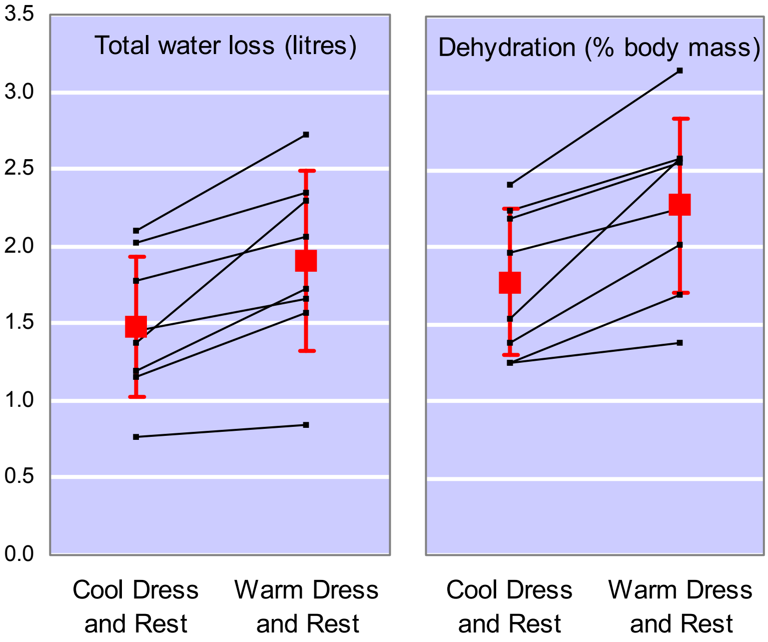

Figure 5

Total water loss (left panel) and dehydration (right panel) in subjects who dressed and rested in cool or in warm conditions

Errors bars are 1 standard deviation. Black lines are individual data for 8 subjects.

4.0 DISCUSSION AND CONCLUSIONS

The increase in heat strain when Dress and Rest were carried out in warm conditions, compared with cool conditions, indicates that even small changes in heat stress will cause changes in the safe duration of the ground Stand-by and Flight phases of operational sorties. It is beyond the scope of this paper to address these issues in detail, but a broad example will show the significance of these changes. If 38.5ºC was selected as the upper acceptable limit of rectal temperature, the ground Stand-by would be reduced by 50% in the conditions simulated in this Study.

This paper is concerned with the issue of dehydration in aircrew operating in very hot conditions. The number of subjects in this Study was small, but unavoidable constraints meant that the number could not be increased. Therefore, we used the limited dataset to calculate the z scores for the measured dehydration levels, from which the risk of various levels of dehydration arising was calculated. If this sample is representative of the fast-jet aircrew population, and the simulations impose a heat stress representative of combat flying in very hot conditions, about 35% of these 1-hour sorties will result in dehydration of 2.5%, and about 10% in dehydration of 3.0%.

Other studies in our laboratory have shown that a combination of moderate heat strain (about 1ºC) and dehydration (about 3% body mass) cause a significant decrement in the performance of tasks similar to those involved in flying a fast-jet aircraft (Bradley and Higenbottam, 2004).

These laboratory simulations were of a single 'sortie', with a very short Flight (60 minutes). Nevertheless, they show that pre-flight activities in even moderately warm conditions can induce dehydration that is likely to impair mental and physical performance in some aircrew. The risk is obviously greater for subsequent sorties following a rapid turn-around. The acceptable level in aircrew of dehydration, and of dehydration and heat strain together, requires to be defined.

5.0 REFERENCE

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Prevention of Heat Illness in Iraq

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ABSTRACT

Preventing heat casualties had been a challenge for the British Army during operations in Mesopotamia and Iraq in World War 1 and 2. In 2003, the UK military medical authorities recognised the risk from the heat from military operations in the Middle East. The environmental temperature in Iraq was greater than the recent experience of UK forces. This was aggravated by the limited availability of air-conditioned accommodation. In addition, the operational situation required personnel to wear ballistic protective equipment. Prevention measures were directed at acclimatisation, managing work rates and fluid replacement. All personnel were advised to drink freely and to aim 'to pee clear once per day'. The issue of 'Camelback' water carriers reduced the practical difficulty of drinking the required volume of water.

The majority of UK heat casualties occurred during extreme temperatures in June, July and August. There were peaks associated with the arrival of unacclimatised troops for the rotation of forces, during a period of extremely high humidity and as a result of an increase in civil disorder in Basra. The medical services treated casualties with classical heat stroke, water-depletion heat exhaustion, salt-depletion heat exhaustion and occasional exertional heat exhaustion. Treatment was aimed at reducing core temperature, restoring plasma volume and correcting biochemical abnormalities. Personnel who experienced one significant episode of heat illness or two hospital admissions were returned to UK.

Clinical staff reported a small number of cases of severe hyponatraemia amongst the heat casualties. This prompted a review of advice on salt replacement and all personnel were advised to add salt to their diet.

Overall acclimatisation and practical experience of the conditions were the most important elements in reducing heat casualties. All personnel understood the importance of fluid replacement of sweat losses. Whilst it was decided not to advise the specific addition of electrolyte replacement to water, it was considered that dietary supplementation of salt intake was likely to be beneficial.

1.0 BACKGROUND

During World War 1, the commission on the British Army campaign in Mesopotamia was critical of the preparations taken to protect the health of the force:

'We do not wish to be thought to belittle much good work done by the medical authorities in combating epidemics. Mesopotamia is a hot-bed of ravaging diseases. Plague, small-pox, cholera, malaria, dysentery and typhus, if not actually endemic, are always menacing in this swamp-ridden and unsanitated

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country. . Each one of these diseases appeared amidst the forces, and any one might have decimated them. On every occasion the efforts of the medical authorities were successful in circumscribing the epidemic and limiting its incidence. These are not despicable results for a large force of British and Indian troops accompanied by a horde of oriental camp-followers and whose headquarters was a Turkish town of some 80,000 inhabitants. But the indictment against the authorities is not a lack of courage in dealing with disease so much as a lack of foresight in dealing with the predisposing conditions of disease. In such matters as water-supply, sanitation, diet, mosquito and sun-protection, et cetera the evidence before both Commissions teems with instances of the failure to take up sufficiently early the weapons which existed in the armoury of modern science against the onslaught of disease Our opinion is that, though the protection of the Mesopotamian Expedition against disease was by no means ineffective, it might and ought to have been a good deal better, if the matter had been earlier taken in hand on a proper scale'(1).

Matters improved, and the official history of World War 1 records '*Heat stroke stations were authorized on the scale of ten to a division and a varying number for each hospital centre, base or post on the lines of communication according to their size. These stations were usually constructed of reed matting with the sides open to allow a free current of air, the roof being double and in some cases treble, with a considerable overhang to provide shade. They were placed at suitable positions in corps, divisional and other areas and were provided with canvas baths and other equipment. Ice was supplied daily on a scale of 40 Ib. per station. They proved of great value during the period of intense heat in the summer months. Other measures were also adopted with a view to preventing heat stroke. The troops were relieved of duty as far as possible between 10 a.m. and 4 p.m. They were given an abundant supply of drinking water and each man had a one-gallon canvas water bottle (chagul) in which the water was cooled by evaporation. Special instructions were issued in army orders on individual measures for mitigating the effects of heat and warning men of the risks of alcohol and other predisposing conditions. Billets and nuts for troops "were supplied as far as possible with electric fans, and tents were protected with matting. Hospitals were equipped with an ample supply of electric fans and ice, and arrangements were made for special wards for the treatment of heat stroke. Patients suffering from other diseases with a tendency to hyperpyrexia were covered with damp sheets and placed in the coolest parts of the ward under a fan. Leave to India and the United Kingdom was opened in the summer, leave to India being given freely. Every division and formation arranged amusements for the men. A light meal was prepared in the middle of the day, and dinner was given at an hour in the cool of the evening when the men were most likely to enjoy it in comfort. This system was doubly useful as the cooks had not to work during the heat of the day. Fatigues and parades were carefully regulated. but in certain places, especially on the Samarra line, defensive work involving hard physical labour had to be undertaken. Regulations regarding dress were relaxed*' (2).

2.0 THREAT

There was no doubt that the UK Armed Forces were aware of the risk from the heat in the Middle East in 2003. The meteorological conditions in Iraq during the summer were likely to be substantially more severe than any other recent experience of UK military forces. The predicted environment temperatures showed an average daily maximum temperature of 40ºC or more from June to September – and the existing guidelines for military operations in the heat precluded any physical exercise above an environmental temperature of 32ºC. In addition, the military threat required our soldiers to wear military protective clothing including helmets, heavy clothing, body armour, and military loads. This both increases physical work and reduces the effectiveness of cooling by the evaporation of sweat.

3.0 CLINICAL PICTURE

Heat stroke describes the clinical syndrome associated with overheating of the body core. It can occur in normal people who physically exert themselves in a hot humid environment and is the leading heat-related condition experienced by members of the UK Armed Forces. In hot humid conditions heat stroke can occur with normal sweating and in the absence of exercise (classic as opposed to exertional heat stroke). The diagnosis of heat stroke is usually easy: a history of collapse with disturbed consciousness during exertion in a hot environment and the presence of a high body temperature (around 41C) and hot dry skin. Water depletion heat exhaustion results from inadequate fluid replacement in a hot environment. Acclimatised personnel are at risk because of the increased production of more dilute sweat, which occurs with acclimatisation. Salt depletion heat exhaustion develops insidiously, particularly in unacclimatised personnel who lose relatively more sodium in sweat. One of the topics central to the management of the risk of heat illnesses in Iraq is the role of active salt supplementation to reduce the risk of this condition. Both water depletion heat exhaustion and salt depletion heat exhaustion may be followed by heat stroke.

4.0 CONTROL MEASURES

There are a number of well-recognised control measures that can be put in place to reduce the risk of heat casualties. Whilst the sun cannot be removed, it is possible to build the necessary infrastructure to move military personnel from austere tented accommodation open to the external environment to living accommodation contained in air-conditioned shelter systems. Unfortunately this takes time and engineer resources and so may UK military personnel spent the hottest part of the summer in 2003 living in primitive conditions. The existing UK Armed Forces guidelines for work/rest cycles are based on USARIEM guidance issued in 1991(3). Unfortunately the environmental temperature frequently exceeded 32ºC for much of the day and military operations could not be stopped completely. Furthermore sedentary duties associated with prolonged heat exposure such as guarding or driving were actually extremely high risk activities. Therefore more pragmatic direction was given to commanders associated with a reinforcement of the need to plan medical support to be able to treat heat casualties quickly and effectively. All UK military personnel arriving in Iraq were briefed to drink frequently and to ‘pee clear at least once per day’. Many soldiers purchased their own ‘camelbak’ water containers to aid continuous intake of water and indeed the Army purchased a bulk order for issue in early summer. Acclimatisation is a well recognised physiological adaptation to the hot environment that provides considerable reduction to the risk of illness from heat exposure. It was necessary to conduct a large rotation of forces in June for operational reasons. This was recognised as a high risk event. Newly arrived troops were directed to undertake a period of acclimatisation in Kuwait for 8-14 days prior to moving North into the operational area. Although the majority of personnel were expected to adjust to the new conditions an increase in the number of heat casualties was anticipated. Additional medical resources were deployed from UK to reinforce the medical unit in the acclimatisation camp.

5.0 TREATMENT CAPABILITIES

The medical services have a vital role in the provision of treatment services for heat casualties. The first element of this capability is the training of medical staff. All medical personnel receive training on the treatment of heat casualties during their basic training. This was reinforced by specific study periods in Iraq for medical staff. Early assessment and resuscitation in primary care centres is the most important element of the overall treatment system. Electric fans are one of the most vital life-saving items of equipment in medical units. Seriously injured casualties may need rapid evacuation to hospital. There are 2 helicopters on permanent standby for the evacuation of casualties to hospital covering the UK area of operations. The the key hospital capability is an intensive care unit. This was staffed for 4 beds with anaesthetic and nursing staff supported by laboratory and x-ray services. Finally, all personnel who had a serious episode of heat illness or who had 2 admissions to hospital were evacuated back to UK to remove them from the conditions. These individuals are to followed-up with a work-in-heat test at the Institute of Naval Medicine to detect anyone with true heat intolerance.

6.0 RESULTS

The preliminary analysis of mandatory heat casualty reports submitted to the UK headquarters in Iraq shows there were 849 cases reported up to 02 Sep 03 with 766 admissions to hospital and 161 patients evacuated to UK. In general there was an extremely low threshold for treatment of heat casualties. Although raised core temperature is the hallmark to heatstroke, many medical officers reported heat casualties based on softer symptoms such as lethargy, exhaustion, headache, nausea etc that could not be attributed to any other condition. There have been 2 deaths where heat might have been a contributing factor but neither case occurred as a result of failed preventive measures.

As anticipated, there was significant increase in the incidence of heat casualties in June as a result of the rotation of troops. More interestingly, there was an increase in the number of heat casualties in August associated with periods of substantially raised humidity in spite of constant environmental temperatures. This matches the anecdotal reports from World War 1 that described these periods as ‘dog days’ when any form of physical activity was high risk.

Medical officers were required to note any known pre-disposing factors that were present in the patient. Recorded associations included: lack of acclimatisation, failure to replace fluids, previous heat illness, sleep deprivation, concurrent dehydrating illness, medication and lack of physical fitness. There is likely to be an element of reporting bias, for instance all cases occurring within the first 14 days of arrival in Iraq would be given the ‘unacclimatised’ label. Unfortunately, it is not possible to estimate the predictive value of these factors from this case series.

A typical case report from a patient being investigated at the Institute of Naval Medicine is shown below courtesy of Dr Howard Oakley. It shows that clinical cases present a much more complicated pathophysiological picture than that described in the textbooks.

‘Previous history – had problems in Cyprus a couple of years ago, but no follow-up investigations.

Arrived at Basrah in May/June, then bussed down to Kuwait for 1 week acclimatisation. The first day of acclimatisation went fine, but as he started to work more, he began to feel unwell in the heat of the day, and very tired by early afternoon with nausea. Was told to add salt to food and to drink plenty of fluids, but found it increasingly hard to eat normally.

Needed to rest, cool and rehydrate (oral dioralyte) in medical tent of 3rd day. Felt rapidly better, but felt unwell in the heat of the next day, when he was given further sachets of dioralyte and told to drink water with added salt.

Selected for the advance party to move North. Acclimatisation curtailed and moved to Al Amarah where temperature some 5-10 degrees higher.

He felt unwell soon after arrival in the new location. Rested in cool and felt better. Advised to add more salt to food and to drink water with added salt. On third day, when working in heat, felt dizzy, nauseated, very unwell, had bad muscle cramps and tingling in his fingers, and then vomited and collapsed.

In the local medical facility, he was cooled and given IV fluids. He started to settle and was transferred to the Field Hospital. On admission he was slightly hyponatraemic and had a low potassium. He felt much better in air-conditioned areas, but over the following days he was unable to return to the heat and could only go outside at night.

Evacuated back to UK. Quite well on return. Slowly building up physical exercise.’

7.0 HYPONATAREMIA

As highlighted in Dr Oakley's case report, our clinical staff reported a number of cases of low serum sodium. Indeed one case of central pontine myelinosis, an extremely rare condition attributable to over rapid correction of low sodium, has been reported (personal communication, Dr M World). A cases series from one of our field hospitals showed 6% of admissions had hyponatraemia as a primary diagnosis. Clinical staff reported that these patients were clinically the same as other heat casualties with normal blood sodium levels. It is also possible that some of these cases were actually water intoxication rather than hyponatraemia but distinguishing between the 2 conditions on biochemical analysis is quite difficult. Our primary care doctors were concerned that some mild heat casualties with significant biochemical abnormalities might have been retained at unit level. It is planned to investigate the use of near patient testing to assist with the identification of patients who require evacuation to hospital in spite of mild symptoms. Although this proposal seems simple, in practice there are concerns over the reliability of near patient biochemical analysers when used in hot environments that exceed the product specification.

These concerns led to debate about increasing dietary intake of sodium to replace sodium loss. Many senior officers remembered being issued salt tablets during the 1950s and 1960s and wondered whether this would be advisable. Our initial medical advice was that salt should be actively added to food. We did not want to encourage the use of electrolyte replacement drinks because absence of evidence that this would have an effect on a population level, the difficulties of supplying such specialist food supplementation and the problems with sterilising water containers that have held sugar solutions. Academic advice from Dr Aidrian Allsop of the Institute of Naval Medicine raised concerns about sodium supplementation if there is a risk of missing meals because the body may not be able to adapt from a sodium supplemented diet to a period of no sodium intake sufficiently fast to prevent salt-depletion heat exhaustion. This is an area that requires further research based on heat exposures over a full 24 hour cycle, particularly during the period of acclimatisation.

8.0 DISCUSSION

The numbers of soldiers requiring medical assistance is an indication of the irreducible risk from the heat. The medical system was able to cope with this surge in demand. There were only 15 cases admitted to intensive care and no deaths attributed to failed prevention measures. We believe that this indicates success in the health risk management of the threat from heat.

The risk factors for heat illness are well known, both from the academic literature and from the case series built from UK heat casualty reports in Iraq. Unfortunately no one has conducted a case-control or cohort study to investigate the relative risk or predictive value of these risk factors. This is a vital piece of science that could be used to identify those personnel at greatest risk and prevent their deployment to hot environments.

Patients who had one significant hospital admission or 2 minor hospital admissions were returned to UK. This led to a large number of personnel being evacuated, which caused concern amongst the operational staff. We took a deliberate medical policy decision to apply a 'safety-first' principle. However it does mean that the operational staff need to be aware of the numbers likely to be evacuated and consider a plan for replacing these personnel with reinforcements. These patients are being followed up with a work in heat test at the Institute of Naval Medicine. It is hoped that the results of this work will be published next year.

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Current U.S. Military Fluid Replacement Guidelines

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CURRENT U.S. MILITARY FLUID REPLACEMENT GUIDELINES

This paper presents a summary of the process to revise the U.S. Military's Fluid Replacement Guidelines. The "old" fluid replacement guidelines provided recommendations for fluid replacement based solely on climatic conditions without consideration for energy expended (activity level) or without hourly or daily limits on fluid consumption. The "revised" fluid replacement guidelines added activity level and hourly and daily limits on fluid consumption. The revised recommendations to the U.S. Army's fluid replacement guidelines were successful as fluid consumption was better matched to sweat losses during hot weather military training.

BACKGROUND

The primary emphasis of the U.S. Military's fluid replacement guidelines is to avoid dehydration, reduce the risk of heat casualties, and thereby eliminate military performance degradation (2, 3, 9). Unfortunately, during the ten-year period between 1989 and 1999, there were 190 hospitalized cases of hyponatremia (caused by over-drinking) during hot weather military training reported. Sixty-seven of these cases of over-drinking/water intoxication occurred in the military training environment at Fort Benning, GA (4, 11). In 1997, eleven hospitalized cases of hyponatremia were reviewed (11). The common characteristics of these cases were that they: 1) occurred early in a military training cycle, 2) were associated with a large fluid intake, 3) presented with mental status changes, and 4) presented with nausea and/or vomiting. All eleven cases occurred during environmental heat stress and in each case considerably more fluid was consumed than recommended by the existing fluid replacement doctrine (2). The number of cases of hyponatremia suggested the fluid replacement guidelines needed to be adjusted in the training environment to prevent possible over-drinking.

In response to the numerous hospitalized cases of hyponatremia, the fluid replacement guidelines for hot weather military training were reviewed and subsequently revised (9). The "old" fluid replacement guidelines provided recommendations for fluid replacement based solely on climatic conditions without consideration for energy expended (activity level) or without hourly or daily limits on fluid consumption. It

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was assumed that any "modest over-drinking" from this guidance would be balanced by increased urine output, and over-hydration would be minimal. However, since Military Leaders are required to enforce fluid replacement guidelines to avoid dehydration and related heat injuries (2, 3), without specific guidance based on energy expenditure and the environmental conditions, the maximal fluid replacement for any "Heat Category" was often employed to avoid dehydration (Table 1, 3rd column). This guidance was further complicated by the commonality between the initial symptoms observed for heat exhaustion and hyponatremia (10, 11) so that water was provided to individuals experiencing dizziness, headache, weakness and nausea often without knowledge of recent fluid ingestion volumes. Unfortunately, it wasn't routinely made known that individuals presenting with heat exhaustion resulting from dehydration respond fairly quickly to fluid replacement, while those with hyponatremia may have their condition aggravated by the oral administration of fluids.

The initial development of the revised fluid replacement guidelines used existing computer model estimates of sweat losses for various activity levels and climatic conditions (9): **(1) Computer Simulation** – estimated work times and fluid intake from an existing heat stress model; **(2) Constructed Table** – easy (250W), moderate (400 W) and hard (600 W) military tasks; 70-110°F, 20-100%rh; **(3) Collapsed Matrix** – WBGT (Heat Category: I-V); sweating rates rounded to 0.25 quart; and **(4) 2nd Computer Simulation** – adjusted matrix for T_{core} (38.5°C) and 4 hour sustained training.

The second step revised these estimates utilizing actual data collected from soldiers wearing the hot weather, Battle Dress Uniform during climatic chamber studies at different climatic conditions and activity levels (9): **(1) Laboratory Validation** –easy, moderate and hard work in three humid climates and moderate work in a dry environment (n=20, men and women); **(2) Compared Results** – constructed tables with hydration guidance; and **(3) Revised Tables** – decreased fluid recommendation; added work intensity.

Table 1. WATER AND WORK\REST CYCLE REQUIREMENTS (OLD; FM21-10, November 1988[2])

CRITERIA		PMM	
HEAT CONDITION/ CATEGORY	WBGT INDEX (°F)	WATER INTAKE QUARTS/HOUR	WORK/REST CYCLE-MINUTES
1	78° - 81.9°	At least ½	Continuous
2	82° - 84.9°	At least ½	50/10
3	85° - 87.9°	At least 1	45/15
4	88° - 89.9°	At least 1 ½	30/30
5	90° - above	More than 2	20/40

These revised guidelines were then "field tested" and compared to data collected under the "OLD" and "REV" guidelines (7): **(1) Field Validation** – 550 recruits were studied over two successive summers (1997, 1998); **(2) 1997** – Field testing at Fort Benning using the "OLD" Fluid Replacement Guidelines (n=277); and **(3) 1998** – Field testing at Fort Benning using the "REV" Fluid Replacement Guidelines (n=273). These studies used heat acclimatized, male basic training recruits during mild to hard work (250-600 W) wearing the battle dress uniform, hot weather (BDU). Serum sodium, body mass and fluid intake were measured pre – post activity. The revised fluid replacement guidance is shown in Table 2 below. This revised guidance applies to the average heat-acclimated soldier wearing the Battle Dress Uniform (BDU), Hot Weather (3, 9). The additional changes to the decreased fluid recommendations were the addition of easy, moderate and hard work (Table 3); limiting the hourly water intake ≤ 1.5 quarts; and limiting the daily water intake ≤ 12 quarts.

Table 2. Revised Fluid Replacement Guidelines for Warm Weather Training(3,9)

Heat Category	WBGT Index, (°F)	Easy Work		Moderate Work		Hard Work	
		Work /Rest	Water Intake (Qt/hr)	Work /Rest	Water Intake (Qt/hr)	Work /Rest	Water Intake (Qt/hr)
1	78-81.9	NL	½	NL	¾	40/20 min	¾
2 (Green)	82-84.9	NL	½	50/10 min	¾	30/30 min	1
3 (Yellow)	85-87.9	NL	¾	40/20 min	¾	30/30 min	1
4 (Red)	88-89.9	NL	¾	30/30 min	¾	20/40 min	1
5 (Black)	> 90	50/10 min	1	20/40 min	1	10/50 min	1

- The work-rest times and fluid replacement volumes will sustain performance and hydration for at least 4 hours of work in the specified heat category. Individual water needs will vary ± ¼ qt/hr.
- NL= no limit to work time per hour.
- Rest means minimal physical activity (sitting or standing), in shade if possible.
- Hourly fluid intake should not exceed 1½ qt. Daily fluid intake should not exceed 12 qt.
- Wearing body armor adds 5°F to WBGT Index
- Wearing MOPP over-garment adds 10°F (Easy Work) or 20°F (Moderate or Hard Work) to WBGT Index.

Specifically, these "revised" fluid replacement guidelines (REV) were compared with the "OLD" guidelines on daily changes in serum sodium concentration (Na+) and body mass (BM) during Basic Combat Training at Fort Benning, GA during two successive summers (1997 and 1998). Data were collected from over five hundred recruits (OLD=277, REV=273). Recruits were tested in the morning before and in the afternoon after, 8-12 hours of hot weather, outdoor, military combat training. The wet bulb globe temperature (WBGT, mean ± SD) averaged 26.6 ± 1.7°C and 27.4 ± 0.9 °C for OLD and REV (NS).

Serum Na+ decreased from 137.5 ± 1.6 mEq/L to 137.0±2.1 mEq/L after outdoor, military training in OLD ($p<0.05$). Twenty-two recruits (8%) had serum sodium fall to below 135 mEq/L during OLD. Serum Na+ increased from 139.0 ± 1.7 mEq/L to 139.4 ± 2.1 mEq/L after outdoor military training in REV ($p<0.05$). Only two recruits (1%) had serum Na+ fall to below 135 mEq/L during REV. BM increased an average of 1.3 ± 1.4 kg ($p<0.05$) in OLD and an average of 0.4 ± 1.7 kg in REV ($p<0.05$). The revised guidelines effectively reversed the decrease in serum sodium, reduced the increase in body mass, maintained hydration and minimized over-drinking during hot weather military training compared to the "OLD" fluid replacement guidelines.

Table 3. Examples of Easy, Moderate and Hard Work for the Revised Fluid Replacement Guidelines for Warm Weather Training

Easy Work	Moderate Work	Hard Work
• Weapon Maintenance • Walking Hard Surface at 2.5 mph, 30 lb Load • Manual of Arms • Marksmanship Training • Drill and Ceremony	• Walking Loose Sand at 2.5 mph, no Load • Walking Hard Surface at 3.5 mph, 40 lb Load • Calisthenics • Patrolling • Individual Movement Techniques. i.e. low crawl, high crawl • Defensive Position Construction • Field Assaults	• Walking Hard Surface at 3.5 mph, ≥40 lb Load • Walking Loose Sand at 2.5 mph with Load

The fluid replacement tables underwent another correction based on soldiers working in mission oriented protective posture (MOPP) Level 1 or Level 4. This process included: **(1) Computer Simulation** – estimated core temperature in a specific environment using existing model; **(2) Laboratory Data** – experimental data in PPE (MOPP1; MOPP4); **(3) Constructed Table** – several WBGT; BDU, MOPP1, MOPP4; low, moderate or hard work; **(4) Collapsed Matrix** – equilibrium core temperature; low and moderate work; WBGT; **(5) Compared Results** – constructed tables with clothing guidance; and **(6) Revised Tables** – adjusted heat category for MOPP4 and moderate and hard work. This iterative process recommended that wearing MOPP at any protective level (1-4) adds 10°F for easy work, and adds 20°F for moderate or hard work. There was no change made for recommendations when wearing of body armor (adds 5°F to WBGT index).

CONCLUSIONS

The changes to the U.S. Army's fluid replacement guidelines successfully minimized the incidence of significant serum sodium loss without increasing the risk of dehydration for soldiers in the military training environment. Serum sodium concentration provided both a good estimate of hydration status (as it accounts for ~50% of plasma osmolality) during exercise-heat stress and provided a direct measure of possible hyponatremia. The revised fluid replacement guidelines decreased the number of outliers (± 2 SD) tending to be hyponatremic without increasing the number of outliers tending to be marginally dehydrated.

The field validation provided a "snapshot" of fluid replacement during outdoor military training. There were two design issues that may have minimized differences observed between the "old" and "revised" fluid replacement guidelines. The fluid replacement tables were revised because of the increased incidence of hyponatremia reported during military training (4, 6, 11). The revisions, to include activity level (energy expenditure) and upper limits for hourly and daily fluid replacement, were intended to provide safe guidelines that would reduce the incidence of hyponatremia [defined here as serum sodium concentration less than 135 mEq/L] without increasing the incidence of dehydration in a military training environment (9). Dehydration in excess of 3% of total body water markedly reduces military performance and increases the thermal stress of exercise (1, 8, 12). The revised recommendations to the U.S. Army's fluid replacement guidelines were successful as fluid consumption was better matched to sweat losses as indicated by a reversal to a slight increase in serum sodium concentration and a smaller increase in body mass during hot weather military training observed in this study. During the time of this investigation at Fort Benning, two cases of hyponatremia were reported during OLD and no cases were reported in REV. These cases were not associated with the recruits participating in this investigation.

The revised fluid replacement guidelines "field tested" in a training environment provided evidence supporting the laboratory and computer model estimations of sweat losses during hot weather training (9). The large number of recruits during hot weather, military training provided an adequate distribution of serum sodium and body mass changes to assess the utility of the revised fluid replacement guidelines. A follow-up of epidemiological data indicated a significant decrease in hospitalized hyponatremia cases in 1998 and 1999 compared to 1997 (under "old" guidelines), further supporting the success of the revised fluid replacement guidelines (5). The number of hyponatremia cases reported at Fort Benning was reduced from ten in 1997 to four in 1998 to one in 1999 (5). The average changes in serum sodium concentration observed during hot weather military training, although statistically significant, were small. An important observation is the direction change in serum sodium concentration after military hot weather training with the new fluid replacement guidelines.

During military training, water is the primary rehydration beverage and electrolytes are replaced during meals as daily sodium intake for garrison or field diets is sufficient to replace most sodium losses from sweat. Sodium is not the only electrolyte that is lost in sweat (potassium, calcium, and magnesium) and the inclusion of sodium or other electrolytes can be an effective source for electrolyte replacement during prolonged periods of profuse sweating in hot weather, especially when meals are not available. However, the findings from the field study, done in a training environment where most heat injuries occur, indicated the revised fluid replacement guidelines effectively reversed the decrease in serum sodium, reduced the increase in body mass, maintained hydration and minimized over-drinking during hot weather military training compared to the "old" fluid replacement guidelines.

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Water Intake and Urine Output during a 194-Kilometre Unsupported Desert March

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ABSTRACT

British troops are required to deploy rapidly to environments that expose them to high levels of heat stress, with limited natural sources of water upon which to survive. Potable water must therefore be supplied by military logistics to reduce the risk of heat illness and degraded physical and mental performance caused by dehydration. Mathematical models can be used to predict water requirements for desert operations, but they often provide estimates that exceed military guidelines (15 litres per man per day) [1] [2]. This study measured the amount of water consumed during a simulated military operation in a hot, desert environment to compare the need with military guidelines [1] [3]. Methods: 5 men (mean (1 SD) aged 41.8 (9.1) years; body mass 81.1 (6.8) kg; body fat (bioimpedance) 17.8 (3.1) %) consented to participate in this Ethics Committee approved study. A 194-km desert march was conducted along the length of Qatar. Mean hourly dry-bulb temperature during the march was 25 (4)^{o}C, and relative humidity averaged 48 (17) %. All water, food (high-energy bars and High5 carbohydrate-electrolyte energysource) and equipment was transported in 2, 2-wheeled carts (total load including carts was 320 kg). The rate of oxygen uptake when pulling the carts in temperate conditions in the UK was measured using a portable expired gas analyser (Cosmed K4b^{2}). This rate was then used during cycle ergometer exercise in controlled conditions (dry-bulb and globe temperatures 40 ^{o}C; relative humidity 50%; airspeed 1ms^{-1}) to estimate the amount of water needed for the expected 60-hour march. A 50-litre per person water budget was allowed. Following a 6-day heat acclimatisation phase in Qatar, subjects began the march hydrated. Body mass was recorded every 6 hours. The mass of water and food intake, urine and faeces output was recorded throughout the march. Other measurements were: heart rate (HR) (every 15s, from which HRreserve was calculated); gastrointestinal temperature (Tgi) (every 10s); and ankle and wrist activity (every 2s). Total body water (TBW) and body fat (%) were recorded by bioimpedance immediately pre- and post-march. Paired data were compared using a t-test. Results: Four of the 5 subjects completed the march in 78-hours. Physical activity (mean relative intensity 58 (7) % of HRreserve) was recorded during 74 of the 78 hours. A total of 46.0 (10.5) MJ were consumed. Water intake was 34.7 (6.4) litres; 2.9 (0.6) litres of urine were excreted. TBW increased by 0.3 (0.4) litres (range of 0.8 to 1.5%) compared with pre-march values ($p<0.05$). Mean Tgi was 38.1 (0.6)^{o}C; occasionally it rose above 39.3 ^{o}C. Fat mass declined ($p<0.05$) by 3.4 (1.0) kg, accounting for the loss in total body mass of 3.3 (1.6) kg. Conclusions: Daily consumption of up to 11 litres of water per man was sufficient to maintain hydration when working at up

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to 58%HRreserve during this prolonged, self-sufficient desert march. These data support the existing military guidelines for the provision of potable water [18].

1.0 INTRODUCTION

Since the end of the Cold War British troops have been deployed in a number of quite diverse environments to conduct a wide range of roles. Military operations are no longer limited to those extremely cold conditions experienced during the Falklands conflict (1982). During the last 10 years deployed personnel have been required to maintain high levels of operational effectiveness to combat a relatively new threat in the predominantly hot climates of Kuwait, Iraq, Oman, and Sierra Leone. The rapid changes in environmental conditions experienced during the low-to-high-altitude operations in Afghanistan, have posed a further threat to the well-being of British troops since the terrorist activities observed on September 11 2001.

1.1 Military operations

Irrespective of the nature and location of the deployment, military operations and training exercises have always been recognised to be very physically demanding (with personnel expending energy at a rate of 11.3 [lowest] to 45.9 [highest] $\mathrm{MJ.day^{-1}}$ [5]). The ability to meet the nutritional requirements of troops during military operations can determine the successful outcome of their mission and indeed the success of the entire campaign. Water is a critical requirement without which no military force can operate effectively. There is a need to identify how much water is required by troops in order to allay the onset of performance-degrading dehydration and the risk of heat illness.

Ruby *et al* 2003 have shown that during arduous and extended assignments, euhydration and energy balance are challenged when total energy expenditure increases to more than 3.6 times the basal metabolic rate [6]. Large decrements in total body water (TBW) and energy balance have been demonstrated during studies of military exercises in hot conditions. Mudambo *et al* 1997 [7] reported a 3.0 (SD 0.1) kg loss in body mass, attributed mostly to a loss in TBW during a 12-day exercise in the African bush. Similarly energy balance has often been compromised in extreme exposure to cold stress [8] during tasks which are representative of military operations. However, the greatest losses in body mass for work scenarios that are representative of military operations have been reported [6] when personnel are exposed to a combination of:

- elevated ambient temperature;
- rough terrain;
- sustained high levels of total daily energy expenditure (TDEE).

Furthermore the authors believed that during active wildfire suppression, TDEE was mostly influenced by the terrain and the duration of each daily shift. The physical demands associated with pulling a line and transporting heavy loads during wildfire suppression was believed to contribute significantly to TDEE and subsequently result in a negative energy balance and loss in TBW. Interestingly the fire-fighters who operated during these wildfire suppression scenarios were seen to ingest a minimum of 6.0 to 8.0 litres of potable water (maximum 9.6 litres) for each of the 5 days that they fought the wildfire.

High daily levels of TDEE are not the sole domain of high-intensity physical activities. Moderate or low intensity work that is sustained over a prolonged period (this can often be achieved in contrast to the high intensity work) is often reported to result in the greatest TDEE [8] [11] and hence present the greater risk when considering the effect on TBW and energy balance [2], [6].

1.2 Qatar

Qatar is a peninsula in the Middle East which borders the Persian Gulf and Saudi Arabia (25°15'N 51°34'E). It has 11,437 km^2 of land that is mostly flat and barren desert covered with loose sand and gravel, and 563 km of coastline. The lowest point in Qatar is found at the point with the Persian Gulf (0 m) whilst the highest point is located near to the border with Saudi Arabia at Qurayn Abu al Bawl (103 m above sea level). Qatar hosted the central headquarters for the American forces During Operation Telic (the War in Iraq, 2003). The nature of the terrain and the characteristics of the environment are very similar to those encountered by British and American forces during military operations that have been conducted over the past decade.

1.3 Predicting the requirement for water

It is important to know how much water personnel need to drink in order to avoid the risks that are associated with dehydration. However, robust and valid mathematical models that have been established following the input of many years of highly relevant, empirical data (from scientific studies with military personnel) are rarely used by military planners to calculate this requirement. Some reports that have utilised such mathematical models have shown that the British military's previous daily, upper limit of 15 litres of potable water issued to each person [1] can often be exceeded for typical operational scenarios [2]. This study applied the predictions provided by the QinetiQ Human Limits Prediction System [12] to determine the requirement for water during the march along the length of Qatar.

1.4 Study objective

The aim of the study was to identify the quantity of water that was required by a small team to successfully complete a prolonged march in a hot desert environment without re-supply. It was also the intention to monitor those variables that may serve to explain the subsequent results. This information will assist military logistics to determine the necessary volume of water with which to provide personnel who conduct such a march in the future.

2.0 METHODS

2.1 The subjects

Five men participated as subjects in this study (table 1), whilst a further two men (the 'safety crew') drove along the route at a distance of approximately 1 km from the subjects throughout the march. Two of the subjects were serving members of the British Army (Corps of Royal Engineers), whilst a third subject had former service with the Royal Signals. One of the remaining subjects was a very experienced explorer and also a qualified practitioner of medicine. The final subject was an extremely experienced adventurer, despite being almost completely blind (98% visual impairment).

2.2 The march

The 194km march commenced by the military 'border post' which separated Saudi Arabia from Qatar at 10:00hrs (local time) 02 April 2002 (this will be referred to as 'M') and was completed 78 hours later at 16:00hrs (local time) on 05 April 2002 (M+78 hours) at Ar Ruwais (a point where the mainland ends and is met by the Persian Gulf, see figure 1). The five subjects transported everything that they needed to complete the march by-hand and without the support of any other source. The provision of 50 litres of water per person, (providing a total of 250 litres of bottled water, contained within 125, 2-litres bottles) was transported within 2 portable handcarts (Charlie's Horse Ltd, USA) (one of the carts is shown in figure 1). Spare parts for the carts, food, protective clothing, a GPS navigation system, scientific monitoring equipment, and two sets of hiking poles (Makalu ultralite titanium air ergo PA AS Poles, LEKI™ Ltd) were contained within these carts. The total mass of the load that was transported by the subjects during the march was 320 kg. The carts were constructed from 6061-T6 aluminium and were fully anodised with all stainless steel components, and their wheels were fibreglass-reinforced nylon with 440 stainless steel sealed bearings (with 16" x 2" micro-cellular urethane (non-pneumatic) tyres). The carts were transported separately, with 2 subjects assigned to each, at any given point during the march. One subject wore a harness which was connected to the front of the cart in order to provide a forward propulsive force (pulling), whilst the second pushed the cart from a point at its rear using the handles provided. With only two subjects on each cart, this afforded the fifth subject a period of 'active rest' whilst navigating (using the hand held GPS system). Throughout the march, and at regular intervals each subject performed each role on a rotation basis (*ie* pulling the cart; pushing the cart; walking alongside the cart whilst navigating). A 45 minute work, 15 minute rest schedule had been planned for the march. It had initially been expected that the march would be completed in 60 hours (*ie* 4 km.hour^{-1} with a total period of 10 hours inactive rest).

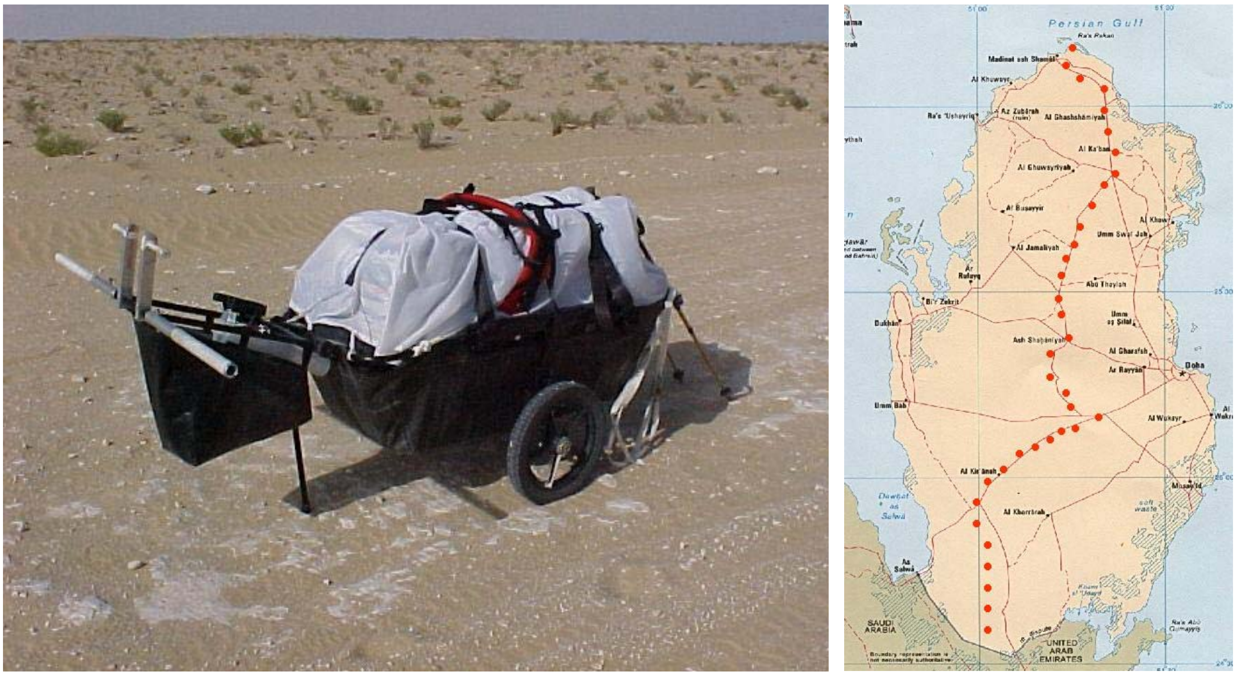

Figure 1: *(Left)* one of the carts that was used to transport the water and food during the march; *(right)* the route that was taken by the subjects in Qatar

A safety crew (composed of 2 men in 2 separate, air conditioned, 4 wheel-drive vehicles) accompanied the subjects at an agreed 1-km distance, and were under instruction not to provide any unsolicited assistance to any subject during the march. The role of the safety crew was to provide visual and documented record and confirmation (using dictaphones, video cameras and a diary) of progress made throughout the march, to provide urgent medical support in the event of a casualty, and to provide the necessary liaison with the interested authorities in Qatar (*ie* the military, event sponsors and the media).

2.3 Pre-deployment preparation

2.3.1 Energy cost of transporting the carts

The energy cost of pushing handcarts has been investigated by a number of researchers in the past [13]. However: (a) the type of cart that was used by the subjects during this march; (b) the diverse nature of the desert terrain in Qatar; and (c) the various methods by which the cart could be transported, demanded a direct assessment of the energy cost to be conducted.

Following a 6-day reconnaissance trip to Qatar (conducted during September 2001) the military training areas at Long Valley and Hawley, UK were identified as appropriate locations to assess the energy cost of transporting the carts (using similar loads, distributed as intended during the march, and over the type of terrain that was evident in Qatar). Unpublished tests to assess the energy cost of pulling and pushing the carts (whilst the carts were loaded to their 'march' weight) were conducted by each subject using a portable breath-by-breath analyser (Cosmed K4b^2 system, Cosmed®, Italy).

Table 1: Descriptive data for the subjects (obtained prior to the march)

Subject	**Age (years)**	**Height (metres)**	**Body mass (kg)**	**Body fat (%)**	**Total Body water (Litres)** (estimated [1])
1	35.0	1.67	74.0	12.8	45.8
2	48.0	1.67	75.0	18.7	45.5
3	32.0	1.85	90.5	17.0	51.4
4	54.0	1.80	82.0	20.0	45.7
5	40.0	1.75	84.0	20.5	42.9
Mean	**41.8**	**1.75**	**81.1**	**17.8**	**46.3**
1 standard deviation	*9.1*	*0.08*	*6.8*	*3.1*	*3.1*

2.3.2 Heat familiarisation (UK)

Four of the subjects completed an initial 2-hour phase in the environmental chamber (25 March 2002: 'M'-190 hours) at QinetiQ two days before they were deployed to Qatar in order to familiarise themselves with the heat (conditions in the chamber were intended to reflect those that had been reported for Qatar at that time, which was 40°C dry bulb temperature; 50% relative humidity, air speed 1m.s^{-1}). Subjects conducted 150W (external work) cycloergometry exercise over a 2 hour heat exposure within the chamber. Changes in body mass over this period were used to estimate sweat loss (table 2).

Table 2: Pre-deployment sweat rates for subjects (unacclimatised to the heat) at M-142 hours conducting 150W cycloergometry for 2 hours under conditions of 40°C dry bulb temperature and 50% relative humidity

Subject	Sweat rate (l.hour^{-1})
1	1.46
2	0.81
3	1.05
4	n/a
5	1.03
Mean	1.09
(1 standard deviation)	(0.27)

2.3.3 Heat acclimatisation (Qatar)

Subjects arrived in Qatar 6 days (142 hours) prior to the start of the march. A daily 2 hour training session with full equipment was conducted under the heat of the mid-day sun (the carts and clothing were used as intended during the march, and at operational tempo) up until the day of the march itself. Subjects

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[1] Total Body Water (TBW) was estimated using measurements of bioimpendance.

monitored their heart rate (using Polar® Vantage NV heart rate monitors, at a 5-second sample rate) during these submaximal training sessions in the heat.

No other measures of adaptation to the heat were made during this period. It was assumed that the subjects would acquire a sufficient degree of acclimatisation to the heat as a result of the daily training sessions. Time was a limiting factor and it was not possible (for practical reasons) to extend the period that was allowed for acclimatisation.

2.4 Measurements

2.3.4 Body mass (BM)

Seca heavy duty analogue floor scales (Seca Ltd, UK) were used to measure body mass. Subjects were weighed immediately before the start of the march, at the end of the march and at 6-hourly intervals throughout the march. The scales were transported by the safety crew.

2.3.5 Body composition

Single frequency bioimpedance (z) analysis (200kHz) was performed with tetrapolar distal limb surface electrodes on each subject using a Bodystat1500 system (Bodystat®, Douglas, Isle of Man) to estimate total body water and relative body fat (% of total body mass). Total body water was calculated as follows (equation 1):

Equation 1: $\text{TBW (litres)} = [(0.24517 \times \text{height}^2)/\text{impedance (200kHz)}] + (0.18782 \times \text{weight}) + 8.197$

These tests were conducted consecutively, before exercise, at least 2 hours after food, and after the bladder had been emptied. Subject's height, weight, date of birth were obtained prior to this test. Measurements were taken pre- and post- march (M-14 hours; and M+83 hours respectively).

2.3.6 Water intake

In order to record water intake in a practical and accurate way, subjects were required to drink water only from the 2-litre bottles that were transported in the carts. Bottles were marked by each subject for their own consumption. Subjects recorded the exact time when each of their allocated water bottles became empty. Those subjects who chose to use a portable 'bag' system from which they could drink water by means of a connecting tube (Camelbak® system, Petaluma, USA) ensured that they emptied the bag completely before re-filling it with another bottle of water. The time at which the bag was emptied following the use of a complete bottle of water, was recorded in the subject's diary.

2.3.7 Food consumed

All items of food that were consumed had been identified prior to the start of the march (each subject packed the food that they wanted to eat during the march in bags that were marked with their name and placed in the carts). Wherever possible at least one of the wrappers from the various food items had been obtained to enable the subsequent estimate of energy intake (Microdiet computer dietary analysis system, Salford University, UK). Subjects recorded the time and the food item that was consumed in their diary. When only part of a standard portion of the respective food item was consumed at a given time, the subject provided a subjective estimate of the quantity eaten.

2.3.8 Urine output

Each cart was equipped with a 1000 ml measuring cylinder (with 1 ml graduations). Subjects ensured that all urine passed during the march was measured using one of the tubes available and recorded in the diary together with the time of the void. The measuring tubes were suspended, inverted from a point close to the axle of each cart with the intention to ensure that any subsequent residue was lost as the cart was transported. The time of defecation was recorded in the subject's diary.

2.3.9 Physical activity (PA)

Two Actiwatch® -AW4 systems (Cambridge Neurotechnology Ltd., UK) were placed on each subject: (1) on the lateral aspect of the subject's right wrist; and (2) lateral aspect of the right ankle. These accelerometry-based systems were set to record movement throughout the march, at 2s epochs. Data were expressed in counts.min^{-1} and they described the number of movements recorded in the vertical (z) axis evident at the wrist and ankle. This enabled the degree of upper and lower body physical activity to be estimated. Periods of sustained inactivity were assumed to describe bouts of 'sleep'.

Subjects recorded in their diary the type of action that they conducted (*ie* rest, pull, push, or navigate) and the time at which they commenced each action. The safety crew provided time-matched, video confirmation of these records.

2.3.10 Distance travelled

The exact route that was taken by the subjects during the march was recorded using a Magellan® hand held global positioning system (GPS), model number 315. This was downloaded to a computer and the distance was calculated for the exact trail that was taken. Military personnel from the Qatar special forces provided an independent verification of the distance that was covered, based upon their recorded observations of the subjects' movements during the march.

2.3.11 Heart rate (HR)

Each subject wore a Polar® Vantage NV heart rate monitor that was set to sample data at 15-second intervals throughout the march. During pre-deployment tests at the QinetiQ laboratories in the UK, baseline data were obtained for resting heart rate. Maximum heart rate for each subject was accepted as the highest reported heart rate resulting from: (a) the pre-deployment training phases conducted at Long Valley and the military training area, Hawley, UK; or (b) 220 - subject age in years. It was possible to assess the relative cardiovascular strain of the march by using the heart rate reserve (HRreserve) method described by Karvonen (this is discussed in detail in [5] and [14]).

2.3.12 Gastrointestinal temperature (Tgi)

All subjects ingested a CorTemp© CT2000 temperature sensitive pill (referred to as a 'radio pill') approximately 2 hours prior to the start of the march and following an initial 'test' to check that the pill was functioning correctly. Transmissions from the radio pill were detected and interpreted using a CT2000 data logger system (HQ Inc., Palmetto, USA), reporting temperature (assumed to reflect deep body temperature) data every 10 seconds, as the radio pill passed along the gastrointestinal tract. These data were downloaded to a computer (using an RS232 to COM1 link) for subsequent analysis at the end of the march. Subjects ingested additional radio pills following each defecation throughout the march.

2.3.13 Environmental heat stress (WBGT)

The Wet Bulb Globe Temperature [2] (°C WBGT) was measured at 1-hour intervals throughout the march and logged using an Edale Instruments Ltd (Cambridge, UK) model PTH-1 data recorder. Data were also obtained from the Meteorological Office (MET Office, Defence and Aviation Climatology Branch,

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[2] WBGT = 0.7(wet bulb temperature) +0.2(150mm globe temperature) +0.1(air temperature)

Johnson House, UK) for a location near Doha, Qatar (25 degrees 15 minutes north, 51 degrees 33 minutes east and at 11.0 m elevation above sea level)).

2.5 Statistical methods

All data have been reported as mean (1 standard deviation). The students' paired t-test was performed (SPSS version 8.0, SPSS Inc., Chicago, USA) to compare pre- and post- march data. Statistical significance was accepted at the alpha = 0.05 level.

3.0 RESULTS

Four of the 5 subjects completed the march in 78-hours. The fifth subject suffered an injury during the march which required medical treatment, and was therefore unable to take any further part in the study. Physical activity was recorded during 74 of the 78 hours, during which the subjects tended to self-select a sustainable work-rate (mean relative intensity 57.8 (9) % of HRreserve). The remainder of this time (4 hours) was spent lying inactive, beside the carts on the desert terrain trying to sleep.

An estimated mean total of 46.0 (10.5) MJ was consumed (table 3) by each subject during the march. Mean total water intake (per subject) was 34.7 (6.4) litres, with only 2.9 (0.6) litres of urine excreted in this period. TBW increased by 0.3 (0.4) litres (range of 0.8 to 1.5%) compared with pre-march values ($p<0.05$). Mean Tgi was 38.1 (0.6) °C but occasionally it exceeded 39.3 °C. Estimated fat mass was found to decline ($p<0.05$) by 3.4 (1.0) kg, accounting for the loss in total body mass of 3.3 (1.6) kg.

Table 3: Results by 24-hour period throughout the march

	Day 1 **M to M+24** 10:00 (02 Apr) to 10:00 (03 Apr)	Day 2 **M+24 to M+48** 10:00 (03 Apr) to 10:00 (04 Apr)	Day 3 **M+48 to M+72** 10:00 (04 Apr) to 10:00 (05 Apr)	Day 4 **M+72 to M+78** 10:00 to 16:00 (05 Apr)	**Data to describe the entire march**
	mean (1 SD) [max, min]				**mean** (1 SD) [max, min]
Water intake (litres)	**14.2** (1.1) [15.6, 13.0]	**8.1** (2.5) [10.2, 4.5]	**10.4** (3.2) [13.2, 6.0]	**2.3** (0.9) [3.0, 1.5]	**34.7** (6.4) [40.8, 27.5]
Urine output (litres)	**0.8** (0.3) [1.1, 0.5]	**0.7** (0.2) [1.0, 0.6]	**1.3** (0.1) [1.4, 1.2]	**0.2** (0.06) [0.3, 0.1]	**2.9** (0.6) [3.6, 2.5]
Change in body mass (kg)	**-2.0** (1.7) [-4.5, -0.5]	**-1.1** (0.4) [-1.5, -0.5]	**0.2** (0.3) [0.5, 0.0]	**-0.4** (0.4) [-1.0, 0.0]	**-0.8** (1.7) [-4.5, -0.5]
Tgi (°C)	**37.9** (0.5) [39.1, 37.1]	**38.3** (0.4) [38.7, 37.8]	n/a	**38.6** (1.0) [40.1, 37.9]	**38.1** (0.6) [40.1, 37.1]
HRreserve (%)	**63.2** (6.9) [80.0, 51.0]	**54.4** (8.4) [67.7, 35.5]	**55.0** (9.6) [63.6, 24.7]	**48.6** (8.0) [58.5, 36.1]	**57.8** (9.3) [80.0, 24.7]
Energy intake (MJ)	**15.8** (4.3) [19.5, 10.8]	**9.7** (1.8) [11.8, 8.2]	**14.4** (5.8) [21.9, 9.2]	**0.3** (0.6) [1.3, 0.0]	**46.0** (10.5) [55.2, 30.8]
Distance travelled (km)	**36.0**	**40.0**	**80.0**	**38.0**	**194.0**
WBGT (°C)	**28.0** (0.7) [28.7, 27.1]	**25.9** (3.7) [28.9, 21.8]	**20.7** (1.3) [22.8, 19.1]	**22.9** (0.3) [23.1, 22.7]	**24.0** (3.6) [28.9, 19.1]
n	*5*	*4*	*4*	*4*	*4*

The pattern observed in the consumption of water, the excretion of urine, and relative cardiovascular strain is shown in figures 2 and 3. The mean environmental heat stress to which the subjects were exposed during the march was 24.0 (3.6) ^{o}C WBGT (table 3). However, figure 4 illustrates the pattern in WBGT data at 4-hourly intervals.

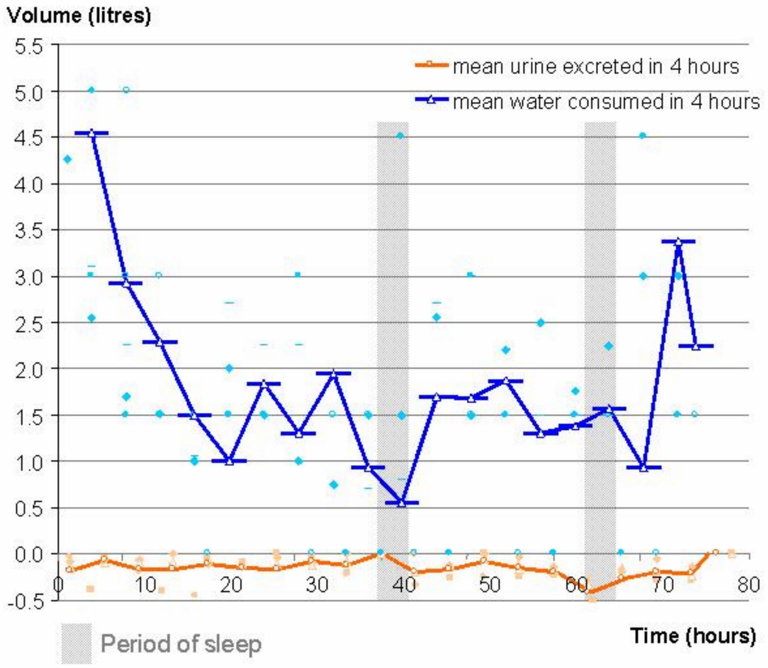

Figure 2: The volume of water that was consumed and urine excreted during the march. Data have been summed for every 4-hour period throughout the march and plotted for each subject (spheres that are connected by a solid line describe the group mean at the end of each 4-hour period)

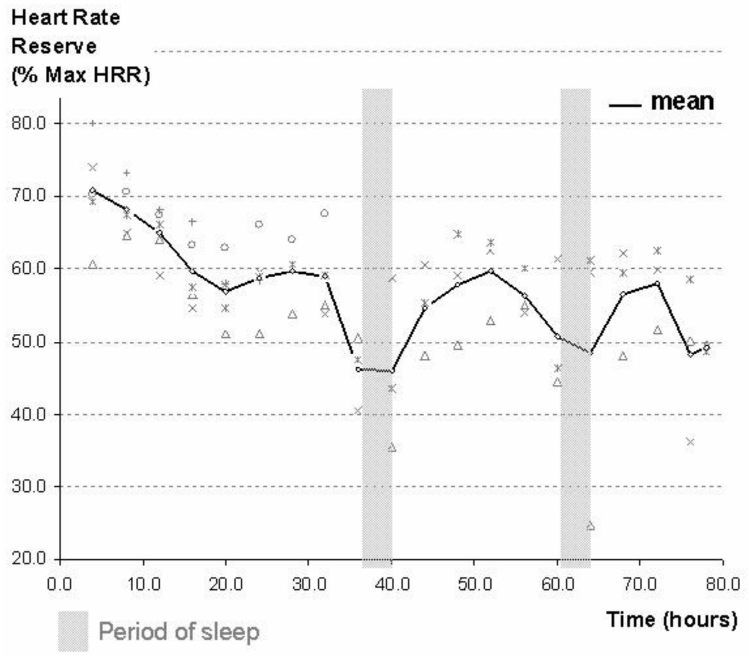

Figure 3: The relative cardiovascular strain during the march (as described by the HRreserve). Mean data for each 4-hour period have been plotted for each subject throughout the march. (spheres that are connected by a solid line describe the group mean data for each 4-hour period)

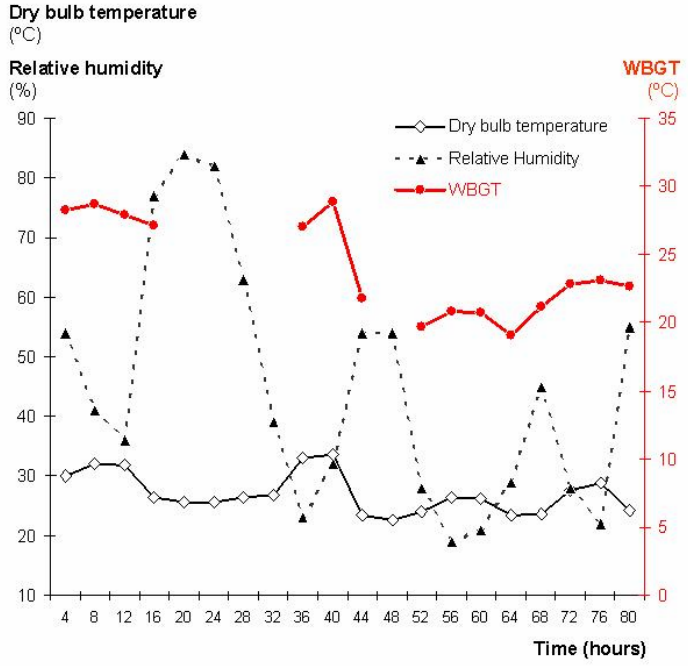

Figure 4: The environmental heat stress reported by the Meteorological Office (UK) for the desert area of northern Doha (Qatar) during the period of the march

4.0 DISCUSSION

4.1 Water policy

During the study, each subject was provided with 50 litres of water to consume *ad libitum*. The subjects ensured that this water allocation was used only for drinking and for no other purpose (*eg* pouring water over the head to attempt to cool the skin, maintaining personal hygiene or to clean equipment). At the end of the march, having consumed 34.7 (6.4) litres of water each, the total body water of the subjects was found to have increased above starting levels. In the absence of any further measurement to assess their hydration status this would suggest that the quantity of water that was consumed had in fact been sufficient to avoid any significant levels of dehydration (perhaps even to maintain or restore euhydration). The latest UK military guidelines suggest that for the conditions that were experienced in this study (mean 24.0 (3.6) ^{o}C WBGT) and the intensity of the work that was conducted (moderate to low intensity) each subject should have consumed water at a rate of approximately 0.5 litres.hour^{-1} (or a total of 37.0 litres of water for the 74 hours of physical activity [11.4 litres.person^{-1}.day^{-1}]). Previous UK military guidelines [1] had suggested that an upper limit of 12 litres of water per person per day should be provided for such a scenario. This study showed that four subjects were able to increase their total body water whilst consuming water at an approximate rate of 10.7 litres per person per day, during a prolonged desert march.

However, it was found (in general) that the rate at which water was consumed during the march, was not constant, but indeed reflected the apparent cardiovascular strain (as determined by the HRreserve). The march was essentially completed in two distinct phases: (a) the soft sand of the dunes; and (b) the harder surface of the rock paths (figure 5). The sand dunes (soft sand) occurred at the start of the march and the subjects were seen to work very hard in an attempt to transport the wheeled carts at this stage. The carts were at their heaviest as very little of the water cargo had been consumed at this stage, and the wheels of the carts often needed to be lifted out of the sand. Furthermore, the environmental heat stress apparent at this time was greater than at any other period during the march. Subjects appeared to self-select a work rate that was sustainable under such conditions (figure 3), and which has seemingly been established by other researchers as achievable for prolonged periods [15].

Figure 5: ***(left)*** **Negotiating the soft sand dunes with two separate carts during the first 32-km of the march;** ***(right)*** **In the latter stages of the march the terrain was much firmer under foot and the subjects chose to join the two carts in tandem.**

Initially, subjects added a carbohydrate-electrolyte powder ('High5 energysource', High5 Ltd, UK) to their water with a view to replacing the essential electrolytes that may be lost under conditions of high rates of sweat loss. This beverage had been used similarly during pre-study training sessions in the UK with good success, and optimal subject compliance (as they were considered to be highly palatable). However, during the initial phase of the march in the sand dunes, one subject reported that he actively stopped consuming water in response to the feeling of nausea which had followed the consumption of this beverage. It wasn't until he was able to work at a lower relative intensity, that he felt able to tolerate consuming plain water in the necessary quantities, supplemented with brief snacks of food items which contained high levels of salt and were savoury in flavour (*eg* peperami sausage sticks, and salted peanuts). Interestingly the food items that were consumed during the march included: High5 energy bars, salted peanuts, peperami sticks, yoghurt bars, Pringles™ potato chips, apricot flavoured pop-tarts and mixed fruit with plain nuts.

The greatest quantities of urine that were excreted during the march occurred in the latter stages of the second phase, when the terrain was perceived to be 'easier going', the work rate was moderate to low, and the environmental heat presented a lesser stress than had previous been observed. This increased excretion of urine occurred with a concomitant rise in the consumption of water (ingestion). Subjects reported a perceived inability to consume water at any greater rate than was evident at each stage during the march. They had ensured that they drank water at every opportunity and that they did not rely on the feeling of thirst to determine their need [16]. The observed loss in total body mass at the end of the march could be accounted for by the estimated loss in fat mass. Therefore, it was believed that the hydration status of the subjects had been maintained effectively on the water budget that was allocated.

Although it cannot be concluded as a finding of this study, it did appear that the total increase in heat strain was associated with a greater perceived intolerance of water and sweet-flavoured foods [3] [17]. It may be that the contribution to the total heat strain of the relatively high work rate in the early stages of the march, was one of the most important factors in determining the subjects' perceived intolerances.

4.2 Heat illness

On a number of occasions subjects felt that they required a rest as a consequence of their increased Tgi, or an opportunity to obtain shelter from the sun. Despite a brief and mild case of prickly heat in one subject during the early stages of the march, the incidence of symptoms of heat illness were few. However, at the end of the march, having successfully reached the end point, the condition of one of the subjects was found to deteriorate suddenly and quite rapidly. This subject was physically among the fittest, he had maintained a good sense of humour during the event, coping very well with the burden of the task before him, and was a very stable and strong character. At this point his Tgi had increased above 39.8 °C, and he reported feeling ‘cold’. Immediate action was taken by a fellow subject who had extensive medical experience, and intravenous fluids were administered (this explains why fewer than 4 data sets were available for bioimpedance analysis post-march) and cold water was poured over his head and body. His body was observed to commence mild convulsions prior to being evacuated by helicopter to the nearest military hospital. Fortunately this subject was treated in a very timely fashion and was released from hospital later that same evening.

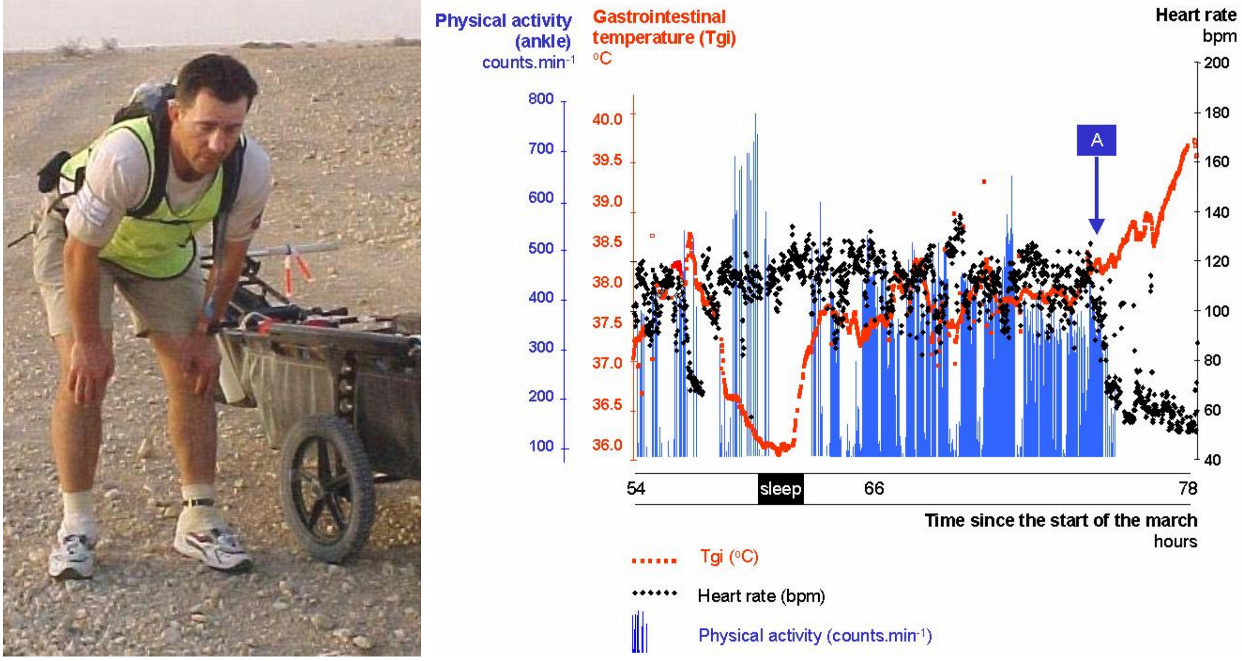

Figure 6: ***(left)*** **The onset of symptoms of heat illness occur in one of the subjects during the final 4 kilometres of the march;** ***(right)*** **Heart rate, Tgi and physical activity observed in this subject prior to, and following the onset of symptoms of heat illness (which occurred at ‘A’).**

Interviewing this subject subsequently, identified a number of early ‘warning signs of heat illness’ which had been evident during the march but which also appeared not to have been noticed by his fellow subjects at that time. In the last few hours of the march this subject reported feeling unwell, lethargic and heavy with fatigue. He had felt nauseous when consuming the carbohydrate-electrolyte beverage, and had decided to drink just plain water. He became quiet, withdrawn and less able to take the role of pulling the cart. At a point only a few kilometres from the end of the march (the end point was clearly visible to the subjects) this subject began to take regular rest stops which increased in duration. He was bent at the waist as he sought rest (figure 6), and in the last 2 kilometres he stopped drinking water (due to an increased feeling of nausea). This stage can be seen in figure 6 as the area on the curve where physical activity was very low (point ‘A’). Soon after this point the subject recognised that he was no longer evaporating sweat from his arms. He managed to reach the finish successfully, before becoming a casualty.

All of the subjects appeared to manage their levels of physical activity during the march in an attempt to regulate their own body temperature. The march was conducted in repeated bouts of low to moderate levels of physical activity (relative to maximum physical capability) often lasting less than 45 minutes. By rotating the role of each subject during the march it was possible to share the burden without unduly stressing anyone (this also complemented effective team dynamics and compliance at times when fatigue and sleep deprivation were perceived by the subjects to be very high). It was the aim of the subjects to work hard during the cooler, darkness hours of each night. However, it was not possible to sleep under the intense, unsheltered heat of the sun during the day, and so 2 brief 2-hour naps were used (providing a total of 4 hours sleep during the 78-hours of the march) as a strategy to alleviate the effects of fatigue. The temperature in the darkness hours (22:00 hours to 04:30 hours) was perceived to be ‘cold’, which was reflected by a dry-bulb temperature of approximately 18 ^{o}C. The example in figure 6 shows how the body’s autonomic control ensured that this subject did not become hypothermic when he took a nap in the final ‘sleep’ period before completing the march. The sustained heart rate at a time when this subject was physically inactive and lying on the ground could possibly be explained by the onset of shivering thermogenesis which avoided this subject’s body temperature (Tgi) falling below 36 ^{o}C.

5.0 CONCLUSION

Daily consumption of up to 11 litres of water per man was sufficient to maintain hydration (on the basis that total body water was increased at the end of the march when compared with pre-march levels) when working at up to 58%HRreserve during this prolonged, self-sufficient desert march. These data support the existing UK military guidelines for the provision of potable water [18].

Acknowledgement:
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Prediction and Validation of Warfighter Fluid Requirements

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Prediction and Validation of Fluid Requirements

Adequate hydration is essential for maintaining fighting effectiveness, and several common operational stresses can result in relatively large alterations in total water blood content and distribution. During most "normal" conditions, humans have little trouble maintaining optimal fluid balance. However, many factors such as sickness, physical exercise, climatic exposure (heat, cold, and altitude), and psychological strain can lead to significant disturbances in water balance. Both physical and cognitive performance is impaired proportionally to the magnitude of body water loss incurred, but even small losses of body water (1 – 2% of body mass) have a measurable detrimental impact on physical work. Conversely, excessive overdrinking can lead to a rare but potentially lethal condition termed symptomatic hyponatremia. Likewise, water transport currently is the second largest logistical source of power consumption on the battlefield. Valid and accurate fluid replacement algorithms are essential in optimizing soldier hydration during work and reducing the logistical burden on the battlefield. The U.S. military currently uses two algorithm/prediction models to predict sweating rates of soldiers. The U.S. Army Research Institute of Environmental Medicine (USARIEM) Heat Strain model is an empirical model that includes an equation to predict sweating rate during work. The second model, called Scenario, is a rational model designed to simulate the time course of heat strain observed during military, industrial and athletic settings. It is being included in robust military operational computer simulation software for use in planning and mission evaluation. The sweating rate algorithm currently used in the USARIEM heat strain model was developed from laboratory experiments for energy expenditures ranging from approximately 75W (rest) up to 475 W (moderate intensity work for a dismounted soldier) over a range of environmental conditions (20-54°C and 10-94% relative humidity) when wearing shorts and T-shirt, military fatigues and fatigues plus overgarment. The derived equation is shown below: Sweating rate = $27.9 \times E_{req} \times (E_{max})^{-0.455}$; $g \times m^{-2} \times h^{-1}$, where, E_{req} is the evaporation required to maintain heat balance, and E_{max} is the maximal evaporative capacity of the environment. This equation was originally validated when it was derived against existing published exercise-heat stress datasets collected in indoor environmental conditions. While the array of exercise and environmental conditions were covered, ongoing research is enhancing the capabilities of the USARIEM Heat Strain and Scenario Models. As prediction of water requirements is essential for more than just missions in hot climates, the algorithm is being extended to accurately predict sweating rates in temperate and cool environment as well as with load carriage and body armor.

Paper presented at the RTO HFM Specialists' Meeting on "Maintaining Hydration: Issues, Guidelines, and Delivery", held in Boston, United States, 10-11 December 2003, and published in RTO-MP-HFM-086.

Introduction

Adequate hydration is essential for maintaining fighting effectiveness, and several common operational stresses can result in relatively large alterations in total water blood (TBW) content and distribution. During most "normal" conditions, humans have little trouble maintaining optimal fluid balance. However, many factors such as sickness, physical exercise, climatic exposure (heat, cold, and altitude), and psychological strain can lead to significant disturbances in water balance (3). Perhaps the best example involves heat stress and physical activity. For sedentary persons in temperate conditions, water requirements usually range from 2 to 4 L per day, and the kidneys primarily regulate fluid balance. For physically active persons who are exposed to heat stress, water requirements can often double (4). Both physical and cognitive performance are impaired proportionally to the magnitude of body water loss incurred (5), but even small losses of body water (1 – 2% of body mass) have a measurable detrimental impact on physical work and negatively impact thermoregulation (6).

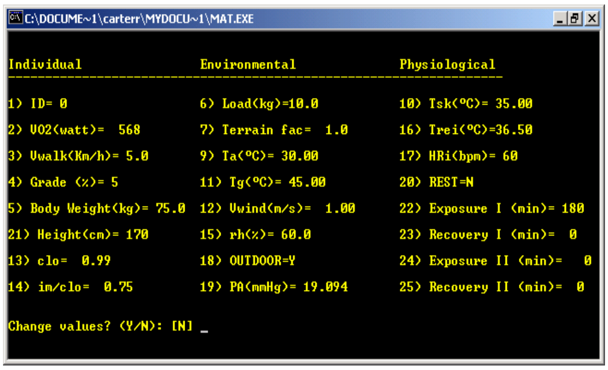
Army Transformation is the process that is taking the Army from where it was in the late 1990s to the Objective Force by 2015. Transformation is designed to take advantage of opportunities presented by emerging technologies and changes in the Army's mission. The Future Force is the ultimate result of transformation, which will enable our Army to deploy with the speed of our current light forces, but with the combat strength of our heavy forces. Fuel, water, and ammunition are major energy consumers and are logistically challenging transport on the battlefield. Reducing consumption of energy required transport water and fuel, lessening the logistical footprint, and enhancing sustainability are key objectives in the transformation process. Presented in Table 1 are the estimated costs of producing and transporting water by various means of transportation. For instance, the one-way cost of transporting water short distances grossly increases the energy required to achieve the task. For that reason, accurate estimation of water is essential to meet the challenges the Objective Force.

TABLE 1. Energy Cost To Transport Water

Means of transport	**1-way transport cost (watt-h per liter-mile)**
Bell 206LR/3	18
Bell 212 helicopter	21.8
Mil M126 helicopter	13.9
Mil 17c helicopter	10.5
Sikorsky S64	16.5
5-ton truck	0.97

Background

The United States Military currently uses two models to predict sweating rates of soldiers during various military scenarios. The first and most often used model is the U.S. Army Research Institute of Environmental Medicine (USARIEM) Heat Strain model. The USARIEM Heat Strain Model was developed using empirically derived equations to predict physiological responses of persons during heat exposure. The USARIEM model is composed of individual predictive equations for rectal temperature, heart rate, and sweat loss (8). Input required for model prediction includes energy expenditure, environmental conditions, and clothing ensemble. Further modifying factors, which have been included in refining the model, are state of heat acclimation, solar load, cardio respiratory fitness, gender, and hydration state. This final equilibrium core temperature may be outside human physiological limits in extreme environments. Using interpolation algorithms, these equations also allow the model to predict core temperature at any given time during exercise prior to reaching the equilibrium core temperature. The second model, called Scenario, is a rational model designed to simulate the time course of heat strain observed during military, industrial and athletic settings. It is being included in robust military operational computer simulation software for use in planning and mission evaluation. The USARIEM Heat Strain Model in combination with the Scenario model is able to provide the most accurate predictions of sweat rate and physiological responses to physical work during most environmental conditions encountered by the American warfighter. These models are the most comprehensive of this type in the world. Ongoing studies at USARIEM are improving the validity and accuracy of the sweat losses predicted by these models. In particular, research effects continue to focus on improving the prediction of sweat rate and physiological responses to long duration physical work, which have not received as much attention (7). While, existing data have been restricted to relatively short duration (2-3 h) exposures, as limited databases exist for thermoregulatory and cardiovascular responses during multiple hours of work.



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C:\DOCUME~1\carterr\MYDOCU~1\MAT.EXE

Individual                Environmental            Physiological
---------------------------------------------------------------------
1) ID= 0                  6) Load(kg)=10.0         10) Tsk(ºC)= 35.00
2) VO2(watt)=  568        7) Terrain fac=  1.0     16) Trei(ºC)=36.50
3) Vwalk(Km/h)= 5.0       9) Ta(ºC)= 30.00         17) HRi(bpm)= 60
4) Grade (%)= 5           11) Tg(ºC)= 45.00        20) REST=N
5) Body Weight(kg)= 75.0  12) Vwind(m/s)=  1.00    22) Exposure I (min)= 180
21) Height(cm)= 170       15) rh(%)= 60.0          23) Recovery I (min)=  0
13) clo=  0.99            18) OUTDOOR=Y            24) Exposure II (min)=   0
14) im/clo=  0.75         19) PA(mmHg)= 19.094     25) Recovery II (min)=  0

Change values? (Y/N): [N] _
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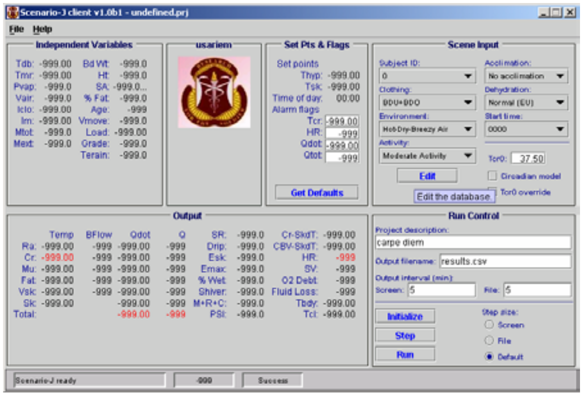
Figure 1. The USARIEM Heat Strain Model. As depicted, individual and environmental factors are manipulated to predict physiological variables and sweat loss.



Tdb: -999.00
Tmr: -999.00
Pvap: -999.0
Vair: -999.0
Iclo: -999.00
Im: -999.00
Mtot: -999.0
Mext: -999.0
Bd Wt: -999.0
Ht: -999.0
SA: -999.0...
% Fat: -999.0
Age: -999
Vmove: -999.0
Load: -999.00
Grade: -999.0
Terain: -999.0

Set points
Thyp: -999.00
Tsk: -999.00
Time of day: 00.00
Alarm flags
Tcr: -999.00
HR: -999
Qdot: -999.00
Qtot: -999

Subject ID: 0
Acclimation: No acclimation
Clothing: BDU+BDO
Dehydration: Normal (EU)
Environment: Hot-Dry-Breezy Air
Start time: 0000
Activity: Moderate Activity
Tcr0: 37.50
☐ Circadian model
☐ Tcr0 override

	Temp	BFlow	Qdot	Q
Ra:	-999.00	-999	-999.00	-999
Cr:	-999.00	-999	-999.00	-999
Mu:	-999.00	-999	-999.00	-999
Fat:	-999.00	-999	-999.00	-999
Vsk:	-999.00	-999	-999.00	-999
Sk:	-999.00		-999.00	-999
Total:			-999.00	-999

SR: -999.0
Drip: -999.0
Esk: -999.0
Emax: -999.0
% Wet: -999.0
Shiver: -999.0
M+R+C: -999.0
PSI: -999.0
Cr-SkdT: -999.00
CBV-SkdT: -999.00
HR: -999
SV: -999
O2 Debt: -999
Fluid Loss: -999
Tbdy: -999.00
Tcl: -999.00

Project description: carpe diem
Output filename: results.csv
Output interval (min):
Screen: 5
File: 5
Step size:
○ Screen
○ File
● Default

Scenario-J ready
-999
Success

Scenario

Figure 2. A Microsoft Windows-based interactive thermoregulatory model useful for prediction of cardiovascular, thermal, and environmental responses over wide activity rates and clothing systems.

The U.S. military revised the recommended hourly fluid consumption guidelines during work in hot weather (1), due an increase incidence of exertional hyponatremia cases (2). As part of the revision process, predicted sweating rates derived from the sweating rate algorithm were validated with laboratory experiments. Figure 3 presents the daily water requirements predicted by the USARIEM Heat Strain Model for variety of work intensities and weather conditions. It is known that dismounted soldiers performing mission responsibilities commonly have energy expenditures of ~4,500 kcal/day. If this work was performed in ambient conditions approximating 30°C wet bulb globe temperature (WBGT), the model would predict a daily water requirement of ~12-13 quarts/day. If actual water needs were actually 25% less than predicted, then only be 9-10 quarts per day would be required. Ongoing investigation laboratory and field studies are being done to clarify how accurately the USARIEM Heat Strain Model and the Scenario model predict the daily water needs of soldiers over a wide variety of operational conditions.

The sweating rate algorithm currently used in the USARIEM heat strain model was developed from laboratory experiments for energy expenditures ranging from approximately 75W (rest) up to 475 W (moderate intensity work for a dismounted soldier) over a range of environmental conditions (20-54°C and 10-94% relative humidity) when wearing shorts and T-shirt, military fatigues and fatigues plus overgarment. The derived equation is shown below: Sweating rate $= 27.9 \times E_{req} \times (E_{max})^{-0.455}$; $g \times m^{-2} \times h^{-1}$, where, E_{req} is the evaporation required to maintain heat balance, and E_{max} is the maximal evaporative capacity of the environment. This equation was originally validated when it was derived against existing published exercise-heat stress datasets collected in indoor environmental conditions.

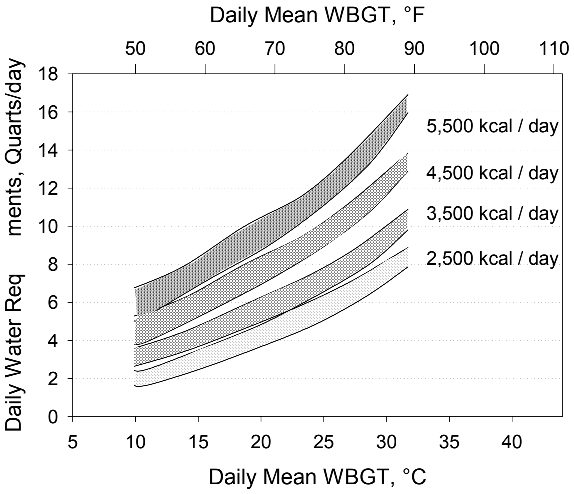


Figure 3. Predicted daily water requirements for soldier wearing BDU by daily energy expenditure. Data derived using the USARIEM Heat Strain Model.

While the array of exercise and environmental conditions were covered, research continues to focus of improving predictions of sweat rate and physiological responses during exercise in temperate or warm environments. Likewise, dismounted soldiers frequently work at metabolic rates beyond those previously included in the equation development. As prediction of water requirements is essential especially during intense, physically challenging missions, the algorithm is being enhanced to better predict sweating rates during most operational conditions encountered by today's soldiers.

Conclusion and Future Studies

Future and ongoing studies are extending the predictive capabilities of the sweating and physiological algorithms and validating that the models can accurately predict sweat losses for most militarily relevant scenarios. Accurate estimates of soldier water needs will continue to enhance the safety, increase sustainability of the soldier, and improve the efficiency of re-supply. The USARIEM and Scenario models are being used in the personal status-monitoring component of the Objective Force Warrior plan for mission planning, personal soldier assessment, and combat casualty care.

The views, opinions, and/or findings contained in this publication are those of the authors and should not be constructed as an official Department of the Army position, policy, or decision unless so designated by other documentation.

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Hydration in Cold Environments

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Abstract

Current guidelines for fluid intake in cold environments simply emphasize the importance of maintaining hydration. Fluid requirements associated with increased metabolic cost of working in winter terrain should be similar to the requirements in neutral environments, assuming individuals are appropriately clothed to avoid body cooling. Direct effects of cold on hydration status appear to be limited to blunted thirst sensation and cold-induced diuresis, both of which contribute to reduced total body water during cold exposure. Soldiers working in cold environments typically dehydrate by 2.5% body weight or more. In a hot environment this degree of hypohydration would decrease cognitive and physical performance and increase risk of heat injury. Hypohydration has been suggested to increase risk of hypothermia and peripheral cold injury, yet little evidence for this exists.

Our laboratory recently completed two studies examining the effect of mild (4%) hypohydration on thermoregulation during cold exposure. The first study compared responses to 120-min whole-body cold air exposure (7ºC) during euhydration (EU), hypertonic hypohydration (HH) and isotonic hypohydration (IH). The hypertonic hypohydration was elicited by exercise in the heat, resulting in sweat losses which were not replaced with fluid intake. The isotonic hypohydration was elicited by using furosemide to induce an isosmotic diuresis. Mean skin temperature fell during all three trials, but plateaued after 90 min during HH and IH, and final mean skin temperature was higher on HH (23.5±0.3ºC) than EU (22.6±0.4ºC) or IH (22.9±0.3ºC). Heat debt (349±14) did not differ among trials. These data suggest weaker vasoconstrictor tone on HH, perhaps resulting from the higher plasma osmolality on that trial (292±1 mosmol/kgH_2O), compared to IH (284±1 mosmol/kgH_2O) or EU (280±1 mosmol/kgH_2O). Hypohydration did not affect body heat balance during 2-h whole-body cold exposure; however, blunted vasoconstriction due to hypertonicity could become important during a more severe cold exposure.

The second study examined peripheral skin temperature response to cold during euhydration (EU) and hypertonic hypohydration (HH). Skin temperature and blood flow were measured during a 30-min cold water (4ºC) finger immersion. Prior to cold-water immersion, a 15 min warm water (42ºC) immersion was used to elicit peak blood flow and to standardize finger temperature before the cold water immersion. Blood flow decreased similarly during both trials (33±11% of peak). Mean nailbed (7.3±1.2ºC) and pad (12.0±1.9ºC) skin temperatures were similar on both trials. Cold-induced vasodilation (CIVD) parameters (e.g., nadir, onset time, apex) were similar between trials. These data provide no evidence that hypohydration alters finger blood flow, skin temperatures, or CIVD during peripheral cooling.

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The results of these studies provide no support for the suggestion that hypohydration per se increases susceptibility to either hypothermia or peripheral cold injury such as frostbite. How hypohydration may affect cognitive or physical performance in the cold needs further investigation.

INTRODUCTION

Fluid balance in cold environments is influenced by increased fluid losses due to cold-induced diuresis and increased respiratory losses in dry air, as well as reduced fluid intake due to blunted thirst and inadequate availability of water. Higher metabolic costs associated with working in mountainous terrain will increase fluid requirements similarly in cold environments as in neutral environments, assuming individuals are appropriately clothed to avoid body cooling. Soldiers working in cold environments typically dehydrate by 2-3% body weight (4), which can largely be attributed to the diuresis that occurs upon initial cold exposure. Increased fluid intake will not offset this diuresis as it only results in greater diuresis (11); however, further dehydration may not occur if fluid intake is adequate (7).

In hot environments this degree of hypohydration increases the risk of heat injury and degrades both cognitive and physical performance (12). Although hypohydration has been suggested to be a predisposing factor for both hypothermia and frostbite, little evidence for this exists. While hypohydration is often noted in victims of cold injury, it may be that the hypohydration is coincident with the circumstances leading to hypothermia or frostbite, rather than a being a causative or contributing factor. Our laboratory recently conducted two studies which examined the effect of hypohydration on thermoregulatory responses to cold during whole-body and peripheral cold exposure. The aim of these studies was to evaluate the effect of hypohydration on vasoconstriction and shivering thermogenesis during cold exposure.

METHODS

Study I, Reference (6)

Introduction Some factors contributing to hypohydration in cold environments cause greater water than solute losses, e.g., sweating due to high work rates, increased respiratory water loss, or insufficient water intake. This results in a hypertonic hypohydration (HH) which was elicited in the present study through a combination of exercise in the heat and limited fluid intake. Cold-induced diuresis causes proportional water and solute losses, resulting in an isotonic hypohydration (IH), which was induced in the present study with furosemide. Using two methods of dehydration allowed us to separately evaluate the effects of hypovolemia and hypertonicity on thermoregulation during cold air exposure.

Protocol Nine men completed three trials: one euhydrated (EU), one during HH, and one during IH. The dehydration procedures were conducted the day before the cold exposure, and target body weight loss was 4-5%. Briefly, for HH subjects completed 3-4 h of intermittent exercise in the heat (40ºC, 20% RH) to induce sweating, and fluid replacement was restricted. For IH, subjects took 40 mg furosemide two or three times during the day to induce an isosmotic diuresis. Subjects were then given a light supper with fluid intake restricted to maintain their body weight loss.

Each experimental trial consisted of 30-min rest in temperate (25ºC) air, followed by 120-min rest in cold (4ºC) air. Subjects arrived at 0700 h after fasting overnight. After body weight was measured, they were instrumented with esophageal and skin thermocouples (chest, upper arm, forehead, back, hand, forearm, thigh, calf and finger), an intravenous catheter, and electrocardiogram (ECG) electrodes. A blood sample was obtained at the end of the temperate period and again at the end of cold exposure, and urine was collected at these same time points.

Results Body weight loss was similar (P>0.05) for HH (4.9±0.2%) and IH (4.3±0.2%). At the end of cold exposure, plasma volume was lower on IH (2.37±0.2 liters) than on EU (2.8±0.1 liters) or HH (2.7±0.1 liters), and plasma osmolality was higher on HH (293±2 mmol/kgH_2O) than on EU (283±2 mmol/kgH_2O) or IH (288±3 mmol/kgH_2O). Urine flow rate was higher during cold exposure than during baseline for EU (2.70±0.54 vs 0.76±0.17 ml/min), but not for HH (0.27±0.05 vs 0.55±0.04 ml/min) or IH (0.28±0.08 vs 0.45±0.12 ml/min).

There was no main effect difference in esophageal temperature, but an interaction effect indicates that Tes began to plateau after 60 min of cold exposure during HH (Fig. 1). There were no differences between trials in the fall in Tsk; however when only cold exposure is analyzed, a significant interaction shows that Tsk began to plateau after 90 min during both hypohydration trials, whereas it continued to fall during EU (Fig. 2). Metabolic rate was higher during cold exposure than during baseline (113.6±4.2 W/m^2 vs 36.5±1.4 W/m^2), but did not differ among trials.

Discussion The two different methods of dehydration used in this study allowed investigation of the independent influences of hypertonicity (elicited during HH) and hypovolemia (elicited during IH) on thermoregulation during cold exposure. Cold-induced diuresis was less during hypohydration, compared to euhydration, confirming the self-limiting nature of this diuresis response. Hypohydration did not alter the metabolic response to cold, nor did body temperatures fall more than during euhydration. The data does suggest that hypohydration may impair the vasoconstrictor response to cold, since skin temperature continued to fall during the entire cold exposure during EU, whereas during both hypohydration trials skin temperature showed a plateau during the last 30 min in the cold. Thus, although hypohydration did not accelerate the decline in core temperature in these experiments, this may not be the case over longer, more severe cold exposures, since blunted vasoconstriction would facilitate heat loss.

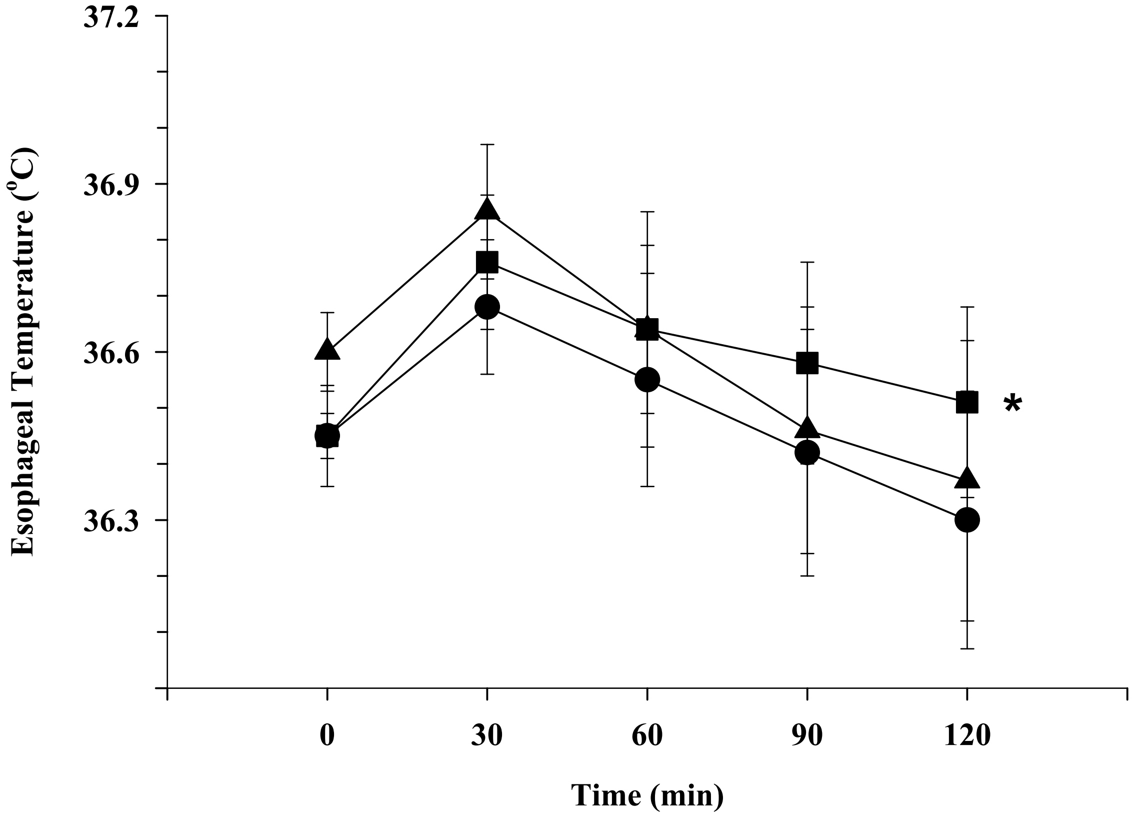

Figure 1: . Effect of cold exposure on esophageal temperature (mean ± SE) during EU (●), HH (■) and IH (▲). There was no main effect between trials ($P>0.05$). * Interaction effect showed a plateau during HH after 60 min, whereas esophageal temperature continued to fall during both EU and IH; ($P<0.05$)

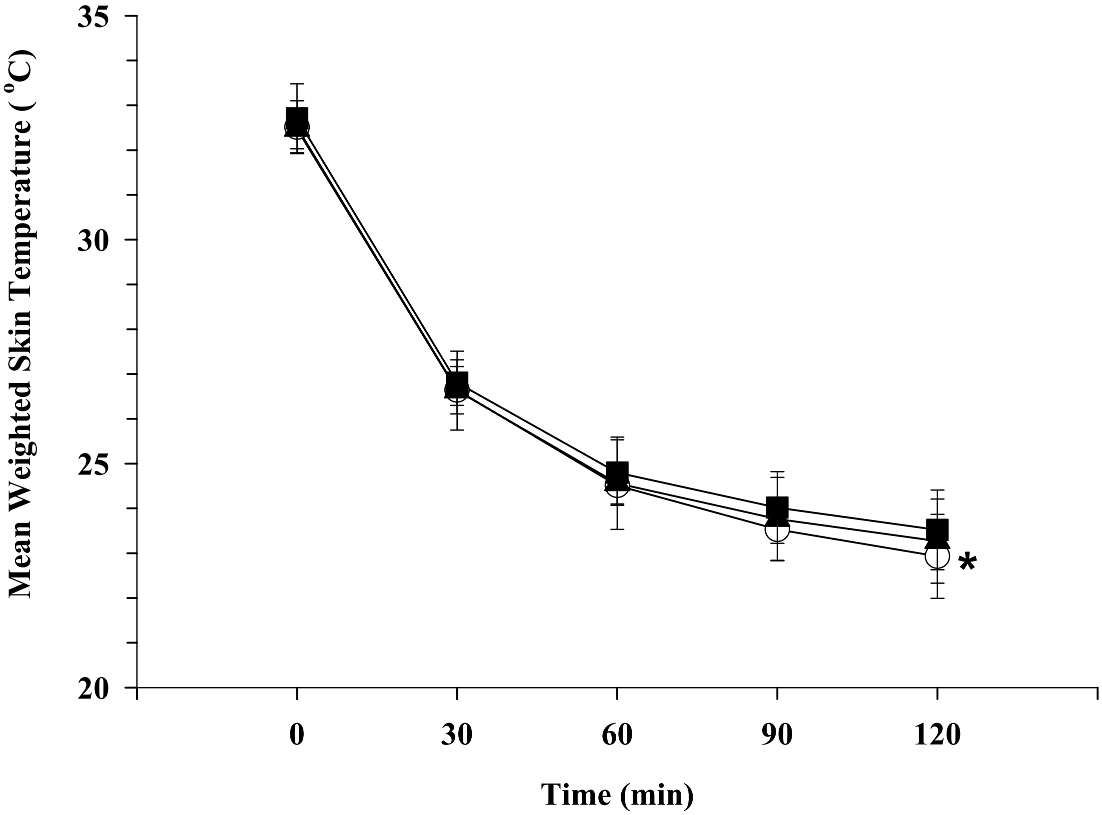

Figure 2: Effect of cold exposure on mean weighted skin temperature (mean ± SE) during EU (○), HH (■) and IH (▲). There was no main effect between trials (P>0.05). When only cold-exposure values were analyzed, an interaction effect showed a plateau during both hypohydraton trials after 90 min. * mean skin temperature continued to decrease during EU; P<0.05.

Study II, Reference (5)

Introduction An interesting and unexpected finding in the preceding study was that subjects maintained warmer skin temperatures during the hypohydration trials, compared to euhydration. Such a response would not support a role for hypohydration to contribute to peripheral cold injury. The limited research that has examined the influence of hypohydration on finger skin temperatures during cold exposure has not been conclusive, therefore further study was merited. The present study examined blood flow and skin temperature responses to cold-water immersion of a single finger. During this immersion, subjects rested in a thermoneutral environment, therefore it was expected that skin temperature would be no lower when subjects were hypohydrated, compared to euhydrated.

Methods Fourteen subjects (12 men, 2 women) completed two trials: one euhydrated, and one hypohydrated by 4% body weight. Hypohydration was induced through three 50-min bouts of moderate-intensity exercise (10 min rest) in the heat (38ºC, 30% RH) with restricted fluid intake. For the euhydration trial, subjects completed the same exercise, but with fluid replacement sufficient to restore their body weight. Subjects rested for ~3 h between the end of the exercise and the beginning of the cold-water finger immersion test, which was intended to provide adequate time for their core temperatures to return to resting levels after being elevated during exercise.

Cold-water finger immersion Subjects sat semi-supine in a thermoneutral environment for this procedure. The middle finger was immersed first in 42ºC water to establish a consistent baseline temperature and to elicit a peak blood flow for comparison of blood flow changes during cold-water immersion. After 15 min, the finger was transferred to cold water (4ºC) for 30 min. Core, mean skin, finger nailbed and pad temperatures were measured. Skin blood flow was also measured on the finger pad.

Results There were no differences in finger skin temperatures or blood flow between the two trials, with the exception of the nadir temperature during cold-water immersion which was higher during hypohydration (10.4±3.8ºC) than euhydration (7.9±1.6ºC). However, six subjects had higher core temperatures on the hypohydration trial because of inadequate recovery time from exercise. A higher core temperature is associated with higher finger blood flow, therefore the elevated core temperature is a confounding factor. When data on subjects with no difference in core temperature were examined, the difference in nadir temperature disappeared and responses in finger skin temperature and blood flow were similar during euhydration and hypohydration (Fig. 3).

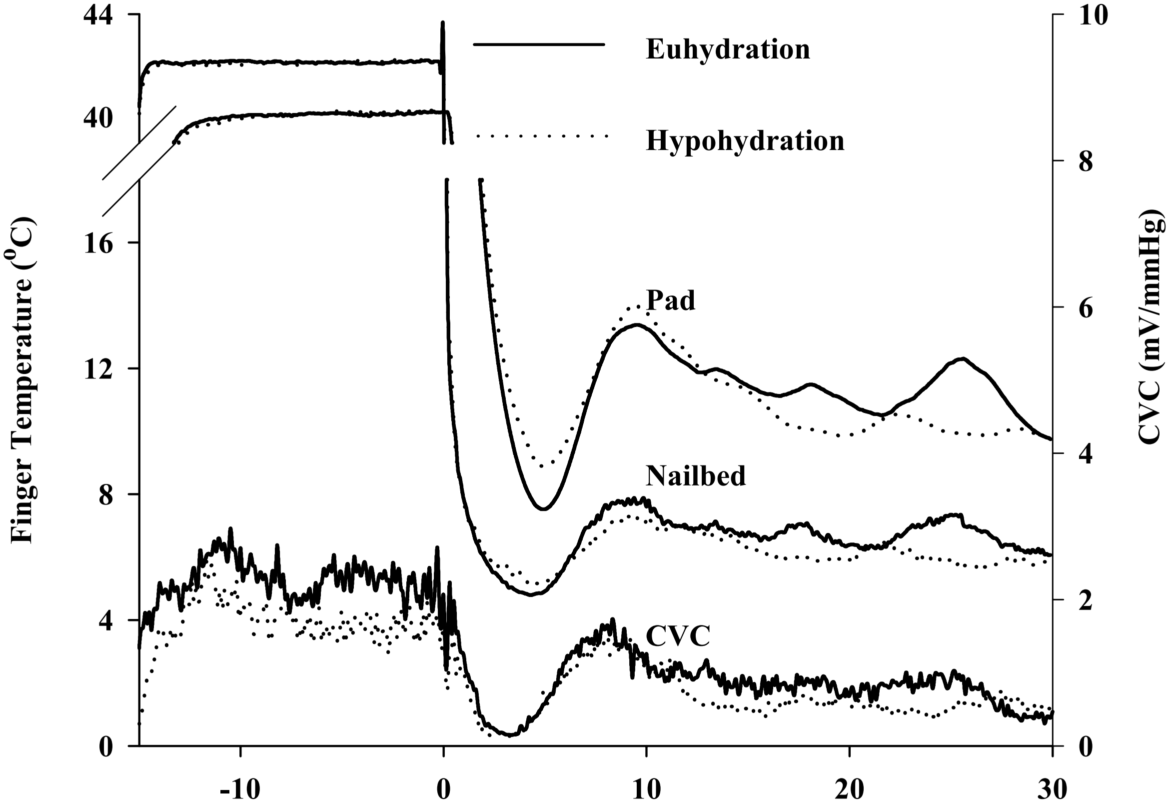

Figure 3. Finger nail bed and pad temperatures and cutaneous vascular conductance (CVC) for 15-min warm water (42ºC) and 30-min cold water (4ºC) immersion during euhydration and hypohydration.

Discussion The results of this study provide no evidence that hypohydration decreases finger skin temperature or blood flow during cold exposure, suggesting that it would not directly increase susceptibility to cold injury. Plasma volume is typically well defended during dehydration through exercise, the method used in this study. Hypohydration induced by diuresis, by decreasing plasma volume, may have a different affect on finger skin temperatures, although there was no evidence for this in our previous study, Study I (6), where skin temperatures at the end of cold exposure were lowest during euhydration.

Performance

In hot environments hypohydration is associated with decreased cognitive and physical performance (12); however, few studies have examined the effect of hypohydration on performance in the cold. Rintamäki (8) reported a decrease in submaximal performance in the cold in subjects who were hypohydrated (-3% body weight), compared to a euhydrated control group, which was attributed to decreased efficiency and earlier onset of fatigue (decreased time to exhaustion). No differences were observed in maximal physical performance tasks (8). Banderet et al. found hypohydrated subjects (-2% body weight) had impaired cognitive performance in temperate conditions compared to a euhydrated control group, but this difference did not persist during cold exposure (1).

High intensity exercise (>70% of maximum) is known to decrease urine production (13); therefore, exercising upon cold exposure may limit the diuresis that would otherwise occur, and could thereby reduce hypohydration. This may explain why Roberts et al. (9) showed no diuresis in euhydrated subjects during several days living in a cold environment, since their subjects were physically active during much of the exposure. Whether such a strategy could be used to limit hypohydration and reduce performance decrements that might otherwise occur in the cold is not known. Further research is needed to fully understand the interaction between hypohydration and performance in cold environments.

Conclusions

To maintain health and performance in the cold, adequate fluid intake must be encouraged. Although blunted thirst and cold-induced diuresis contribute to an initial hypohydration, this can be limited as long as individuals have access to water. The modest hypohydration that occurs, 2-3% of body weight, does not adversely impact thermoregulation in the cold, although there is some evidence that submaximal physical performance may be diminished. The biggest challenge for maintaining hydration in the cold is therefore logistical, due to difficult water delivery over snow, ice, and mountainous terrain and the large fuel requirements if frozen water supplies are used (2). Once access to water is established, ad libitum intake will likely meet hydration needs in cold environments, assuming individuals are given the opportunity to eat and drink (3).

The views, opinions and/or findings contained in this publication are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation. The investigators have adhered to the policies for the protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 45 CFR Part 46.

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Force Health Protection Issues Related to Water Management: Operation Iraqi Freedom and Beyond

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Hands Free Hydration Systems: A Practical Solution to Dehydration and Heat Stress

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Summary

The management of heat stress is of primary concern to the military because heat stress can significantly affect individual performance. The most effective defense against heat stress in a tactical environment is proper hydration of military personnel, and the Hands Free Hydration System has been field proven as an effective tool to hydrate the soldier on the move. Real world combat operations and formal field trials have consistently validated the effectiveness of the Hands Free Hydration System as a personal water delivery system. To be truly effective in every combat environment, including NBC warfare, a tactical hydration system must be durable, easy to use, easy to maintain, modular in design, and capable of integration with the soldier's equipment.

Management of Heat Stress in Military Operations

Minimizing heat stress casualties during training and on the battlefield has always been a priority for military leaders. Today's military professionals are especially concerned about dehydration and heat stress. The extreme heat of desert battlefield conditions, concerns over safety, and a greater understanding of the effects of dehydration and heat stress have led to an broader interpretation of heat stress management. Furthermore, lessons learned from recent conflicts in Iraq, Afghanistan, and Africa have demonstrated the importance and the complexity of preventing heat casualties for troops under extreme conditions.

There is a wide range of unproductive and dangerous side effects from heat stress and dehydration on the battlefield, all of which can negatively affect at-risk personnel operating in extreme environments. Generally, military personnel suffering from heat stress and dehydration are more apt to feel physical discomfort, possess low morale, and perform below their capabilities. Research conducted for the National Safety Council[i] indicates that the effect of heat stress can include an increase in accidents and injuries due to decreased dexterity and alertness. Unsafe actions and work-related mistakes in two industrial plants were counted over a period of time and compared to the corresponding temperatures of the work areas. Data from this study clearly revealed a relationship between thermal conditions and unsafe work behavior. As the temperature rose, so did the number of potentially harmful mistakes. For example a temperature change from 66 F to 95 F resulted in an increase in mistakes of from 50 to 100 %. Furthermore this study concluded that the longer personnel are exposed to heat, the more safety diminishes.

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The inability to escape heat and humidity is a pervasive problem for the military. Hardworking military personnel, from front line forces to rear echelon support personnel, are exposed to hot, humid environments throughout the year and throughout the world. Ultimately if military leaders do not take preventative measures and fail to respond to the initial indications of heat casualties, the serious health effects of dehydration and heat stress can include extreme discomfort, nausea, unconsciousness, and, ultimately, death.

Solving the Heat Stress Problem in the Field

Even though dehydration and heat stress are complex problems, there are a number of ways military leaders can protect the troops under their command. Preventative measures that can help to combat dehydration and heat stress include the following:

- Acclimatizing personnel to the heat
- Increasing rest period frequency and length
- Scheduling heavy work for cooler parts of the day
- Wearing lightweight, loose-fitting, light-colored clothes
- Adding ventilation or spot cooling to high-heat areas
- Training personnel to recognize and treat heat stress symptoms
- Keeping personnel hydrated

Due to the mobile nature of tactical operations, it may be extremely difficult for military professionals to practice many of these preventive measures. Clearly the fast-paced, arduous nature of military operations often renders specific measures, such as increasing rest periods or spot cooling, impractical. Keeping personnel hydrated, however, is one preventative measure that must always be successfully achieved. As such, ensuring personnel stay well hydrated is the key to combating the harmful effects of dehydration and heat stress in the field. Providing a clean source of water for troops while on the move is the single most effective way for military leaders to combat dehydration and heat stress.

The Physiology of Hydration

Staying hydrated ensures that the body has enough water available to use its natural defenses against heat stress. Water does two critical things. First, water helps cool the body, keeping it operating at its peak, without overheating. Secondly, water acts as the primary ingredient in the blood stream, carrying oxygen and nutrients to the brain and muscles.

At rest and during work, the human body tries to maintain an internal temperature of 98.6 F. In moderate temperatures and with low physical activity, the body is easily able to maintain a temperature of 98.6 F. Hot weather and heat sources such as engines or machinery make it harder for the body to maintain its preferred temperature. To shed this heat, blood transfers heat from the body's core to the skin's surface where excess body heat dissipates to the cooler environment.

Regardless of ambient temperature, hard working muscles can generate 8-10 times the heat they do when a person is at rest. The body must eliminate excess heat to keep its internal temperature within safe limits. If the circulatory system's rate of heat transfer to the ambient air is insufficient, the body starts sweating, and the evaporation of sweat on the skin's surface aids in the cooling process. If performing heavy work, the body can lose 1-2 liters of water per hour through heat reduction and sweating. If a person does not replace these lost fluids, he or she may become physically uncomfortable and thirsty and begin to notice a loss of energy and strength. By sweating, the body has lost some of the fluid required for optimum blood circulation, and it is not shedding excess heat as efficiently. Reduced blood volume also means that the transport of oxygen and energy supplies is reduced. When this happens, less oxygen and nutrients go to the active muscles, the brain, and other internal organs.

After several hours of intensive work, the dehydrated person may start to experience headaches, muscle fatigue, heat cramps, and nausea. Strength declines, and fatigue occurs sooner than it would otherwise. Alertness and mental capacity are also affected. Those who must perform delicate or detailed work may find their accuracy suffering, and others may find their comprehension and retention of information lowered. The longer a body sweats, the less blood there is to shed excess heat or carry oxygen and nutrients to muscles. A person may start to experience headaches, muscle fatigue, heat cramps, nausea, loss of strength, reduced alertness and loss of accuracy and dexterity. After a full day of intense heat and little or no water, the body is in serious danger, causing dizziness and irritability. Heat exhaustion and heat stroke are likely. Core body temperatures can rise to levels where hospitalization is required.

Humidity is one of the most significant environmental factors contributing to the debilitating effects of heat stress. Under conditions of high humidity, the evaporation of sweat from the skin is decreased significantly and the body's efforts to maintain a normal temperature are significantly impaired. For military personnel protective gear, such as body armor or NBC suits, may compound the problem further, preventing sweat from evaporating, trapping moisture near the skin.

Importance of Hydration on the Move

Military operations are often characterized by intense, prolonged work sessions with few or no breaks. As a result, a soldier's muscles are generating an excessive amount of heat, and using all of the body's natural defenses against dehydration and heat stress. If personnel cannot break to get water or water is not readily available, the body's defenses against both the environmental and jobsite factors are diminished greatly. The availability of water is critical; therefore, it is only logical that the soldier carries the water he needs with him at all times.

Recommended quantities of drinking water for the soldier are available to the U. S. Military. USARIEM recommends water intake of from ½ to 1 quart of water per hour depending on heat category and work difficulty.[ii] Guidance from civilian industry can also be useful in determining the required water intake for military personnel. In industry, OSHA and the EPA[iii] identify dehydration as one of the primary causes of heat illness and recommend replacing fluids lost from sweating as the best way to control heat stress, keeping workers productive, safe, and alert. Specifically, NIOSH and ACGIH[iv] recommend drinking 5-7 ounces of fluid every 15-20 minutes to replenish the necessary fluids in the body. This rate of 5-7 ounces every 15-20 minutes corresponds to the rate at which the body absorbs water.

In order to drink the recommended quantities at the recommended rate, personnel need to keep water near them. If it is easier for them to access water, it is more likely that they will stay hydrated. It is important to drink before, during and after physical labor to replace fluid lost in sweating. Personnel cannot wait until they are thirsty to drink. By the time someone is thirsty, he or she is already dehydrated.

Providing personnel with enough clean water is often easier said than done. Often it may appear that having an adequate supply of water available to personnel is sufficient, but industry research has shown that drinking water must be easily accessible to be effective. In a recent report by CalOSHA[v], in the majority of heat stress deaths that occurred in the State of California, water was available to nearly all personnel. In these cases the individuals did not adequately hydrate even though the water was available. Most often an individual's failure to hydrate results from his or her own behavioral habits. He is focused on his job. He does not want to interrupt his work for water, take too many breaks, or walk to the water source. He will drink when the job is done. Unfortunately, as shown in the Cal OSHA study, waiting for the end of the job can be too late.

How can military leaders enable their personnel to achieve the optimum hydration regime? Hands Free Hydration Systems, such as the CamelBak system, provide a solution to the water accessibility issue. A hand free hydration system, as shown in Figure 1, consists of a 2L or 3L polyurethane reservoir of drinking water or electrolyte fluid connected to a delivery tube. The reservoir is held by a backpack-like carrier, placed inside a rucksack or affixed to tactical vest or other load bearing equipment. The drinking tube is routed from the carrier to the vicinity of the soldier's mouth. The tube can be routed over or under the shoulder inside or outside of clothing and gear. The soldier drinks without using his hands by biting on the Bite Valve at the end of the tube and sucking water through the delivery tube as shown in Figure 2. These systems provide military personnel with drinking water on demand, hands-free access, and hydration convenience. By providing sufficient quantities of fresh clean water, Hands Free Hydration Systems optimize the soldier's hydration, which leads to increased mobility, increased lethality, and increased mission tempo.

Figure 1 - Hands Free Hydration System

Figure 2 - Soldier drinking from a CamelBak Hands Free Hydration System

CamelBak - Proven Success in the Field

The Hands Free Hydration System is combat proven. Hundreds of thousands of Hands Free Hydration Systems such as CamelBak have been fielded in the military. For examples the U.S. Army's MOLLE System and the U.S. Marine Corps' soon to be available ILBE System include stowable Hands Free Hydration subsystems from CamelBak. Hands Free Hydration Systems have been used in every major conflict since the first Gulf War. According to recent U.S. Army After Action Reports (AAR) from the Operation Iraqi Freedom *"the CamelBak-type hydration system is the way to go. Soldiers stopped even using their 1 qt canteens once the NBC threat subsided.*[vi]*"*

Likewise the U. S. Army's 10th Mountain Division AAR from the conflict in Afghanistan indicated that soldiers preferred Hands Free Hydration Systems to canteens particularly in the cold environments where water in the canteens often froze. The report stated:

> *"Most Soldiers prefer the CamelBak [to the canteen] for carrying water. Most started with a 3 days supply of water. Water was from streams and treated with Iodine. …Water is essential for Soldier performance. High altitude also contributes to dehydration."*

Formal field studies throughout the world have also demonstrated that Hands Free Hydration Systems provide the best way to access clean water while troops are on the move or at work. The backpack or stowable hydration systems are portable, easy to integrate with other gear, a convenient way to access water, and a comfortable way to drink when on-the-move.

Hands Free Hydration Systems have been proven effective in formal field trials by numerous militaries around the world. Results of some of these trials follow.

British Forces Trial of CamelBak Individual Hydration Systems.

The British Army at the Jungle Warfare Wing, School of Infantry in Brunei conducted a Hands Free Hydration field trial. In this experiment, members of the Recce platoon of the First Battalion, The Royal Gurkha Rifles (1RGR) wore CamelBak Hydration Systems in both normal camp based routine and a two-week deployment into deep jungle in a mountainous area on the Brunei Sarawak border. This trial provided extremely positive results in favor of using individual Hands Free Hydration Systems as shown below:

> *"Usefulness. The products were considered by the users as being extremely useful in a jungle environment where heat stress and exhaustion are exacerbated by inadequate hydration. Users also found that both products [CamelBak systems] were ideal for both tactical exercises as well as arduous physical training where they could easily be carried during runs and forced marches.*
>
> *Water Intake. Users found that they drank far more water by continually sipping from the CamelBaks that they would have done using conventional water bottles that require infrequent water stops.*
>
> *Tactical Employment. Water was easily available and its consumption did not impact on tactical awareness. Water could be consumed with the user maintaining an alert position with both hands on the weapon during ambushes and patrolling.*
>
> *Water Carriage. Both products allowed users to carry more water when away from water sources and therefore increase patrolling range. The method of carrying water on the back rather than on a belt around the waist was greatly preferred."*

The trial report concluded "the ability to continuously drink water while on the move in hot wet environments allows soldiers to remain tactically alert and at the same time reduces the risk of heat stress illness and exhaustion. The water hydration products… were extremely well received by all users and the Battalion would like to receive a complete issue as soon as possible."

Canadian Land Forces Hydrations Systems Trial

A Canadian Land Forces hydration systems trial in East Timor concluded the "hands-free hydration system, like the CamelBak systems tested, is a major improvement over our current in-service hydration system."[vii] 95% of participants in this trial rated the system as being 'much better' than the one-quart canteen system. 88% rated the hydration system as easier to use than the one-quart canteen and 83% rated the hydration system more durable than the one-quart canteen. As a result of this study, it was recommended that a cleaning kit be included when deploying this system.

U. S. Army's Soldier Hydration System Limited Objective Experiment

As demonstrated by CamelBak's acceptance by the international military community, the Hands Free Hydration System provides an ideal way to supply clean water to personnel who are operating in a hot environment at a high level of exertion. When NBC gear is worn, the risk of heat stress increases significantly. According to the USARIEM Fluid Replacement and Work/Rest Guide, 20 °F should be added to WBGT index for moderate to hard work when wearing NBC clothing (MOPP 4). This added safety factor represents the serious increase in heat stress which an individual experiences when he or she dons a protective suit. The Hands Free Hydration System is a particularly valuable in combating dehydration in an NBC environment.

In 2000 the U.S. Army Maneuver Support Center in Fort Leonard Wood conducted a Nuclear, Biological, Chemical (NBC) Soldier Hydration System (SHS) Limited Objective Experiment to assess the effectiveness and suitability of using the Soldier Hydration System, a 2-liter 70-oz liquid capacity polyvinyl reservoir "similar to the butyl rubber chemically protected version produced by CamelBak." This experiment demonstrated the SHS to be an excellent alternative to the canteen for hydration purposes while in Mission Oriented Protective Posture Four (MOPP 4).

Unlike the canteen, the SHS enabled soldiers to effectively hydrate while on the move and during the performance of mission critical tasks. On average, soldiers using the SHS consumed 25% more water than soldiers using the canteen. Soldiers determined that it was significantly easier to hydrate with SHS than with canteens. On the ease of hydrating scale with 1 being "Very Difficult" and 5 being "Very Easy" the SHS rated a 4 while the canteen rated a 2. Likewise on the ease of accomplishing the mission scale with 1 being "Very Difficult" and 5 being "Very Easy" the SHS rated a 4.3 while the canteen rated a 2.2.

This experiment also proved that the SHS did not require more time to don MOPP 4 equipment when donned in a non-emergency situation. Soldiers did not experience hose snagging when the system was worn on the outside of their MOPP gear. As their mission progressed, soldiers using the canteen were less likely to hydrate because of the additional effort and time associated with using the canteen. Soldiers using the SHS felt their physical endurance was better than when they used the canteen. Soldiers also preferred to wear the SHS on the outside of their MOPP gear in order to facilitate refill of the SHS reservoir.

The SHS experiment concluded that a hydration system, which enables soldiers to hydrate on the move and during the performance of mission essential tasks, is preferred over the current canteen method for hydrating in MOPP IV.[viii]

Required Features of Tactical Hydration System

With its primary focus on hydration technology, CamelBak continues to develop cutting edge equipment to keep troops safe and moving in the field. Since inventing the Hands Free Hydration System over 15 years ago, CamelBak has refined the features of the tactical hydration system. Tactical hydration systems must be durable, easy to clean and maintain, and must integrate seamlessly with existing soldier equipment. A tactical hydration system must be designed with the specific needs of the military in mind. Like any piece of gear used by the soldier, it is crucial that the Tactical Hydration System be designed based on feedback from the troops in the field and be rigorously field tested in realistic military operations. For example, all of CamelBak's new military products are field tested by members of the 509th Airborne Infantry Battalion, the Opposing Forces (OPFOR) at the U.S. Joint Readiness Training Center at Fort Polk, LA prior to their release to production. The feedback received from these field tests is invaluable in identifying hydration system requirements of the soldier and incorporating continuous product improvement. A description of the key features of a tactical hydration system, learned as a result of extensive field-testing, is provided below.

- Rugged and Leakproof - Hydration systems must be rugged enough to withstand extreme conditions. Ruggedness is required in all three sub-assemblies of the system: the carrier, the reservoir and the delivery tube. The carrier must be abrasion resistant, strong enough to carry the soldier's load, and puncture resistant enough to protect the reservoir from all external point loads such as those from sharp equipment forced against the system when packed in a ruck. To protect against puncture and abrasion, CamelBak carriers are constructed from durable, US-made, 1000D Dupont Cordura and reservoirs are built by RF welding a 12 mil Ether-based Polyurethane film. The polyurethane material and seams are rated to an Ultimate Tensile Strength (UTS), over 5000 psi. CamelBak also uses high strength materials to manufacture the delivery tube and all molded components.

  To prevent inadvertent flow, a tactical system requires secure closure on the drinking end. Camelbak uses a redundant valve system consisting of a manual HydroLock™ "On-Off" valve, which prevents flow when the system is not in use and the patented Big Bite™ Valve, a mouth actuated Bite Valve, which supplies unmatched water flow, allowing the user to drink hands free." CamelBak's patented HydroLink™ provides functionality to change out components quickly.

- Easy to Use - A tactical hydration system must be both easy to fill and easy to drink from. CamelBak's medical grade silicon Big Bite™ Valve is easy to operate. The user just bites and sips to drink. Likewise the HydroLock valve is simply open or shut to turn the water flow on or off. CamelBak's patented OMEGA Reservoir can be loaded quickly and easily. It holds 3L of water and the large opening makes it ideally suited for accepting ice when available. Another critical element of an easy to use tactical hydration system is ergonomic carrier design. CamelBak's carriers are carefully designed to evenly distribute the load and include a patent pending Velcro Strap Management system which keeps straps in check and out of the way.

- Easy to Clean and Maintain - A tactical hydration system must be designed so that it can be easily cleaned and maintained in the field. Maintainability has been designed into the CamelBak product. New HydroGuard™ Anti-Microbial technology is a safe and effective way to keep the reservoir and delivery tube clean and taste-free. This FDA-approved, EPA registered anti-microbial technology is embedded directly into reservoir and delivery tube, so it works continuously to inhibit microbial growth on surfaces and eliminates the growth of common bacteria and fungus in reservoirs and tubes. The large opening of the OMEGA reservoir allows the user to reach in to clean every corner. A compact field cleaning kit was recently developed with all the tools necessary to clean the reservoir when no soap is available. This kit includes cleaning tablets and sponges and brushes specially designed to fit into every corner of the reservoir. Lastly, a bite valve cover is being incorporated into the standard system to protect the bite valve from dirt or other contamination prevalent on the battlefield.

- Integrated with Existing Soldier's Equipment - A tactical hydration system must integrate well with the rest of the soldier's load. This can be accomplished through several options. The system can fit inside a pack, attach to the outside of load bearing equipment or be worn with shoulder straps. CamelBak's stand alone Hydration System, the 3-liter ThermoBak® has an ergonomic design which keeps it comfortable for hours on end. Quick-release straps stow away inside built-in pockets and D-ring attachment points allow easy integration with load-bearing equipment or web harness platforms. In larger CamelBak packs and U. S. military sponsored designs (MOLLE system, ILBE system, Land Warrior system prototype, and Objective Force Warrior system prototype) a reservoir pocket or sleeve has been built in to hold the reservoir and optimize the soldier's load.

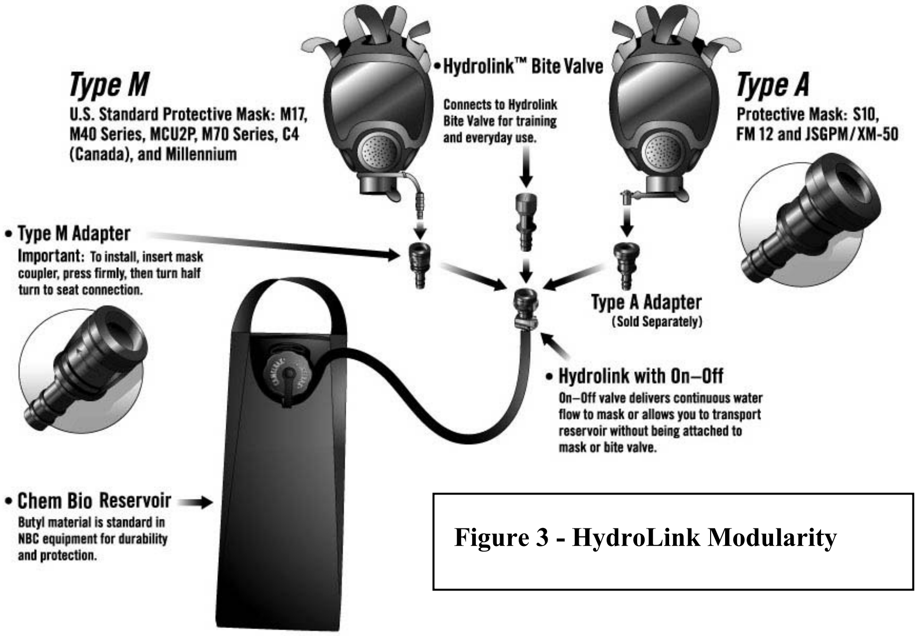

Figure 3 - HydroLink Modularity

- Modularity (HydroLink) - The recent trend in hydration systems is toward modularity. This trend has been driven by the need for the system to better integrate with individual soldier systems and water logistics systems. CamelBak's revolutionary patent-pending HydroLink™ Modular Attachment System allows the user to interchange reservoirs and accessory components easily and quickly. For example HydroLink™ Modularity lets a user easily transition from a standard environment with polyurethane reservoir and a bite valve to an NBC environment with a Chemical and Biological Resistant Reservoir, and a protective mask. By utilizing this modular design concept, hydration system adapters can be easily customized for any brand of gas mask. For example, in a conventional warfare environment, a soldier has a steady flow of water using CamelBak's lightweight polyurethane reservoirs with a standard HydroLink™ Bite Valve. The same polyurethane reservoir can be used to train in an NBC environment. The quick release mechanism on the delivery tube makes changing out HydroLink components quick and easy. When the soldier shifts into MOPP gear training, he or she simply swaps out the Bite Valve with the appropriate gas mask adapter for his or her gas mask. Finally when normal combat turns into an NBC threat, the soldier can switch from a standard polyurethane reservoir to the Chemical Biological Resistant (CBR) Reservoir in seconds, and then quickly attach the drink tube directly to the protective mask. CamelBak's current chemical resistant system has been designed and tested to meet USACHPPM standards against Mustard and Sarin gases and a new high strength, low-weigh, low-cost is in the final stages of development.

  Modularity also provides integration of additional functionality such as individual filtration, rapid filling, rehydration of field rations, and incorporation into complex soldiers systems. For example a HydroLink In-line MicroFilter can be snapped in place as shown in Figure 4 allowing the soldier to fill the reservoir from an untested source. The exclusionary microfilter filters the water as the soldier drinks hands free, on the move.

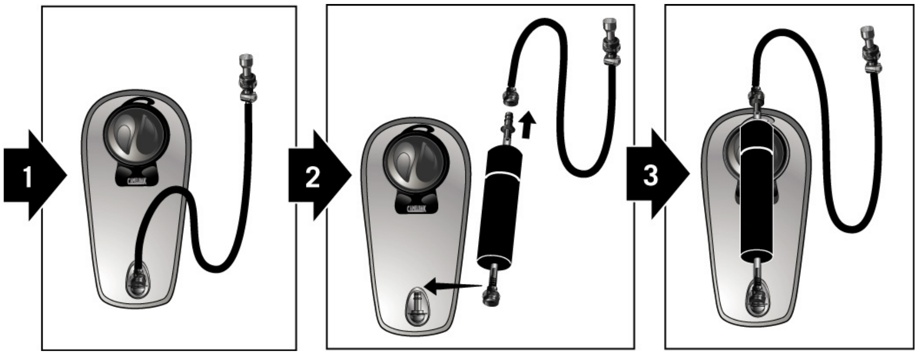

Figure 4 - MicroFilter connects in line with delivery tube as shown. Water filtered as user drinks.

The Future of Personal Water Delivery

According to U. S. Army doctrine[ix], "combat forces operating on the fast paced modern battlefield will require more responsive water distribution methods and capabilities for emergency water purification and resupply." Hands Free Hydration Systems are ideally suited to support this need. In the future hydration systems will become increasingly integrated with the soldier load and standard military water logistics systems. One day, load-bearing equipment may even be designed around hydration considerations. Under one future concept when the soldier would transition from a movement to an assault mode, he would quickly drop the sustainment load but retain his assault load which would include adequate water for the assault. To refill, a soldier would simply snap his transfer/delivery tube into a drinking water manifold with a quick release fitting. Multiple personnel would be able to fill up quickly at a hydration station equipped with several quick release ports. Advances in inline filtering and purification would enable military personnel to fill their hydration system from any source because a personal in line purifier would remove all harmful chemicals, bacteria and viruses from the water while the soldier drank on the move. These and many other creative features must be incorporated into future personal water delivery systems in order to benefit the soldier. The Hands Free Hydration System is the key building block around which to build these personal water delivery systems.

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Military Land-Based Water Purification and Distribution Program

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1. Background

Potable water is one of the Army's most basic logistics requirements, particularly in arid environments. It directly affects the health and welfare of the individual soldier as well as the combat readiness of committed forces. During World War I, health problems associated with poor drinking water quality prompted the U.S. Army to address the issue of providing potable drinking water to the field. The principal piece of equipment developed was the "Mobile Water Purification Unit" featuring sand filtration and chlorination. During World War II, it became increasingly apparent that this technology was only partially effective in providing potable and uncontaminated water for drinking, washing, culinary, bathing and laundering purposes. Subsequent to World War II, a complete line of water purification equipment, each designed for use on a different type of source water was developed and fielded. During the 1960's, the Army realized that although these units provided potable water, there was, from a logistical and training standpoint, a distinct need for a single water purification unit capable of purifying raw fresh water, seawater and brackish water. In addition, there was now a need to purify water contaminated with nuclear, biological and chemical (NBC) warfare agents. Consequently, the Army funded research in reverse osmosis technology which resulted in the development and procurement of two systems, the 600 and 3,000 gallon per hour (GPH) reverse osmosis water purification units (ROWPUs). They were fielded in 1981 and 1989 respectively, and are still used today by the Army, Marine Corps, and Air Force.

2. Current Doctrine

Direct support (DS) water sustainment to divisional units is provided by supply point distribution in the present day Army except for light infantry battalions (LIB) where water purification personnel provide distribution to the LIB combat trains, as outlined in FM 10-52 Water Supply in Theaters of Operations [1]. DS support is capable of supplying the divisional water requirements in temperate, tropical, and arctic regions. However the DS support must be augmented by (general support) GS support in arid regions where sufficient water supplies are not available. To provide DS water sustainment water specialists from the supply & service company in the main support battalion (MSB) establish water supply points in each of the brigade support area (BSA) and at up to two locations in the division support area (DSA). When a source of water sufficient to support the purification requirements is available in the BSA water purification and supply points are established in the BSA using Reverse Osmosis Water Purification Units (ROWPU) and water storage assets. When there is no suitable water source available within the BSA a dry water supply point is established in the BSA using the organic water storage assets and purification is conducted at the nearest source. A Water purification point is then set up at the nearest suitable source using ROWPUs to purify the water and transported to the dry water supply point in the BSA using distribution assets, primarily the semi

Paper presented at the RTO HFM Specialists' Meeting on "Maintaining Hydration: Issues, Guidelines, and Delivery", held in Boston, United States, 10-11 December 2003, and published in RTO-MP-HFM-086.

trailer mounted fabric tank (SMFT). All units (less light infantry companies) must use their organic water distribution equipment to pick up water from the approved water point. The unit must dispatch an organic prime mover and a 400-gallon water trailer, 160 gallon pillow tank or 250 collapsible drum to the BSA water point. Due to the limited vehicular mobility of the LIB water distribution is performed by unit distribution. Water is moved forward from the BSA to the LIB by water section forward area water point supply system and transferred to 160 gallon pillow tanks operated by the battalion supply trains. The water will then be taken forward to companies and platoons. Units must pick up their water resupply at the battalion distribution points. Unit distribution of water is only provided for LIB. All other units in the Light Infantry Division use supply point distribution.

The equipment in the army's inventory has been developed to support this doctrine and in most cases is well suited for the task. Water purification equipment consists of the 600 gallon per hour ROWPU and 3,000 gallon per hour ROPWU which are currently fielded and the 1500 gallon per hour tactical water purification system and 125 gallon per hour light weight water purifier, which are ready to enter production. These systems can rapidly purify any type of source water including rivers, lakes and oceans and produce quantities to meet the brigade, division, corps and theater of operation requirements. Distribution is accomplished using the Semi-trailer Mounted Fabric Tank (SMFT) or (Forward Area Water Point Supply System) FAWPSS for bulk distribution and 400 gallon water trailer, 250 gallon collapsible drum and 160 gallon pillow tank for retail distribution. A 2000 gallon tank rack that may be transported on a Load Handling System (LHS) or trailer is under development to replace the SMFT to address the significant draw back of not being able to transport the SMFT partially full. The HIPPO and CAMEL are under development to increase the capacity of the unit water trailer from 400 gallons to 900 gallons.

Due to the significant logistics footprint (weight and volume) associated with storing water current doctrine only requires units to maintain water in organic water containers and optional CTA equipment, where water sources to support water purification operations are readily available. For an average unit this means only maintaining enough water to get through that day's operations. Under these conditions units must resupply daily. In arid regions where water sources are extremely limited units must make use of all organic and optional CTA equipment. Combat brigades and divisions, and hospitals are assigned additional water storage and distribution equipment. This ensures that one day of supply is maintained at each echelon level. GS storage and distribution assets are required to maintain adequate supply levels.

3. Review of Existing Equipment

The development of the 600 gph ROWPU was completed in 1979. The system is a highly mobile, versatile and rugged system that may be rapidly deployed and used anywhere on the battle field. The unit uses a combination of physical and chemical treatment processes to produce potable water from any available water source. The ROWPU consists of five major systems: raw water intake, clarification, purification, distribution, and Nuclear, Biological, and Chemical (NBC) decontamination. The raw water intake typically consists of an intake strainer, a raw water pump, and the necessary hoses and valves. In the clarification system the raw water is coagulated by the addition of a cationic polyelectrolyte, then pumped through a multi-media filter followed by a set of 5 micron cartridge filters. The purification system consists of the high pressure pump, eight 6" diameter reverse osmosis elements, and a chlorine injection pump. The chlorine injection pump provides a chlorine residual required by the Army Surgeon General to ensure the water is not recontaminated during storage and distribution operations. The distribution system has 3,000 gallon collapsible fabric storage tanks, a distribution pump, a distribution nozzle, and the necessary hoses and valves. The NBC decontamination system has activated carbon and mixed-bed ion exchange filters to remove NBC contaminants from the purified water. The 600 GPH ROWPU produces up to 12,000 GPD from sources with 35,000 ppm. On waters with lower salinity, the ROWPU will produce more water. The operating day for a ROWPU is 20 hours. The remaining four hours are used for routine cleaning and maintenance. There are three models of 600 GPH ROWPUs: a trailer-mounted unit for the Army, a skid-mounted unit for the Marine

Corps and Navy, and a skid-mounted unit wired for use with the bare base electrical system for the Air Force. The 600 GPH ROWPU is powered by a 30 kW generator. All versions can be transported by 5 ton truck, air transported, air-dropped, rail transported, carried on shipboard, or sling-loaded by a cargo helicopter.

The development of the 3000 gph ROWPU was completed in 1987. The system design is similar to the 600 gph ROWPU with the same five major systems: raw water intake, clarification, purification, distribution, and Nuclear, Biological, and Chemical (NBC) decontamination. A major difference is addition of a cyclone separator mounted on the raw water pump to provide initial removal of large suspended particles. The purification subsystem includes twelve 8” diameter RO elements arrayed in two parallel streams with six RO elements in series. The water treatment system and controls are housed in a 8 foot by 8 foot by 20 foot ISO container and mounted on a 40 foot semi-trailer along with a 60 kW generator set and the high pressure pump. The system may be transported by truck, rail, ship, or air.

4. Review of Developmental Equipment

The 1500 gph Tactical Water Purification System (TWPS) will replace the existing 600 GPH ROWPU in the Army and U.S. Marine Corps (USMC) inventory. The design of the 1,500 GPH TWPS uses state-of-the-art technology to increase the potable water output without increasing the size, weight, or deployment features in comparison with the 600 GPH ROWPU, and to improve water production efficiency and flow rates from sources with high salinity contents. The existing 600 GPH ROWPU has insufficient water production and uses outdated pretreatment technology. The existing system is not capable of providing acceptable quantities of potable water from seawater with extremely high total dissolved solids (TDS) levels, such as those encountered during Operation Desert Shield and Desert Storm. Also, it is not capable of providing acceptable quantities of potable water from low temperature (e.g. 32 degrees Fahrenheit) water sources. The 600 ROWPU’s pretreatment filters require excessive backwashing and/or replacement when operating on turbid source waters (greater than 20 nephelometric turbidity unit (NTU)). Another consequence of operating the current system on turbid source waters is that the pretreatment system may allow colloidal particles to travel through the filters and enter the Reverse Osmosis (RO) elements. This will typically result in premature cleaning of the RO elements and may possibly cause such significant fouling that the expensive RO elements will need to be replaced.

The 1,500 GPH TWPS is a fully contained mobile water purification system consisting of seven process systems: a raw water system, a microfiltration (MF) system, an RO system, an air system, a chemical injection system, the product distribution system, and a NBC purification system. The system utilizes MF pretreatment to remove suspended solids and bacteria, and high rejection spiral wound RO membranes to produce potable water from fresh and brackish water sources as well as from salt water up to 60,000 mg/l TDS. The TWPS produces a minimum of 1500 GPH of potable water from fresh water sources, as well as a minimum of 1200 GPH from brackish, salt, and nuclear, biological, and chemical (NBC) contaminated water. The TWPS has two configurations, one for the U.S. Army and one for the U.S. Marine Corps. The Army’s TWPS is mounted on a flatrack and the USMC TWPS is a skid-mounted unit, but does not include the power source (i.e. generator).

The raw water system pumps raw water from the water source to the TWPS through a floating inlet strainer with an anchor and rope, raw water suction and discharge hoses, a cyclone separator, and a static mixer. The TWPS also has an ocean intake structure system (OISS) which is used for drawing raw water through beach well point intakes for raw water sources with surf or extreme tidal conditions. MF feed water is drawn through dual 600-micron strainers, and then to each of 12 MF modules in parallel. Entering each module, the feed flows around the outside of the fibers and then through the 0.2 micron nominal membrane surface of each fiber and into the hollow core. The filtered feed water flows to the high pressure pumps that discharge to the pump end of the power recovery turbocharger where the pressure is boosted before entering the first of five RO pressure vessels arranged in a series array. Each vessel contains two 8” x 40” spiral thin film composite polyamide RO elements installed with a blanking plug between the permeate tubes. From the last vessel the concentrated feed water, now reject, discharges to the turbine side of the turbocharger where the pressure is converted to energy to run the pump side. A chemical injection system adds calcium hypochlorite to provide a residual of up to 10-mg/l free chlorine prior to discharge to one of two 3,000 gallon product distribution tanks. The NBC filter system is a separate component, to be used when purifying NBC contaminated water, that consists of ion exchange resin and activated carbon.

The Lightweight Water Purifier (LWP) provides the U.S. Army with the capability to produce a safe, reliable supply of potable water to support ground, amphibious, air mobile, and airborne units. The primary mission of the system is to purify water obtained from a broad range of sources, including NBC contaminated sources, to meet requirements for small military units and detachments, Special Operations Forces (SOF), and temporary medical facilities during a large range of military contingency operations to include combat, stability operations, and support operations. The LWP will be primarily transported over land in the rear compartment of the High Mobility Multi-Purpose Wheeled Vehicle (HMMWV) M1097A, and by air inside the C-130 aircraft or an UH-60 helicopter. The LWP produces 125 GPH of potable water from a fresh water source and 75 GPH of water from a seawater source. The LWP is a modular system that consists of the following process systems and modules: raw water feed system, ultrafiltration module, high pressure pump module, RO module, chemical injection/ cleaning module, NBC post-treatment system, product water distribution system, and power source.

The raw water system consists of an electrically powered feed pump, coagulant injection system, and a collapsible fabric tank settling tank. The settling tank is used for the raw water source and allows suspended solids to settle to the bottom of the tank. The settling tank will reduce the solids loading on the ultrafiltration (UF) membranes thereby increasing the time between cleanings. Clarified water from the settling tank is fed to the UF Module by an electric motor driven pump. The UF module is a welded aluminum pipe frame that houses the three 0.1 micron UF membrane cartridges. The HP module houses a diesel engine driven high-pressure plunger pump that pressurizes the feedwater prior to treatment by reverse osmosis. The RO Module contains seven 2.5" diameter RO membranes in Titanium pressure vessels. The chemical injection/cleaning module houses a 20-gallon tank used for batching, mixing, and heating the cleaning solutions for the UF and RO system and to hold fresh product water. There are three, 2.5-gallon tanks for either sodium bisulfite (dechlorinating agent) or coagulant depending on the source water, antiscalant solution for the RO membranes, and a hypochlorite solution for disinfecting the product water. The NBC filter assembly consists of activated carbon to remove chemical warfare agents and ion exchange resin to remove radioactive contaminants. The system is only employed if the presence of NBC agents is suspected. The product water, after chlorination and NBC post treatment (if required) is stored in a 1000 gallon collapsible fabric tank.

5. Future Force Sustainment Concept

Conventional U.S. Army water sustainment doctrine and equipment will have difficulty meeting the challenge of supporting the emerging Future Force sustainment and operational concepts. New material is critical to transform water sustainment so that it will achieve the goals of the Future Force sustainment and operational concepts. Current water sustainment doctrine is based on locating a source of water sufficient for bulk water purification, purifying large quantities of water rapidly, and then distributing the purified water forward via hose systems, vehicles, and finally trailers, pillow tanks, and jerry cans to reach the maneuver companies.

To meet the needs of our nation in the 2015-2020 timeframe, the Army must have a new tactical force—the Unit of Action Combat Brigade. Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) and force sustainment will become even greater multipliers on the battlefield than in legacy and interim force operations. The Army must rethink organizations and doctrine to capitalize on these multipliers. The Army is continually developing more lethal systems, restructuring organizations, and refining doctrine. The Future Force Operational Concept fulfills the Army Vision of fielding combat brigades capable of deploying in 96 hours from the departure of the first unit from a continental United States (CONUS) base. The operational concept for the UA leverages the integration of advanced information and material technologies interconnected by an info-sphere with the employment of tactical combined arms units capable of rapidly deploying from strategic distances and able to fight –on arrival.

Sustainment is generating, maintaining, and regenerating combat power and a corresponding operational tempo. Sustainment operations aim at minimizing the frequency and duration of operational and tactical transitions where momentum is lost. UA units are sustained through pulsed logistics, reducing its footprint. Unit sustainment is provided through mission staging and sustainment replenishment events that are synchronized with the maneuver commander's battle rhythm. Mission staging is an intense, time-sensitive operation which includes all preparations for an upcoming mission: planning, troop leading, rehearsals, training, reconnaissance and surveillance, reconstitution, tailoring for next mission, information operations, etc. to ensure mission success. Sustainment replenishment is a quick, in-stride, sustainment operation that is designed to maintain the operational tempo. This is similar to a "pit stop" operation. Sustainment replenishment can either be a deliberate or a hasty operation if an opportunity exists or circumstances insist. This replenishment operation provides arm, fuel, fix, medical support and personnel replacements only as required to meet the immediate needs of the maneuver commander. Sustainment pulses are used to minimize the logistical risk associated with non-secure lines of communication and grey space. As a result of the pulse concept units will need to operate with out external resupply for extended periods. The sustainment concept calls for pulses will be 3 days for high intensity operations and 7 days for low intensity operations. Which means to units must operate without external resupply for these lengths of time. Brigade combat team sustains itself for three days of high tempo operations and seven days in smaller-scale contingencies without replenishment from external sources. Soldiers conducting dismounted operations receive sustainment support from their FCS platform (e.g. on-board water generation).

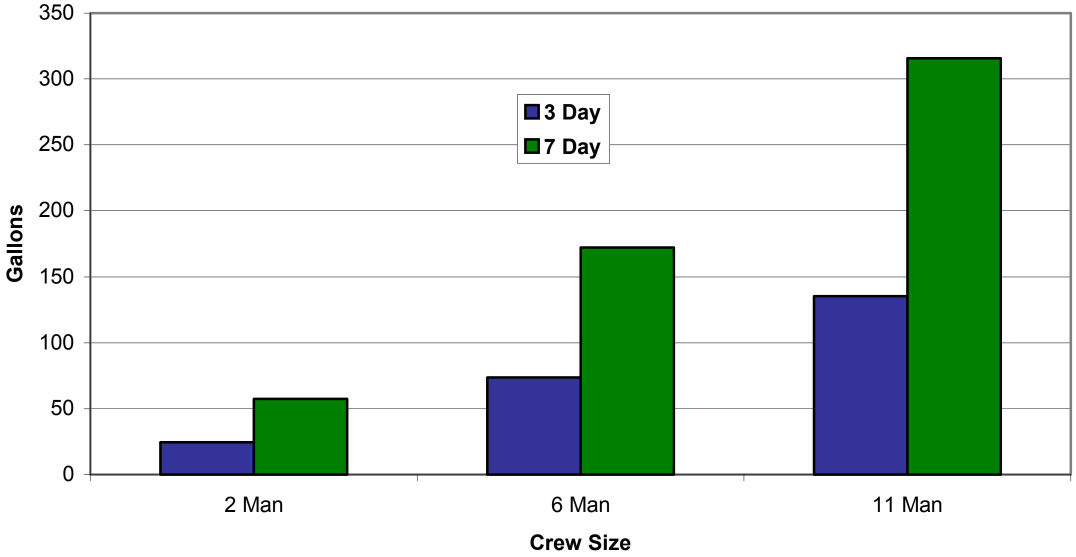
In order to achieve the Future Force desired concept of 3 to 7 days of operation without external resupply or a resupply pulse the Future Combat System (FCS) must have enough water storage to support the organic crew members. This is in contrast to the current doctrine of having just enough water storage for today. The concept calls for 3 days independent operation during high intensity operations and 7 days of independent operation during low intensity operations. However, unlike other classes of supply such as fuel and ammunition, water consumption remains relatively constant regardless of the intensity of the operation. The "Water Consumption Planning Factors Study Report" prepared by the U.S. Army CASCOM in 1999 [2] provides minimum and sustaining water consumption factors related to military personnel in the force structure in hot, temperate, and cold environments (Table 1). The minimum water requirement for drinking is 1.5 gallons per soldier per day in a temperate environment, 2.0 gallons in a cold environment and 3.0 in a hot environment, including both tropical and arid. The universal unit level include factors for personal hygiene, field feeding, heat injury treatment, and vehicle maintenance. The minimum water consumption figures range from 3.26 gallons per soldier per day for a temperate environment to 4.96 in a hot arid environment. The sustaining water consumption factors range from 6.01 gallons per soldier per day in a temperate environment to 7.71 in a hot arid environment. The nominal planning factor the FCS is 4.1 gallons per soldier per day. This provides the flexibility of reducing the daily consumption to 3.0 to achieve an extended operational time frame in emergency situations and doubling the time before resupply is required. Using the nominal water consumption-planning factor the size and weight of the required water storage in the FCS may be calculated for various crew sizes (Figure 1). For an FCS with a crew of 2 the required water storage for 3 days of operation without resupply is 24.6 gallons or 204.2 pounds. The 7 day requirement for the same configuration is 57.4 gallons or 476.4 pounds. For an FCS with a crew of 6 the required water storage for 3 days is 73.8 gallons or 612.5 pounds. The 7 day requirement for the 6 man crew is 172.2 gallons or 1429.3 pounds or almost 3/4 of a ton. For an FCS variant with a 11 man which has 11 organic soldiers it must support the required water storage for 3 days of operation is 135.3 or 1123.0 pounds or over ½ a ton. The 7 day requirement to support 11 soldiers is 315.7 gallons or 2620.3 or over 1 ¼ tons. In all cases the 7 day requirement represents a significant fraction of the overall FCS weight budget. In the cases of the 6 and 11 man crew this will seriously impact the ability to achieve the FCS required capabilities. For the larger crew sizes 6 and 11 soldiers even the 3 day requirement will be a significant portion of the total weight budget and impact the ability to provide all the required capabilities. For the Objective Force to achieve the desired 3 to 7 days of operation without external resupply either each individual FCS will have to dedicate a significant portion of its total weight allotment to water storage or pull a water trailer. The other option for the Future Force to achieve the desired 3 to 7 days of operation without external resupply is for the Unit of Action to include a large number of water trailers that can be rapidly brought forward to each individual FCS for resupply

Table 1 Extract from Potable Water Consumption Planning Guide, Jun 99

CONVENTIONAL THEATER

FUNCTION	HOT				TEMPERATE		COLD	
	TROPICAL		ARID					
	Sustaining	Minimum	Sustaining	Minimum	Sustaining	Minimum	Sustaining	Minimum
Universal Unit Level Consumption	7.51	4.76	7.71	4.96	6.01	3.26	6.51	3.76
Level I and II Medical Treatment	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Central Hygiene, Shower, Laundry (M-85)	*8.30*	*0*	8.30	0	*8.30*	*0*	*8.30*	*0*
Central Hygiene, Shower, Laundry (LADS)	*2.05*	*0*	2.05	0	*2.05*	*0*	*2.05*	*0*
Level III and IV Medical Treatment	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Mortuary Affairs Operations	*0.01*	*0.01*	0.01	0.01	*0.01*	*0.01*	*0.01*	*0.01*
Engineer Operations	*1.20*	*0*	1.20	0	*1.20*	*0*	*1.20*	*0*
Aircraft Maintenance Operations	*0.20*	*0.20*	0.20	0.20	*0.20*	*0.20*	*0.20*	*0.20*
Potable Planning Factor (M-85)	8.75	6.00	18.66	6.41	7.25	4.50	7.75	5.00
Potable Planning Factor (LADS)	8.75	6.00	12.41	6.41	7.25	4.50	7.75	5.00
Nonpotable Planning Factor (M-85)	*9.71*	*0.21*	*0.00*	*0.00*	*9.71*	*0.21*	*9.71*	*0.21*
Nonpotable Planning Factor (LADS)	*3.46*	*0.21*	*0.00*	*0.00*	*3.46*	*0.21*	*3.46*	*0.21*
10% Loss Factor w/M-85	0.88	0.60	1.87	0.64	0.73	0.45	0.78	0.50
10% Loss Factor w/LADS	0.88	0.60	1.24	0.64	0.73	0.45	0.78	0.50
Total Theater w/M-85	19.34	6.81	20.53	7.05	17.69	5.16	18.24	5.71
Total Theater w/LADS	13.09	6.81	13.65	7.05	11.44	5.16	11.99	5.71

Figure 1 FCS Water Requiements



6. Current Research Efforts

No single technology will be able to meet the challenges of the Future Force, however, technology advances will develop a suite of technologies that may be used collectively to meet the requirement. New technology will provide a more distributed water production capability moving production closer to or right at the point of use. This will significantly reduce the water distribution requirements. This probably will not be able to provide all the water required for the Future Force it will potentially reduce the water distribution requirements by 50 to 66% and enable units to operate for 3 to 7 days without external resupply. This will provide a more flexible, mobile and agile force better adapted to independent operations. While water sustainment of the future force will likely require a suite of technology including legacy and new technology new technology is a must to enable 3 to 7 days without resupply and to reduce the overall logistics footprint. Water is projected to be up to 40 % of the daily sustainment requirement. A 50 to 66% reduction in water sustainment translates into a 20 to 26 % reduction in the amount of supplies which must be delivered and will have even a larger cascading effect. The cascading effect will reduce the amount of water purification and distribution equipment, which must be deployed and the soldiers to operate this equipment. It will reduce the distribution assets and manpower required in the battlespace leading to reductions in the overall water requirement, the logistics requirements to support the soldiers, and the fuel for distribution. New technology will reduce the water storage requirements and the water demand of the combat units. The water produced will augment water storage to provide enough water for a unit to operate for 3 days without resupply.

The goal of the Water Production Technology Research and Development Program is to reduce the sustainment requirement and logistics footprint associated with water production and distribution for the Future and Current Forces. Advances in water sustainment technology are needed to minimize the logistics footprint of the Objective Force Unit of Action. The U.S. Army TARDEC and DARPA are developing revolutionary technologies to produce water anywhere on the battlefield, thereby reducing the logistics footprint by creating distributed water production that reduces the frequency and quantity of resupply. The goal of reducing the water logistics burden will be achieved by pursuing two complementary objectives. The first is the development of water purification technologies that are more energy efficient, lightweight and compact than current state-of-the-art water treatment technologies. The second objective is to generate or recover water on demand from non-traditional sources such as vehicle exhaust and ambient air. These objectives are being pursued under four main thrust areas, Individual Soldier Water Purification, Water from Exhaust, Water from Air, and Next Generation Water Purification Systems. This technology will reduce the logistics footprint by projecting water production forward to the point of use and create a more mobile and flexible water sustainment capability. Integration of potable water generation into combat and tactical vehicles provides units a source of water resupply and is critical for meeting the 3 days without external resupply during periods of high operational tempo and 7 days during periods of low to medium operational tempo without external resupply sustainment concept. Embedded potable water generation would provide the soldiers with the water required to operate without resupply, reduce the logistics footprint for resupply and reduce the need for securing supply routes throughout a noncontiguous battlespace. The capability enhances flexibility of supply operations, and increases available combat power. These technologies will provide military units with a radically more mobile and flexible water production capability, the ability to efficiently purify water in a decentralized manner. The technology will reduce the logistics footprint by creating distributed water purification and production capabilities that may be projecting forward to the point of use reducing the amount of water that needs to be provided by the logistics system. These systems could revolutionize battlefield water sustainment by producing supplemental drinking water wherever the soldier is and thus reducing the quantity and frequency of water resupply.

The Army ROWPU improvement program will consist of investigating three improvements. Improved pre-treatment systems to enhance removal of solids from the raw water and improve the quality of the feedwater to the RO elements to extend the operating life of the elements, reduce cartridge filter replacement, and increase water production. Improved RO element cleaning, preservation procedures, and chemicals to decrease frequency of element replacement, and improve long term storage of elements. New diagnostic techniques and equipment kit for identifying individual elements that are defective and need to be replaced in the field rather than replacing and disposing of all elements at once including those, which are still usable.

The Army advanced reverse osmosis work is developing technology to mitigate the effects of concentration polarization and biological fouling. To reduce biological fouling new membrane chemistries are being created by Separation Systems Technology that are resistant to chlorine. Chlorine will quickly degrade the current membrane materials. Chlorine resistant membranes will enable chlorination to eradicate the microorganisms fouling the membrane. MIOX Corporation is developing a hand held pulsed RO system with advanced spacers. Modeling has shown that pulsing the flow to the membrane will reduce the build up of contaminants at the membrane surface reducing both concentration polarization and fouling. A mechanical pulsing device is being tested to validate the modeling results. Reverse osmosis membranes most commonly come in a spiral wound element. The current spacer material is usually a diamond-patterned mesh that is rolled between layers of membrane. These meshes are not optimized to maximize flow and provide a location for fouling to occur. New spacers that can be directly printed on the membrane are being investigated. These spacers may be created in a wide variety of shapes, sizes, and heights, to improve the flow characteristics reducing concentration polarization and fouling, which are not possible to achieve in a mesh material. The pulsing and new spacer design will reduce the pressure required to operate the system and the frequency with which the system must be cleaned thus reducing operation and maintenance costs. These technologies may be applied to the whole spectrum of Army water purification systems and devices including modular small unit and individual soldier.

The Army is investigating forward osmosis as a technology for individual soldier water purification devices. The device consists of a hydration bag with an FO membrane and a nutrient or “gatorade” type solution used on the product side, which has a higher osmotic potential than the source water. Therefore osmosis occurs across the forward osmosis membrane which is similar to the RO membrane in that it allows the passage of water while rejecting materials down to the ionic level. Forward osmosis has the advantage of being a low pressure process so a system may be made out of lightweight materials and little to no external energy is required for the process since the driving force is provided by the osmotic potential of the product solution. New membrane materials are being developed along with implementation concepts and fabrication techniques to create an individual water purification system. Development of a new hollow-fiber forward osmosis membrane, which will improve production rate through increased surface area, is being performed by Separation Systems Technology.

Figure 2 MIOX Disinfection Pen

In the Individual Soldier area MIOX is finalizing the development of the electrolytic disinfection pen (Figure 2). The pen has been demonstrated to be more effective and faster than chlorine and iodine and will purify 150 to 300 liters of water using only salt and water on a single pair of lithium batteries. At normal disinfection concentrations chlorine is ineffective against protozoan oocysts such as cryptosporidium and giardia. At similar concentrations of 2 to 5 ppm mixed oxidants have inactivated 99.9% of cryptosporidium oocysts in less than 10 minutes as well as removing 99.9999% of bacteria. This technology is scaleable from the individual soldier to bulk water purifiers. The pen should be on the shelves in stores in 6 to 12 months and has been accepted as a candidate under the Soldier Enhancement Program to facilitate transition to the soldier. Preliminary testing has been conducted using GD at Dugway Proving Grounds which indicates the MIOX Pen will be effective at destroying certain chemical warfare agents. A large-scale MIOX system has been designed, installed and is undergoing testing on the 3,000 gallon per hour ROWPU. Mesosytems Technology and Mountain Safety Research have been developing an integrated individual soldier water purification, storage and hydration system. The system will include an NBC resistant bladder, filtration, a MIOX disinfection cap, forward osmosis (FO), and an adsorbent. The team has demonstrated an NBC resistant bladder that has been provided to the Marine Corp for field demonstration.

Figure 3 Biosource Capacitive Deionization

Biosource Incorporated is developing a new water purification technology based on the concept of capacitive deionization (Figure 3). This concept will be applied to a flow through capacitor, which charges high surface area electrodes to electro-statically remove ions from solution. This technology will be able to produce potable water from any type of source water including seawater. The technology is theoretically more thermodynamically favorable than traditional methods for the purification of water. However, due to materials limitations this technology has not been feasible for seawater purification in the past. Recent material developments by the Biosource Team in carbon technology have provided new materials that enable the development of integrated carbon electrodes with a high electrical conductivity and may be fabricated in a manner to maximize the surface area to pore volume ratio. The fundamental understanding of the critical parameters for capacitive deionization coupled with the developments in carbon technology and a new charge barrier layer were critical breakthroughs for the development of a prototype that has demonstrated the ability to purify seawater. The FTC has also demonstrated a strong potential for use in the purification of exhaust condensate due to its ability to remove ionic species, raise pH, and the good chemical stability of wetted components. The offeror has demonstrated an innovative energy management and recovery techniques based on the fact that the capacitor is essentially an energy storage device which has a finite adsorption capacity. Therefore, the energy within the capacitor must be periodically discharged to regenerate the adsorption capacity. This energy may be shuttled to a second capacitor to recover the energy. The theoretical maximum for simple energy transfer is 25%, however, the team has developed a novel energy transfer concept that has been able of 60%. The flow through capacitor may enable the development of small unit modular water purification system, vehicle embedded systems and reduce the size weight and operating cost of larger systems.

One of the most promising concepts for producing water from non-traditional sources under development is the recovery of water from internal combustion engine exhaust. LexCarb LLC demonstrated that the water in the exhaust could be collected and purified to drinking water standards, which led to further work to understand the fundamental concepts and apply them to the development of an optimized system. The primary combustion products of diesel fuel are water and carbon dioxide:

$$C_{12}H_{22} + 17.5\ O_2 \rightarrow 11\ H_2O + 12\ CO_2$$

Theoretically, one (1) gallon of diesel fuel produces approximately one (1) gallon of water. In order to recover potable water from engine emissions the water must be condensed from the exhaust gas and then purified. The condensate contains oxides of nitrogen and sulfur from the combustion process that make the water very acidic, as well as, soot particles, organic compounds from incomplete combustion, unburned hydrocarbons, metals, and contaminants from fuels, oils, and corrosion.

To recover water the exhaust gas must be cooled below its dew point, thus initiating condensation. The quantity of water collected is a function of the volume of air treated and the difference between the concentration of water in the exhaust gas and in the cooled saturated exhaust exiting the system. The temperature to which the exhaust gas must be cooled was calculated for recovery efficiencies of 50 to 70%, with recovery defined as gallons of water produced per gallon of fuel consumed. A heat exchanger was designed based on the calculations and preliminary measurements of temperature and flow of the exhaust gas. The cooling energy that must be provided is the sensible heat to cool the exhaust gas from the inlet to desired temperature plus the latent heat of condensation of the water collected. The energy required was determined based on the coefficient of performance of the chiller and the efficiency of the heat exchanger. Trade-off studies were conducted on system size and energy requirements and the optimum recovery was determined to be in the range of 50

Figure 4 On-Board Water Recovery Unit

to 70%. Test results using the original prototype led a 35% smaller system that consistently recovered 50 to 60% of the theoretically available water.

Water quality analysis identified soot particles, polar and non-polar organics, and metals in the exhaust condensate. The total organic carbon (TOC) varied from 60 to 360 ppm depending on condensate collection conditions. The primary factors affecting TOC concentration were exhaust system temperature, water yield, engine load, and catalytic converter age. Inorganic contaminants identified included aluminum, zinc, boron, phosphorus and iron. The initial treatment train consisted of filtration, activated carbon fiber monolith (ACF), and ion exchange resin. The filtration step was effective in removing soot particles (initial concentration typically 20 to 100 ppm) and improved condensate appearance from a black liquid to a clear brownish-yellow. The ACF removed small non-polar organics, but was unable to remove larger organics or polar organics and consequently was only able to reduce the TOC by 40 to 50%. The ion exchange material was effective in removing all inorganics except boron. The ion exchange material also had a capacity to remove polar organics reduce TOC. These initial results were used to optimize the water purification process. A wood-based granular activated carbon (GAC) was selected to remove large organics and polar organics resulting in TOC concentrations of 0.1 to 0.3 ppm. A mixed ion exchange resin was formulated to enhance boron removal. The final water treatment was effective in removing all regulated contaminants below drinking water standards. This technology will reduce the logistics footprint by projecting water production forward to the point of use and create a more mobile and flexible water sustainment capability. The technology may enable FCS and units to operate for 3 to 7 days without external resupply of water.

Atmospheric humidity is the most widely and evenly distributed source of water on earth. However, water vapor is always a dilute component of air and in extreme hot, dry environments is only about 1% of the air volume. The mass of water available for recovery from the atmosphere is sufficient to support the soldier even in these hot dry environments, but due to the low concentration the process either requires large quantities of energy to remove the water by condensation or large volumes of adsorbents to concentrate the water vapor coupled with energy requirements that are still quite significant. Approximately 630 watt hours are required to condense a single liter of water and in the hot dry environment this may be only 10% of the total energy requirement if a sufficient quantity of air to produce 1 liter of water must first be cooled to the dew point, from roughly 120 degrees F to 20 degrees F. Unfortunately, conventional methods of collecting this water are too large and energy intensive applicable to battlefield requirements. A system to produce water from air built using current technology and concepts would be over 35 times larger and use 40 times as much energy as conventional Army water purification equipment. In order to have military utility water from air systems must obviously be brought more in line with current water purification equipment.

Promising technologies under development by the Army and DARPA such as, humidity concentration using zeolite and chemically surface modified activated carbon combined with innovative low energy condensation concepts, may make battlefield water generators a reality. In order to reduce the size and energy requirements of water generation systems, cooling based systems must be consistently fed a high humidity source air or new condensation concepts need to be developed using alternatives to cooling. The humidity concentrator collects water from the source air as it flows through the channels of the concentrator. Once a channel has collected all the water it can hold the flow is reversed. This removes the water from the channel and creates a highly humidified product stream. The key to the humidity concentrator is a chemically surface-modified activated carbon that adsorbs the water in the channels. During the project's proof-of-concept phase funded by DARPA, Nanopore Inc., and Mesosystems Technology demonstrated a chemically surface modified activated carbon that could adsorb more water than traditional adsorbents. Of equal importance the team was able to show that the water could be removed from the carbon with less energy than required for traditional adsorbents. This device may be coupled with any device that creates water from air to enhance the system's performance and create a compact, energy efficient system. Another project will be an adsorbent based system that will focus on enhancing performance through the development of more efficient lighter weight adsorbents coupled with innovative condensation approaches. Other approaches supported by

DARPA and TARDEC will investigate new ways to condense water based on facilitated membrane transport, variable surface energy materials, and electrostrictive polymers coupled with extremely high coefficient of performance cooling cycles. Under the facilitated membrane project membranes will be developed that act in a manner similar to biological membranes which can pump molecules across the membrane against a concentration gradient. Materials with an affinity for water can be embedded in these membranes to enhance the transport across the membrane and reduce the power requirements. In the variable surface energy project membranes are under development in which water affinity through a pore can be induced to change. In the case of the variable surface energy materials the hydrophobicity/ hydrophilicity can be varied using electric potential. A material can be made to be water loving (hydrophilic) as the source air is fed across the membrane. After the membrane is saturated with water the membrane can be converted to a water hating surface (hydrophobic) by an electric potential causing the water to bead up.

Water from air technology has the potential to enable the development of small modular water purification devices including stand alone water generators for the individual soldier, small units, and subsystems embedded in combat systems or closed-loop water recovery for combat systems. The technologies described above may reduce the size by 5 to 15 times and reduce the power requirements by 2 to 5 times. This power requirement would logistics footprint by 4 to 10 times since each gallon of fuel consumed would produce 4 to 10 gallons of water at these reduced power requirements.

7. Summary and Conclusion

Potable water is one of the most basic logistic requirements for ground based military forces, particularly in arid environments. Water directly affects the health and welfare of the individual soldier as well as the combat readiness of deployed forces. The core technology in the Army and Marine Corp fielded tactical water purification units is reverse osmosis. While the current systems have provided the Army with the capability to purify any source water with sufficient quality and quantities to support deployed troops, both near and mid term improvements are needed to support the water sustainment concept and transformation to a lighter, more mobile and deployable force. Near term improvements are needed in membrane technology and systems to reduce the size and weight of the systems, reduce power, improve resistance to fouling, and improve rejection of potential chemical threat agents. The U.S. Army, Office of Naval Research, and Defense Research Project Agency (DARPA) are conducting collaborative research efforts to develop new membranes, new pretreatment technology, and new membrane system concepts to address the limitations of current technology for military water purification applications. Water distribution is projected to be 30 to 40% of the daily sustainment requirement for a unit of action in a future force using current technology. The goal of mid term research being conducted the U.S. Army and DARPA is to reduce the sustainment requirement and logistics footprint associated with water production and distribution. The goal of reducing the water logistics burden will be achieved by pursuing two complementary objectives. The first is to develop advanced water purification technologies that are more energy efficient, lightweight, and compact than current state-of-the-art water treatment technologies, providing the core technology for the next generation of water purification systems. The second objective is to generate or recover water on demand from alternative sources such as, vehicle exhaust and ambient air, to produce water when no traditional source (river, lake, or ocean) is available providing the core technology for new water generation systems. Two of the most promising concepts under development are water recovery from combustion engine exhaust and water generation from air. In response to changing missions and priorities, the Army is transforming into a lighter, flexible, more responsive force and its ability to purify water must transform as well. Technology to enhance fielded purification systems will provide safe drinking water to all US forces and while improving deployability and reducing sustainment requirements. Future technologies being developed will take things a step further by providing military units with a radically more mobile and flexible water production capability. These technologies will reduce the logistics footprint by projecting water purification and production capabilities forward to the point of use, greatly reducing the amount of water that needs to be provided by the logistics system.

8. References

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Self Hydrating Ration

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SELF HYDRATING RATION

Water logistics continues to be an important issue for maintaining the hydration status and performance of the warfighter. Potable water requirements add considerably to the overall weight and volume of the soldier's load. Water re-supply in remote areas is difficult and places a burden on logistics. The development of a Self Hydrating Ration (SHR) would allow the direct re-hydration of dehydrated ration components, (especially electrolyte/carbohydrate based beverage powders) by non-potable water sources, providing hydration and nutrition while enhancing performance. Semi-permeable membrane technology coupled with food osmotic potential can be integrated into the SHR for the safe and effective re-hydration of dried beverages and foods by non-potable water sources. Forward Osmosis (sometimes referred to as Direct Osmosis) is a technology that shows promise for providing the warfighter with potable liquids that are obtained from water sources of unknown quality. Hydration bags containing two compartments, one to hold the non-potable water and the second to hold the nutrient powder, were developed for testing. Water purification is achieved by osmosis through a semi-permeable membrane that forms part of the inner compartment. Charging that vessel with nutrients of high osmotic potential will drive the osmotic process. The semi-permeable membranes have a molecular selectivity similar to reverse osmosis membranes, which means water can pass through the membrane from non-potable water but bacteria,

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viruses and parasites cannot. Studies evaluating the osmotic potential of different nutrients used to produce drinks and foods were analyzed for their effects on the flux of water through the membrane. Membrane stability at elevated temperatures typical to those exposed to by military subsistence was also tested. Results demonstrated that the membranes when stored in military packaging were stable at 100^{o}F for more than 3 months (the study is still in progress). The effect of mmols of specific food ingredients on flux (mL of water filtered/hour) was identified. This data coupled with sensory testing will allow for the development of SHR based ration items with improved rates of re-hydration from non-potable water sources using the semi-permeable membrane hydration bags. Future work will focus on the integration of the membrane with military packaging for SHR development.

1.0 INTRODUCTION

The United States Military has continuously been searching for ways to reduce the weight and volume that the soldier carries with him into the field during a mission. This is a primary concern of the Army's Objective Force Warrior (OFW) program, its flagship Science and Technology initiative for developing and demonstrating revolutionary capabilities for creating a lightweight, overwhelmingly lethal, fully integrated individual combat system. Today, soldiers on combat patrols in Afghanistan typically carry 92 to 105 pounds of mission-essential equipment. This can include extra ammunition, chemical protective gear, cold-weather clothing, food and water. The ultimate requirement for the OFW system is to weigh no more than 45 to 50 pounds. The Training and Doctrine Command (TRADOC) has established minimum weight requirements depending on the soldier's current mission. The fighting load has a minimum of 50 pounds, no food requirement and 2 quarts of water. The approach marching load is based on the needs for 24 hours with re-supply and has a minimum weight load of 72 pounds that includes 2 Meals Ready-to-Eat (MRE) and 5 quarts of water. The emergency approach load is for when the soldier is not expected to be re-supplied within 24 hours and can have a weight up to 120 pounds. Minimum requirement for food and water are 4 MREs and 7 to 10 quarts of water depending on the climate of the mission. The Office of the Surgeon General (OTSG) requirements for 24 hours is a minimum of 3 MREs (3,600 calories per warfighter per day) and 10 quarts of water. The primary reason that TRADOC requirements and OTSG requirements do not agree is because of the need to reduce the overall weight that the soldier must carry on a mission.

Table 1 provides the current metrics for military field rations and the metrics requirements for OFW. A quart of water weighs approximately 2.1 pounds. A single MRE weighs approximately 1.5 pounds and requires nearly 1.4 pounds of water to rehydrate all the beverages provided with each MRE and provides approximately 1,300 calories (Natick PAM 30-25). The total minimum weight for a 24-hour mission would be 3 pounds for 2 MREs and require 2.8 pounds of water to rehydrate the dehydrated components or 27% of the warfighter's potable water. To meet the OTSG 24 hour minimum requirement of 3 MREs would add 4.5 pounds to the load of the soldier and require 4.2 pounds or 40% from his potable drinking water to rehydrate all the dehydrated items in the ration. The Long Range Patrol (LRP) is a restricted calorie ration that weighs approximately one pound and requires 4.1 pounds of water or 39% of the available potable water to rehydrate all of the rations components. LRP was designed to be an extended life operational ration used to sustain personnel during initial assault, special operation and long-range reconnaissance missions (Natick PAM 30-25).

The SHR concept was developed from the need to reduce the weight of the food carried by the individual soldier while maintaining nutritional requirements and performance. The SHR concept will allow for soldiers to utilize non-potable water sources to rehydrate their electrolyte/nutritional beverages and ration components without added weight. Additionally, the SHR will help improve the warfighter's hydration status by providing an additional source of water and preserve his potable water specifically for hydration needs.

Table 1: Field Ration metrics for one day (OTSG requirements)

Meal Ready-to-eat: (MRE)

4.5 lbs and 0.16 Cu. Ft./day (3600Kcal). 4.3 lbs water to rehydrate beverage components. Total weight 8.8 lbs/day.

Meal, Cold Weather:

3 lbs and 0.12 Cu. Ft./day (4500 Kcal). 12.3 lbs to rehydrate ration.

Total weight 15.3 lbs/day.

Long Range Patrol:

1 lb and 0.04 Cu. Ft./day (1500 Kcal). 4.1lbs of water to rehydrate ration.

Total weight 5.1 lbs/day.

Acceptable Metrics for OFW: < 3 lbs. 0.12 Cu. Ft./day

2.0 SELF HYDRATING RATON

The goal of the self-hydrating ration program is to develop and integrate semi-permeable membrane technology with military packaging charged with osmotic enhanced food materials for the hydration and sustainment of individual soldiers from non-potable water resources. Semi-permeable membrane technology coupled with osmotically effective food ingredients can be developed into the SHR for the safe and effective rehydration of dried beverages and foods by non-potable water sources. Forward Osmosis (sometimes referred to as Direct Osmosis) is a technology that shows promise for providing the OFW with potable liquids that are obtained from water sources of unknown quality. Creating a liquid containment vessel from a customized membrane, charging that vessel with nutrients of high osmotic potential to drive the osmotic process, and adding non-potable water to the outer reservoir of pouch/membrane complex can produce potable liquids or rehydrated meals in a silent manner without the use of mechanical aids. The process requires zero power, reduces cube and weight that the soldier carriers, provides performance enhancement and endurance.

2.1 Forward Osmosis

Osmosis is the natural diffusion of water through a semi-permeable membrane from a solution containing a low concentration of dissolved species to a solution having a higher concentration of dissolved species. A semi-permeable membrane is a barrier that works like a molecular sieve; it allows small molecules such as water to pass through it, but blocks larger molecules such as salts, sugars, starches, and proteins. The semi-permeable membrane also blocks viruses, bacteria, and parasites. Osmosis is the process that occurs when two different solutions contact opposite sides of a semi-permeable membrane. The only molecule that can theoretically move through the membrane is water. Water molecules will therefore move from one solution to another to achieve maximum mixing, i.e. equilibrium. Thermodynamically, the strength of this mixing tendency is measured by the solution's "osmotic potential," or "osmotic pressure." The osmotic potential is high for concentrated solutions and low for dilute solutions, and is roughly proportional to the molar concentration of dissolved species. When a semi-permeable membrane separates two solutions, water always moves from the solution with lower osmotic potential to the solution with higher osmotic potential. Also, the greater the difference in osmotic potential, the faster water moves through the membrane. It is important to note that the osmotic potential depends on the molar concentration, not the weight of dissolved species. Molar concentration is a measure of the number of molecules dissolved, not the weight of material in solution. This means 100-g/liter solution of a small molecule like table salt has a far higher osmotic potential than 100-g/liter solution of a large molecule like starch.

Osmotic pressure is the pressure that must be applied to a solution to prevent a net transfer of water into the solution across a semi-permeable membrane. Table 2 shows the osmotic pressure for some compounds.

Table 2. Osmotic Pressure of Aqueous Solutions (HTI White Paper, 2003)

Compound	Osmotic Pressure, psi (kPa)
Sea water, 3.5%	400 (2,800)
Fructose, 15%	400 (2,800)
Fructose, 6%	130 (900)
Human Blood	100 (700)
Sucrose, 6%	80 (540)
Muddy, brackish water 1,600TDS	20 (140)

Mathematically, the rate of water crossing the membrane (Q) is roughly proportional to the membrane area (A) times the difference in the concentrations of dissolved species on the two sides of the membrane (C_N and C_W), where C_N and C_W represent the dissolved concentration in the nutrient drink and contaminated water, respectively. A mass-transfer coefficient, which is actually only a proportionality constant (K), is used to create an equation. This constant is a fairly strong function of temperature, increasing about 2% for each degree Celsius. Commonly, the constant is measured at 20°C (68°F), leading to the following equivalent equations (HTI White Paper, 2003):

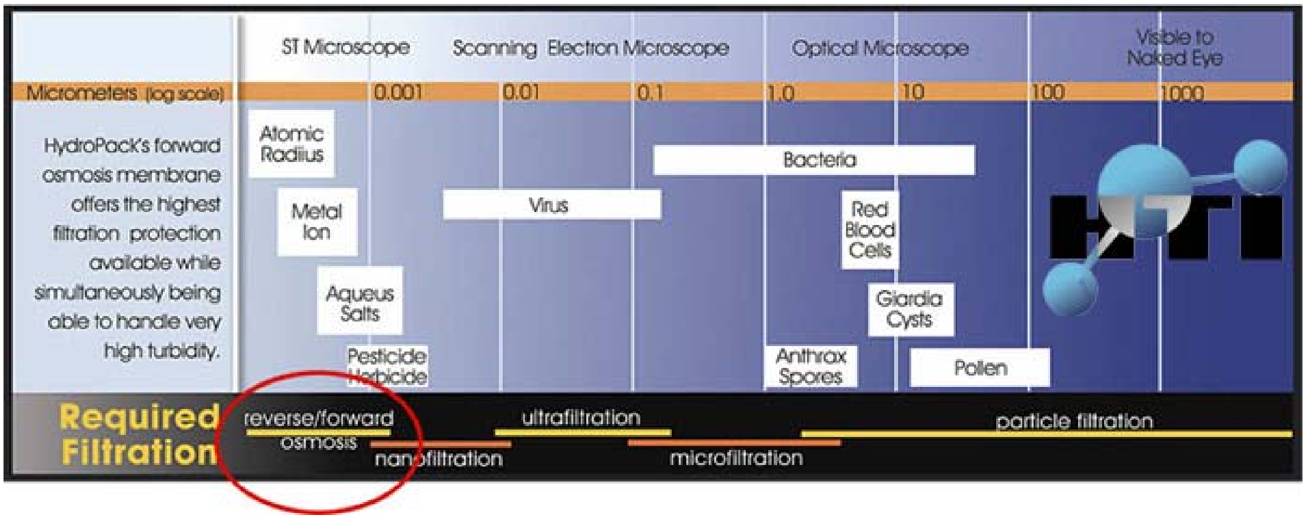
$Q = K_{@20°C} * 1.02_{(T-20°C)} * A * (C_N – C_W)$ [1] or $Q = K_{@20°C\ (=68°F)} * 1.011_{(T-68°F)} * A * (C_N – C_W)$

The mass-transfer coefficient represents the resistances that the water encounters as it moves from the contaminated water into the membrane, then across the membrane's rejection layer, and finally into the nutrient drink. The coefficient will increase if the solutions are pumped across the surface of the membrane.

2.2 Hydration Technologies Inc.'s Semi-permeable Membrane

HTI has developed a man-made version of naturally occurring membranes by casting thin sheets of a water-absorbent cellulose-based plastic. There are several characteristics of the membrane that have been optimized to produce superior performance. Membrane selectivity is categorized by their pore sizes. Microfiltration (MF) membranes have pore sizes larger than 0.1 micron and are capable of filtering parasites and suspended particles from water. Ultrafiltration (UF) membranes have pore sizes between about 0.01 and 0.1 microns and are capable of filtering bacteria and the majority of proteins and viruses from water. Nanofiltration (NF) membranes block all biological species as well as medium sized molecules such as sugars and pesticides. Reverse osmosis (RO) and forward osmosis (FO) membranes block all species except water and the lightest uncharged molecules such as ethanol and urea. HTI's osmotic membrane is a very selective FO membrane that has been developed to reduce the levels of heavy metals, pesticides and organic toxins in the water by up to 95%. Figure 1 presents the filtration range of the various membrane technologies.

Figure 1: Filtration Technologies



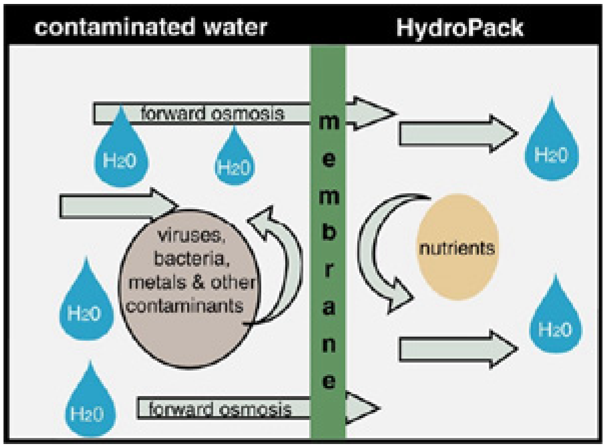
The nominal pore size of the HTI forward osmosis membrane is 3-5 angstroms. The size of bacteria ranges from 2,000 to over 500,000 Å. The smallest viruses are 50 to 1,000 Å.

HTI's membranes are made from cotton-derived, celluloseester plastics. These membranes have the advantage that they are extremely water absorbent, which allows water to easily diffuse through them. Common RO membranes that have the same selectivity are far more water repellent, making them unsuitable for osmosis. Since osmosis is a diffusion-based process, water transfer rates through the membrane tend to be slow. An important method in improving water transfer rates is to make the selective part of the membrane as thin as possible. Diffusion through a MF membrane is much faster than that through a FO membrane, so HTI produces membranes with a very thin (10 micron) FO membrane on top of a microfiltration membrane. Mechanical strength is provided to the membrane by imbedding the MF membrane in a fabric backing. The mechanical strength provided by HTI's membranes are a primary reason for investigating their use in military field rations. Previous attempts by Natick Soldier Center identified membranes with good flux potential (Zelman 1983 and 1990 and Ilias and Schimmel, 1992), however these membranes proved to be fragile and could tear easily making them unsuitable for military field operations.

2.2.1 Forward Osmosis Verses Reverse Osmosis

Forward osmosis is different from reverse osmosis, which uses hydraulic pressure to force liquid through a membrane. That requires a piece of machinery and a power source. With forward osmosis, you have no moving parts, and the pressure is what is called osmotic potential, which simply takes advantage of the natural tendency of any two substances to want to mix together when placed in contact. The nutrient mixture inside the bag and the water outside the bag want to mix, and so they do, but the mixing can only take place inside the bag because the nutrient particles are too big to get out. Because the contaminants in the water are also too big, they can't get in. Reverse osmosis is defined as “the pressure driven transport of water through a semi-permeable membrane in opposition to an osmotic potential.” In this definition, “pressure driven transport” means that if a solution is contacted to one side of a semi-permeable membrane and pressure is applied to the solution, water is forced through the membrane. This water transport is useful because the molecular selectivity of the membrane permits purified water to pass while preventing other species from leaving the solution. Reverse osmosis is widely used in a variety of applications such as desalinating seawater and filtering unpalatable tap water. The term “in opposition to an osmotic potential” refers to the separation of water from a solution in opposition to its natural tendency to stay mixed. As an example, if dilute apple juice is subjected to reverse osmosis, water will be squeezed from the juice and a concentrated juice will remain. This separation requires pressure and energy to overcome natural osmosis, and is therefore termed reverse osmosis (HTI White Paper, 2003).

Figure 2: HTI’s Forward Osmosis Membranes



The requirement for high pressure makes reverse osmosis impractical for passive, man-portable water filtration. HTI’s forward osmotic filters have the advantage that they require no pumps or energy. Water filtration occurs by contacting one side of a semi-permeable membrane with a nutrient syrup or powder, and contacting the other side with contaminated water, Figure 2. Osmosis then causes water to move through the membrane from the dirty water into the drink concentrate. Perhaps the biggest advantage of forward osmosis is their tolerance of extremely muddy water (up to 1000 NTU). Because forward osmosis works by diffusion instead of pressure, particulates are not forced into the membrane pores and the performance in muddy water is essentially identical to that in clear water.

2.3 Evaluation of Semi-Permeable Membrane Pouches

An important feature of the SHR that may require optimisation for eventual fielding of the product is the time required to rehydrate the product prior to consumption. This is associated with membrane flux, the amount of fluid passing through the membrane and is usually expressed as the volume per unit membrane area per unit time, i.e. $L/m^2/hr$ (Cheryan, 1986). Semi-permeable membrane pouches from HTI were used to evaluate the flux of different powdered drinks as well as to identify ways of increasing flux through the membrane. All data is based on ingredients used for producing a twelve-ounce (340 grams) beverage. The osmotic potential of different food ingredients was also examined to identify their individual effect on flux. This data will help with the final development of products for the SHR. The osmolality of the developed products will depend on whether the use is for hydration or for providing calories. If the product is for hydration then the optimum osmolality would be slightly below that of normal human serum (295 mOsm/L). If the purpose is to provide calories then the osmolality can be significantly higher. Solutions with higher osmolalities generally will have a greater flux rate through the membrane. Lastly, the semi-permeable membranes must have a shelf life that matches that of the ration they will be used with. Present military shelf-life requirement for field rations is 3 years at 80^{o}F and 6 months at $100\,^{o}$F.

2.3.1 Evaluation of Commercial and Military Powdered Drinks on Flux

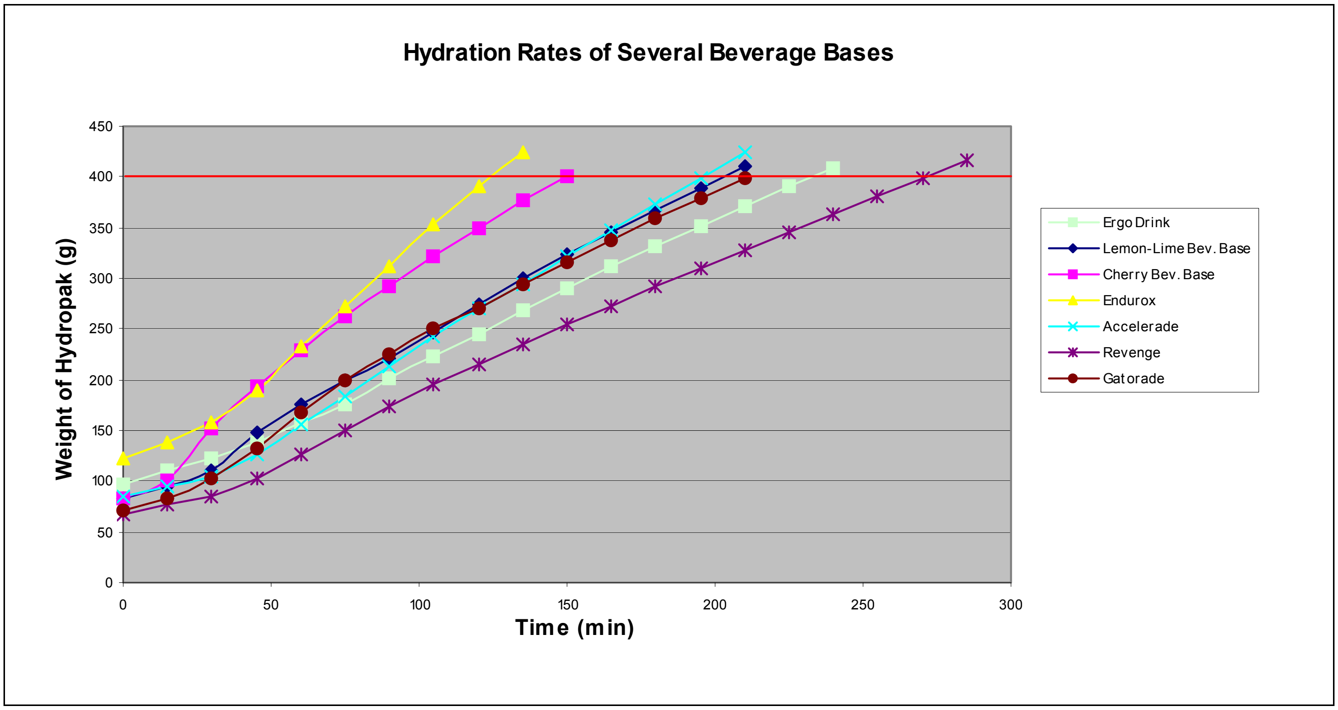
Four commercial and three military produced beverage powers were evaluated with the HTI membrane pouch for the time to produce a twelve-ounce beverage. The membrane pouches were charged with the required amount of recommended powder for a twelve-ounce beverage for each of the test samples. Table 3 list the beverage sample, the initial weight of powder for a twelve-ounce drink and the osmolality of the drink. The osmolality of each drink was determined with a Wescor Vapro® Vapor Pressure Osmometer, Logan, UT. Revenge produced by Cytosport, Benicia, CA is a sports drink marketed as a sustained energy drink for endurance. Accelerade is a sports drink marketed to improve muscle performance recovery as well as extend endurance. Endurox is a performance recovery drink manufactured by the same people (PacificHealth Laboratories, Woodbridge, NJ) who also produce Accelerade. Gatorade, which contains electrolytes, is marketed as a well-known thirst quencher/hydration drink. The Military beverage bases, cherry and lemon-lime, are found in military field rations and contain no electrolytes. Lastly, ERGO Drink is a special complex carbohydrate drink developed by the military to enhance performance. ERGO also does not contain electrolytes.

Table 2. Osmotic Pressure of Aqueous Solutions

Beverage	Revenge	Accelerade	Endurox	Gatorade	Military Cherry	Military Lemon Lime	Military ERGO TP
Grams/12oz	20	36.5	74	24	34	34	47
Osmolality	191	259	641	283	276	201	300

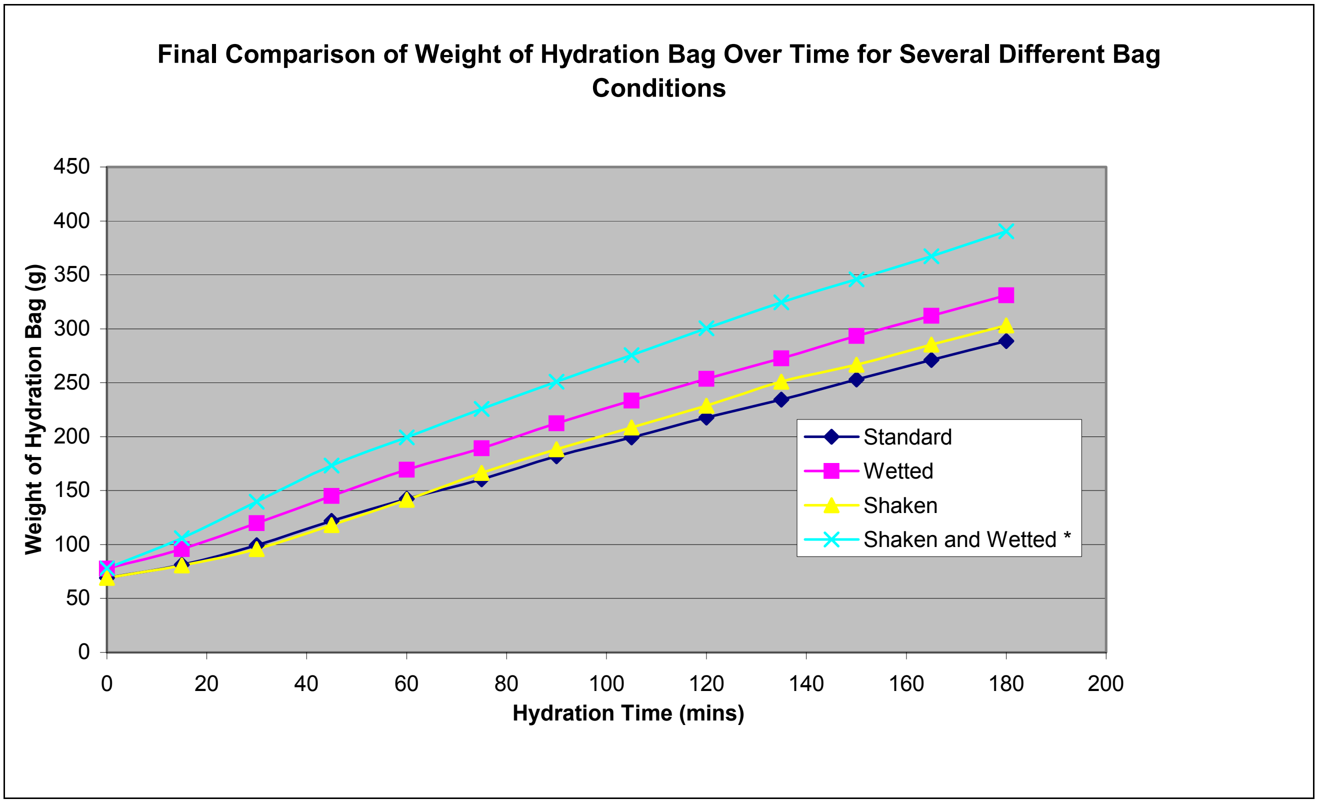
The membrane pouches containing the different drink samples were placed in containers of tap water at 60 ^{o}F and the time to rehydrate the powder was observed. The results from this study are shown in Figure 3. The results showed that Endurox and the cherry beverage base had the greatest flux through the FO membrane, less than three hours. Accelerade, Gatorade and the lemon-lime beverage based had fluxes slightly over three hours. While Revenge and ERGO were both over four hours. Endurox may have performed the best because it contained more than double the dry weight than any of the other drink powders for a twelve-ounce serving and also more than double the osmolality. The military formulated ERGO drink had poor flux results despite the relatively large dry powder amount (47 g) and the second highest recorded osmolality (300mOsm/L). ERGO does not contain any electrolytes and has maltodextrins as its primary carbohydrate source. The powder is also very difficult to dissolve and requires extensive shaking. Based on the dry weight of the powder and the osmolality of the final drink solution, the military cherry beverage base performed the best overall followed by Endurox, Accelerade, Gatorade and the lemon-lime beverage base.

Figure 3: Flux data for beverages rehydrated through Forward Osmosis Membrane



A study exploring ways for improving flux through the membrane was conducted with Gatorade as the control nutrient component. Three other variables were evaluated (agitation, wetting effect and a combination of both) for their potential of improving flux. These three variables were chosen since it was determined that these improvements could be conducted by a soldier in the field by either adding a small amount of his potable water to the nutrient side of the membrane, by carrying the pouch in his pocket while on the move for agitation or both. Results of this study are shown in Figure 4. The data clearly indicates that the rate of flux can be reduced by either wetting the contents prior to submersion of the semi-permeable membrane into water source or by agitation. One of the controlling effects for the rate of flux through the membrane is the initial wetting effect of the dry product. When evaluating the flux data from Figure 3, it was observed that the initial rate of flux through the semi-permeable membrane was very slow and then increased with time until the flux rate reached a plateau state around one hour, then slowly decreased over time (data not shown). Methods for improving the initial flux rate would reduce the overall time to rehydrate the beverage by forward osmosis. From the data provided in Figure 4, it is evident that the combination of wetting the powder (10 ml/sample) prior to exposure to the source water followed by continuous shaking over time (1000 RPM) had the greatest effect on improving flux. The time improvements were 20% as compared to just pre-wetting the powder, 33% better than shaking only and 37% greater than by simple passive rehydration of the powder.

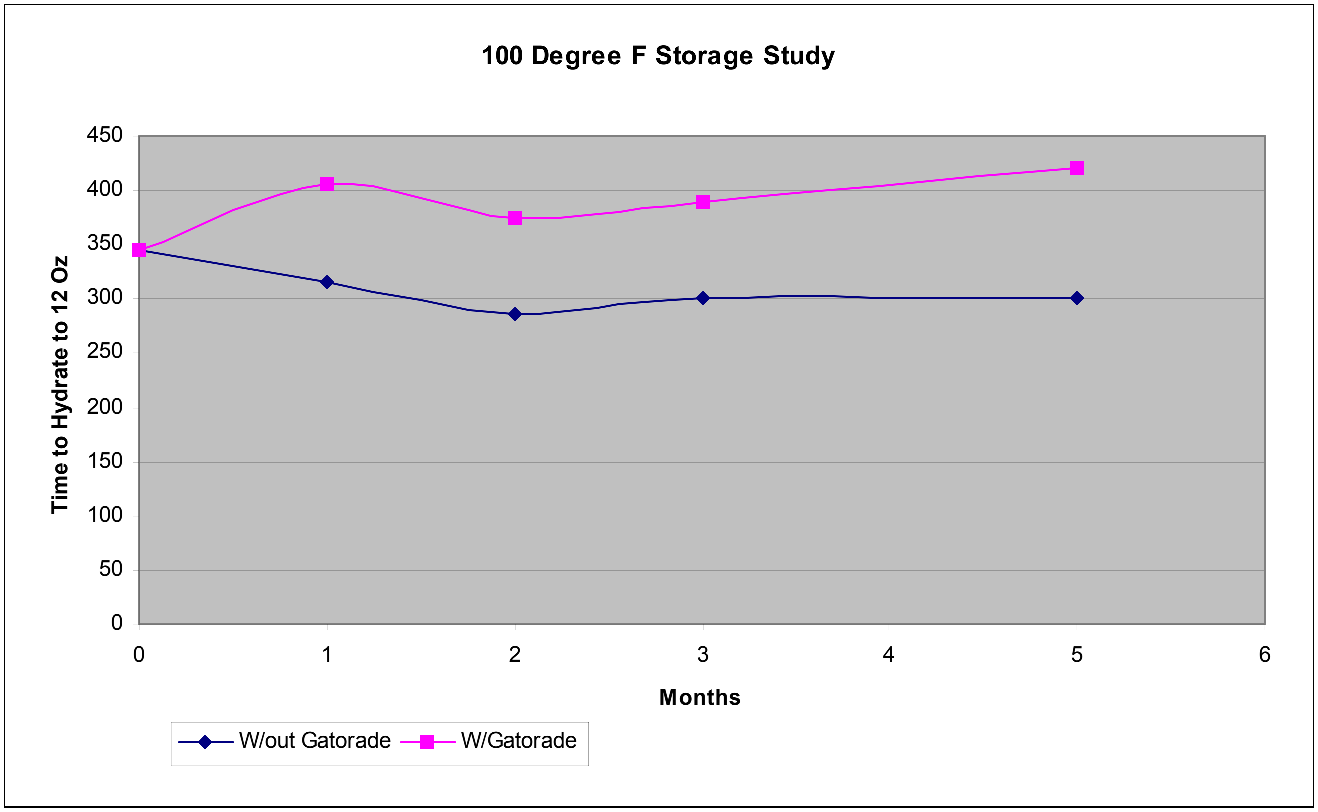
Figure 4: Flux data for wetting and shaking Gatorade FO membrane pouch samples



2.3.2 Shelf-Life Studies of Semi-Permeable Membranes

Military Rations have shelf-life requirement because they are pre-positioned at strategic locations around the world. Ration pre-positioning allows for a rapid deployment of troops during the early stages of a conflict. To meet this need, rations must be nutritionally wholesome, safe and acceptable to the palate. These are difficult constraints that are built into military field rations. If the SHR is to be used as a military field ration it must also past the 3-year 80°F or 6 month 100°F shelf-life requirement for all field rations. The SHR has a semi-permeable membrane that is the crucial element of the ration system. If the membranes are compromised during storage, then the technology will have no value in military feeding. A storage study was conducted to determine the effects of storage temperature and nutrient contact on the membrane. The membrane pouches were stored at 80°F and 100°F with and without Gatorade for 1year and six months respectively. Data for the higher temperature study has been collected up to the fifth month and is displayed in Figure 5. The lower temperature study has only had two data points collected to data and will not be presented at this time. The data from Figure 5 demonstrates that the membranes stored without Gatorade had flux rates greater than the initial membrane before storage. This was not the case with the membranes that contained Gatorade. These membranes had increased rates of flux over time. Reasons for this have not presently been identified. The data does suggest that the membranes themselves are not negatively effected by storage but that the membrane nutrient component interaction might be. Effects may be due to partial blocking of the membrane pores by the food material. Completion of the 80°F storage study will help determine if this phenomenon is due to storage time or temperature. Future studies will look at the effects of different food ingredients on the membrane flux during storage to help with the design of the SHR

Figure 5: Effects of storage on flux of Semi-Permeable membranes



3.0 Summary

Initial efforts have demonstrated the potential for using forward osmosis as a means for rehydrating military ration components, especially beverage items with non-potable water sources. The integration of a semi-permeable membrane pouch within a military foil laminated pouch will enable the warfighter to purify non-potable water and rehydrate ration items simultaneously while on the move and assist in preserving their potable water resources for hydration needs. The self-rehydration ration requires zero power, reduces cube and weight that the soldier carriers, provides performance enhancement and endurance. The integrated FO membrane/foil laminate pouches will be charged with the proper osmotic agents and nutrients, and designed for individual use in sizes based on operational requirements.

[1] Zelman, Allen, “Rehydration of Products in a Membrane Pouch”, Contract # DAAK60-82-C-0021, March 1983.

[2] Zelman, Allen, “Membrane Pouch”, United States Patent #4,920,105, April 24, 1990.

[3] Ilias, Shansuddin and Keith A. Schimmel, “Evaluation of Permeable Membranes”, Contract # DAAK60-92-C-0069, October 1993.

[4] Cheryan, Munir, “Ultrafiltration Handbook”, Technomic Publishing Company, Inc. 1986.

[5] Annonymous, “Operational Rations of the Department of Defense”, Natick PAM 30-25, 5th edition, April 2002.

[6] Hydration Technologies, Inc.’ “Forward Osmosis - White Paper, Osmotic Water Purification Devices”, www.hydrationtech.com/Osmosis_White_Paper March 17, 2003.

Hydrating the Force: Perspectives from Operation Iraqi Freedom

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HYDRATING THE FORCE: PERSPECTIVES FROM OPERATION IRAQI FREEDOM

This presentation reviews the recent U.S. experience regarding soldier hydration and heat illness of a unit in support of Operation Iraqi Freedom. A 3,600 soldier Brigade Combat Team deployed in April 2003 to a hot and arid environment. During the initial movement and acclimatization, which occurred for fourteen days prior to movement into Iraq, water was plentiful and logistically provided by distribution of cases of bottled water. During four days of convoy operations water was rationed to two to three 1.5 liter bottles per soldier. Upon establishment of an area of operations in northern Iraq, water initially continued to be rationed until logistics and supply lines were solidified.

During the initial movement and acclimatization period there were relatively few heat casualties. Heat casualties were higher during the convoy movement and the initial phase of establishing our area of operations. The heat casualties were mostly heat exhaustion cases that were successfully treated by cooling and intravenous infusion. Our impression was that water rationing contributed to the increased number of heat casualties. Water was mainly supplied in cases of bottled water until establishment of the reverse osmosis purification unit (ROWPU). With a significant increase in water production, the standard U.S. Army water buffalo was then used for water distribution. As water supply issues/logistics became solidified and the water restriction was lifted in our unit, the number of heat casualties decreased. In addition, a water source was located on our base and with the assistance of local Iraqi contractors, a well was dug which served as an additional water source.

Our unit did not see any cases of heat stroke, but we did see one case of volume overload/iatrogenic pulmonary edema. Heat exhaustion, heat illness, and dehydration were primarily the heat casualties seen. Factors that were felt to contribute to poor water intake among soldiers were water palpability, water temperature, and inadequate rest due to mission tempo.

Paper presented at the RTO HFM Specialists' Meeting on "Maintaining Hydration: Issues, Guidelines, and Delivery", held in Boston, United States, 10-11 December 2003, and published in RTO-MP-HFM-086.

INTRODUCTION

This presentation reviews the recent U.S. experience regarding soldier hydration and heat illness of a unit in support of Operation Iraqi Freedom. A 3,600 soldier Brigade Combat Team deployed in April 2003 to a hot and arid environment. During the initial movement and acclimatization, which occurred for fourteen days prior to movement into Iraq, water was plentiful and logistically provided by distribution of cases of bottled water. During four days of convoy operations water was rationed to two to three 1.5 liter bottles per soldier.

BODY

Upon establishment of an area of operations in northern Iraq, water initially continued to be rationed until logistics and supply lines were solidified. It was felt that this rationing contributed to the number of heat injuries seen. The desert temperatures reached highs of 125-135 degrees F during the summer months. Efforts were made to provide cool drinking water by submerging bottles in coolers with non-potable ice bought on the local economy. As the logistics became more solidified, more bottled water became available. Along with this the reverse osmosis water purification unit provided another bulk source of water. Water temperature and palability remained issues that hindered consumption. Some soldiers did not trust or understand the production of water from the ROWPU and were hesitant to use the water buffalo for oral hydration. The majority of heat injuries were treated with rest and intravenous normal saline. Heat exhaustion, heat illness, and dehydration were primarily seen. Figure 1 show the number of heat injuries during the course of deployment months. The abrupt drop in heat injuries in the hottest part of the summer is attributed to the significant increase in water availability. In addition, a water source was located on our base and with the assistance of local Iraqi contractors, a well was dug which served as an additional water source.

We did not see a case of heat stroke; however we did have one case of volume overload/iatrogenic pulmonary edema. A young soldier was flown in for possible heat stroke. He was alert, mentating, but seemed slightly confused. He had received total of 4 liters upon arrival to our clinic. He had a mild temperature, electrolytes were within normal limits, and his pulse oximetry was 82% on room air. His chest x-ray was consistent with volume overload. He was given 40mg IV Lasix with good response. His mental status improved and oxygen saturation increased to 98% on room air.

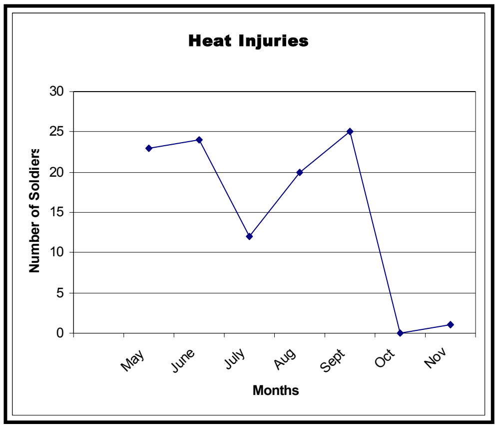

Figure 1: Heat Injuries per Month

The second peak seen during deployment was felt to be related to the increased operational tempo. As the number of attacks on US troops increased so did the number of missions. An increased number of heat injuries seen at the Echelon 1 level of care were reported but these soldiers did not require evacuation to Level II facilities.

CONCLUSION

Water rationing contributes to an increased number of heat injuries. Water temperature and palability remain factors that contribute to poor intake among soldiers. Soldiers can maintain adequate hydration without the risk of hyponatremia with good clinical guidance.

Cognitive Performance: Effect of Drug-Induced Dehydration

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ABSTRACT

Dehydration levels of 1-2% body weight are commonly observed in aircrew of both fixed- and rotary-wing aircraft, while dehydration to levels of 3% or more have been observed during UK helicopter Search and Rescue operations. Although the physical effects of dehydration are known to increase the risk of heat illness and reduce exercise capacity, the effects of dehydration on cognitive performance are less well understood. Previous laboratory studies, using exercise-in-the-heat to induce dehydration, indicated that levels of dehydration of 1-2% were unlikely to impair cognitive performance, whereas with levels of 3-5% dehydration impaired psychomotor performance was observed. At present, the contribution of dehydration, in the absence of heat strain and/or fatigue, to the impairment of cognitive performance is unknown. Some quantification of the risk to aircrew operational efficiency of dehydration, whether or not accompanied by heat strain, would inform guidelines for optimal hydration status of UK aircrew. The study described therefore investigated the effect of dehydration per se, (ie in the absence of physical fatigue and heat strain) on cognitive performance. The performance of 7 male subjects was tested on complex (Multi-Attribute Task battery) and simple tasks (choice reaction time, memory, sustained attention) after dehydration was induced by ingestion of the diuretic drug, frusemide. The study was designed controlled for the effect of a drug-induced (ie unrelated to dehydration) impairment of performance. Mean dehydration levels based on weight loss were 3.5 (range 2.4 to 5.0) %. There were no changes in cognitive performance related to dehydration. Together with our previous studies, results indicate that for hot environments in which aircrew may operate, heat strain sufficient to increase deep-body temperature by 1.0^{o}C, or dehydration levels of up to 3.5%, are, by themselves, unlikely to impair cognitive performance. However, heat strain combined with levels of dehydration greater than 3% does impair cognitive performance. It appears, therefore, that the co-existence of heat strain and dehydration in aircrew may pose a risk to aircrew performance and operational efficiency. The risk of dehydration and concomitant heat strain needs to be considered whenever military personnel are operating under conditions requiring various combinations of high work rates, heavy or insulative protective clothing, and hazardous environmental conditions.

1.0 INTRODUCTION

Under conditions of raised ambient temperature, laboratory performance of simple cognitive tasks is reported to show minimal or no impairment. However, performance of more complex cognitive tasks that are more representative of military or industrial type work is reported to become impaired when environmental conditions exceed 30-33°C wet bulb globe temperature (WBGT) [1]. Such environmental conditions are not uncommon in the cockpits of both fixed- and rotary-wing aircraft and this suggests that any heat strain resulting from operating in such environments may be detrimental to aircrew performance and, at present, poses an unquantified risk. Additionally, heat strain, whether as a result of exposure to hot

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environmental conditions, or as a result of physical effort, is often accompanied by dehydration. To what extent dehydration may be implicated in impaired cognitive performance in the heat is unclear.

In order to understand further the relationship between thermal physiological responses and impaired cognitive performance, we carried out 3 studies (Study 1, 2 and 3). In all 3 studies, performance on simple and complex tasks involving various aspects of cognition was investigated. The difficulty level of the tasks was the same for all studies. In Study 1, subjects were exposed to thermal environments above 33°C WBGT, which were considered likely to increase thermal strain (an anticipated deep-body temperature rise of 0.5 - 1.0°C). In Study 2, subjects were dehydrated to levels of 1, 3 and 5% body weight loss as a result of exercise in the heat. In Study 3, dehydration was induced in the absence of heat strain or physical fatigue by the ingestion of a diuretic drug. Thermal strain (rectal temperature, mean skin temperature, heart rate) was measured in Study 1 and 2.

A brief description of Study 1 and 2 will be given to help inform the rationale for Study 3, which will be described in more detail in this paper. There were minor differences in the methodology for the measurement of cognitive performance between studies; these will be mentioned as appropriate in the description of each study.

2.0 METHODS

2.1 Performance tasks

Performance on a range of cognitive and subjective tasks (Table 1) was assessed during sessions of 40-60 minutes duration. The multi-attribute task (MAT) battery [2] (described below) is considered a complex task and has been used in a variety of studies [3, 4, 5, 6]. Performance on the MAT battery and Digit Symbol Substitution (DSS) were assessed in all 3 studies. The other tasks described in Table 1 were included in Study 2 and Study 3. Subjects were trained on all the tasks before the start of each study. For the MAT battery, at least 10 training sessions, each lasting 1-hour, were required for those unfamiliar with the battery. The MAT battery and all other tasks, except DSS, were displayed on a desktop monitor and controlled by desktop computer software. During training and the studies, subjects carried out the tasks seated at a desk. They made responses to the tasks using a conventional keyboard. DSS was a paper and pencil task.

Task type	Task(s)
‘Simple’	Sustained attention; Choice reaction time; Memory recall; Digit Symbol Substitution
‘Complex’	Multi-attribute task battery¶
Subjective	Alertness; Workload and Performance; Mood
¶Multi-attribute task battery consists of 4 tasks: System Monitoring, Communications, Tracking, Resource Management (described below)	

Table 1. Subjective and objective performance tasks

2.1.2 Objective tasks

2.1.2.1 ***The multi-attribute task (MAT) battery*** [2] is software designed for laboratory studies of pilot performance and workload, and incorporates tasks analogous to aircrew in-flight activities. The parameters of each task can be altered to provide different levels of demand on the subject. In each study the level of difficulty was pre-set and was the same for each performance session. The task comprised four tasks analogous to some of those carried out by aircrew, and were ‘System Monitoring’ (consisting of 2 sub-tasks, ‘Lights’ and ‘Scales’), ‘Tracking’, ‘Communications’ and ‘Resource Management’:

System Monitoring	Observing and responding to the presence and absence or red and green 'Lights', and to moving 'Scales' indicators
Tracking	Maintaining a randomly moving circle on a central target by means of a hand-held joy-stick
Communications	Identifying own 'call-sign' (auditory signal) and responding to instructions
Resource Management	Maintaining target levels of 'fuel' within 2 tanks by activating and de-activating fuel pumps

The tasks were displayed on a monitor screen divided into four 'windows', each window displaying one of the tasks (Figure 1). The System Monitoring and Resource Management tasks were continuous; the Communications and Tracking tasks were intermittent.

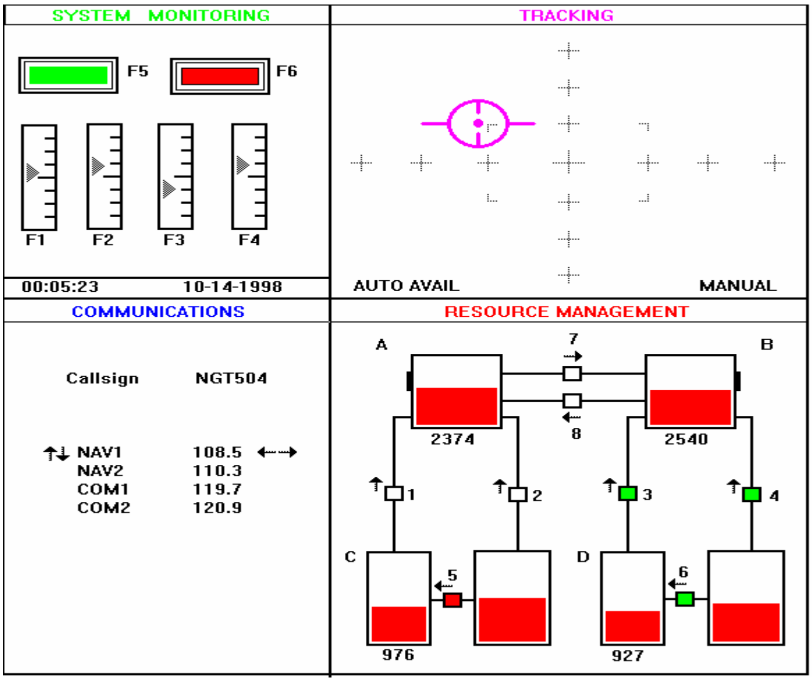

Figure 1. Multi-attribute task (MAT) battery

2.1.2.2 ***Sustained attention*** [7] was used to assess working memory. A random sequence of letters was presented one at a time on a monitor at a rate of one per second. Two letters, the critical stimulus, were displayed continuously at the top left-hand corner of the screen. Subjects were required to press a response button within 0.75 seconds whenever the letters of the critical stimulus were displayed consecutively during the random sequence. There were between 60 and 85 critical stimuli during the task.

2.1.2.3 ***Memory recall*** [8] was used to assess encoding and decoding in working (short-term) memory. A series of single-digit numbers (1-9) was presented simultaneously above and below a horizontal line. The subjects were required to memorise the digit below the line and compare it with a digit above the line in the next presentation. Subjects were asked to respond by pressing the appropriate button for a 'same' or a 'different' number. The task was self-paced with each presentation lasting a maximum of 2 seconds.

2.1.2.4 ***Choice reaction time*** [9] was used to assess visual response time to a series of crosses individually presented in one of four positions on a screen - top right, top left, bottom left, bottom right. The subjects were required to press one of 4 response buttons, corresponding in spatial arrangement to the 4 possible positions of the cross on the screen, as soon as possible after the appearance of the cross. The task was self-paced with a total of 160 trials presented.

2.1.2.5 ***Digit symbol substitution*** [10] required the subject to substitute symbols for digits according to a code, as fast as possible, for 2 minutes.

2.1.3 Subjective tasks

2.1.3.1 ***Alertness*** [11]: The subjects chose one of seven statements that best described their arousal level. The extremes of the scales were 1:fully alert; wide-awake; extremely energetic, and 7:completely exhausted; unable to function effectively.

2.1.3.2 ***Mood*** [12]: Analogue scores (intersection point on a 10-cm line) were recorded for 12 aspects of mood.

2.1.3.3 ***Task Load Index*** [13]: Subjective assessments of six aspects of performance on the MAT battery were assessed using the NASA Task Load Index (NASA TLX). For five of the scales (Mental Demand, Physical Demand, Temporal Demand, Effort and Frustration), subjects were required to rate their perceptions on a graded scale from 'Low' (0) to 'High' (100). For assessment of their 'Own Performance', the graded scale was from 'Poor' (0) to 'Good' (100).

2.2 Performance measures

Performance measures for each of the tasks are given in Table 2.

Task	Measure
MAT battery (4 tasks): - System Monitoring (Lights and Scales) - Communications	- Number of correct responses - Response time for correct responses - Number of false alarms - Number of missed responses
- Resource Management	- Mean deviation from target level of 'fuel' - Responses per minute
- Tracking	- Root mean square error score (deviation from target in pixel units)
Digit Symbol Substitution	- Number of substitutions
Sustained attention	- Number of correct responses - Response time for correct responses - Number of false alarms - Number of missed responses
Choice Reaction Time	- Number of correct responses - Response time for correct responses
Memory	- Number completed - Number of correct responses - Response time for correct responses - Number of missed responses
Mood rating scales (12 assessments)	- Analogue scale 0-100 mm
Alertness rating scale	- Score/Scale 1-7
NASA TLX (workload and own performance)	- Analogue scale 0-100 mm

Table 2. Performance tasks and measures

2.3 Physiological strain

Rectal temperature was recorded every minute. Skin temperatures at four sites (biceps, chest, thigh, calf) were recorded every minute and the area-weighted mean skin temperature was calculated [14]. Heart rate was monitored continuously and recorded every 5 minutes. The level of dehydration for Study 2 and 3 was calculated as the change in body weight (corrected for food, urine and faeces) at various time points, from the start (*ie* before exercise-in heat- or drug- induced dehydration procedures), assuming that at their starting body weight each subject was fully (100%) hydrated (euhydrated). Additionally, for Study 3, body water content was measured by the method of bioelectrical impedance.

2.4 Subject restrictions

Subjects abstained from drinking alcohol for 24 hours before each Study and from caffeinated beverages (tea, coffee, chocolate and cola drinks) the evening before, and throughout, each Study. They retired to bed at their usual time on the night preceding a Study and did not take part in any physically stressful activity (*eg*, squash, football, aerobics *etc*) or intense mental activity during the day or evening preceding each Study. Subjects ate a light breakfast before each Study day.

2.5 Statistical analysis

Analysis of variance (ANOVA) was the statistical methods for the analysis of performance and physiological data. To satisfy the criteria for ANOVA (homogeneity of variance, normality and additivity), some data required transformation before analyses could be carried out. Any significant differences ($P<0.05$) observed after ANOVA were further analysed using Newman Keuls range test.

3.0 STUDY 1

3.1 Introduction: Cognitive performance is reported to be degraded when environmental conditions exceed 30-33°C WBGT [1]. The aim of Study 1 was to assess the effect of exposure to thermal environments above 33°C WBGT on cognitive performance.

3.2 Methods: On three occasions, at least one week apart, 3 male and 3 female subjects, dressed in Royal Air Force (RAF) Tornado, summer, aircrew equipment assembly (excluding helmet and gloves), were exposed for 2 hours in an environmental chamber to each of three sets of environmental conditions (Table 3).

Dry-bulb temperature (= globe temperature)	Relative humidity	Airspeed	WBGT
24°C	40%	0.3-0.5ms^{-1}	18.2°C
40°C	60%	0.3-0.5ms^{-1}	35.1°C
42°C	57%	0.3-0.5ms^{-1}	36.5°C

Table 3. Environmental conditions in which cognitive performance was tested

During each exposure, subjects rested for the first 5 minutes and then carried out performance tasks (MAT battery for 30 minutes; DSS and NASA TLX for the following 5 minutes). This rest and performance sequence (40 minutes duration) was carried out twice more during the 2-hour exposure.

3.3 Results: There were no effects of heat on objective measures of cognitive performance. Subjects were more frustrated, and perceived that a greater physical demand and a greater effort were needed to carry out the MAT battery in the last (third) test session compared with the first test session during exposure (P<0.01), and that the effort needed to carry out the MAT battery in the 42°C environment was greater than the effort needed in 24°C environment (P<0.05). Evidence of thermal strain was indicated by an increase in heart rate, in rectal and mean skin temperatures, and in sweat loss, in the 40°C and 42°C environments compared with the 24°C environment (P<0.001). The increase in heart rate and in rectal temperature was greater in 42°C than in 40°C (P<0.001 & P<0.05, respectively; Figure 2). The increase in rectal temperature at the end of exposure to the 40°C and 42°C environments was approximately 0.5 and 0.7°C, respectively, above that observed in the 24°C environment.

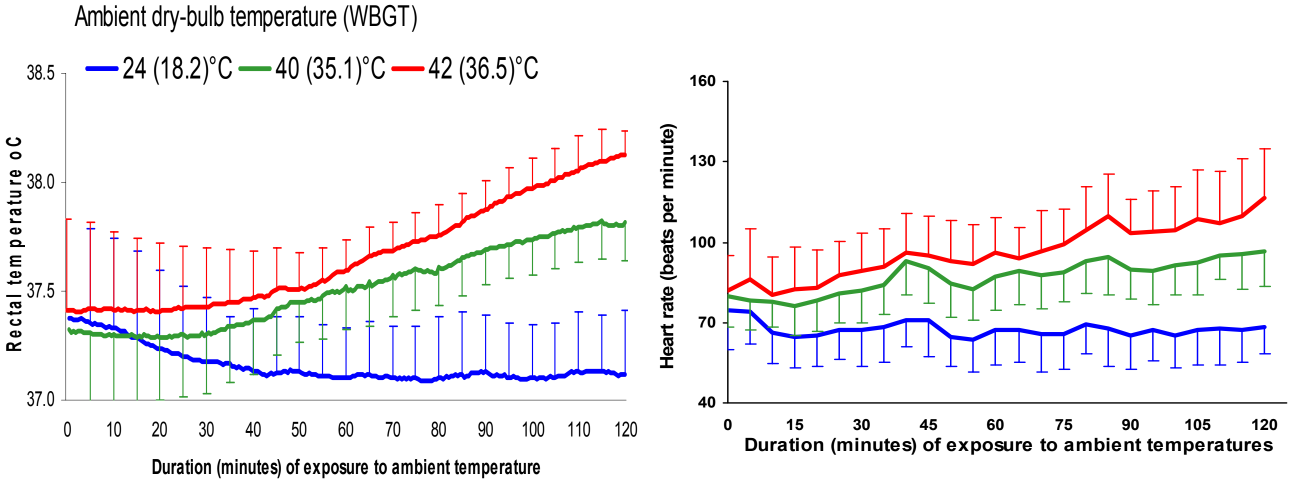

Figure 2. Rectal temperature and heart rate (1SD) during exposure to warm environments

4.0 STUDY 2

4.1 Introduction: Analysis of the data for cognitive performance, subjective comfort and sweat loss, from Study 1 and several similar, published studies, predicted that body water loss, rather than heat strain *per se*, might be an important factor in the determination of impaired performance in the heat [15]. To investigate this prediction further, Study 2 investigated the effects of euhydration and 3 levels of hypohydration (dehydration to 1, 3 and 5% of body weight) on cognitive performance.

4.2 Methods: Seven men carried out 4, consecutive, 65-minute sessions of cognitive performance tasks and subjective assessments (Table 4) in a thermoneutral environment (air temperature [= globe temperature], 24ºC; relative humidity, 30%; air movement, minimal, uncontrolled). Between performance sessions they carried out 3 periods (45, 90 and 90 minutes duration) of exercise (cycles of 9 minutes exercise on a motor-driven treadmill, 3 minutes rest) at 60% of their maximal oxygen uptake, in a warm environment (air temperature [= globe temperature], 35ºC; relative humidity, 30%; air speed, 0.8-1.0ms^{-1}).

They carried out the schedule of 4 performance sessions (Sessions 1, 2, 3 and 4) and 3 exercise periods on 2 occasions, separated by at least 6 days. On one occasion, they carried out the schedule without drinking during the exposure (Dehydration condition) to induce, by sweating, hypohydration levels of 1, 3, 5% of initial (*ie* before the first performance session) body weight, before the commencement of sessions 2, 3 and 4, respectively. On the other exposure, they were required to drink sufficient water throughout the schedule to maintain the same body weight as measured at the start of the schedule (Euhydration condition). The first session (Session 1), before exercise, was baseline performance.

Task	Task duration (minute)
Subjective alertness	0.5
Sustained attention	9
Choice reaction time	3
Memory recall	3
Digit symbol substitution	2
Multi-attribute task battery	30
Subjective workload and performance	1
Subjective mood	2

Table 4. Performance tasks and duration during each performance Session

As a fully euhydrated state was considered unlikely under normal situations, and individuals are often voluntarily dehydrated to 1% body weight, contrast analysis was used to compare data for the mean of sessions 1 and 2 against the mean of 3 and 4, for both the Euhydration and Dehydration conditions.

4.3 Results - Physiological strain and hydration status: Subjects were unable to drink sufficient water to maintain a euhydrated state throughout all sessions for the Euhydrated condition, and were 0.5, 0.9 and 0.9% dehydrated during performance Sessions 2, 3 and 4, respectively. Levels of dehydration attained for the Dehydration condition for performance Sessions 2, 3 and 4 were 1.2, 3.4 and 5.0%, respectively. Dehydration levels were higher for the Dehydrated than Euhydrated condition for Sessions 3 and 4 (P<0.001; Figure 3). Mean skin temperature and heart rate increased throughout exercise periods. Rectal temperature increased throughout exercise periods, and for Session 4 was higher in the Dehydrated than the Euhydrated condition (P<0.05; Figure 4).

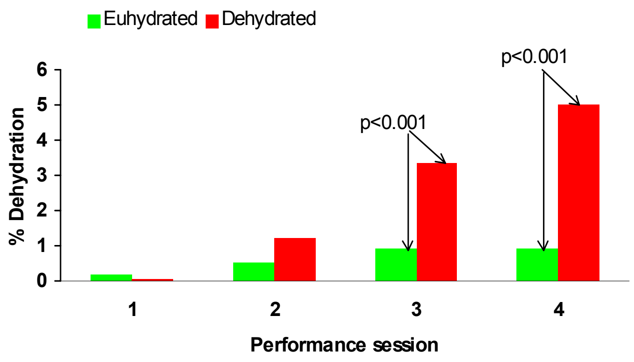

Figure 3. Dehydration level (% body weight) attained at each session for Euhydrated (control) and Dehydrated conditions

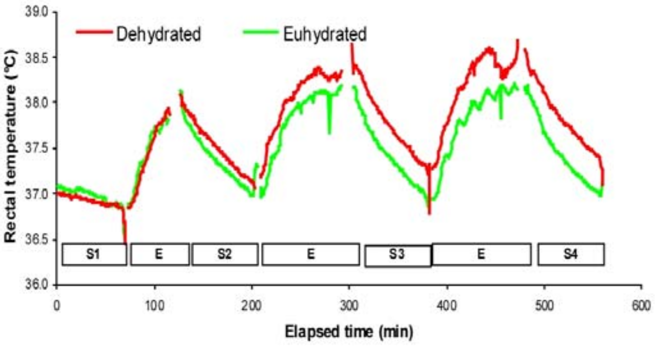

Fig 4. Rectal temperature during exercise (E) and performance Sessions (S1-4)

4.4 Results – Cognitive performance: For the mean over Sessions 3 and 4, tracking error score was greater in the Dehydrated than the Euhydrated condition (P<0.05; Figure 5). For the Dehydration condition, an increase in missed responses for the scales indicators monitoring task, and an increase in response time on the sustained attention task, was observed with the mean over Sessions 3 and 4 (3-5% dehydration) compared with the mean over Sessions 1 and 2 (0-1% dehydration) (P<0.05). Subjectively, alertness was decreased and fatigue was increased in the Dehydration condition compared with the Euhydration condition (P<0.05).

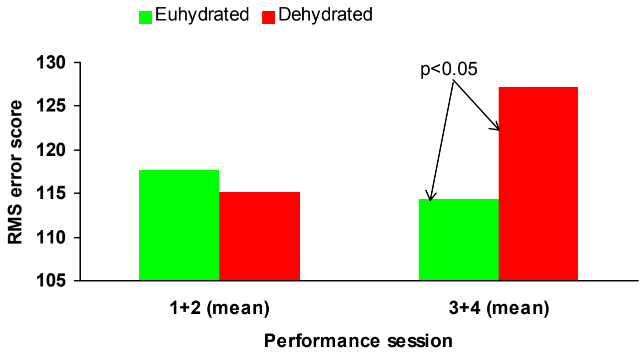

Figure 5. Deviation from target score on MAT battery Tracking task

5.0 STUDY 3

5.1 Introduction: Study 2 indicated that levels of 3-5% dehydration impaired cognitive performance on the tracking task. To further aid our understanding of the role of hydration level in maintaining optimum performance, Study 3 investigated the 'pure' effect of dehydration (*ie* in the absence of physical fatigue and heat strain) on cognitive performance.

5.2 Methods: On 4 occasions, separated by a minimum of 5 days, 7 male subjects carried out cognitive and subjective tasks during 2, 1-hour performance sessions, separated by 2 hours. The tasks used were the same as in Study 2 (Table 4), except that the MAT battery was of 40 minutes duration. On each of the 4 occasions, the tasks were carried out following 1 of 4 Treatments. The Treatments (Euhydration, Euhydration control, Dehydration, and Dehydration control) commenced the day before (Day 1) the cognitive tasks were carried out (Day 2). The order of administration of the 4 treatments was randomised for each subject and comprised the following:

- **Dehydration (D):** administration of the diuretic, frusemide, with restricted water consumption (to induce dehydration)
- **Dehydration control (DC):** administration of frusemide with *ad libitum* water consumption (to control for a drug effect)
- **Euhydration (E):** no administration of frusemide, with *ad libitum* water consumption
- **Euhydration control (EC):** administration of frusemide and sodium supplementation, with *ad libitum* water consumption (to control for the known effect of sodium loss from the body as a result of ingesting frusemide)

For the 3 occasions where frusemide was administered, an initial dose of 40mg was ingested, followed by 80 mg, 4 hours later. A previous study using 80-120mg frusemide ingestion to induce dehydration achieved a mean dehydration level of 4.4% body weight loss after 24 hours [16]. For Treatment EC, a total of 30 tablets each containing 600mg sodium chloride, equivalent to approximately 10mEq of Na^+ (230mg sodium) were ingested in addition to frusemide. By this means, the majority of the estimated frusemide-induced sodium loss was replaced. It was recognised that some additional sodium would be gained from the diet (evening meal on Day 1 and breakfast on Day 2).

5.2.1 ***Day 1:*** On arrival at the laboratory, the subject voided urine. He was weighed nude and clothed, had his body water content measured (bioelectrical impedance), and had a sample of blood taken for subsequent measurement of haematocrit and haemoglobin to calculate change of plasma volume [17]. On the 3 occasions that frusemide was given, the subject ingested 40mg frusemide at 09:30 hours and 80mg at 13:30 hours. On the 1 occasion that sodium was given, the subject ingested 10 sustained release tablets of sodium chloride at 15:30, 16:30 and 17:00 hours. From 09:30 hours, subjects rested quietly for the remainder of the day, being weighed periodically. Other than for Treatment D, and particularly when frusemide was ingested (Treatments EC and DC), subjects were encouraged to drink sufficiently to maintain the same body weight at the value recorded at the start of Day 1.

5.2.2 ***Day 2:*** Subjects followed the same procedures as for Day 1 (body weight and bioelectrical impedance measured; blood sample taken) until 09:30 hours when subjects carried out the first performance session (Session 1) of the cognitive tasks. For subjects on Treatment D, a period of re-hydration, with *ad libitum* water followed (from 10:30 to 12:00 hours). Subjects were asked to drink at frequent intervals in order to attain a sustained water intake, as far as possible, during this period. Body weight and bioelectrical impedance were again measured and a blood sample taken before subjects carried out the second performance session (Session 2) of the cognitive tasks at 12:30 hours.

5.3 Statistical analyses: ANOVAs of the performance data considered the 4 Treatments (E, EC, D, DC) and 2 Sessions (Session 1 and 2) as fixed factors; ANOVAs for the body water data considered 4 Treatments and 3 Times (T1 = pre-Treatment; T2 = pre-Session 1; T3 = pre-Session 2) as fixed factors; ANOVAs for the plasma volume data considered 4 Treatments (E, EC, D, DC) and 2 Times (% change from pre-Treatment to pre-Session 1, and from pre-Treatment to pre-Session 2) as fixed factors. For all ANOVAs, subjects (7) were considered as a random factor. For the data for body water, outliers were excluded for the purposes of analyses.

Prior to analysis, the assumptions of ANOVA (homogeneity of variance, normality, additivity) were studied by considering transformations of the raw data. Where data were transformed for the purpose of analysis, they were back-transformed and corrected for transformation bias for presentation of the results. Newman-Keul's *post hoc* test was used to compare the mean values between Treatments and Sessions. Statistical significance was taken at P<0.05.

5.4 Results – Hydration status

Body weight: The percentage dehydration, expressed as the % change in body weight, for each Treatment is illustrated in Figure 6. The mean (over 7 subjects) dehydration level for Treatment D was 3.5 (range 2.4 – 5.0)%.

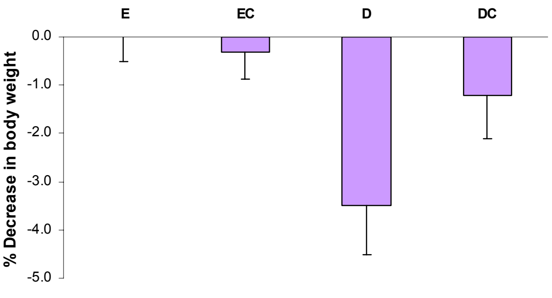

Figure 6. % Dehydration (1SD) after each Treatment

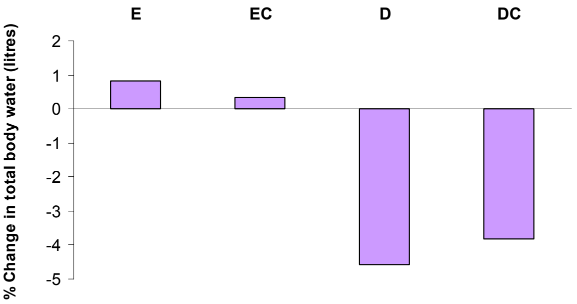

Figure 7. Change in total body water after Treatments

5.4.1 Plasma volume: For Treatments D and DC, plasma volume was decreased compared with E (P<0.01) and EC (P<0.01 and P<0.05, respectively). The result for Treatment DC is consistent with the body weight data, indicating that subjects were unable to offset completely the dehydrating effect of frusemide by *ad libitum* drinking.

5.4.2 Body water: The change in total body water after treatments is illustrated in Figure 7. Total body water was decreased after Treatments D and DC compared with pre-Treatment values (P<0.001). Within pre-Session 1 and pre-Session 2, total body water was decreased with D and DC Treatments compared with E and EC Treatments (P<0.001). The result for Treatment DC is consistent with the body weight and plasma volume data, indicating that subjects were unable to offset completely the dehydrating effect of frusemide by *ad libitum* drinking. Similarly, the 1.5-hour period of rehydration for Treatment D (and DC) was insufficient to return subjects to a euhydrated state.

5.4.3 Water consumed: When the diuretic, frusemide, was ingested and drinking was allowed (Treatments EC and DC), some loss of body weight was observed, being more marked for DC than EC. This suggests that, despite drinking *ad libitum*, subjects were unable to offset completely the dehydrating effect of the drug, but that sodium supplementation (EC) improved hydration status to a level not much different from the euhydrated state (E). These findings were supported by the data for plasma volume and total body water. It is suggested that sodium supplementation stimulated the consumption of water (450ml more than for Treatment DC) and thus improved hydration status, compared with Treatment DC, in the direction of a euhydrated state (Figure 8).

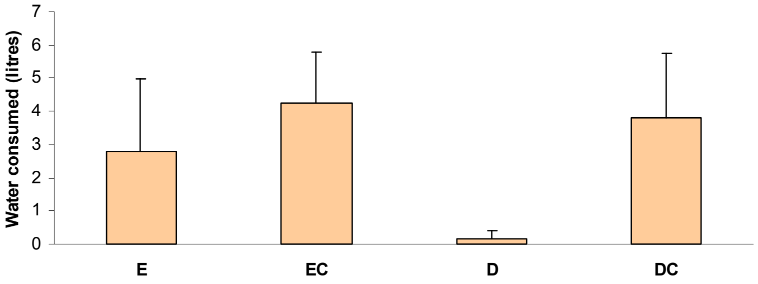

Figure 8. Water consumed (1SD) from the start of Treatments until performance Session 1

During the rehydration period (90 minutes) between Sessions 1 and 2, water consumed was 0.56, 0.40, 1.53 and 0.44 litres for Treatments E, EC, D and DC, respectively. As indicated by the results for body water, the amount of water consumed during this period for the D (and DC) Treatment was insufficient to restore body water levels to that of the euhydrated state (E).

5.5 Results – Performance: No consistent effects of Treatment or Session were observed on cognitive performance or on subjective measures.

6.0 DISCUSSION

Study 3 suggests that dehydration, at least up to 3.5% body weight loss, is without effect on cognitive performance. Study 2, and other studies using exercise-in-the-heat to induce dehydration [18, 19], where both fatigue and heat strain were present, demonstrated impaired psychomotor performance and short-term memory at dehydration in the range 3-5%. In one of these studies [18], the involvement of physical fatigue in the impairment of cognitive performance was shown to be unlikely to cause the decrement because passive heating (*ie* heating without exercise) to induce dehydration also impaired cognitive performance. So these findings suggest that the decrement in performance could be due to heating.

However, in Study 1 we showed that moderate heat strain alone, induced by hot environmental conditions above the range within which performance on complex mental tasks is reported to start to become impaired [1], was without effect on the performance of the cognitive tasks used in that Study. The presence of heat strain was confirmed by the increase in rectal temperature of approximately 1°C, to 38.2°C. A deep-body temperature of 38.0°C is defined as the safe upper limit for industrial workers [20].

It therefore appears that for hot environments in which aircrew operate, heat strain sufficient to increase deep-body temperature by 1.0°C, or cause dehydration up to 3.5%, are, *by themselves,* unlikely to impair performance on well-practised, complex cognitive tasks. However, when heat strain and dehydration co-exist, the potential for impaired performance remains. It is currently unclear how these combined stressors interact to degrade cognitive performance.

7.0 IMPLICATIONS FOR AIRCREW AND OTHER MILITARY PERSONNEL

Dehydration levels of 1% to 2% are commonly observed in aircrew of both fixed-and rotary-wing aircraft carrying out single sorties [21]. Similarly, for rapid turn-round, multiple, low-level sorties under a nuclear, biological, chemical-simulated threat, 1% to 2% dehydration levels have been observed during field trials of RAF Jaguar aircrew in a Mediterranean climate [22]. Dehydration to levels of 3% of body weight or more have been observed in 2-hour sorties for RAF Sea King pilots during Search And Rescue operations [23].

Maintaining adequate hydration is often difficult or impossible for aircrew. Such situations may include those where it is difficult to drink (*eg*, when wearing an NBC respirator) and/or when there is insufficient time for re-hydrating adequately (for example, during intense, prolonged operations or combat in hot environments). Even at quite moderate levels of dehydration, voluntary, unimpeded re-hydration to achieve normal levels may take a long time (>1 hour). Additional factors that may also cause dehydration include lengthy runway ‘standbys’ in a hot environment, physically taxing ground duties between sorties, and poor airfield conditions (no air-conditioned briefing room; no standing protection of the aircraft against solar radiation).

Another consideration for commanders in charge of military operations is that the potential for dehydration is not unique to aircrew or ground forces operating in hot environments. Heat strain and associated dehydration are also not uncommon in military personnel working in cold environments and whom are undertaking high physical workloads while wearing clothing of high thermal insulation. Thus, the risk of dehydration and concomitant heat strain needs to be considered whenever military personnel are operating under conditions requiring various combinations of high work rates, heavy or insulative protective clothing, and hazardous environmental conditions.

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Hypohydration and Exercise-Induced Shifts in the Scaling Property of Heart Beat Interval Series

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Abstract

Electrocardiographic "R wave-to-R wave" interval (RRI) series from euhydrated and hypohydrated volunteers (n = 8) were analyzed. The objective was to assess whether RRI data could be used to differentiate euhydrated from hypohydrated states. Volunteers exercised in the heat (T_a = 31°C) at 60%VO_2 peak for 90 min with or without fluid-restriction. The RRI was derived from continuous ECG data recorded during pre-exercise, exercise and post exercise periods. The inherent non-stationarity in RRI limited the use of conventional spectral analytical approaches. To address this issue, the RRI data were wavelet transformed, as wavelet transformed data tend to achieve stationarity. Two mathematically distinct methods were used to analyze wavelet transformed RRI data from euhydrated and hypohydrated subjects at rest and exercise. (1) Using the Cumulative Variation Amplitude Analysis (CVAA) approach, the analytic signal was formed and normalized probability distribution profiles generated. Previous work has shown that the normalized probability distribution patterns of normal control subjects are similar (overlapping), whereas these distributions tend to be dispersed for subjects suffering from obstructive sleep apnea. (2) In the second method, normalized weighted singular value (WSV) distribution profiles were generated. At rest, but not at exercise, both the CVAA and WSV distribution profiles of normal euhydrated subjects were similar (overlapping), whereas with hypohydration these distributions were dispersed. Conclusion: These analytical methods may be useful in detecting disruptions in normal resting RRI patterns that appear to occur with hypohydration.

Key words: ECG · sweating · non-linear dynamics · heart rate · humans

Introduction

Euhydration is defined as the state in which a person exhibits a "normal" total body water (Sawka and Coyle, 1999). Hypohydration is the state in which there is a total body water deficit, with water losses from both intracellular and extracellular fluid compartments. Plasma volume decreases and plasma osmolality increases with the degree of hypohydration. At low levels of hypohydration, about 2% loss of body weight,

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water loss occurs principally from the extracellular fluid compartment. However, during more profound hypohydration, with 4 to 6% body weight loss, water loss occurs equally from both the intra- and extracellular compartments (Sawka et al. 1992a; Sawka and Coyle 1999).

Adolph et al. (1947) believed that with hypohydration, the rise in core temperature during heat stress was likely due to failure of the peripheral circulation. Herztman (1959) first suggested that physiological status information supplied by thermoreceptors, osmoreceptors, and volume receptors, might act in a mutually contradictory manner with a final effector output influencing both the sweat gland (sudomotor) and vascular (vasomotor) control systems.

In healthy individuals, hypohydration is a reproducible and easily reversed perturbation to an otherwise normal physiological state. During hypohydration, core temperature rises as sweating rate decreases – with the time course depending on the magnitude of total body water loss, ambient temperature, and exercise intensity. Several indices of cardiovascular dynamics are also concomitantly altered: heart rate is increased and the gain of the peripheral circulation to central nervous system (CNS) drive is lessened in the hypovolemic state (Fortney et al. 1981; Sawka et al. 1989). In previous studies, Sawka and coworkers (1992b) showed that exercise at various levels of hypohydration, coupled with uncompensable heat stress, caused physical exhaustion more quickly and at a lower core temperature (38.7 ºC) than during exercise when euhydrated (Tcore = 39.1 ºC). Changes in heart rate and stroke volume are due to both a decrease and a re-distribution of blood volume (Montain and Coyle 1992a, 1992b). In a study by Montain and Coyle (1992a), when blood volume was preserved as subjects became progressively dehydrated during a two-hour moderate intensity exercise in a warm environment, the heart rate rise was attenuated but not reversed. Also, the extent of hyperthermia and rise in heart rate, as a consequence of the downward drift of central venous pressure and drop in cardiac stroke volume ("cardiovascular drift"), was shown to be a direct function of the magnitude of hypohydration (Montain and Coyle, 1992b). Gonzalez-Alonso et al. (1997) showed that dehydrated individuals, exercising in a warm environment, displayed the highest cardiovascular strain as indicated by reductions in cardiac output and blood pressure, and increased vascular resistance. Interestingly, in the same study when individuals exercised (70-72% $\dot{V}_{O2}$ max) in the dehydrated state (-4 % body weight loss) in the cold (2 ºC), there was a consistent increase in heart rate and a reduction in stroke volume but no adverse effects on other measures of cardiovascular strain. Thus, Gonzalez-Alonzo et al. (1997) showed that when blood volume was reduced during progressive dehydration, but central blood volume (CBV) was restored by acute cold stress, heart rate rise was attenuated but not prevented. Montain et al. (1998) also demonstrated that cardiac output decreases with progressive hypohydration and is reduced with high intensity exercise. The important fact from the above studies is that the hypohydrated state per se can lead to varying degrees of cardiovascular strain that can be alleviated by replenishment of blood volume.

The effects of various stressors, such as heart disease or exercise, on heart rate variability (HRV) has been widely studied (Akselrod et al. 1981; Bruce et al. 1980; Cerutti et al. 1995; Gibbons et al. 1989; Kurths et al. 1995; Malik and Camm 1995; Poon and Merrill 1997). With increasing strain on the cardiac system with congestive heart failure, it has been observed that the dynamics in the heart rate interval series, that is, the electrocardiographic R-to-R interval pattern (henceforth called RRI series), tends to decrease (Poon and Merrill 1997) with increasing strain on the cardiac system. However, little research is available on the effects of exercise and dehydration (with or without accompanying hyperthermia) on the dynamic complexity of heart rate variability (HRV).

The present study compares two different analytic approaches to assessing the effects of exercise and hypohydration on HRV in normal subjects: (a) the Cumulative Variation Amplitude Analysis (CVAA) approach, which parallels that used in a study comparing normal subjects and cardiac patients with obstructive sleep apnea (Ivanov et al. 1996), and (b) a novel approach using Weighted Singular Value (WSV) distribution profiles.

The hypothesis was that HRV profiles generated by the CVAA and WSV approaches could be used to differentiate euhydrated from hypohydrated states at rest and during exercise.

Mathematical Background

Wavelet Transform:

The continuous wavelet transform is given by

$$T_{x}^{\Psi}(\tau, s) = (1/\sqrt{|s|}) \int_{-\propto}^{\propto} x(t)\, \Psi^{*}((t-\tau)/s)dt$$

where the transformed signal is a function of two variables, τ and s, the translation and the scale parameters respectively, and Ψ is the transforming function or the mother wavelet. When s is large, the basis function $\Psi(t)$ is stretched, which is useful for the analysis of low frequencies, whereas small values of s can facilitate high frequency analysis using contracted mother wavelet. So the choice of the scale (s) dictates the frequency spectrum of the wavelet-transformed signal. Thus wavelet transform can produce a cumulative measure of the variations in the R-R interval series, absorbing nonstationarity, if any. In the present work, the RRI series obtained from the ECG data were wavelet transformed using Morlet wavelets with scaling factor of 8. The Morlet wavelet is a modulated form of the Gaussian function ($e^{-t^2/2}$): $\Psi(t) = e^{-i\omega_o{}^{2}t}e^{-t^2/2}$, where $\omega_o = \pi\sqrt{(2/ln2)} = 5.336$, which ensures $\int \Psi(t) = 0$, a basic requirement for the wavelets (Strang and Nguyen 1996). In the present context, the suitability of a particular wavelet is based on the nature of the data analyzed, for which there is no unique approach.

Methods

Physical characteristics of the 8 male test volunteers were: (mean ± SD): age 22 ± 4 y; height 176 ± 6 cm; weight 74.5 ± 9.9 kg; $\dot{V}_{O2}$ peak = 41.7 ± 3.8 ml·kg^{-1}·min^{-1}. Peak aerobic power tests were performed prior to experiments in order to establish a value from which we could calculate the relative level of submaximal exercise (60% $\dot{V}_{O2}$ peak) necessary in this study. The testing was conducted on a recumbent cycle ergometer using a continuous, stepwise procedure. After a 4-5 minute warm-up period pedaling against zero resistance, the test subject began pedaling at 60 watts of resistance. Every minute, the intensity was increased by 30 watts until the subject could no longer continue pedaling. In some subjects exercise was terminated before a plateau in $\dot{V}_{O2}$ was achieved, so the subject was given a resting period for 5 minutes and tested again starting at the next higher work level after a one-minute warm-up. Peak aerobic power on the cycle ergometer ($\dot{V}_{O2\ \mathrm{peak}}$) was determined as an increase of less than 200 ml·min^{-1} $\dot{V}_{O2}$ concurrent with an increase in exercise intensity. During the peak aerobic effort testing, the subject breathed though a mouthpiece connected to a metabolic system for online expiratory gas analysis conducted and recorded every 20s using a Sensor Medics 2900 (SensorMedics, Yorba Linda, CA).

The ECG and heart rate during the aerobic testing and submaximal exercise runs were monitored using a Colin Pilot BP/ECG Analysis System (San Antonio, TX) employing chest electrodes placed in a modified V5 positions (CM5). Analog ECG records were digitized and analyzed following each experiment. Experimental testing was conducted in a U.S. Army Research Institute of Environmental Medicine environmental chamber at a dry bulb temperature of 31°C, a dew point of 10°C, and a wind speed of 1 m·s^{-1}. Test subjects were (a) not heat acclimated, (b) tested while lightly clothed (shorts and athletic shoes), and (c) familiarized with the test equipment. Subjects were tested on a recumbent cycle ergometer at a workload equivalent to 60% of the individual's $\dot{V}_{O2\ \mathrm{peak}}$ as previously determined on the same ergometer.

Measurements

Before experimental testing, each subject's baseline nude body weight was measured after voiding and before eating breakfast for 5 days at the same time of day (0700-0900h). Each subject's percent body fat (%BF) and free-fat mass (FFM) was determined using whole body dual energy X-ray absorptiometry (DEXA) prior to beginning the experimental procedures. A procedure similar to Mountain and Coyle (1992) was employed to hypohydrate the subjects to about 4% body weight loss. In brief, following a resting period of thirty minutes, subjects exercised for 90 minutes at 60% $\dot{V}_{O2\,\text{peak}}$ at the above ambient conditions without fluid replacement. During the control runs, a sports drink was provided prior to exercise and at 15 min intervals up to the 75th min of exercise. Each subject's physical characteristics (body weight, height, $\dot{V}_{O2\,\text{peak}}$, %BF) were initially used as input into a prediction model (SCENARIO) to establish exact body weight loss and fluid requirements needed to maintain the person in a euhydrated state. The total volume predicted for each person was divided into 7 aliquots with the subject consuming two drinks during the preliminary setup procedures containing 20% of the fluid. The other 5 aliquots containing 12% of the total volume was given during each 15 min period of exercise up to the 75min. All fluids provided were kept at a temperature of 37°C.

Sweat losses were determined from changes in nude body weight, measured with a sensitive balance (±1.0 g; Mettler-Toledo, Inc., Columbus, OH, 43240), adjusted for water intake and urine loss. Because heart rate and core temperature each have a definite circadian periodicity with peak increases occurring late in the day, all exercise testing occurred before 1300 h.

Upper arm sweating rate was measured with a ventilated dew point sensor (Graichen et al. 1982). Skin temperatures were monitored with calibrated thermistor/heat flow sensors at 3 sites (chest, thigh and upper arm) with mean weighted skin temperature and mean weighted heat flux calculated by appropriate body surface area weighting (T_{sk} = 0.42 × chest temperature + 0.39 × thigh temperature + 0.19 × upper arm temperature) (Gagge and Gonzalez 1996).

Core temperature of each volunteer during the exercise phase was monitored by use of a telemetric temperature system using a calibrated temperature pill (T_{pill}) (CorTemp, Human Technologies, Inc, St Petersburg, FL). The temperature pill was ingested the night before a morning experiment with fasted test subjects. This technique has been found to be a valid core temperature monitoring method within a root mean square deviation of 0.23°C of esophageal temperature (O'Brien et al. 1998). Sweating rate (m_s, $mg \cdot cm^{-2} \cdot min^{-1}$) is generally modeled as a function of central temperature (i.e., in this study:T_{pill}), skin temperature (in this study: $T_{sk} = 32°C$ and constant) and the corresponding threshold temperatures ($T_{pill,0}$ and $T_{sk,0}$) (Gagge and Gonzalez 1996). A change in the slope of m_s to T_{pill} therefore indicates alterations in the sweat gland responding to the central neural signal while a change in the T_{pill} threshold indicates a actual change in the central nervous system temperature threshold point (Gagge and Gonzalez 1996). It is not known how such changes manifest themselves during hypohydration and whether they impact the parasympathetic or sympathetic nervous systems directly affecting central cardiac responses. After arriving in the lab at 0700h, subjects had their nude body weight measured, and were instrumented. Subjects rested for 30 min on the recumbent bike. The resting phase of 30 minutes included a time period during which final adjustments to instrumentation of the subject were made, 20 min of resting ECG data were recorded, and a 2 min $\dot{V}_{O2}$ measurement was recorded. After the resting phase, the subject began 90 min of work at a rate previously calibrated at 60% $\dot{V}_{O2\,\text{peak}}$. An exercise $\dot{V}_{O2}$ measurement was taken during the 45th min, and just before cessation of the exercise (90th min). In the post-exercise period, 20 min ECG data were also recorded. Some data from all 8 subjects doing the experiments had to be discarded due to instrumentation or recording problems with the temperature pill (one in the euhydrated state). Six of the 8 subjects had complete sweating and temperature pill data from which a matched, repeated measures of $\Delta m_s/\Delta T_{pill}$ determined from each individual's regression equation was done for each hydrated condition (Fig 2b).

Statistical analyses of the sweating and core temperature responses were conducted using SAS Version 6 (Cary, NC), using a one- and two-way repeated measures ANOVA (time and condition). Differences in the regression coefficients for the relationship of sweat rate to core temperature were analyzed by paired-T tests. The criterion for statistical significance for all tests was $P<0.05$.

Analytical methods

Subsequent to wavelet transform, the RRI series were analyzed two different approaches.
(i) Cumulative variation amplitude analysis (CVAA),
(ii) weighted singular value (WSV) distribution profiles.

Cumulative variation amplitude analysis (CVAA)

In this approach (Ivanov et al. 1996), the data series is wavelet transformed (w), and an analytic signal formed: $(w + j\hat{w})$, where $\hat{w}$, the quadrature component of w, is obtained by Hilbert transform. The amplitude of the analytic signal is given by $A = \sqrt{(w^2 + \hat{w}^2)}$. The probability distributions $P(x)$ of the magnitude of the analytic signal is normalized to unit area by scaling the amplitude by $P_{\max}$, plotted against x rescaled by $1/P_{\max}$. Ivanov *et al.* (1996) showed that the probability distributions tend to merge for healthy subjects, whereas for subjects with obstructive sleep apnea the normalized probability distributions tend to be dispersed.

The procedure for CVAA may be outlined as follows:
(i) The R-R interval data series is wavelet transformed
(ii) A quadrature component of the wavelet-transformed series is formed using Hilbert transform.
(iii) An analytic signal is formed using the components obtained in steps (i) and (ii).
(iv) The series of absolute magnitude of the analytic signal is formed.
(v) The probability distribution of the so obtained series is normalized to unit area.
(vi) The normalized profiles for the data series obtained from pre-exercise euhydrated is compared with the profiles for pre-exercise hypohydrated; similarly, the exercise stage and the post exercise stage were compared.

Singular value decomposition (SVD) and the generation of WSV distribution profiles

To perform singular value decomposition, the data series $\{x(k)\}$ is configured into an mxn matrix **A**. Singular Value Decomposition (SVD) (Golub and Van Loan 1996; Kanjilal 1995) of **A** produces $\mathbf{A} = \mathbf{U}\Sigma\mathbf{V}^T$, where **U** and **V** are orthogonal matrices (i.e. $\mathbf{U}^T\mathbf{U} = \mathbf{U}\mathbf{U}^T = \mathbf{I}$ etc.), and $\Sigma = \text{diag}(\sigma_1, \sigma_2,..., \sigma_r{:}\mathbf{0})$, $r = \min(m, n)$ contains the singular values arranged in nonincreasing order along the diagonal: $\sigma_1 \geq \sigma_2 \geq ... \sigma_r \geq 0$. The SVD provides the orthonormal basis of the range and the null space of the matrix **A**. The number of nonzero singular values (σ_i) gives the rank of **A**. The following cases deserve attention:

(a) For a *strictly periodic* $\{x(k)\}$ with period length N, i.e. $x(k) = x(k+N)$, **A** will be a strictly *rank one* matrix, if row length $n = N$. Here, σ_1 is nonzero but $\sigma_2 = \ldots = \sigma_r = 0$; $\sigma_1/\sigma_2 = \propto$.
(b) If the rows of **A** are nearly repetitive, $\sigma_1 >> \sigma_2 \geq ... \sigma_r$; then **A** can be approximated as $\sigma_1\mathbf{u}_1\mathbf{v}_1^T$, where $\mathbf{u}_1$ and $\mathbf{v}_1$ are the first columns of **U** and **V** respectively.
(c) As $\{x(k)\}$ deviates from periodicity in terms of repeating pattern, or as periodicity shifts from row length n, **A** tends to lose rank-oneness (Kanjilal 1995). If $\{x(k)\}$ is truly random, **A** will be a full rank matrix with the singular values having comparable magnitudes. So, for most physiological series like the heart rate interval series, the distinguishing features of $\{x(k)\}$, are expected to be reflected in the distribution of the *nonprime*

singular values. Hence, for assessing process dynamics, the following scheme of weighted singular value distribution can provide a meaningful platform.

The general procedure for the generation of the weighted singular value distribution profiles (WSV) is as follows.

(1) The data series $\{x(k)\}$ is configured into mxn matrices **A**, with varying row length n, and SVD of **A** is produced. For each configuration, the total energy in **A** (=$\{\{a_{ij}\}\}$) is given by $Q_A = \sum_i \sum_j a_{ij}^2 = \sum \sigma_{ij}^2 = ||\mathbf{A}||_F^2$.

(2) For each configuration of **A**, the singular values obtained are normalized preserving the Frobenius norm ($||\mathbf{A}||_F$) as follows. Since the maximum rank (p) of **A** will be different for different configurations of **A**, a value R close to the minimum value of p is chosen, where the value of R is not a limitation. For each configuration of **A**, the total energy Q_A is linearly mapped to R normalized singular values, ensuring conservation of the normalized energy as embedded in the mapped singular values.

(3) For M different values of row length n, M sets of R normalized singular values are obtained from which the mean singular values $Fm(i)$, ($i = 1$ to R) are computed.

(4) The scaled distribution $Z(i) = i^2 Fm(i)$ is computed for $i = 1$ to R; $\{Z(i)\}$ is normalized as $\{Z(i)/Z(i)_{max}\}$ and is plotted against index i.

The proposed scaling for the normalized singular values appears justified. While the varying row-lengths permit the mapping of the underlying process in different dimensions, the aperiodicity embedded in the time series $\{x(k)\}$, is reflected in the non-prime singular values. So the increasing weighting of the singular values of decreasing magnitudes can help distinguish between the aperiodicities of the signals under analysis.

RESULTS

Figure 1 shows a typical RRI series and its wavelet-transformed counterpart. To demonstrate the effectiveness of the wavelet transform, recurrence plots (Casdagli, 1997) were examined. Average nude body weight changes after each recumbent exercise run were 72.4 ± 9.5 kg for the hypohydrated condition and 75.9 ± 9.8 kg for the fluid replacement runs. Percent body weight changes following exercise for the fluid restricted state averaged -3.8 ± 0.2 % compared to the euhydrated state ($P<0.05$). The profiles of sweat rate and body temperature in the euhydrated and hypohydrated states (Fig. 2 a, b) show the reduced eccrine sweating to core temperature (T_{pill}) drive prevailing throughout the exercise in the hypohydrated state (Fig. 3) . The thermoregulatory changes during a mild hypohydrated state were reflected in a significant decrease in the gain of the sweating sensitivity response ($\Delta m_s/\Delta T_{pill}$, $P<0.01$ euhydrated vs. hydrated state), changes that were presumably associated with changes in central cardiac dynamics and the observed alterations in HRV.

Cumulative variation amplitude analysis

The normalized probability distributions were computed for the wavelet transformed heart beat interval series for the hypohydrated and the euhydrated conditions both during the exercise and during the pre-exercise stages. The results are shown in Figs. 4 and 5. At rest, the normalized probability distributions tend to merge when the volunteers are euhydrated (Fig. 4a), but tend to disperse when the volunteers are hypohydrated (Fig. 4b). This suggests that, in the hypohydrated condition, the cardiac system is under strain at rest. At rest with euhydration, the CVAA normalized probability distributions can be expressed in terms of a single scaling function, but this scaling property is lost with hypohydration. For the exercise stages, in both for the euhydrated (Fig. 5a) and the hypohydrated conditions (Fig. 5b), the probability distributions are dispersed with a lack of any single scaling function.

WSV Profiles

The WSV profiles were generated from resting RRI series with 1200 data points and 12 normalized singular values (which is not a limitation). Given the CVAA findings, exercise data were not analyzed using the WSV approach. As with the CVAA analysis, the pre-exercise (resting) stages for the euhydrated and the hypohydrated conditions showed conspicuous difference, as shown in Fig. 6. The profiles tend to merge together for the euhydrated case, whereas the same tend to remain dispersed for the hypohydrated case.

DISCUSSION

Two methods (CVAA and WSV) were used in the nonlinear analysis of the RRI series from resting or exercising test volunteers under euhydrated and hypohydrated conditions. Compared to euhydration, hypohydration was associated with an increased dispersion in CVAA probability distributions of RRI and increased dispersion of the WSV profiles. In contrast, no difference was evident during exercise, where a dispersed CVAA probability distribution pattern was evident in both the euhydrated and hypohydrated states.

The CVAA and WSV analyses suggest the cardiac system is under strain during hypohydration at rest, whereas in the euhydrated condition the characteristics of the findings are similar to healthy state. For the exercise stages, both for the euhydrated (Fig. 5a) and the hypohydrated conditions (Fig. 5b), the probability distributions remained dispersed. The physiological strain is also apparent in the tempered eccrine sweat gland response to CNS drive, suggesting an exercise-induced compromised central cardiovascular state during fluid restriction. This was first alluded to by Hertzman and reported also by Montain and Coyle (1997) and Gonzalez-Alonzo (1997).

The WSV profile, which is a novel method for the analysis of RRI signals, also shows similar characteristics for the RRI series under hypohydrated and the euhydrated conditions. These results of the present study support the importance of monitoring the hydration state of the subject under stressful conditions, as an individual would be expected to be more vulnerable under exercise and environmental stress conditions if hypohydrated. The proposed method of monitoring hydration state may have practical value for firefighters and chemical cleanup crews working under hot conditions, and for the elderly, where hypohydration and fluid and electrolyte imbalances are common (Hodgkinson et al 2003). For example, if the probability distributions show increasing degree of dispersion, the subject's cardiac system may be experiencing strain. In the absence of physical exertion, the shift in the scaling property would commonly be due to hypohydration; so the subject can be pre-warned that his/her hydration level may be inadequate. It is concluded that the mutual dispersion of the probability distributions of the magnitude of analytic signal or the distributions of the WSV profiles can provide a direct noninvasive assessment of hypohydration-induced cardiac strain in humans.

It is important to view this type of ECG analysis in context. That is, HRV analysis of a single individual, without reference to other physiologic or contextual factors, or to the physiology of cohorts, may be of limited value. However, when other physiologic and contextual indices are know, such as ventilation, antecedant exercise patterns, water consumption, biophysical conditions, etc., the analysis of HRV can be valuable part of detecting and managing hydration state. Ambulatory (wearable) systems for monitoring physiologic status that are being developed by the US Army and others will be capable of providing the contextual data needed to use HRV data to detect hypohydration.

In conclusion, the present study compares two different analytic approaches to assessing the effects of exercise and hypohydration on HRV in normal subjects. The findings suggest that both the the Cumulative Variation Amplitude Analysis (CVAA) approach, and the novel Weighted Singular Value (WSV) approach, can detect hypohydration in resting individuals.

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adhered to the policies for the protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 45 CFR Part 46. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations. This work was supported by the Military Operational Medicine Research Program, US Army Medical Research and Materiel Command, Ft. Detrick, MD 21704-5014.

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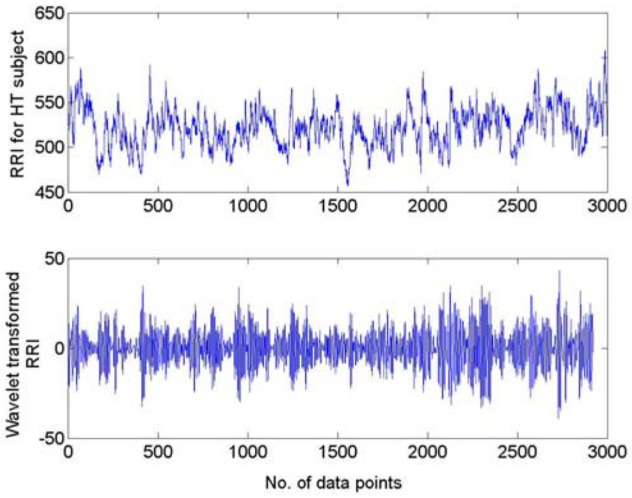


Fig. 1 A typical RRI series and its wavelet transform. Morlet wavelet with a scaling factor of 8 has been used.

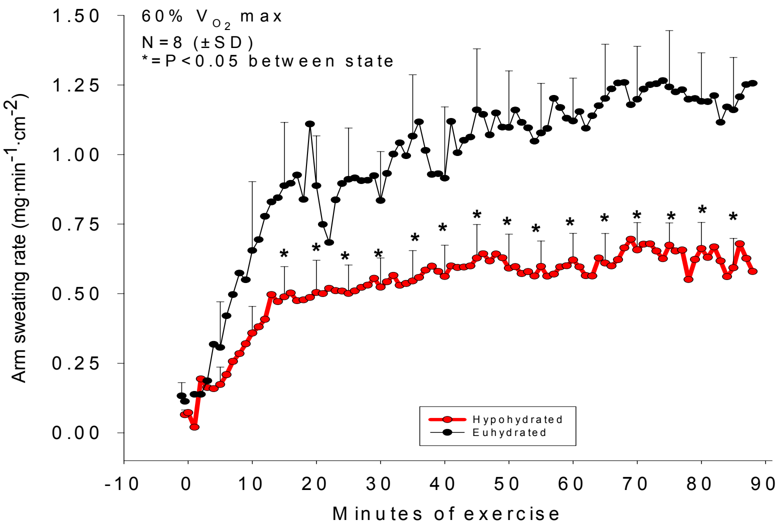


Fig. 2 (a) The sweating rate against time during the exercise for the euhydrated and the hypohydrated subjects (N=8).

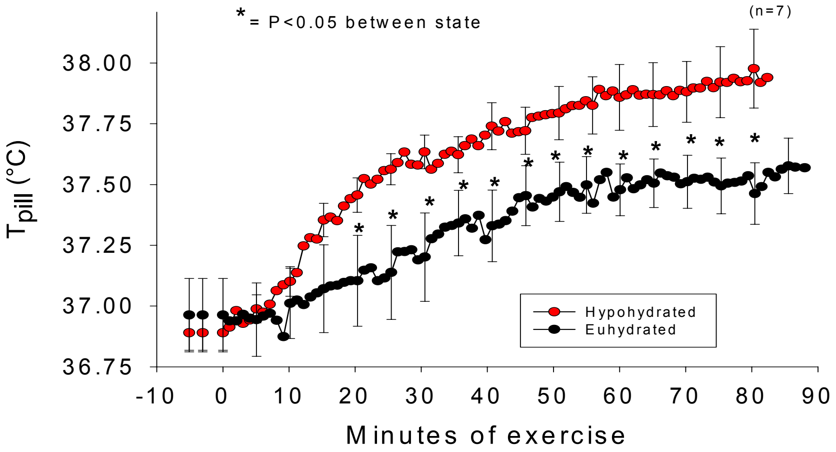


Fig. 2 (a) The sweating rate against time during the exercise for the euhydrated and the hypohydrated subjects (N=8). (b) The core temperature against time during exercise (N = 7; matched individuals).

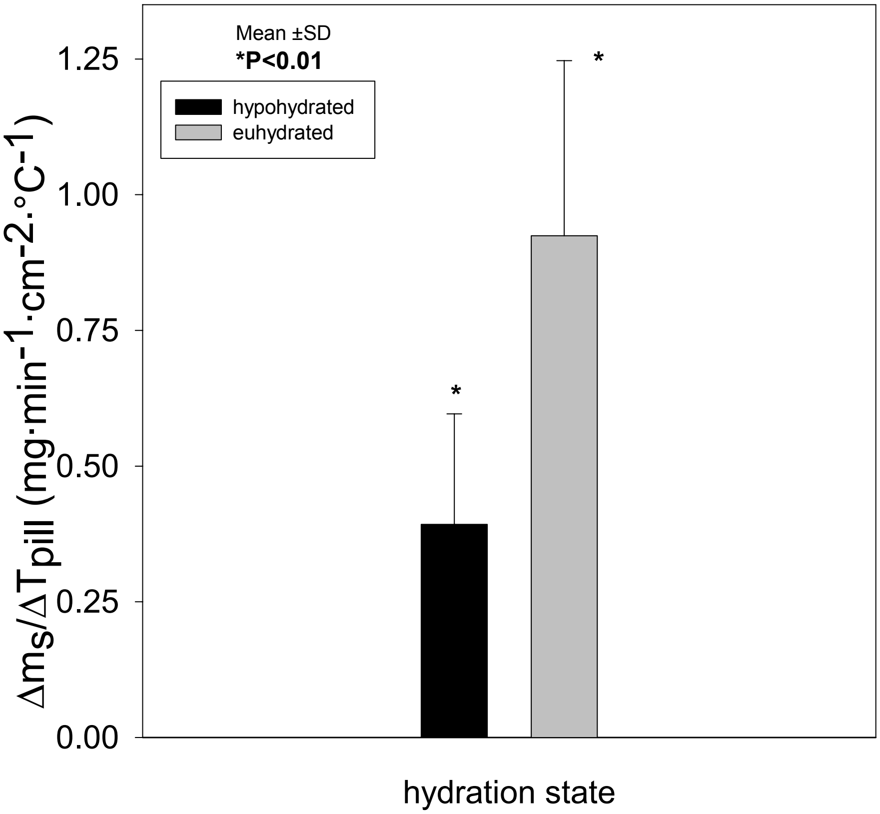
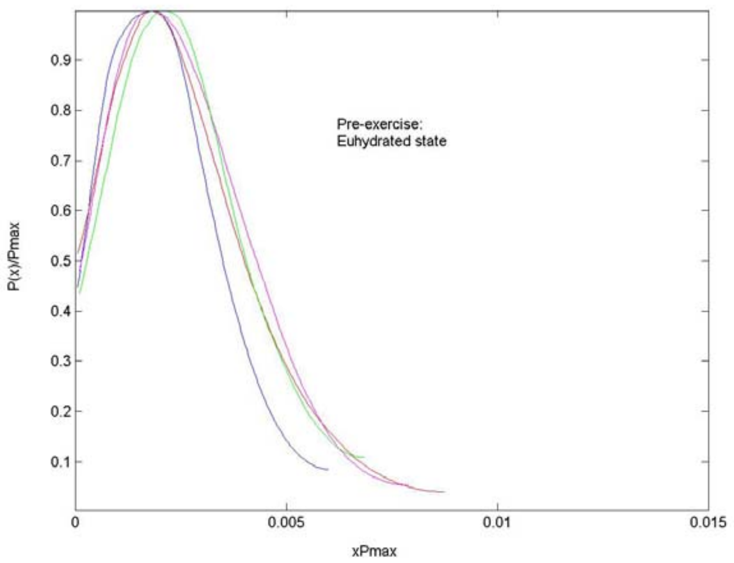


Fig. 3 The sweating sensitivity for the two hydration states, showing significantly less change in sweat production for a given change in core temperature in the hypohydrated as opposed to the euhydrated state.



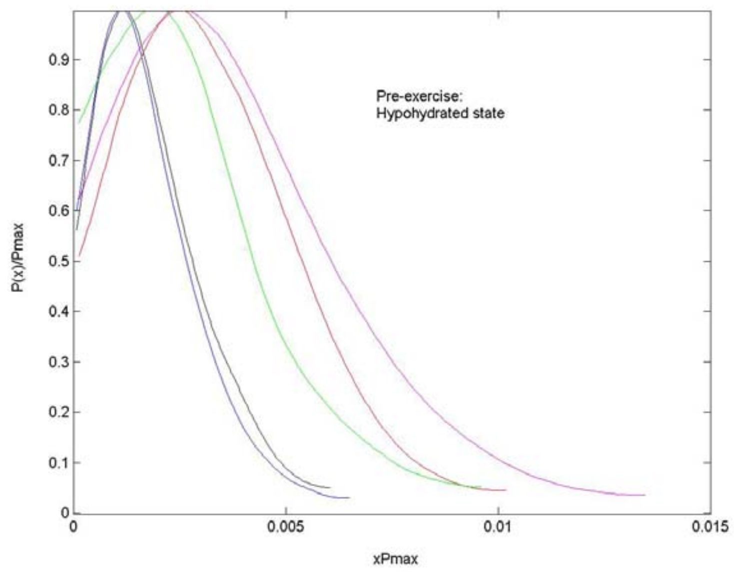


Fig. 4 (a) The normalized probability distributions *P*(*x*) of R-R interval variations for euhydrated, resting test volunteers. The profiles tend to merge together implying the scaling property of the underlying process. (b) The normalized probability distributions *P*(*x*) of R-R interval variations for hypohydrated, resting test volunteers. Note the conspicuous increase in dispersion in the distribution profiles.

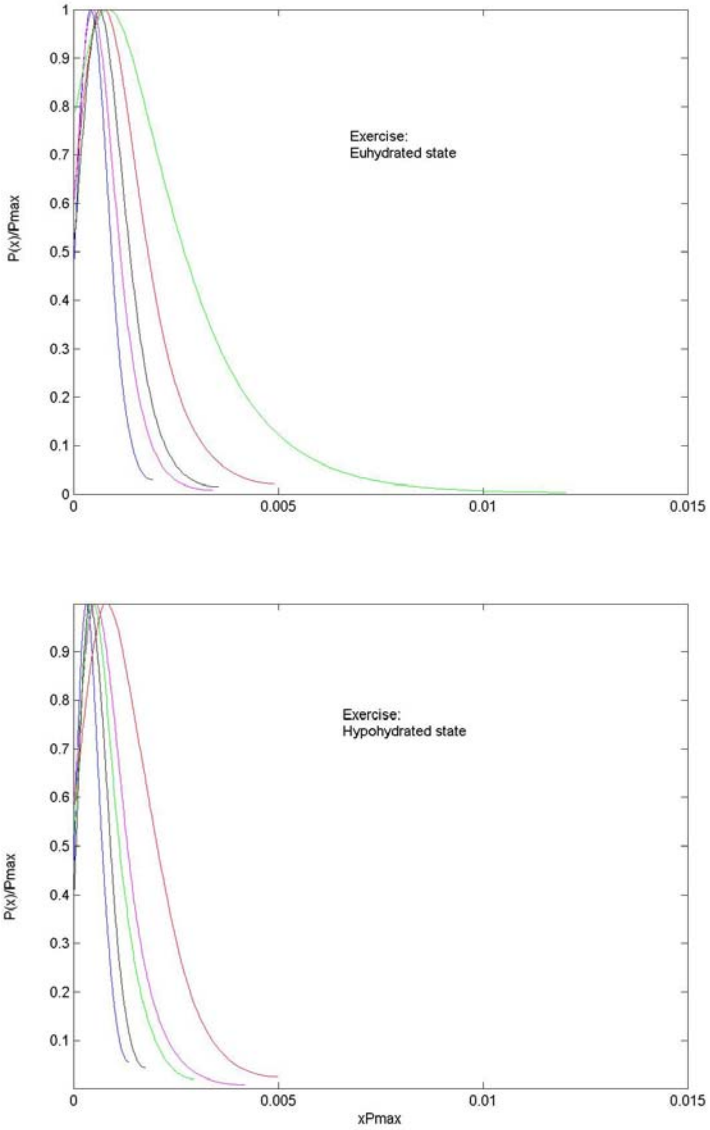


Fig. 5 (a) The normalized probability distributions $P(x)$ R-R interval variations during exercise in the euhydrated state, showing significant dispersion of the profiles. (b) The normalized probability distributions $P(x)$ of R-R interval variations during exercise in the hypohydrated state, also showing significant dispersion of the profiles.

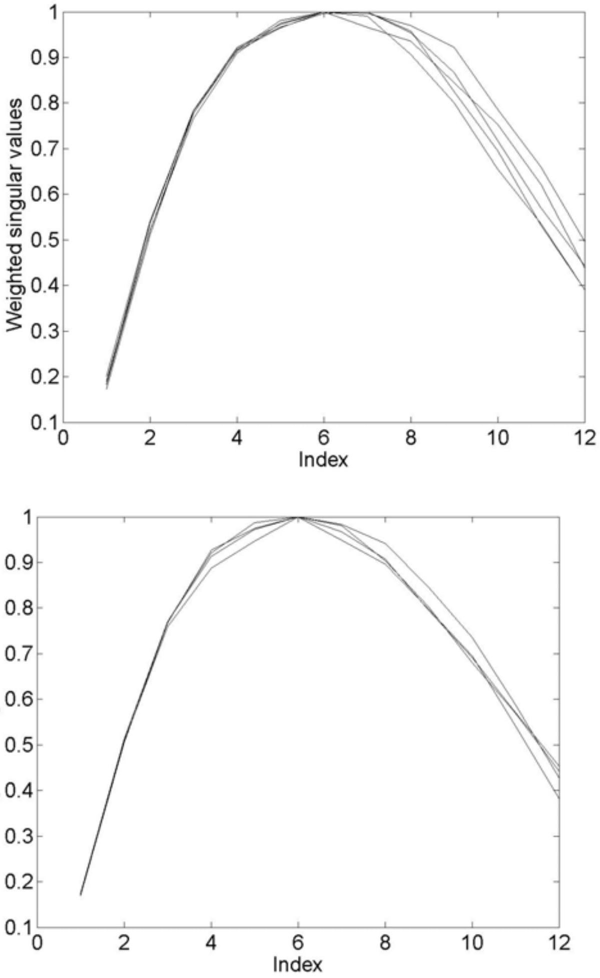


Fig. 6 (a) Nearly overlapping weighted sinular values (WSV) profiles for the RRI series of euhydrated subjects at the pre-exercise stage; (b) the WSV profiles for the hypohydrated subjects at the pre-exercise stage showing dispersion among the profiles.

Quantifying Exercise Induced Dehydration

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Abstract

Dehydration is the loss of body water that causes shifts in water content of the various fluid compartments. Animal (dog and rat) and human studies suggest that the intracellular and plasma volumes are given preference and that the interstitual fluid compartment is compromised during dehydration. Therefore, a ratio of the interstitual to the extracellular fluid may be an excellent measure of dehydration when compared to normative data. Next Vital Signs, Inc. has developed proprietary software that assesses a hydration index (HI) based on the ratio of interstitual to extracellular fluid. This would represent a single measure assessment of hydration status. This study compared changes in body weight (WT), plasma volume and the HI in 11 males and 17 females after one hour of exercise in the summer heat of Houston, Texas. WT and estimated changes in plasma volume (%PV) are common methods to assess exercise-induced dehydration. Subjects (age 43 ± 16 years, 72 ± 12 kg, 171 ± 8 cm) reported to the laboratory prior to exercise for baseline measures of WT, hematocrit (to estimate %PV from finger prick blood), and sitting measures of bio-impedance using an Agilent LCR meter and the proprietary software that determined the HI. Subjects completed one hour of exercise at their normal intensity levels and then returned to the laboratory to repeat the base line measures. All three measures showed significant ($p<0.001$) reductions after exercise: WT –1.9% (2.6 to 0.8 Kg), %PV –4.2% (-10.8 to 2.2%), and HI –2.3% (-10.6 to 5.1%). However, there were no significant correlations among the three measures of dehydration. The small changes in WT and HI may have been tempered by metabolic water and the release of intracellular water bound to muscle glycogen. The lack of correlation may reflect the narrow range of each data due to the individualized nature of the exercise performed. We conclude that Next Vital Signs, Inc.'s hydration index bears further investigation and may be useful in determining hydration status without the need of obtaining a baseline measurement.

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Introduction

Heat related illnesses decrease performance or can lead to incapacitation or death (1). Four physiologic conditions that are related to heat related illnesses are dehydration (4-10,14,15), cardiovascular strain (11), increase in core temperature (11), and altered central nervous system function. Figure 1 shows the relationship of decreases in the volume of body fluids due to loss (sweating or respiratory fluid loss) or shifting of fluid (from interstitial to intra-vascular) to these four factors. The loss of total body water is a common measure of dehydration (4-10,14,15), while the percentage change in plasma volume (%PV) is a measure of hemo-concentration (2,8). Closer examination of figure 1 shows the interstitial fluid space (ISF) as a cross roads of shifting fluid volumes. Animal (dog and rat) and human studies suggest that the intracellular and plasma volumes are given preference and that the ISF compartment is compromised during dehydration and hypohydration (4-7,10,14). Clinical relevant decreases (% decrease) occurring in a single compartment does not have universal agreement.

Next Vitals Signs, Inc. conducted an Internet survey of 5000 physicians asking three simple questions (personal communications from Next Vital Signs, Inc.). First, what fluid compartment is compromised during clinical dehydration? All medical specialty groups indicated a loss of total body water was the key compartment. Emergency room physicians and obstetrics/gynecologists also indicated decreases in extracelluar fluid (ECF) was an important fluid compartment. The second question asked at what percentage decrease in the fluid volume would clinically significant changes occur? The averages among like specialties ranged from 6 to 20% for total body water and 10 to 15% of ECF volume. The last question asked which ratio of fluid compartments would be useful in understanding clinically important dehydration? All groups stated the PV to TBW was of importance in the emergency room and office environments. The ratio of the ISF to ECF was important to most groups in the operating room. The results of the survey suggest that understanding the degree of dehydration is clinically important and that the ratio of PV to ECF or ISF to ECF may be clinically relevant.

The normal fluid levels of men and women for various compartments are shown in Table 1. The ratio of the fluid volumes to total body water and ECF were computed. The ratio of PV to TBW for men and women were small for euhydrated individuals (3). This leaves little room for decreases and even less room if fluid volumes are estimated by methods such as bio-impedance. In addition, the change in PV can be influenced by trapping of PV in the periphery as a result of thermoregulation (11) shifts in blood distribution. These limitations rule out the use of the PV:TBW as a single measure of hydration. The ISF:ECF ratio may be a better prospect of a single measure of hydration. A single measure of hydration assumes that no pre or before measure is needed and that the change in hydration status is a decrease from accepted norms. This ratio is high and fairly tight in a normal population. Data from Siconolfi et al (12,13) show the average ISF:ECF ratio (83 ± 2.1 %) to be higher than predicted from table 1. This may be due to testing of subjects who were long time residents of Houston Texas and have an expanded fluid volume due to heat acclimatization. Based on the standard deviation of this data, one could expect to find ~95% of the population to be within 4.2% of the norm. Therefore real changes in hydration could be seen with as small of change in 5% of ECF (~1.5 liters). This produces a level of sensitivity that is easily within the range that physicians thought were clinically significant (10 to 15% for ECF and 6 to 20% for total body water). This suggests that the ratio, ISF:ECF, may be a clinically relevant measure of hydration. Therefore, this study compared changes in the ISF:ECF ratio after exercise in the heat to changes in body weight (an indicator of loss of total body water) and estimated changes in PV. For the purposes of this paper the ratio of ISF to ECF is referred to as the hydration index (HI).

Methods

Subjects:

30 subjects were recruited from the community surrounding the University of Houston-Clear Lake. The subjects' characteristics are in table 2. Each subject was required to be "normally healthy" with no known diseases. There was no "fitness" requirement for this study, however, the subjects were required to be "fit" enough to complete at least 45 minutes of moderate intensity exercise in the summer heat of Houston, Texas. Subjects signed a university approved informed consent statement.

Height / Weight:

Each subject was measured for height using a wall-mounted stadiometer. The subjects were required to remove his/her shoes and place their feet, buttocks, shoulders, and head against the wall. Height was recorded in centimeters. Each subject was measured for weight using a floor scale with accuracy to ±0.1 kg. Weight was recorded in kilograms.

Hydration Index:

Silver/silver-chloride electrodes were placed on the subject's dominant wrist and ankle as described by previous research (12,13). Three bio-impedance measures were taken in a sitting position. Each subject was seated without any part of their body being in contact with the other side (e.g., right inner thigh not touching left inner thigh). The bio-impedance measures were taken within 5 minutes of assuming the sitting position (usually within 3 minutes). Bio-impedance was recorded over 10 frequencies using an Agilent LCR meter. Proprietary software from Next Vital Signs, Inc computed the HI.

Exercise with Heat-Stressor:

We induced dehydration by having subjects exercise in hyperthermic environmental conditions. Since the study was conducted in Houston, TX, this was achieved by using the local summer ambient conditions.

Specifically, the subjects arrived at the lab and initial (pre-exercise) data was collected for body weight, hematocrit, and hydration status (HI). Subjects were normally hydrated (self-report) upon arriving at the lab (not in a fasting state). There were no food restrictions on this aspect of the study (i.e., the subjects were free to arrive at the lab having just eaten a meal). However, the subjects knew they were going to be exercising, so the majority of them had not eaten in about 1.5 – 2.0 hours.

After baseline determination of body weight, hematocrit, and hydration, each subject was instructed to exercise at a self-selected pace sufficient to attain 70%VO_2max (70% Heart Rate Reserve) work intensity. This exercise bout was conducted in an ambient temperature of $\geq 95^{o}$F for at least 45 minutes (maximum of 60 minutes). Each subject was allowed to use a heart rate monitor or rating of perceived exertion to quantify his or her work intensity. The subjects were not allowed to perform any re-hydration during the exercise bout.

After exposure to the exercise and thermal stressor, each subject had his/her body weight, hydration status (amount of dehydration), and hematocrit re-measured. A percent change was calculated for each subject using the pre to post data. The subjects were allowed re-hydration only after all post-exercise data had been collected.

Hematocrit Procedure:

Hematocrit was determined by use of 35-ul aliquots of blood collected into Drummond Hemato-Clad heparin zed 75-mm hematocrit capillary tubes. Each 35-ul aliquot of blood was drawn from a finger by a standardized finger-stick procedure. At least two capillary tubes of whole blood were collected for each hematocrit measure. The capillary tubes were spun at 12,000 rpm for five minutes in an International Equipment Company (IEC) MB Micro- Hematocrit Centrifuge. The hematocrit measure was then determined by using an IEC Micro-Capillary reader (both tubes were read and an average taken for the hematocrit measure). All sharps, gloves, gausses, etc. that were contaminated with the subject's blood were disposed of in an appropriate biohazard container.

Results

Change in body weight (assumed change in total body water), percentage change in PV, and the change in HI were significantly ($p<0.001$) lower after exercise as shown in table 3. Each correlation of the percentage changes (pre to post) among the three measures of dehydration did not reach a level of significance (table 3).

Discussion

The small change in WT (mean of –1.9%) may have been tempered by metabolic water production and the release of intracellular water bound to muscle glycogen. The change in body weight of only –1.9% is much smaller than those observed in other studies. The other studies had planned decreases on 3-6% of body weight due to exercise or chemical (diuretic) dehydration (2,4,7-9,14). Strict controls on pre-exercise diet, muscle biopsy for glycogen content, and other direct measures may have increased the size of the decrease in body weight. However, from a practical point of view, we wanted to examine the possibility of using the HI as a measure of dehydration in athletes that routinely exercise in the heat. It appears, that our subjects had a higher level of hydration prior to exercise when comparing the HI to the normative values in table 2. This "extra" water may have been stored in the intravascular compartment or within the IF. Initial water loss would have been from this extra supply. Both these scenarios would account for the larger decreases in fluid from the PV and ISF compared to the loss of total body water (suggested by the decrease in body weight).

The small change in HI (mean of –2.6%) also may have been tempered by metabolic water production and the release of intracellular water bound to muscle glycogen. Figure 1 shows how the release of metabolic water and bound water may have offset the shift of fluid from the ISF to the PV space. This would decrease the size of the change in HI. In addition, these subjects were heat acclimatized and may have had larger initial plasma volumes. This larger initial volume would produce a smaller shift in fluid from the interstitial space to the intra-vascular space. The larger change in PV (-4.6%) may reflect some trapping of plasma volume in the periphery after subjects exercise in the heat (11) and loss of serum sodium (7, 15) that helps hold PV. Possible differences in local skin temperature at the sampling site may also have accounted for the larger decrease in PV (1),

The lack of correlation among the measures of dehydration may reflect many factors. First is the narrow range of each data set due to the individualized nature of the exercise performed. Second, each measure examines a different part of the thermoregulation / fluid volume paradigm (figure 1). Finally, the heterogeneity of the subject population (age 22 to 72 years) may have added to the scattered results indicated by such low correlations.

Many individuals have commented that bio-impedance is not a suitable tool to assess hydration status since it is greatly influenced by changes in osmolality. The advantage of the ISF to ECF ratio is the relatively small change in osmolality in both compartments. The major change in osmolality that occurs in the fluid compartments of the body during exercise and heat stress occurs in the vascular system (7). This is another reason that supports the concept of not using the PV to total body water ratio as an index of hydration when bio-impedance is the tool used to assess fluid volumes.

We conclude that Next Vital Signs, Inc.'s hydration index bears further investigation and may be useful in determining hydration status without the need of obtaining a baseline measurement. The ability to assess hydration changes in euhydrated to the hypohydrated states should be considered.

Acknowledgements

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Table 1: Normal Fluid Volumes in a 70 kg male and a 50 kg female (3).

	Liters		%TBW		%ECF	
	M	F	M	F	M	F
Total Body Water	41	25	100	100		
Intracellular	27	15	67	60		
Extra cellular	14	10	33	40	100	100
Plasma Volume	3	2	7	8	25	20
Interstitial	11	8	27	32	75	80

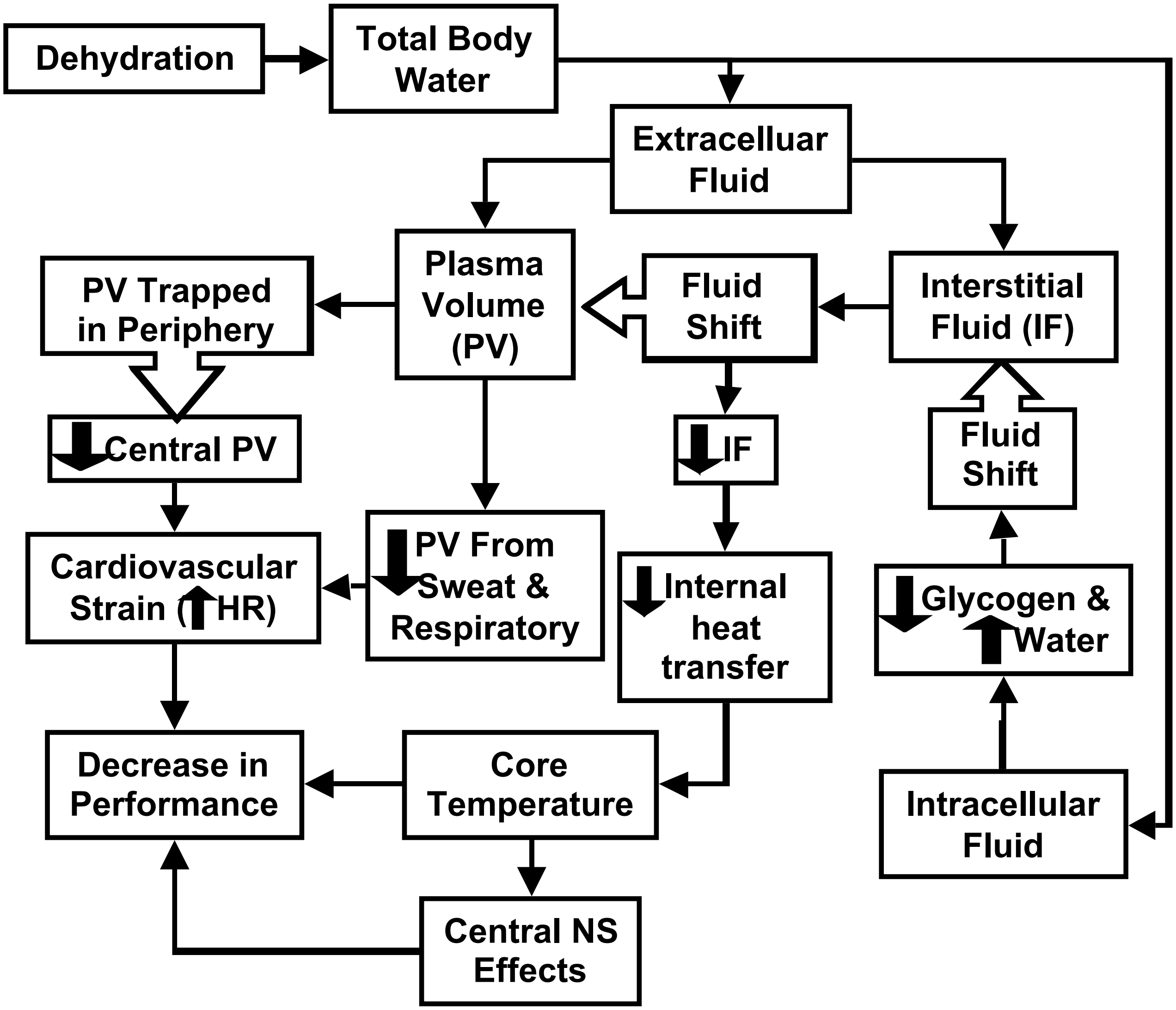
Table 2: Subject Characteristics

	Age (yr)	Weight (kg)	Height (cm)	IF:ECF (%)
Males (11)	41.8	80.4	176.6	77.7
SD	18.0	11.9	4.2	4.3
Females (17)	43.8	65.8	165.3	83.5
SD	14.7	8.5	6.2	5.4

Table 3: Changes in three measures of hydration status after exercise in the heat.

Variable	Pre	Post	%of Pre	r	t-Test
Weight	72.1	70.6	-1.9	0.999	$p<0.001$
SD	11.7	11.6	0.7		
Hct (%▲PV)	42.4	44.1	-4.2	0.876	$p<0.001$
SD	2.6	2.7	3.2		
IF:ECF	80.9	78.6	-2.9	0.872	$p<0.001$
SD	5.7	6.8	4.4		

Figure 1: The relationship of changes in fluid compartments and the four heat-related factors that affect performance.



Hypohydration Measurements by Radio Frequency*

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SUMMARY

A new method based on frequency dependent absorptiometry of radio waves passing through tissues was applied to measure dehydration status. The aim of this study was to examine a new non-invasive method of measuring hydration state in vivo, based on the comparison of attenuation of radio waves by tissue at two frequencies: a low range - at the beta dispersion region, representing the solute quantity in the tissue under examination, and a higher range- at the gamma dispersion region, representing the water quantity in the same tissue. Comparing the attenuations at these two frequencies is thus indicative of the ratio of the quantities of ionic solutes and the water in the tissue examined, namely, the osmolality in this tissue. A new device utilizing this method was constructed and applied for a group of twelve males (24+1 yr), who were exposed on two different days to heat stress. Each subject performed 2 exercise sessions, which differed in their hydration state. In one exposure session, subjects were allowed to drink ad libitum, while in the other they had to refrain from drinking. In both heat stress exposures (euhydration and hypohydration), the subjects performed the same protocol. Hypohydration level was determined by measurements of fluid balance based on body weight measurements corrected for water intake, before and at the end of the exposure. Concomitantly, measurements of radio frequency (RF) absorption were taken from the wrist. Sweat rate and hypohydration were calculated from changes in body weight. The RF measurements were used to construct a new prediction model for hydration status level. A correlation was found between this new prediction model and total body weight loss (TBW) for the hypohydration groups (R2=0.734). Therefore, we concluded that the changes observed in the RF transmission measurements were due to changes in hydration status, and that the RF methodology should be further developed for consideration as a non-invasive tool to measure dehydration.

INTRODUCTION

The human body consists of about 60% water. Body fluids are divided into intracellular and extracellular fluids. The fluid of each cell contains its own individual mixture of different constituents but the concentrations of these constituents are reasonably similar from one cell to another. Therefore, the intracellular fluid for all different cells is considered to be one large fluid compartment. The extracellular fluids amount to 22% of the total body fluid, and can be further divided into interstitial fluid and plasma. Heat

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* US and International Patents pending.

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stress can lead to a shift of fluid to the extracellular space causing haemoconcentration or haemodilution, by increasing body temperature and promoting increased skin blood flow through arteriolar vasodilatation (14). This effect alone leads to increased hydrostatic pressure in the capillary beds, which results in shifting fluid. However, during prolonged or high exercise intensity, especially in hot climates, fluid and electrolytes are lost mainly through the skin by sweating.

Active populations, including athletes, blue-collar workers and military personnel, under heat stress, frequently become hypohydrated by 2-4% of their total body water (TBW). These values are equivalent to a loss of 1-3.5L for a 75kg individual. This amount is enough to increase heat strain (12) and cardiovascular strain (10, 18), and to reduce or degrade aerobic and anaerobic (21) exercise performance (3, 4, 17, 21). Hypohydration might accelerate depletion of energy stores, accumulation of metabolites (e.g., lactate, H+, Pi), and induce changes in intracellular electrolyte concentration (5, 6, 7, 12), which is expressed in the reduction of muscle endurance. The reduction in body water increases heat strain during exercise, and the higher the reduction, the higher the elevation in core temperature (2, 10, 11, 19, 20). The latter is due mainly to the fact that hypohydration impairs the ability to dissipate body heat.

Electromagnetic (EM) waves have a strong interaction with tissue water and solutes, depending on the wave frequency. At a few MHz (~3) ion currents are induced in the tissue fluid. It should be noted that although a free conduction path does not exist for most of the fluids, a large capacitive conduction prevails. This is due to the very large (total) cell membrane area versus its very small thickness, resulting in a large capacitance. The electrical conduction in this frequency range depends strongly on the quantity of water solute available for conduction. This conduction process results in energy absorption from the EM wave by the tissue, and consequently, in the attenuation of the wave amplitude, which depends on the solute quantity (15). This absorption process is defined as the Beta dispersion of EM waves in tissue (16).

Hydration status can be accurately analyzed by current technology only by blood samples, performed in medical laboratories. Under many scenarios, especially for wounded or collapsed individuals, there is a dilemma regarding fluid resuscitation in maintaining correct body fluid levels. Development of a new device, originally introduced in *Physiol Meas* (13), based on a non-invasive method for measuring hydration status would be of value. The aim of this study was to develop a new method consisting of a non invasive device, capable of measuring hydration state in vivo, based on the comparison of absorption of radio waves at various frequencies by tissue. This device would issue an alarm when excessive deviation from the normal state of hydration is detected.

MATERIALS AND METHODS

Subjects – 12 young, healthy males volunteered to participate in this study. The physical characteristics of the subjects were as follows (mean±SE): age 24±1yr; height 175±2cm; weight 71.54±3.13kg; and body surface area 1.71±0.15m^2. Prior to the experiment, each subject underwent a medical examination that included a complete medical history, electrocardiogram at rest, urine analysis and blood screening biochemistry. Subjects were informed as to the nature of the study and potential risks of exposure to exercise in a hot climate.

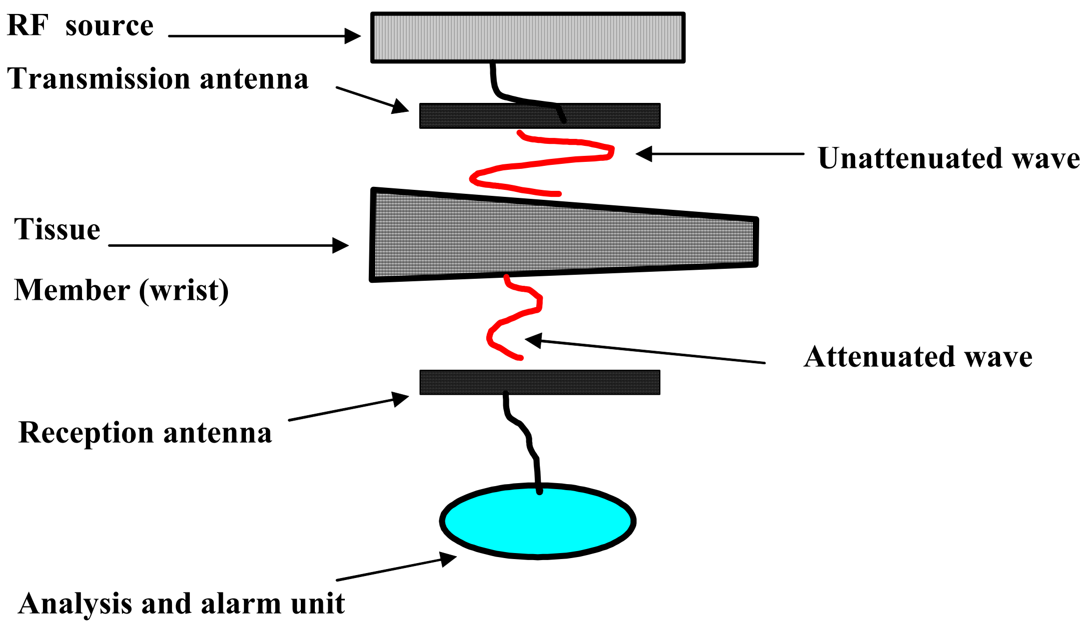
Protocol – The study was conducted in the climatic chamber at the Heller Institute of Medical Research, Sheba Medical Center, Tel Hashomer, Israel. Twenty-four hours before exposure, subjects were in good medical condition and had not taken any prescribed or unprescribed medication or alcohol. The subjects wore only shorts and sport shoes, and performed exercises in hot-dry climatic conditions of 40°C, 40% relative humidity (RH) for 70 min, consisting of two 30-min bouts of treadmill walking separated by 10-min rest.

Each subject performed 2 exercise exposures, which differed in their hydration state. While in one exposure, subjects were allowed to drink ad libitum, in the other they had to refrain from drinking. In both heat stress exposures (hypohydration and euhydration), the subjects walked or ran for two 30min bouts on a treadmill at 2, 3, 4, 5, 6, and 7 mph (5min at each speed) separated by 10-min rest. Hypohydration level was determined by measurements of fluid balance in body weight corrected for water intake at 3 different times: before the exposure, and at the end of each bout (after 30 and 60min, respectively).

Measurements – During the exposures, rectal temperature (T_{re}) and heart rate (f_c) were continuously monitored and recorded at 1-min intervals. T_{re} was measured by a thermistor probe inserted 10cm beyond the anal sphincter (Yellow Spring Instruments series 401). Heart rates were monitored and recorded on-line through bipolar chest leads using Polar belt electrodes (Polar CIC). Sweat rate and hypohydration were calculated from changes in body weight (Shinko Denski ±5g) before, after 30 min, and after 60 min of the heat stress corrected for water intake and urine. The measurement device consisted of a power source (Wavetek 2002A signal generator operating at 13dBm output), two antennas (1/8λ at the low frequency), a power sensor (Bontoon 51013), and an exposure chamber, holding the transmission and reception antennas and incorporating a space for the insertion of the wrist (9). A schematic description of the device is presented in Figure 1.

Statistical analysis – physiological responses and body weight loss measured by the scale and absorption of RF were analyzed by two-way analysis of variance. All statistical contrasts were accepted at the $P<0.05$ level of significance. Data are presented in this study as mean±SE.

Figure 1: A schematic description of the RF absorption device for hydration status measurement.



RESULTS

The loss of body water in sweating is expressed in an easily observable loss of weight. In the present experiment, the weight loss for the hypohydration exposures during the 30 min of heat stress was about 0.78±0.06 kg, and after 60 min was 1.59±0.08 kg. This parameter is widely recognized (1) as a reliable dehydration indicator, representing dehydration for these subjects at a range of 1.0-2.5% from total body weight (TBW). Thus, the data obtained in the present experiment were the changes in the RF absorption pattern in comparison to the weight loss, mainly due to sweating.

The transmitter was operated throughout the experiment in a constant power mode (10 mW total power) and the electric field at the reception antenna was measured. Since our analysis was based on the comparison of absorption, which was a relative quantity, no translation of the received voltage to actual electric field was necessary. Thus, a new model to predict TBW due to hypohydration was developed as follows:

$$\mathrm{TBW}=\mathrm{IF}-2.805\mathrm{x}10^{(-3)}\mathrm{S}960$$

where IF is an individual factor which is the measurement of the RF absorption at 960MHz before exposure to heat stress.

The prediction of this model highly correlated ($R^2=0.998$) to the actual measurements of body weight obtained from all subjects, who differed in their weight loss due to sweating (Fig. 2, bottom panel), with residuals distributed symmetrically around the zero line (Fig. 2, top panel).

Accordingly, a new model to predict body weight loss (BWL) due to hypohydration was developed. This new model included all first and second-degree factors of the RF measurements (s1-s4), and an individual factor for each subject. The model was fitted by the least squares method and by using the backward elimination method, where at each stage the variable with the smallest F-value was dropped from the model. The backward elimination resulted in a model that included 9 independent factors as follows (13):

$$\mathrm{BWL} = \mathrm{IF}+5.77\cdot10^{-4}\cdot s4+3.82\cdot10^{-6}\cdot s1\cdot s3-1.344\cdot10^{-6}\cdot s3\cdot s4+2.236\cdot10^{-1}\cdot s1/s3-5.98\cdot10^{-2}\cdot s2/s3+1.094\cdot 10^{-1}\cdot s2/s4-3.743\cdot10^{-1}\cdot s3/s4-2.84\cdot10^{-6}\cdot s1^{2}$$

where IF is the individual factor calculated from each initial RF measurement and s1, s2, s3 and s4 are the measurements at 450, 916, 2120, and 1360MHz, respectively.

In Fig. 3 (bottom panel), high correlation ($R^2=0.734$) is depicted between measured and predicted body weight loss reflected in hypohydration in all the subjects participating in this study, with the residual distribution (top panel) around the zero line.

Figure 2: Comparison of predicted total body weight (TBW) with measured body weight from euhydration and hypohydration exposures due to sweating (bottom panel) and residual scattergram (top panel).

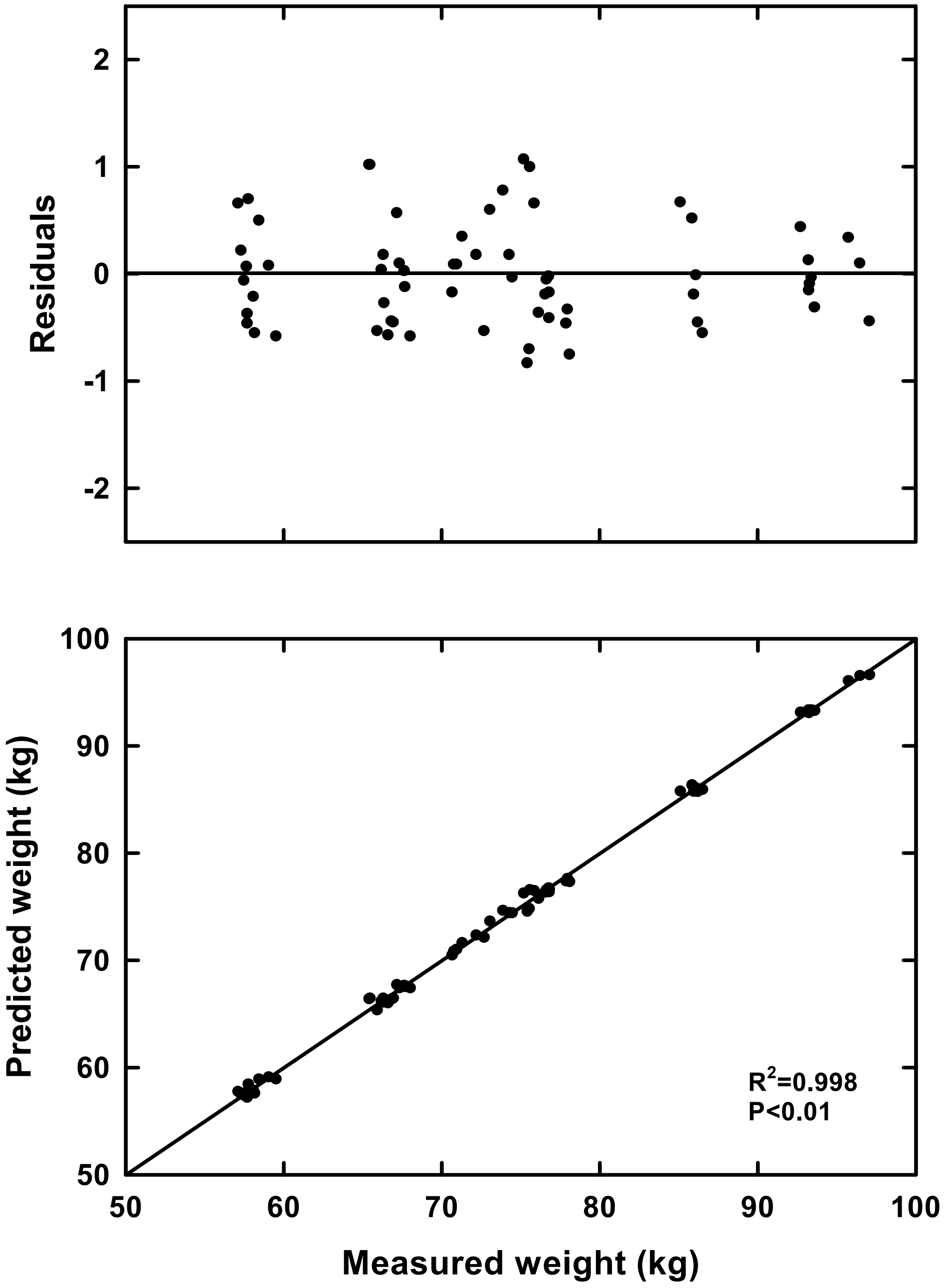
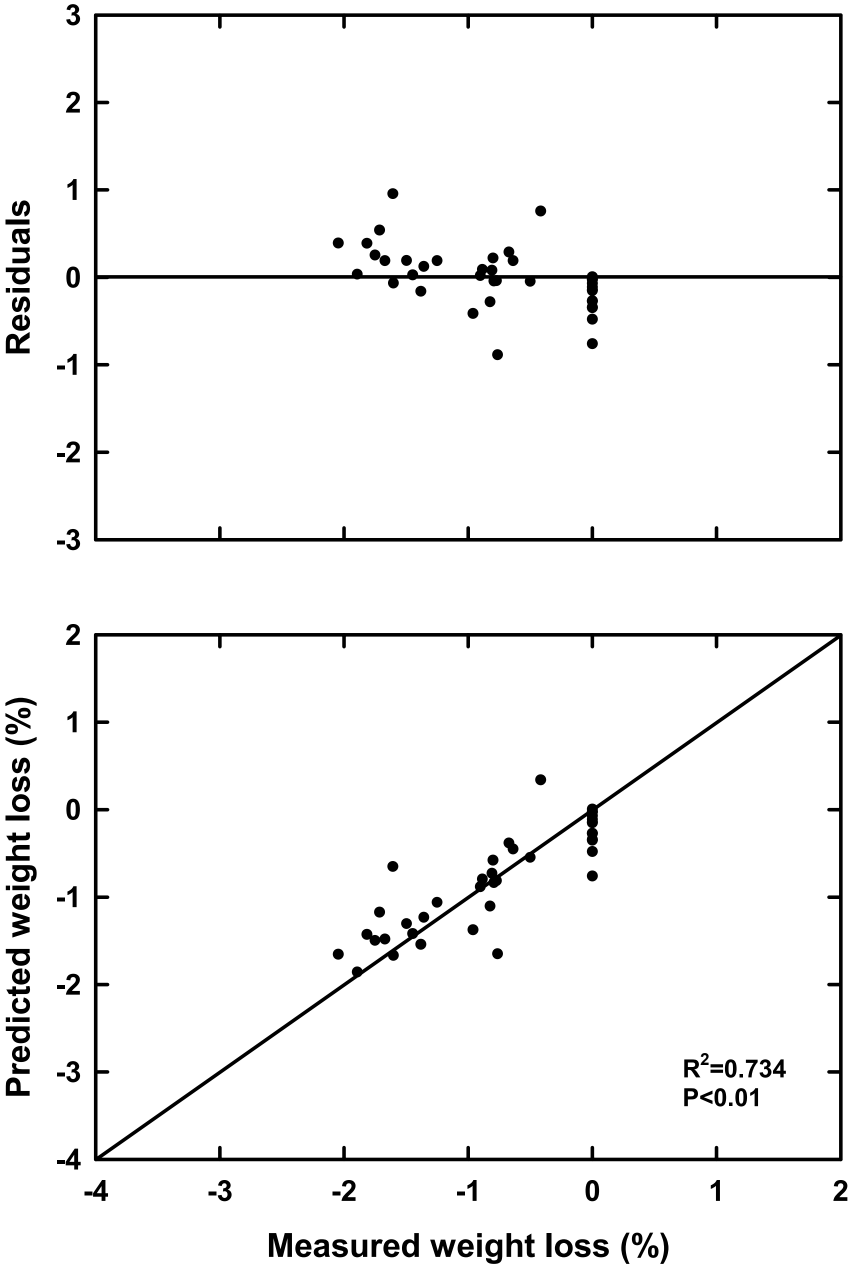


Figure 3: Comparison of predicted body weight loss (BWL) with measured BWL in euhydrated and hypohhydrated subjects due to sweating (bottom panel) and residual scattergram (top panel) [Redrawn from Moran et al, (13)]



DISCUSSION

In this study we developed and built a prototype device that enabled measuring the absorption of the EM at different frequencies from the wrist. This prototype was tested on 12 subjects at different levels of hypohydration (0.5-2.5% from TBW). The hydration levels were measured by both a new suggested method and the conventional method of body weight loss due to sweating. Each subject was tested twice, during euhydration and hypohydration heat stress exposures.

The data obtained from this study was used to develop 2 prediction models. The first was the prediction of total body weight (TBW) due to hypohydration, and the second was for the prediction of body weight loss. Prediction of TBW revealed with very high correlation ($R^2=0.998$) between measured and predicted values, whereas prediction of BWL revealed with lower correlation, but still moderate ($R^2=0.734$). Both models were based on an individual factor, which is the initial RF measurement before the exposure. This fact should be considered as a shortcoming of the concept because we cannot obtain hydration status without the RF initial measurement, which might not always be available. However, considering the existing alternative, invasive methods for monitoring hypohydration levels, these suggested prediction models are considered a big stride forward.

Comparing the absorption of RF in tissues at two different frequencies - one at the low frequency range and the other in the high range - yielded information on the ratio between the water content of the tissue and its solute content, namely, the tissue osmolarity. The RF absorption measurements presented above involve a short (a few sec) exposure to radio waves from a small part of the body at a very low intensity. In the experiment conducted, the power density at the wrist was ~1 μmW/cm^2, (determined by a Wandel & Golterman EMR 300 RF power density monitor, under valid calibration), which is less than 0.005% of the whole body continuous exposure permitted by the American Conference of Governmental Industrial Hygienists (ACGIH) (1) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (8) RF exposure limitation.

In conclusion, this study suggests a state of the art non-invasive method, which depicts hydration status immediately and accurately. No syringe, no withdrawn blood, and no medical laboratory are necessary. The individual will be able to measure and diagnose his hydration status by himself and determine whether he is in need of additional fluids. Thus, this newly developed method suggests an aid tool, which can be used in the decision making process, especially for exercising individuals and physical workers who are at risk for hypohydration. This work might present a breakthrough in non-invasive diagnostic measurement for dehydration. However, further studies should be conducted for different levels of hypohydration (e.g., 3-5% body weight loss), body mass and different selections of RF and antennas.

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Water consumption
Water treatment

14. Abstract

Maintaining body hydration at normal or euhydrated levels is essential to optimize both physical and cognitive performance. Inadequate fluid replacement and a state of dehydration or hypohydration can lead to an increased risk of heat injury. Medical support teams should be prepared to deal with an expected increased incidence of heat injury, including heat stroke, and the rare cases of hyponatremia that may occur with overhydration. New technologies that provide a source of water supply while the soldier is on the move are critical for sustaining operations for the Objective Force warrior and soldier of the future.

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