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RESEARCH AND TECHNOLOGY ORGANISATION

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RTO TECHNICAL REPORT **TR-HFM-132**

Real-Time Physiological and Psycho-Physiological Status Monitoring

(Suivi en temps réel de l'état physiologique et psycho-physiologique)

Final Report of Task Group HFM-132.

Published July 2010

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The Research and Technology Organisation (RTO) of NATO

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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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- HFM Human Factors and Medicine Panel
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- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

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RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Real-Time Physiological and Psycho-Physiological Status Monitoring

(RTO-TR-HFM-132)

Executive Summary

Dismounted warfighters can benefit from the medical status information that body-worn computerized physiological sensor systems can provide. This report reviews the state-of-the-art in real-time assessment and prediction of the physiological and psycho-physiological status of modern dismounted warfighters.

Specifically, Mr. Buller's chapter provides an overview of typical physiological monitoring system architectures from both hardware and software points of view. The discussion touches on various issues including methods for managing artifacts in sensor data, extracting thresholds, trends and features from data streams, applying algorithms and models to the data, and defining physiological state with an accompanying metric of data confidence. The chapter by Dr. Gunga reviews thermal strain assessment methodologies, including the innovative "double sensor" for estimating core temperature. Dr. Nevola provides a broad review of human hydration, including the importance and physiology of hydration, the consequences of under- and over-hydration, and markers and methods of assessing hydration state. He culminates with the vision of sensors capable of measuring muscle hydration directly. Dr. Ledderhos provides a practical discussion of altitude illness, from Acute Mountain Sickness (AMS) to High Altitude Pulmonary and Cerebral Edema (HAPE/HACE). In addition, a review of the value, applications, and limitations of oximetry in detecting disturbances of acclimatization to high altitudes are discussed, as well as the possibility of near real-time monitoring of acclimatization status under operational conditions at high altitude.

Dr. Valk reviews the importance of sleep, and how circadian disruptions and sleep deprivation can lead to physical and mental fatigue and degraded cognitive performance. He also discussed the various methodologies and mathematical models for assessing sleep status. Dr. Varoneckas reviews the relationship of heart rate variability and fatigue, focusing on how heart rate variability might be used to assess human states during sleep-wake cycles. Dr. Convertino reviews the use of ambulatory physiologic monitoring for combat casualty care, describes plans to develop improved algorithms that will enable medics to clinically assess wounded soldiers, and discusses the goal remote vital signs detection. Finally, Mr. Smrcka and co-workers provide an example of an integrated prototype physiological monitoring system that can be used to monitor and analyze real-time physiological responses of military personnel.

Conclusions and Recommendations

Real-time physiological status monitoring systems for military personnel, inherently complex medical systems, have evolved over the past decade to the point of providing practical value to warfighters. In addition, the war fighting professionals are increasingly recognizing the value of medical state information from both research and development and tactical points of view. Future research should: a) explore ways to maintain the data security without imposing overly heavy encryption requirements on lightweight wearable systems; and b) focus on providing field commander with information regarding warfighters' readiness to fight based on real-time continuous ambulatory physiological and cognitive state measurements. These efforts could be advanced through the use of practical test-bed venues, such as those offered by military training sites, to develop, acquire, test, and validate new ambulatory physiological monitoring sensor systems.

Suivi en temps réel de l'état physiologique et psycho-physiologique

(RTO-TR-HFM-132)

Synthèse

Les combattants débarqués peuvent bénéficier de suivi médical grâce aux systèmes de senseurs physiologiques informatisés transportables sur le corps. Le présent compte-rendu a pour but de présenter l'état actuel des connaissances en matière d'évaluation et de prévision en temps réel de l'état physiologique et psycho-physiologique des combattants débarqués modernes.

Le chapitre de M. Buller fournit notamment une présentation des principales architectures matérielles et logicielles des systèmes de suivi physiologique existants. Les débats ont porté sur différents sujets : méthodes de gestion des artefacts des données recueillies par les senseurs, méthodes d'extraction de seuils, de tendances et de caractéristiques à partir des flux de données, méthodes d'application aux données d'algorithmes et de modèles, méthodes de définition d'un état physiologique associé à une mesure de fiabilité des données, etc. Le chapitre du Dr. Gunga énumère les méthodologies d'évaluation des tensions thermiques, et présente notamment l'utilisation innovante de « doubles senseurs » pour estimer la température interne. Le Dr. Nevola aborde de manière détaillée les aspects relatifs à l'hydratation humaine, notamment l'importance et la physiologie de l'hydratation, les conséquences d'une soushydratation ou d'une surhydratation, ainsi que les marqueurs et méthodes utilisables pour évaluer l'état d'hydratation. Il conclut en laissant entrevoir la possibilité de développer des senseurs capables de mesurer directement l'hydratation des muscles. Le Dr. Ledderhos aborde quant à lui de manière pratique les troubles liés à l'altitude, dont le syndrome d'Acosta (ou mal aigu des montagnes) et l'œdème cérébral (OCHA) ou pulmonaire (OPHA) de haute altitude. En outre, le présent document étudie la valeur, les applications et les limitations de l'utilisation de l'oxymétrie dans la détection des troubles d'acclimatation aux altitudes élevées, ainsi que la faisabilité d'un suivi quasiment en temps réel de l'état d'acclimatation à haute altitude en conditions opérationnelles.

Le Dr. Valk aborde l'importance du sommeil et montre combien l'interruption circadienne et la privation de sommeil peuvent générer une fatigue physique et mentale et dégrader les performances cognitives. Il énumère également les différentes méthodologies et différents modèles mathématiques permettant d'évaluer l'état de sommeil. Le Dr. Varoneckas étudie la relation entre la variation du rythme cardiaque et la fatigue, en insistant sur les possibilités d'évaluation de l'état de fatigue en fonction de la variation du rythme cardiaque durant les cycles veille-sommeil. Le Dr. Convertino aborde l'utilisation d'un suivi physiologique ambulatoire pour le soin aux blessés, et décrit les méthodes de développement d'algorithmes améliorés devant permettre aux médecins d'évaluer l'état clinique des soldats blessés. Il aborde également le thème de la détection à distance des signes vitaux. Enfin, M. Smrcka et ses collaborateurs présentent un exemple de prototype de système intégré de suivi physiologique, pouvant servir à suivre et analyser en temps réel les réponses physiologiques du personnel militaire.

Conclusions et recommandations

Les systèmes de suivi en temps réel de l'état physiologique du personnel militaire, par essence des systèmes médicaux complexes, ont considérablement évolué ces dix dernières années pour désormais offrir la perspective d'une réelle valeur pratique pour les combattants. De plus, les militaires reconnaissent de plus en

plus l'importance de l'information médicale, que ce soit à des fins de recherche et de développement ou à des fins tactiques. Les futures recherches devront : a) s'intéresser aux moyens de maintenir la sécurité des données sans imposer de trop fortes contraintes de chiffrement sur des systèmes transportables forcément légers ; et b) s'intéresser à la transmission aux commandants d'unités de l'état de préparation au combat des soldats, c'est à dire à la transmission de mesures ambulatoires continues et en temps réel de l'état cognitif et physiologique de chaque combattant. Ces recherches pourraient s'accompagner d'essais pratiques organisés en environnement de test (centres d'entrainement militaires, par exemple) afin de développer, d'acquérir, de tester et de valider de nouveaux systèmes de senseurs de suivi physiologique ambulatoire.

Chapter 1 – REAL-TIME PHYSIOLOGICAL AND PSYCHO-PHYSIOLOGICAL STATUS MONITORING FOR HUMAN PROTECTION AND OPERATIONAL HEALTH APPLICATIONS

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1.1 INTRODUCTION

Our group focused on the real-time assessment and prediction of the physiological and psycho-physiological status of modern dismounted warfighters [1], [2]. Dismounted warfighters are of particular interest because of their importance in modern warfare and the fact that they commonly face mentally and physically demanding missions. Environmental conditions can be extreme; water, food, and sleep are often restricted, and missions can last weeks or more.

Dismounted warfighters can benefit from the medical status and geo-location information that mobile networked sensor systems can provide [3]. Over the course of a typical mission cycle – consisting of training, deployment, mission review, and recovery phases – physiological and geo-location information could be used to:

a) Assess baseline physiological characteristics (e.g., aerobic fitness, sleep history);

b) Support mission planning (e.g., predict thermal/work strain and water and food logistical requirements);

c) Provide mission support (e.g., improve "who, where, when" situational awareness, guide acute and chronic work/rest cycles, and reduce the likelihood of environmentally related injuries such as heat stroke);

d) Facilitate casualty evacuation; and

e) Improve the quality of after action reviews.

The family of physiological status monitoring technologies extends from personal sensors that record and display heart rate, ventilation, skin temperature, and body position (e.g., Equivital, Hidalgo, Swavesey, Cambridge, UK; http://www.hidalgo.co.uk/pdf/Emergency_Services.pdf), distance traveled (e.g., Dead Reckoning Module, Honeywell International, Plymouth, Minnesota; http://www.ssec.honeywell.com/magnetic/new/20050909_drm3.html), and sophisticated research devices that store physiological data for post hoc analysis [4], to networked systems capable of real-time collection of digital medical information in field environments (e.g., VitalSense, Mini Mitter Corp., Bend, OR; http://www.minimitter.com/Products/VitalSense/). Arguably, physiological status monitoring – the collection, interpretation, dissemination and use of physiological information – is one of the more vibrant "network life science" activities within the broad arena of "Network Science" [5].

1.2 CHARACTERISTICS OF REAL-TIME PHYSIOLOGICAL STATUS MONITORING SYSTEMS

Wirelessly networked wearable sensor systems capable of generating useful physiological and psycho-physiological status information are inherently complex. Hardware components commonly include:

1) Job- or mission-specific sets of wearable physiological sensors;
2) Wireless personal-area and squad-area network technologies; and
3) Personal digital assistants and other hand-held displays.

Software and firmware modules:

a) Manage streaming data – identify outliers due to motion artifact, cope with missing data, provide measures of statistical confidence; and
b) Apply on-the-fly algorithms and predictive models to synthesize, analyze, discard, store, transmit, and display useful physiological state information [6], [7], [8].

Finally, these systems need to be validated [9], an important but often time-consuming process.

Interestingly, ambulatory physiological monitoring systems for field environments commonly include sensors and algorithms that provide both situational- and medical-awareness. The interpretation of medical data typically requires geo-location information such as that provided by GPS (global positioning system). An obvious example is the need to know an individual's location in the event of injury. Less obviously, time series geo-location data provide information about rates of movement and, when linked to map data, terrain characteristics. This information can be used in the estimation metabolic cost of locomotion [10], thermal status, water requirements, and work/rest cycles [11].

1.3 SENSORS: KEY PHYSIOLOGICAL PARAMETERS TO MONITOR

The wearable sensor array used varies with the application and what is technologically possible. For example, the assessment of thermal status in hot conditions might involve monitoring heart rate, skin temperature, and core temperature. While in cold environments, core temperature and peripheral temperatures (e.g., digit temperatures) become more important. Hydration state assessment might involve monitoring fluid intake, urinary output or, ultimately, tissue hydration. Remote assessment of life signs, which varies significantly from the assessment in a clinical environment (see Dr. Convertino's chapter below), might rely on measures such as body position, motion, heart rate, respiration, and skin temperature [12]. Blood oxygen saturation (oximetry) appears to be useful in assessing altitude acclimatization state [13], particularly when combined with measures of acute mountain sickness obtained by questionnaire and a knowledge of the normal physiological responses to acute hypoxia.

Technologically, ambulatory physiological sensing has evolved. For example, sensing at the thoracic network node has grown from consumer-grade devices reporting only heart rate to medical-grade systems that monitor heart rate, ECG snippets, respiratory frequency, motion, and body position. Classic analog thermometer pills are being transcended by systems using digital thermometer pills that transmit identification, time, and temperature (VitalSense; Mini Mitter Company, Bend, OR; www.mini mitter.com), and are easier to use than analog pills that simply broadcast a temperature-dependent frequency.

New physio-sensor designs can benefit from increasingly powerful microprocessors (e.g., Blackfin, Analog Devices; http://www.analog.com/processors/blackfin/). These microprocessors can perform multiple tasks, from running network communications to executing algorithms and models [14], [15], [16], [17] that transform raw signals with missing data and outliers into useful measures of physiological state.

1.4 NETWORKS

Wireless mobile sensor networks have been used to collect, store, and interpret physiologic data on-the-fly [6] and is of keen interest to academia [18]. However, the use of "black box/gray box" commercial off-the-shelf (COTS) network technologies can be problematic. Specifically, when access to relevant software and hardware layers is subject to proprietary restrictions, scientific and engineering progress is

often impeded. The solution is to use transparent, purpose-built network technologies for both on-body and longer range data communication.

On-body wireless physio-sensor networks are generally highly distributed – that is, the computational capabilities of sensor nodes at the edges of the network are maximized and less reliable, and more energy intensive tasks associated with communicating are minimized. Typically, thresholds, trends, and features are extracted from complex physiological signals at the sensor node, thereby minimizing communication needs.

1.5 PSYCHO-PHYSIOLOGICAL ASSESSMENT: COGNITIVE STATUS IN THE CONTEXT OF PHYSIOLOGICAL STATE

Complex cognitive processes are affected by physiological state. For example, research has shown that dehydration, thermal state, and fatigue degrade performance on cognitive and fine motor tasks [19], [20]. Presently, the use of a wrist-worn watch that assesses the amount and quality of sleep through actigraphy has received significant attention. Prediction of one's cognitive capability based on their sleep history is assessed through the Sleep, Activity, Fatigue and Task Effectiveness (SAFTE) model [21]. A developed tool called the Fatigue Avoidance Scheduling Tool (FAST) allows commanders to assess the likely cognitive degradation due to sleep deprivation of warfighters [21]. Other psycho-physiological assessments of cognitive state include measuring electroencephalography (EEG) and evoked potentials (EP) in real time and relating those measures to cognitive decision making. This is hard to do, but efforts have begun with some field testing of prototype systems embedded into the helmets of warfighters [22]. However, to reliably assess cognitive state through EEG or EP measurements is likely more futuristic in nature. In the near-term, prediction of cognitive and fine-motor task performance through models that use more well-established physiological measures obtained during ambulation, such as heart rate, core or skin temperature, and body motion and body position (obtained through accelerometers), will allow commanders to determine if their warfighters need a recovery break to ensure mental fatigue is not leading to poor decision making that may compromise the mission or safety of personnel (e.g., friendly fire incidents).

The following sections in this report provide:

a) A more detailed consideration of system software architect;

b) A novel approach to thermal status assessment;

c) Methods for assessing hydration;

d) New approaches to helping warfighters manage the effects of hypoxia and sleep deprivation;

e) A review of combat casualty care issues; and

f) An example of prototype physiological status monitoring system.

1.6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Progress towards a real-time physiological status monitoring system capability has come from:

a) Identifying the minimal requirements for a system, and then actively constraining requirements placed on the system by others;

b) Recognizing that each group of customers has somewhat unique needs that demand tailored products; and

c) Maintaining flexibility by utilizing technologic approaches that can easily be adapted to meet new needs.

Future research might explore ways to maintain the privacy of health data and meet essential operational security needs, without imposing inappropriately heavy encryption requirements on lightweight wearable systems. Due to the inherently limited size, weight, power, cost, and computational capacity of wearable systems, there is a need for Spartan approaches to encryption. Information that is only transiently sensitive could be secured with lighter weight methods than would otherwise be needed, avoiding overly burdensome encryption techniques that could cripple wearable digital systems. To date, most of the research with physiological monitoring has focused on the health of the warfighter, whether for use in combat casualty care or in preventing illnesses and injuries. Future research may focus more attention on providing the commander with information regarding warfighters' readiness to fight based on real-time continuous ambulatory physiological and psycho-physiological measurements.

1.7 REFERENCES

[1] Hoyt, R.W. and Friedl, K.E., (2004). Current status of field applications of physiological monitoring for the dismounted soldier. In: Metabolic Monitoring Technologies for Military Field Applications, Poos, M. (Ed.) National Academy of Sciences, National Academy Press, pp. 247-257.

[2] Shaw, G.A., Siegel, A.M., Zogbi, G. and Opar, T.P., (2004). Warfighter physiological and environmental monitoring: a study for the U.S. Army Research Institute in Environmental Medicine and the Soldier Systems Center. MIT Lincoln Laboratory, Technical Report ESC-TR-2004-077, ADA428022, http://stinet.dtic.mil/.

[3] Institute of Medicine, (2004). Monitoring Metabolic Status: Predicting Decrements in Physiological and Cognitive Performance. Food and Nutrition Board, Institute of Medicine, Washington, DC, http://books.nap.edu/books/0309091594/html.

[4] Zhang, K., Werner, P., Sun, M., Pi-Sunyer, F.X. and Boozer, C.N., (2003). Measurement of human daily physical activity. Obes Res, January, 11(1):33-40.

[5] Network Science, (2005). National Research Council's Committee on Network Science for Future Army Applications. The National Academies Press, Washington, D.C., http://books.nap.edu/openbook.php?isbn=0309100267.

[6] Hoyt, R.W., Buller, M., Zdonik, S., Kearns, C., Freund, B. and Obusek, J., (2001). Physio-Med Web: Real-time monitoring of physiological strain index (PSI) of soldiers during an urban training operation. In: NATO Research and Technology Organization publication RTO-MP-076, "Blowing Hot and Cold: Protecting Against Climatic Extremes," October, Dresden, Germany, pp. 32-1 to 32-11, ftp://ftp.rta.nato.int/PubFullText/RTO/MP/RTO-MP-076/MP-076-32.pdf.

[7] Tharion, W.J. and Kaushik, S., (2006). Graphical User Interface (GUI) for the Warfighter Physiological Status Monitoring (WPSM) System – U.S. Army Medic Recommendations. USARIEM, Natick, MA, Technical Report T07-04, ADA 459 019, November.

[8] Weyand, P.G., Kelly, M., Blackadar, T., Darley, J.C., Oliver, S.R., Ohlenbusch, N.E., Joffe, S.W. and Hoyt, R.W., (2001). Ambulatory estimates of maximal aerobic power from foot-ground contact times and heart rates in running humans. J Appl Physiol, 91:451-8.

[9] Beidleman, B.A., Tharion, W.J., Buller, M.J., Hoyt, R.W. and Freund, B.J., (2004). Reliability and validity of devices for a life sign detection system. USARIEM, Natick, M.A., Technical Report T-05-01, September.

[10] Pandolf, K.B., Givoni, B. and Goldman, R.F., (1977). Predicting energy expenditure with loads while standing and walking very slowly. J Appl Physiol, 43:577-581.

[11] Kraning, K.K. and Gonzalez, R.R., (1977). A mechanistic computer simulation of human work in heat that accounts for physical and physiological effects of clothing, aerobic fitness, and progressive dehydration. J Therm Biol, 22: 331-342.

[12] Borsotto, M., Savell, C.T., Reifman, J., Hoyt, R.W., Nunns, G. and Crick, C., (2004). Life-signs determination model for Warfighter Physiological Status Monitoring. In: NATO Research and Technology Organization publication RTO-MP-HFM-109 "Combat Casualty Care in Ground Based Tactical Situations: Trauma Technology and Emergency Medical Procedures," August 2004, St. Pete Beach, FL, pp. 28-1 to 28-10, ftp://ftp.rta.nato.int/PubFullText/RTO/MP/RTO-MP-HFM-109/MP-HFM-109-28.pdf.

[13] Muza, S.R., Rock, P.B., Zupan, M.F., Miller, J.C., Thomas, W.R. and Cymerman, A., (2004). Residence at moderate altitude improves ventilatory response to high altitude. Aviat Space Environ Med, 75:1042-1048.

[14] Moran, D.S., Shitzer, A. and Pandolf, K.B., (1998). A physiological strain index to evaluate heat stress. Am J Physiol, July, 275(1 Pt 2): R129-34.

[15] Chen, L., McKenna, T., Reisner, A. and Reifman, J., (2006). Algorithms to qualify respiratory data collected during the transport of trauma patients. Physiol Meas, September, 27(9):797-816. Epub 27 June.

[16] Savell, C.T., Borsotto, M., Reifman, J. and Hoyt, R.W., (2004). Life sign decision support algorithms. MEDINFO, M. Fieschi, et al. (Eds.). IOS Press, Amsterdam, pp. 1453-1457.

[17] Kraning, K.K. II and Gonzalez, R.R., (1991). Physiological consequences of intermittent exercise during compensable and uncompensable heat stress. J Appl Physiol, December, 71(6):2138-45.

[18] Tatbul, N., Buller, M., Hoyt, R.W., Mullen, S. and Zdonik, S., (2004). Confidence-based data management for personal area sensor networks. Proceedings of the First Workshop on Data Management for Sensor Networks (DMSN 2004), August 2004, Toronto, Canada, http://db.cs.pitt.edu/dmsn04/.

[19] Lieberman, H.R., Bathalon, G.P., Falco, C.M., Kramer, F.M., Morgan, C.A. and Niro, P., (2005). Severe decrements in cognition function and mood induced by sleep loss, heat, dehydration, and under-nutrition during simulated combat. Biological Psychiatry, 57:422-429.

[20] Szinnai, G., Schachinger, H., Arnaund, M.J., Linder, L. and Keller, U., (2005). Effect of water deprivation on cognitive-motor performance in healthy men and women. Am J Physiol: Reg Integr Compar Physiol, 289:R275-R280.

[21] Hursh, S.R., Redmond, D.P., Johnson, M.L., Thorne, D.R., Belenky, G., Balkin, T.J., Storm, W.F., Miller, J.C. and Eddy, D.R., (2004). Fatigue models for applied research in warfighting. Aviat Space Env Med, 75(3):A44-A53, 2004.

[22] Dorneich, M., Ververs, P.M., Mathan, S. and Whitlow, S., (2007). DARPA Improving Warfighter Information Intake Under Stress – Augmented Cognition. Honeywell Program Final Report under Contract DAAD16-03-C-0054, Minneapolis, MN, 28 February.

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Chapter 2 – SYSTEMS ARCHITECTURE

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ABSTRACT

Real-time ambulatory health applications often require a unique combination of sensors and algorithms, since direct assessment of physiological state in free-living humans can be quite challenging. This necessarily leads to an architecture where sensor measurements and algorithmic health state determination are treated as separate elements linked by an information management process. The physical architecture of physiological and psycho-physiological monitoring systems will often contain four common components: smart sensors – that understand noise and malfunction; a sensor network – that minimizes power usage, inter-cell interference, and detectability; a computational engine – that manages the sensor network, and processing of data; and off-body communications. Overlaid on this physical architecture is an information architecture where models, algorithms, and state determination can be personalized, and provide a standard interface with statistical confidences for the input and output of data. Utilizing these architectural principals can enable a versatile modular physiological or psycho-physiological monitoring system to suit many mission needs.

2.1 SYSTEMS ARCHITECTURE: PHYSICAL SENSORS AND ALGORITHM INDEPENDENCE, IMPORTANCE OF INFORMATION MANAGEMENT

This chapter provides principles that can help guide the development of robust physiologic and psycho-physiologic human protection and operational health applications. Real-time ambulatory health applications often require a unique combination of sensors and algorithms, since direct assessment of physiological state in free-living humans can be quite challenging [1]. This realization leads to an architecture where sensor measurements and algorithmic health state determination are separate elements linked by a robust information management process. This chapter will initially examine the physical architecture of the sensors, sensor network, computational engine, and off-body communications, and then describe how the information architecture relates these components to the algorithms and models that determine health state.

2.2 PHYSICAL ARCHITECTURE: SENSORS, NETWORK, COMPUTATIONAL ENGINE, OFF-BODY COMMUNICATIONS

A typical physical architecture is comprised of a set of body worn sensors, a data transport system or local area (body) network, a center for computational functions to take place, and a means to transfer the information from the body to some remote location (e.g., to a medic, commander, or hospital). Figure 2-1 shows a typical physical architecture. An array of body-worn sensors communicates via an on-body network to a computational engine. This computational engine controls the on-body network, which aggregates sensor data for use by algorithms and models that specify and predict warfighter's health states.

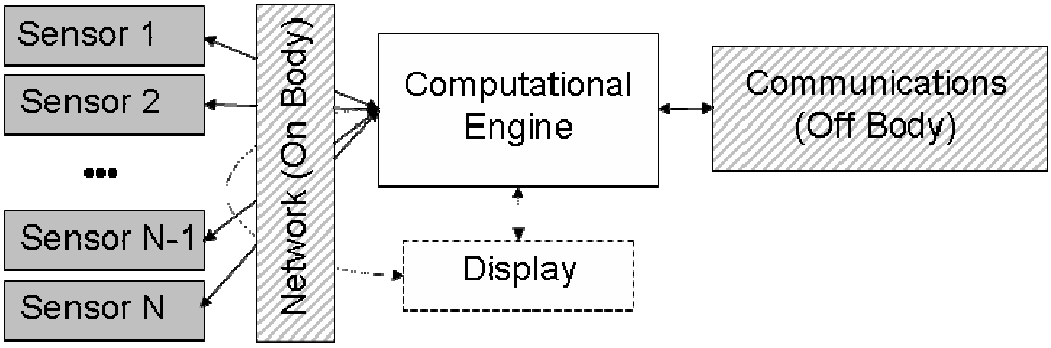


Figure 2-1: Typical Physical Architecture of a Warfighter-Worn Physiological Monitoring System.

2.2.1 Sensors

Sensors need to be "smart" in that they not only measure a signal but derive useful information from that signal. For example, heart rate or inter-beat interval derived from electrocardiogram (ECG) signals are often noisy due to motion artifact or muscle electrical artifact. Estimates of statistical confidence in the derived parameter are needed to define when a signal is no longer reliable or valid. Typically, each smart sensor provides a uniquely identified output to the warfighter's on-body network sub-board. For example, in Figure 2-2, the fluid intake sensor microprocessor subcomponent provides a digital output to the circular communications sub-board, which wirelessly links the sensor to the central on-body computational engine.

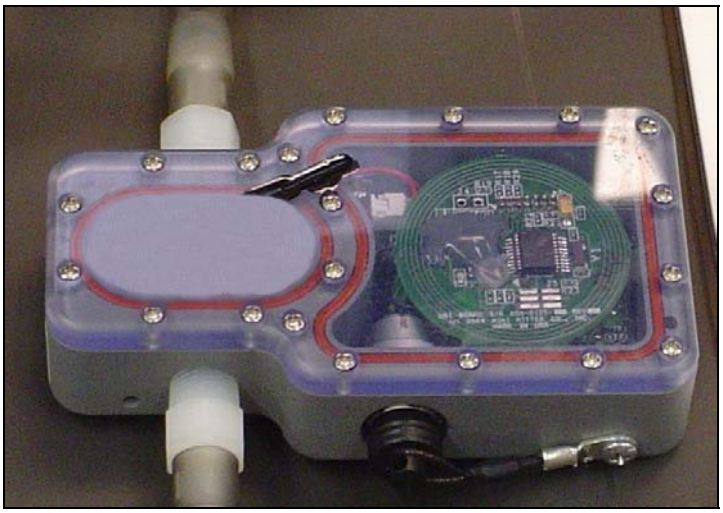
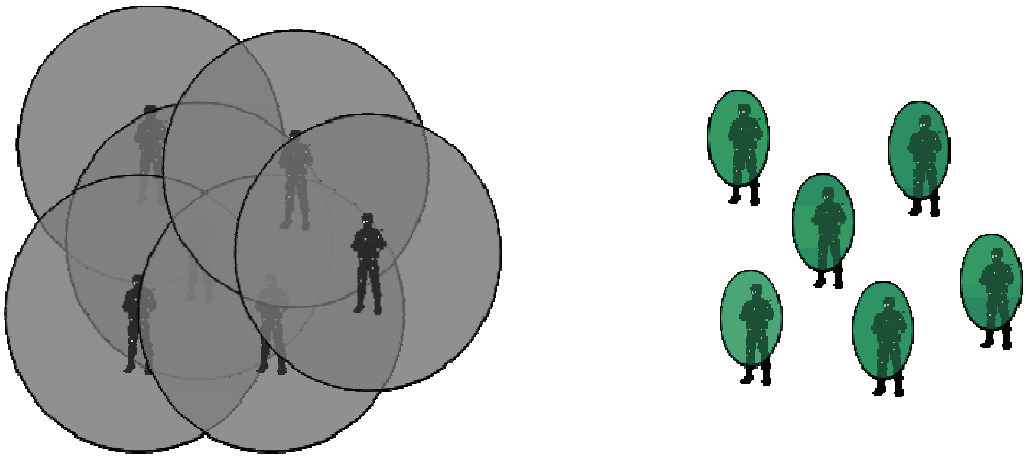


Figure 2-2: Warfighter Physiological Status Monitoring – Initial Capability (WPSM-IC) Fluid Intake Monitor (FIM) Sensor Module. This is an example of sensor independence from a network. A network sub-board is clearly seen inside the sensor casing. This sensor can very simply be upgraded to a new or different network by the use of a new network sub-board.

2.2.2 Network

The on-body network is a critical piece of the system. It must provide a reliable communications link from the sensors to the central computational engine with minimal power consumption and acceptable data loss [2]. The network must be designed to minimize inter-cell interference or cross-talk among sensors on adjacent warfighters (Figure 2-3). By choosing the appropriate network technology, the amount of inter-cell interference can be reduced.



a) Typical Radio Frequency (RF) Body Area Network b) Desired Body Area Network

Figure 2-3: Issue of a) Inter-Cell Interference of Typical Radio Frequency (RF) Body Area Networks and the b) Desired Inter-Cell Interference Characteristics of the Body Area Network.

The Massachusetts Institute of Technology Lincoln Laboratory, Lexington, MA, reviewed the technologies available for on-body networking in 2004 and suggested that current commercial networking solutions do not fully meet the needs of the dismounted Soldier [3]. Wired solutions provide data integrity, high bandwidth, centralized power, central processing, and allow sensors to be no more than electrodes or probes. However, wires transition poorly between clothing layers, and centralizing processing also adds a significant processing burden. Wireless network solutions such as WiFi or IEEE802.11b/g, Bluetooth®, and even Zigbee are current emerging commercial standards that provide reliable data transfer with quite high bandwidth, but are "expensive" in terms of power. However, nascent, magnetic induction networks under development show promise in providing a low-power network with a small inter-cell interference footprint, with a low likelihood of detection, or stealth capability.

Currently, the US Army's WPSM-IC system network operates within an unlicensed Radio Frequency (RF) industrial, scientific, and medical (ISM) band. Data are transmitted from sensors to a medical hub in a pseudo-random push transmission scheme (patented). The timing schedule of sensor transmissions is established when sensors are initialized and associated with a hub. Knowing the transmission schedule allows the hub to power up only when it expects a transmission from a sensor. This conserves power consumption in the hub receiver (~0.1% duty cycle) and also guards, to some degree, against cross-talk from other sensors. The network is designed with an effective range of 18" to avoid cross-talk when large numbers of warfighters are in close proximity, but unlike magnetic induction, is less stealthy. For future optimization of network and sensor power resources, it is essential that the network be designed to provide two-way communication, even if the data link to the sensor has a severely restricted bandwidth.

2.2.3 Computational Center

The computational center or hub has multiple functions. First, it manages and controls the on-body area network, ensuring that it recognizes the sensors that it has been assigned, and provides data in an optimal transmission scheme based on requested levels of service and power consumption strategies. The second function of the hub is to manage the information flow to include the following: data routing, model and algorithm selection, confidence calculations, and health state classification. Third, the hub manages the output of health state information to the users through the off-body communications network. Figure 2-4 shows an example of the WPSM-IC hub.

Figure 2-4: WPSM-IC Computational Center (Hub), Showing the Insertion of the Personal Information Carrier (PIC – A Memory Card Containing Medical Records and Personalization Information for the Algorithms). Once the PIC is inserted, the hub will be keyed to an individual and the personal information used to personalize the models and classifiers.

2.2.4 Off-Body Communications

Off-body communications are beyond the scope of this panel. However, any physiological monitoring system should be able to interface to a broader communications network. Thought should be given to the interface specification so that output from the system can be readily routed to the appropriate users and that data can be incorporated into higher level information "rollups" and information displays. For example, Buller et al. [4] describe an extensible output format based around the extensible markup language (XML) with spatial, temporal, and entity based identification dimensions.

2.3 INFORMATION ARCHITECTURE

2.3.1 Algorithmic State Determination

There are a number of steps to get from sensor data to a confident health state determination. Steps typical of this process are illustrated in Figure 2-5.

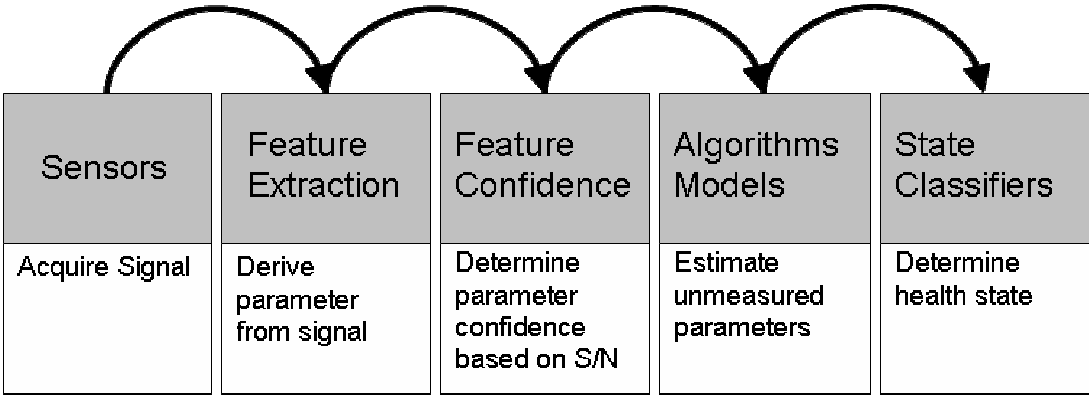


Figure 2-5: Shows the Data-Information-Knowledge Process Used in the WPSM-IC System. Sensors acquire raw signals that need processing to derive features or parameters of interest. Feature confidence is determined from the signal-to-noise ratio of the sensor signal. Algorithms and models combine multiple features, with confidences to produce estimates of unmeasured parameters. Features, confidence, and unmeasured parameters are used by classification algorithms to output a final state determination.

The state classification process can occur completely in one sensor, as with the WPSM-IC Vital Sign Detection System (VSDS), or be spread across several sensors or multi-sensor nodes, and involve multiple models and state classification algorithms. Estimation of thermal state in the WPSM-IC system would be an example of this [5] (see Figure 2-6).

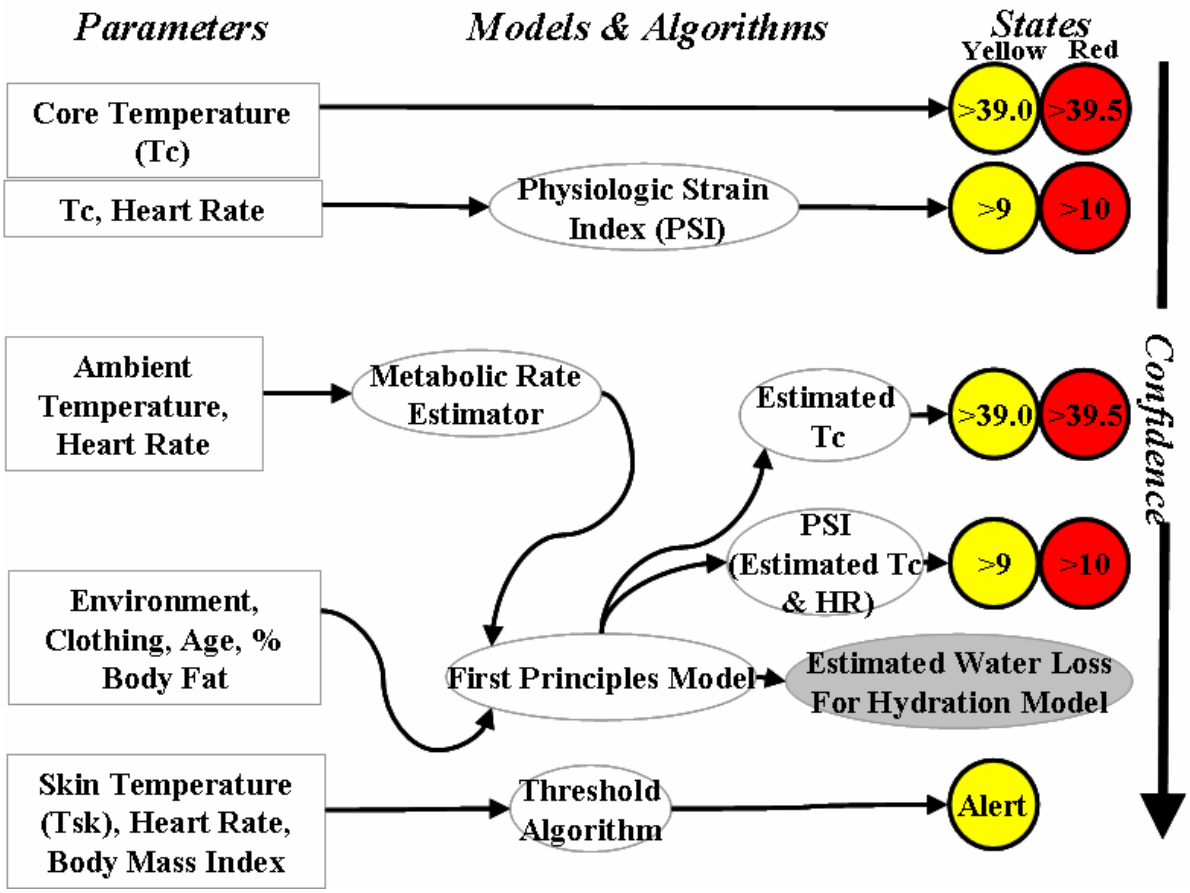


Figure 2-6: An Example of Thermal State Estimation from the WPSM-IC System and how Graceful Failure can be Implemented Using a Variety of Different Algorithms and Sensors Built in a Layered Fashion. [6]

2.3.2 Principles of the Information Architecture

We suggest four simple information architecture principles:

1) Independence;
2) Individualization;
3) Interface versatility; and
4) Confidence.

Independence refers to "state determination" being independent of models and algorithms, and that models and algorithms should be independent of the sensors. In this way, new and better sensors or models can be easily substituted or added without costly and time-consuming software modification. **Individualization** refers to the sensors and the system being associated with or linked to an individual, and the use of personal biographic and anthropometric and physiologic information to improve system functionality. **Interface**

versatility refers to the use of standardized but versatile information interfaces between sensors, models, algorithms, and state classification code. One such architectural approach is "publish and subscribe" architecture [6]. Under this architecture a sensor would publish its data (e.g., core body temperature), and a model needing that input information would then subscribe to the sensors producing that required type of data. **Confidence** refers to the statistical confidence that can be assigned to a piece of information. Each component of the system that produces information should also provide a confidence measure. A confidence-based data management methodology would not only allow a system to fail gracefully (i.e., not crash when one parameter is missing, but rather provide less confident results with the remaining sensors), but also provide a basis for methods to husband resources such as power based upon required confidence levels [7]. For example, Figure 2-6 shows the WPSM-IC thermal state estimation process and how various parameter inputs and model selections affect the overall confidence of the state output. When multiple techniques are used in parallel, the system has redundancy allowing for alternate methods to be used when some parameters become unavailable.

2.4 CONCLUSIONS

Careful thought should be given to the architectures of physiological and psycho-physiological monitoring systems. Designing a system with a sound architecture that can accept the addition of new sensors, networks, models, and state classifiers is essential. This type of architecture will facilitate the integration of work from all North Atlantic Treaty Organization (NATO) members and avoids country-specific solutions. An example of a real-time physiological monitoring system was demonstrated in 2000 during a series of field exercises at Ft. Benning, GA, USA [8]. The WPSM-IC system is another example of such a system and was demonstrated in a field exercise at Aberdeen Proving Ground, MD, USA, in 2006 [9]. Given that a basic infrastructure now exists, it can be envisioned that with some modest integration effort, a multinational physiological monitoring system can be developed from the current work efforts of the RTG-132 panel members.

2.5 REFERENCES

[1] Hoyt, R.W. and Friedl, K.E., (2004). Current status of field applications of physiological monitoring for the dismounted soldier. In: National Academies of Science, Monitoring Metabolic Status – Predicting Decrements in Physiology and Cognitive Performance. The National Academies Press, Washington, D.C., pp. 247-257.

[2] Blackadar, T., Wronski, J., Hoyt, R., Buller, M.J., et al., (1998). Mobile Medical Monitoring. IEEEP802.11 Wireless LANs.

[3] Shaw, G.A., Siegel, A.M., Zogbi, G. and Opar, T.P., (2004). Warfighter physiological and environmental monitoring: a study for the U.S. Army Research Institute in Environmental Medicine and the Soldier Systems Center. MIT Lincoln Laboratory, Technical Report ESC-TR-2004-077.

[4] Buller, M.J., Siegel, R.M., Vaillette, G.P., et, al., (2002). Automated data management for Warfighter Physiologic Status Monitoring. USARIEM, Natick, MA, Technical Report T-02/12, AD A398541.

[5] Buller, M.J., Hoyt, R.W., Ames, J.S., Latzka, W.A. and Freund, B.J., (2005). Enhancing Warfighter Readiness through Situational Awareness – The Warfighter Physiologic Monitoring – Initial Capability. 11th Conference on Human Computer Interaction Processings (Augmented Cognition).

[6] Eugster, P.T., Felber, P.A., Guerraoui, R. and Kermarrec, A., (2003). The many faces of publish/ subscribe, ACM Computing Surveys (CSUR), Vol. 35 No. 2, p. 114-131, June.

[7] Tatbul, N., Buller, M.J., Hoyt, R.W., Mullen, S.P. and Zdonik, S., (2004). Confidence-based data management for personal area sensor networks. International Workshop on Data Management for Sensor Network, 30th International Conference on Very Large Data Bases, Toronto.

[8] Hoyt, R.W., Buller, M.J., Zdonik, S., et al., (2001). Physio-Med Web: Real-time monitoring of physiological strain index (PSI) of soldiers during an urban training operation. In: Proceedings from RTO/HFM Panel Symposium on Blowing Hot and Cold: Protecting Against Climatic Extremes. RTO-MP-076, ISBN 92-837-1082-7, Dresden, Germany.

[9] Tharion, W.J., Buller, M.J., Karis, A.J. and Mullen, S.P., (2007). Acceptability of a wearable vital sign detection system. Proceedings of the Human Factors Society 51st Annual Meeting. Human Factors and Ergonomics Society, Santa Monica, CA, Volume 51.

Chapter 3-1 – THERMAL MONITORING SYSTEMS

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3-1.1 ENVIRONMENTAL CONSIDERATIONS

Even today, heat stroke remains a severe, potentially lethal heat injury in humans. In particular, warfighters and special military forces such as chemical, biological, or bomb disposal squads are at risk because they are:

i) Frequently exposed to hot environments;

ii) Have to perform high physical workloads; and/or

iii) Must wear heavy armor protective clothing that impairs dissipation of heat from the body [1].

Under these conditions the body core temperature can change rapidly, reaching deleterious levels. Not surprisingly, heat injury is a concern to the military and has negative effects on both training and operations [2]. The American Army reported over 1800 heat injury cases during 2002 [3]; of these, nearly one-sixth were diagnosed as the more serious condition of “heat stroke”. An estimated dollar cost to the military was calculated from earlier heat injury data (1989 – 1999) at over $10 M per year, based on duty days lost, the cost of hospitalization, replacement, and disability [4]. Therefore, it is very helpful to monitor any changes in core body temperature as closely as possible in order to be able to initiate appropriate actions at an early stage. Usually, under experimental conditions the core temperature is measured by inserting a thermosensor in the esophagus, nasopharynx, rectum, or tympanum/auditory meatus. However, none of these methods are really applicable during daily routines. This is due to the fact that the requirements for a method serving to measure body core temperature are demanding; the thermosensor has to:

i) Be non-invasive;

ii) Be easy to handle;

iii) Must fulfill basic hygiene standards;

iv) Be unbiased towards various environmental conditions;

v) Register changes should quantitatively reflect small changes in arterial blood temperature; and

vi) Respond to changes in temperature in the shortest time possible [5], [6].

These requirements are essential because several studies in humans have shown that if high environmental temperature and humidity prevail, especially in combination with heavy physical workloads and fluid loss (sweating) with inadequate re-hydration, the heat load will lead to a rapid rise in the body core temperature, subsequently resulting in heat stress-related injuries such as heat stroke [1]. If thermoregulatory impairments due to fever or drugs prevail, the deleterious developments may occur even faster [7], [8].

3-1.2 CURRENT STATUS/LIMITATIONS

Currently there is no accurate and easy method to measure core temperature in a field setting. The definitions of various temperature measurements used in wearable body activity monitors are summarized in Table 3-3

[9]. The relative advantages and disadvantages of core temperature measurement sites including the time response of the different kind of sensors, have been intensively discussed ever since the first benchmark investigations on this topic by Claude Bernard in 1876 [10]-[16], and will be briefly described in the following section.

3-1.3 SENSORS

3-1.3.1 Core Temperatures (Esophageal, Rectal, Tympanic Temperature)

The most common places for measuring core body temperature are the esophagus, rectum, and tympanum/ auditory meatus. Most thermal physiologists agree that the esophageal temperature is the best non-invasive index of core temperature for humans. It responds rapidly to changes in blood temperature elicited by extracorporeal circulation [6], [17] and by body cooling by anesthesia [12]. The esophageal temperature is obtained by inserting a catheter, containing a thermocouple or thermistor, through the nasal passage into the throat and then swallowing it. It is best used in research settings, but it is highly problematic in clinical or field assessments. This holds for the other core body temperatures as well (rectal and tympanic/auditory meatus); they are all impractical for warfighters to use in the field [2]. The rectal temperature is obtained by inserting a temperature sensor a minimum of 5 cm past the anal sphincter, because temperature measurements are uniform within the rectum from 5 – 27 cm past the anal sphincter [8], [18]. During exercise it takes approximately 25 – 40 minutes to achieve a steady-state rectal temperature value [8], [18], [19]. These steady-state rectal temperatures are usually ~0.4°C higher than the mean skin temperatures [1] and 0.2° – 3°C higher than simultaneously measured nasopharyngeal and esophageal temperatures [13], [15], [19], [20]. The rectal and esophageal temperatures are largely independent of the environmental temperature [15], [21]-[23]. As a result, the steady-state rectal temperature provides a good index to assess body heat storage [20], [23]. The main problem with the rectal temperature is that it shows a slow response in comparison to the other measurement sites, a fact that has been proven again recently in 60 patients who underwent a post-operative re-warming [24]-[26]. The reason for the slow response is probably:

i) A low rate of blood flow to the rectum compared to other measurement sites [17], [27], and

ii) The mass of organs located in the body cavity.

This greater mass of tissue in the lower abdominal cavity requires a far greater amount of energy to cause a rapid temperature change. Tympanic temperature is obtained by inserting a small temperature sensor into the ear canal and advancing it until it rests against the tympanic membrane. Proper placement is determined by the subject hearing a sound when the temperature sensor touches the tympanic membrane. Some subjects find this contact to be uncomfortable [11]. In addition, there are reports of the temperature sensors perforating the tympanic membrane [28]-[30]. Because of the potential discomfort and trauma, as well as the placement problems associated with tympanic measurements, some investigators have chosen instead to measure the temperature of the external auditory meatus. For this measurement, a temperature sensor is placed in an ear plug and inserted into the external auditory meatus. Placement of the temperature sensor is important, since there is a substantial (~0.5°C) temperature gradient along the wall of the meatus. In addition, several studies have shown that tympanic/auditory meatus temperature measurements do not provide a reliable index of the level of core temperature during either rest or exercise [3], [18], [19], [31]-[33]. Depending upon the environmental conditions, tympanic/auditory meatus temperature values can be lower or higher than simultaneously measured steady-state rectal [18] and esophageal temperature values [31]-[33]. In addition, local head heating and air flow to the face will bias the temperature of the external meatus [16], [18], [19], [31]-[33].

3-1.3.2 Radio Pill

The best and most reliable method of assessing thermal state in operational environments is direct measurement of core body temperature by using the network-enabled ingestible core temperature sensor. However, the use of a core temperature ingestible sensor is impractical for routine use, so these devices are reserved for use during high thermal stress missions, while encapsulated in nuclear, biological, and chemical protective suits, and if use is indicated by medics during combat casualty care such as cooling interventions, in case of heat injuries [34].

3-1.3.3 Skin Temperature

Although the skin surface is more easily accessed than the other body core temperature sites mentioned above, this measurement site has many flaws, because the skin temperature is largely affected by coetaneous blood flow and sweat evaporation. Furthermore, environmental changes such as air temperatures, humidity, wind speed, and radiation will alter the skin temperature. That is why thermal physiologists prefer to determine mean skin temperature, a sum of weighted individual skin temperatures taken at up to 16 different skin surface sites, or for certain questions, even more [35], [36]. For the warfighters present purpose, such a complex, heavily wired temperature measurement set-up is highly impractical. Other concepts have shown that it is very difficult to use a single skin temperature sensor, even when it is combined with the Body Mass Index (BMI), the knowledge of the clothes worn, to result in a reliable and accurate body core temperature [37].

3-1.4 WAY FORWARD (REQUIREMENTS FOR THE FUTURE)

3-1.4.1 Heat Flux Sensor (Double Sensor)

Gunga et al. (2005) have introduced a combined skin temperature and heat flux sensor (Double Sensor) (Patent No. DE 100 38 247, DE 101 39 705, 2003) [38]. In contrast to similar methodological attempts in the past [38]-[41], this zero heat flux sensor principle has been miniaturized and used without extra heating, and has been specially sealed and integrated into the straps/webbing of a firefighter's helmet. It is placed at the vertex of the head and has been tested under various physical and environmental conditions (i.e., changing workloads and ambient temperatures of 10°, 25°, and 40°C). A measurement comparison of the new sensor with the rectal temperature revealed that the Double Sensor:

i) Differed between -0.16°C to 0.1°C from the average of the rectal temperature;

ii) Showed, with increasing ambient temperatures, increasing concordance correlation coefficients (CCC) (all work periods: 10°C = 0.49; 25°C = 0.69; 40°C = 0.75; all rest periods: 10°C = 0.39; 25°C = 0.81; 40°C = 0.74); and

iii) Exhibited a more rapid response to the body core temperature changes for all resting periods at all ambient conditions, as compared to rectal temperature ($P<0.01$) [42].

If these data from the heat flux sensor in the helmet are combined with cardiovascular data (i.e., for example heart rate), then it might be possible to predict thermal physiological strain (PSI) in humans, according to Moran et al. [43]. However, they observed limitations of the heat flux sensor in cold environments that have to be investigated further.

3-1.4.2 Double Sensor and Data Acquisition Unit

The main components of the Double Sensor Unit hardware are shown in Figure 3-1.1. The positions of the Double Sensors are shown in Figure 3-1.2.

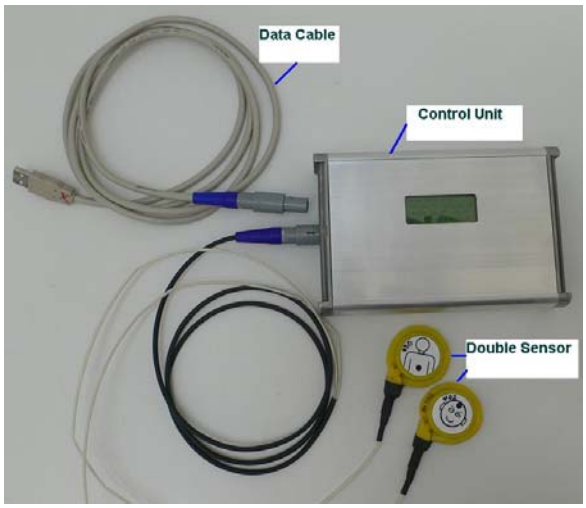

Figure 3-1.1: Double Sensors, Data Acquisition Unit, and Data Cable.

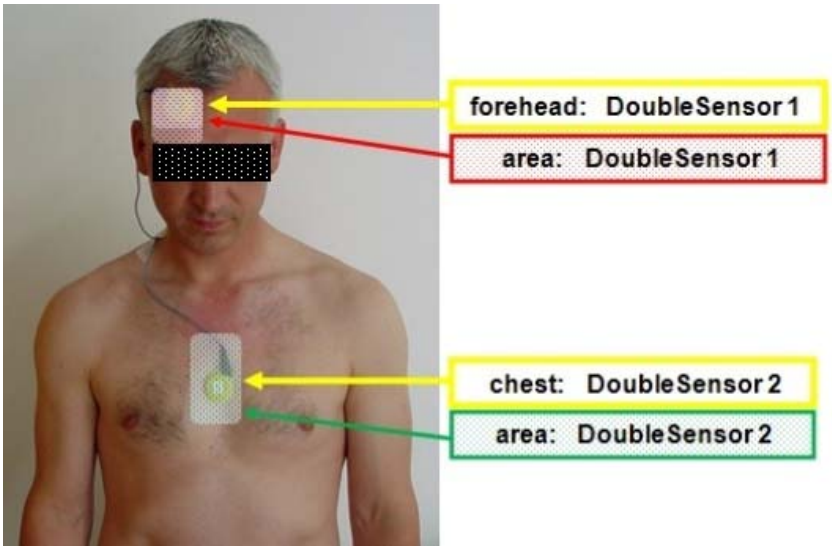

Figure 3-1.2: Usual Positions (Forehead and Sternum) for Placing Double Sensors.

3-1.4.3 Integrated Systems Life Monitoring Systems (WPSM-IC)

Since 2004 the Warfighter Physiological Status Monitoring – Initial Capability (WPSM-IC) program has developed a Soldier wearable system that provides health state information to Soldiers, medics, and commanders. The system utilizes a proprietary low power data network, which helps to reduce sensor size, extend battery life, and thereby enhances its applicability in the field. The WPSM-IC System, which is comprised of a series of sensors, a health hub, and algorithms, can monitor core body temperature (currently limited to radio pill use) and the hydration states by using a drinking counting device (Hoyt et al. [44]). The latter device is important in helping to prevent heat injuries, because it has been frequently shown that besides high core body temperatures, dehydration enhances the risk to the warfighter of decreased physical and cognitive performance, or heat injuries or even heat stroke [16], [45], [46]. It seems a worthwhile challenge to integrate the combined skin temperature and heat flux sensor (Double Sensor) into the WLSM-IC device, to overcome the given time and logistical limits of the radio pill system and to ensure reliable, continuous body core temperature monitoring of the warfighter in the field.

3-1.5 SUMMARY

Heat stroke still remains a dangerous, potentially lethal illness. Particularly at risk are firefighters, and civil and military Special Forces who must wear protective sealed clothing. There is currently no accurate and easy method to measure core temperature in a field setting. We suggest integration of the Double Sensor (heat flux measurement device) into the WPSM-IC system to:

i) Continuously monitor core body temperature changes under various physical and environmental conditions; and

ii) Determine the physiological strain index (PSI) by simultaneously obtained cardiovascular data from the WPSM-IC.

Such a device might provide useful information to the warfighter and/or the commander chief to estimate the physical capabilities and/or to initiate appropriate countermeasures to avoid heat injuries in warfighters at an early stage. Furthermore, we expect that such a non-invasive and easy-to-handle device to monitor physical fitness, including body core temperature, will increase our knowledge from a statistical point. The device under testing will have a value in itself, to define the limitations and workloads of the warfighter in the field in a much better and safer way.

3-1.6 REFERENCES

[1] Wenger, C.B., (2001). Human adaptation to hot environments. In: Textbooks of Military Medicine, Pandolf, K.B. and Burr, R.E., (Eds.). USARIEM, Natick, MA, Volume 1, pp. 51-86.

[2] Buller, M.J., Hoyt, R.W., Ames, J.S., Latzka, W.A. and Freund, B.J., (2005). Enhancing warfighter readiness through situational awareness – the warfighter physiologic monitoring – initial capability. 11th International Conference on Human-Computer Interaction Proceedings. Lawrence Erlbaum Associates Inc., Philadelphia, PA.

[3] U.S. Army, (2003). Heat related injuries. MSMR Medical Surveillance Monthly Report, 12(5), http://amsa.army.mil.

[4] Hoyt, R.W., Reifman, J., Coster, T.S. and Buller, M.J., (2002). Combat medical informatics: present and future. Proc AMIA Symp, 335-339.

[5] Cooper, K.E., Cranston, W.I. and Snell, S., (1964). Temperature in the external auditory meatus as an index of central temperature changes. J Appl Physiol, 19:1032-1035.

[6] Shiraki, K., Konda, N. and Sagawa, S., (1986). Esophageal and tympanic temperature responses to core blood temperature changes during hyperthermia. J Appl Physiol, 61:98-102.

[7] Clark, W.G. and Lipton, J.M., (1984). Drug-related heatstroke. Pharmacol Ther, 26:345-388.

[8] Nielsen, B. and Nielsen, M., (1962). Body temperature during work at different environmental temperatures. Acta Physiol Scand, 56:120-129.

[9] Liden, C.B., Wolowicz, M., Stivoric, J., Teller, A., Vishunubhatla, S., Pelletier, R. and Farringdon, J., (2002). Accuracy and Reliability of the SenseWear™ Armband as an Energy Expenditure Assessment Device. Online. BodyMedia™. Accessed September 23, 2003, http://books.nap.edu/ openbook.php? record_id=10981&page=66.

[10] Aikas, E., Karvonen, M.J., Piironen, P. and Ruosteenoja, R., (1962). Intramuscular, rectal and oesophageal temperature during exercise. Acta Physiol Scand, 54:366-370.

[11] Brengelmann, G.L., (1987). Dilemma of body temperature measurement. In: Man in a Stressful Environment; Thermal and Work Physiology, Shiraki, K. and Yousef, M.K. (Eds.). Charles C. Thomas, Springfield, IL, pp. 5-22.

[12] Cooper, K.E. and Kenyon, J.R., (1957). A comparison of temperatures measured in rectum, oesophagus and on the surface of the aorta during hypothermia in man. Br J Surg, 44:616-619.

[13] Cranston, W.I., Gerbrandy, J. and Snell, E.S., (1957). Oral, rectal and oesophageal temperatures and some factors affecting them in man. J Physiol London, 126:347-358.

[14] Mairiaux, P., Sagot, J. and Candas, V., (1983). Oral temperature as an index of core temperature during heat transients. Eur J Appl Physiol, 50:331-341.

[15] Saltin, B., Gagge, A.P. and Stolwijk, J.A.J., (1970). Body temperatures and sweating during thermal transients caused by exercise. J Appl Physiol, 28:318-327.

[16] Sawka, M.N. and Wenger, C., (1986). Physiological responses to acute exercise heat-stress. In: Human Performance Physiology and Environmental Medicine at Terrestrial Extremes, Pandolf, K.B., Sawka, M.N. and Gonzalez, R.R. (Eds.). Cooper Publishing Group, Traverse City, Michigan, pp. 97-152.

[17] Molnar, G.W. and Read, R.C., (1974). Studies during open-heart surgery on the special characteristics of rectal temperature. J Appl Physiol, 36:333-336.

[18] Greenleaf, J.E. and Castle, B.L., (1972). External auditory canal temperature as an estimate of core temperature. J Appl Physiol, 32:194-198.

[19] Nadel, E.R. and Horvath, S.M., (1970). Comparison of tympanic membrane and deep body temperatures in man. Life Sci, 9:869-875.

[20] Saltin, B. and Hermansen, L., (1966). Esophageal, rectal and muscle temperature during exercise. J Appl Physiol, 21:1757-1762.

[21] Gunga, H.C., (2005). Wärmehaushalt und Temperaturregulation. In: Physiologie, Deetjen, P., Speckmann, E.J. and Hescheler, J. (Eds.). Urban & Fischer, München, pp. 669-698.

[22] Stolwijk, J.A., Saltin, B. and Gagge, A.P., (1968). Physiological factors associated with sweating during exercise. Aerosp Med, 39:1101-1105.

[23] Strydom, N.B., Wyndham, C.H., Williams, C.G., Morrison, J.F., Bredell, G.A.G. and Joffe, A., (1965). Oral/rectal temperature difference during work and heat stress. J Appl Physiol, 20:283-287.

[24] Braeuer, A., Weyland, W., Fritz, U., Schuhmann, M.U., Schmidt, J.H. and Braun, U., (1977). Bestimmung der Körpertemperatur. Anaesthesist, 46:683-688.

[25] Braeuer, A., Martin, J.D., Schuhmann, M.U., Braun, U. and Weyland, W., (2000). Genauigkeit der Blasentemperaturmessung bei intraabdominellen Eingriffen. Anästhesiol Intensivmed Notfallmed Schmerzther, 35:435-439.

[26] Melette, H.C., (1950). Skin, rectal and intravascular temperature adjustments in exercise. Am J Physiol, (Abstract) 163:734.

[27] Aulick, L.H., Robinson, S. and Tzankoff, S., (1981). Arm and leg intravascular temperature of men during submaximal exercise. J Appl Physiol, 51:1092-1097.

[28] Dickey, W.T., Alhgren, E.W. and Stephen, C.R., (1970). Body temperature monitoring via the tympanic membrane. Surgery, 67:981-984.

[29] Tabor, M.W., Blaho, D.M. and Schriver, W.R., (1981). Tympanic membrane perforation: complication of tympanic thermometry during general anaesthesia. Oral Surq Oral Med Oral Pathol, 51:581-583.

[30] Wallace, C.T., Marks, W.E., Adkins, W.Y. and Mahaffey, J.E., (1974). Perforation of the tympanic membrane, a complication of tympanic thermometry during anesthesia. Anesthesiology, 41:290-291.

[31] Marcus, P., (1973). Some effects of cooling and heating areas of the head and neck on body temperature measurement at the ear. Aerosp Med, 44:397-402.

[32] Marcus, P., (1973). Some effects of radiant heating of the head on body temperature measurements at the ear. Aerosp Med, 44:403-406.

[33] McCaffrey, T.V., McCook, R.D. and Wurster, R.D., (1975). Effect of head skin temperature on tympanic and oral temperature in man. J Appl Physiol, 39:114-118.

[34] Weller, A.S. and Withey, W.R., (2005). Comparison of telemetry pill and rectal measurement of deep-body temperature during treadmill walking and running in the heat. ICEE Ystad Sweden 2005, p. 611ff.

[35] Mitchell, D. and Wyndham, C.H., (1969). Comparison of weighting formulas for calculating mean skin temperature. J Appl Physiol, 26:616-622.

[36] Murgatroyd, D. and Hardy, J.D., (1970). Central and Peripheral Temperatures in Behavioral Thermoregulation of the Rat, Hardy, J.D., Gagge, A.P., and Stolwijk, J.A.J. (Eds.). Thomas, Springfield, IL, Phys Behav Temp Reg, 58:874-891.

[37] Yokota, M., Moran, D.S., Berglund, L.G., Stephenson, L.A. and Kolka, M.A., (2005). Non-invasive warning indicator of the “Red Zone” of potential thermal injury and performance impairment: A pilot study. Proceedings for the 11th International Conference of Environmental Ergonomics, Lund University, Sweden, pp. 514-517.

[38] Gunga, H.C., Sandsund, M., Reinertsen, R.E., Sattler, F. and Koch, J., (2005). The “Double sensor” – A new non-invasive device to measure continuously core temperature in humans. In: Environmental Ergonomics XI, Holmér, I., Kuklane, K. and Gao, C. (Eds.). Proceedings from the 11th International Conference on Environmental Ergonomics, Ystad, Sweden, pp. 286-289.

[39] Fox, R.H. and Solman, A.J., (1971). A new technique for monitoring the deep body temperature in man from the intact skin surface. J Physiol, 212(2):8P-10P.

[40] Smith, P., Davies, G. and Christie, M.J., (1980). Continuous field monitoring of deep body temperature from the skin surface using subject-borne portable equipment: some preliminary observations. Ergonomics, 23(1):85-86.

[41] Taylor, N., Wilsmore, B., Amos, D., Takken, T., Komen, T., Cotter, J.D. and Jenkins, A., (1998). Indirect measurement of core temperature during work: Clothing and environmental influences. Abstracts of the 8th International Conference on Environmental Ergonomics, San Diego, CA, USA, p. 97.

[42] Gunga, H.C., Sandsund, M., Reinertsen, R.E., Sattler, F. and Koch, J., (2008). A non-invasive device to continuously determine heat strain in humans. J Therm Bio, 33:297-307.

[43] Moran, D.S., Shitzer, A. and Pandolf, K.B., (1998). A physiological strain index to evaluate heat stress. Am J Physiol, 275:R129-134.

[44] Hoyt, R.W. and Friedl, K.E., (2004). Current status of field applications of physiological monitoring for the dismount Soldier. In: Metabolic Monitoring Technologies for Military Field Applications, Poos, M (Ed.). National Academy of Sciences, National Academy Press, Washington, D.C., pp. 247-257.

[45] Montain, S.J., Sawka, M.N. and Wenger, C.B., (2001). Hyponatremia associated with exercise: risk factors and pathogenesis. Exerc Sport Sci Rev, 29:113-117.

[46] Pandolf, K.B., Sawka, M.N. and Gonzales, R.R., (1988). Thermoregulatory responses of middle-aged and young men during dry-heat acclimation. J Appl Physiol, 65:65-71.

Chapter 3-2 – APPLICATIONS OF THE ARCHITECTURE: ENVIRONMENTAL CONSIDERATIONS – HYDRATION

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*"The first consideration in maintaining or enhancing performance is to endeavour to ensure that troops are in a **well-hydrated**, rested and well-nourished state, including optimal amounts of all essential micronutrients, plus the best in military training, both physical and mental, in advance of anticipated periods of stress."*

Committee on Military Nutrition Research, 1994 [1]

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The overriding requirement of the Armed Forces is to achieve and to maintain the highest level of operational effectiveness. To perform effectively, military personnel must be sufficiently robust to cope with the physical and psychological demands of a role that may expose them to numerous types and intensities of operational stress. Strategies to minimise the resulting operational strain in preparation for impending duty may serve to promote operational readiness. The energy expended during military work (i.e., training and operations) has been shown to reach levels that compare with the most extreme of competitive sporting events (~45.9 $MJ \cdot day^{-1}$ [2]).

Large decrements in total body water (TBW) and prolonged negative energy balance have often been reported for such work, particularly when undertaken in hot environments [3]. Meeting the nutritional requirements of military personnel plays a key roll in determining whether the outcome of their mission, and indeed the entire campaign, will be successful. Water is a critical requirement without which no military force can operate effectively. There is a need to identify the water requirements of military personnel in order to reduce performance-degrading dehydration and mitigate the consequent risk of heat illness.

3-2.1 DEFINITION OF HYDRATION STATUS

For the purpose of this report, the term 'hydration' has been used to describe the inclusion of water within the human body and the extent to which water is contained within the body's fluid compartments. Therefore, hydration status defines the extent to which these fluid compartments have been adequately filled. Hydration status may be considered to be:

- 'Normal' (i.e., euhydrated) when the total body water (TBW) is equal to the quantity of water required to hydrate the human body and to correctly fill its fluid compartments (to the level of turgidity that affords homeostasis);
- 'Lower than normal' (i.e., *hypo*-hydrated or a deficit in TBW) when the TBW fails to match the quantity of water required to hydrate the human body and to correctly fill its fluid compartments; and
- 'Higher than normal' (i.e., *hyper*-hydrated) when the TBW exceeds the volume required to match the quantity of water needed to hydrate the human body and to correctly fill its fluid compartments.

The term dehydration refers to the dynamic process of losing water from the body during the transition from hyper-hydration to euhydration to *hypo*-hydration [4], [5]. Reference to hypovolaemia describes a deficit in the volume of blood within the human body.

3-2.2 WHY DO WE NEED WATER?

Water is the largest single constituent of the human body (~60% of total body weight) and is essential to sustain life, health and performance (both physical and cognitive). While the human body can healthfully subsist on a diet lacking various micronutrients for several weeks or months, it can survive no longer than ~100 hours without access to a water source. The many unique physical properties of water make it integral to the normal function of the human body by allowing it to serve as:

- A solvent and separating medium for molecular interactions (e.g., gaseous exchange within the lungs and cellular respiration);
- The transporter and distributor of nutrients, metabolites, hormones and other materials around the body and within cells;
- A facilitator of waste disposal (e.g., urine and faeces);
- A reactant in many metabolic reactions;
- A thermoregulator (due to its high specific heat and heat of evaporation);
- A lubricant between bodily structures, the formation of mucous, as well as facilitating necessary structural shifts in macromolecules such as proteins and nucleic acids;
- A structure-former, maintaining cellular shape (and turgor pressure);

- The medium upon which postural stability is afforded; and
- A protective shock absorber (e.g., for the brain).

Furthermore, cell hydration has been suggested to be an important signal to regulate cell metabolism and gene expression [5]. The average water content of the human body varies between individuals. Total body water (TBW), comprising extracellular fluid (ECF) and intracellular fluid (ICF), averages approximately 60% of body weight (BW) (see Figure 3-2.1), with a range from approximately 45% to 72% BW [6], where the variance is primarily due to differences in body composition. TBW is usually measured by volume distribution of an appropriate tracer (e.g., antipyrine, deuterium oxide, tritium oxide), and it generally declines with increased age from an average ~90% of total body weight (BW) as a foetus to 74% BW as an infant, 60% BW as a child, 60% BW as a teenage boy (56% BW for a teenage girl), 60% BW as an adult man (50% BW as an adult woman)[1] to 56% BW in men older than 50 years (47% BW for women older than 50 years).

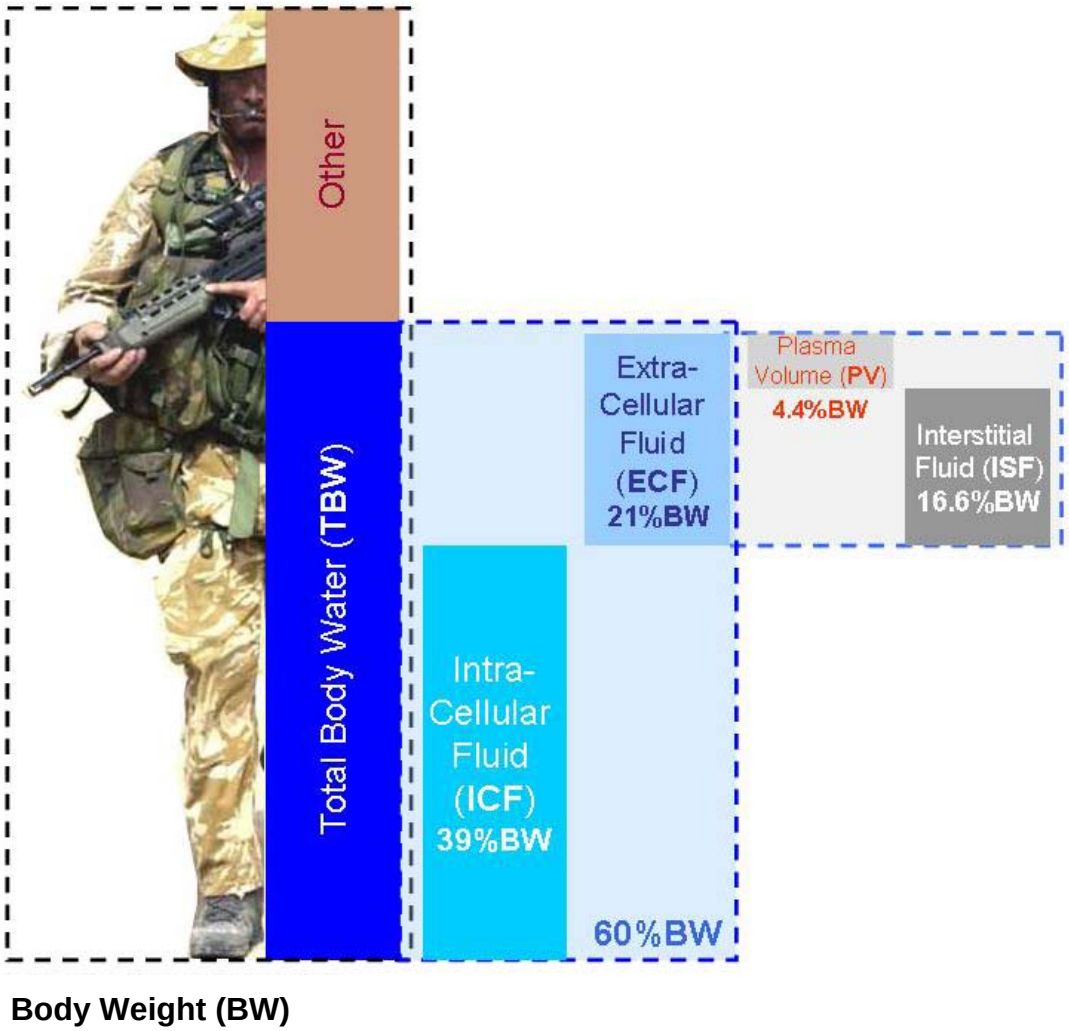

Figure 3-2.1: The Relationship between the Constituent Fluid Compartments of the Body and Body Weight.

[1] The gender differences from puberty onwards are due to differing levels of body fat, as is the decline in TBW in the elderly who replace muscle mass with fat mass.

Body water is distributed between the ICF and the ECF, which contain 65% TBW (39% BW) and 35% TBW (21% BW), respectively (see Figure 3-2.1). The ECF is further divided into the interstitial and plasma spaces. An average 70-kg man has approximately 42 L of TBW, 28 L of ICF, and 14 L of ECF, with the ECF comprising approximately 3 L of plasma and 11 L of interstitial fluid. These are not static volumes, but represent the net effects of dynamic fluid exchange, with varying turnover rates between compartments [5]. Water is free to move between the ICF and the ECF with any net movement controlled by the effective osmotic and hydrostatic pressures. The majority of the ions in the ICF are K^+ and protein anions, whereas in the ECF, they are Na^+, Cl^- and bicarbonate. Perturbations such as exercise, heat exposure, fever, diarrhoea, trauma, and skin burns will greatly modify the net volumes and water turnover rates between these fluid compartments.

Water loss through the skin occurs via insensible diffusion and secreted sweat. For the average adult, loss of water by insensible diffusion is approximately 450 $mL \cdot day^{-1}$ (see Table 3-2.1). During heat stress, eccrine sweat glands secrete sweat onto the skin surface, which cools the body when water evaporates from the sweat. In hot weather, sweat evaporation provides the primary avenue of heat loss to defend the deep body temperature. For sedentary persons in temperate conditions, water requirements usually range from 2 to 4 $L \cdot day^{-1}$, and water balance is regulated primarily by the kidneys. For physically active people exposed to heat stress, water requirements can often double [4], and it would not be unusual for physically active, heat-stressed individuals to incur water deficits of several litres.

Table 3-2.1: Estimated Minimum Daily Water Turnover for Euhydrated Adults in the Absence of Fluid Intake

Source	Loss in Body Water ($mL \cdot day^{-1}$)		Production of Body Water ($mL \cdot day^{-1}$)		*Supporting Evidence*
	Range		*Range*		
Respiratory loss	-250.0	-350.0			*Hoyt and Honig 1996 [7]*
Urinary loss	-500.0	-1000.0			*Adolph 1947b (cited in [5])*
Faecal loss	-100.0	-200.0			*Newburgh et al. 1930 (cited in [5])*
Insensible loss (skin)	-450.0	-1900.0			*Kuno 1956 (cited in [5])*
Metabolic production*			+250.0	+350.0	*Hoyt and Honig 1996 [7]*
Total	-1300.0	-3450.0	+250.0	+350.0	
Net loss ($mL \cdot day^{-1}$)	**-1050.0**	**-3100.0**			

** These data assume that there is minimal water loss from sweating.*

Exercise heat stress not only stimulates fluid loss, primarily by sweating, but also it induces electrolyte imbalances and changes in renal function. As a result, fluid deficits with and without proportionate solute changes can occur.

In addition, exercise heat stress alters transcompartmental and transcapillary forces that redistribute fluids between various compartments (see Figure 3-2.1), organs, and tissues [4]. For these reasons, the accuracy of most methods used to assess hydration status is limited by the circumstances in which they are undertaken and the purposes for which they are intended.

Recommended reading (information within this section has been adapted from):

> Sawka, M.N., (2005). Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate: Chapter 4 'Water'. Panel on Dietary Reference Intakes for Electrolytes and Water Standing Committee on the Scientific Evaluation of Dietary Reference Intakes, Food and Nutrition Board. Institute of Medicine of the National Academies, The National Academies Press, Washington, DC, www.nap.edu [5].

3-2.3 WHY IS HYDRATION STATUS IMPORTANT?

Identifying the state of hydration of the human body serves to establish the *need*, and the *urgency*, for ingesting water at that time. The ability to monitor the state of hydration of the body facilitates detection of the period when TBW is rapidly declining (i.e., dehydration) in sufficient time to take corrective action and to restore any deficit in TBW. A deficit in TBW challenges the ability of the human body to maintain homeostasis, particularly during perturbations (e.g., sickness, physical exercise, and environmental stress). The validity of water tables (widely reported in various publications), which attempt to prescribe the rate of fluid intake required by individuals from the general population in order to mitigate the risk of *hypo*-hydration, remains contentious. The utility of *generalised* guidance concerning fluid intake is often impractical and lacking the necessary specificity for military operations (and may risk ill-advised practices if complex guidance is misinterpreted). In the early stages of dehydration (loss of TBW equivalent to 0.5% BW) few signs or symptoms are apparent, and it is often the case that (in the absence of the stimulus for *thirst*) the initially euhydrated individual is unaware of such a small deficit in TBW.

However, as dehydration progresses, the symptoms associated with the more marked *hypo*-hydration results are well-established[2] (see Table 3-2.2). Although identifying such 'marked' symptoms may be quickly undertaken by eye, the correct (and necessary) diagnosis requires a more empirical approach in order to reduce the risk of administering inappropriate treatment.

Table 3-2.2: Symptoms Associated with the Extent of Total Body Water Loss
(Adapted from Greenleaf JE and Fink WJ 1982 [9])

% Body weight loss (litres for a 70 kg man)	**Symptoms**
1 (0.7 litres)	Thirst threshold at rest, impaired ability to thermoregulate during exercise
2 (1.4 litres)	Thirst threshold during exercise, vague discomfort, loss of appetite
3 (2.1 litres)	Increasing thickening of the blood, dry mouth, reduction in urine production
4 (2.8 litres)	Increased effort of exercise, flushed skin, impatience, apathy, exercise capacity (stamina) is reduced 20%-30% below normal
5 (3.5 litres)	Difficulty in concentrating, headache, impatience
6 (4.2 litres)	Severe impairment of exercise temperature regulation, increased heart rate, risk of heat stroke
7 (4.9 litres)	Likely collapse if combined with heat and exercise
8 (5.6 litres)	Dizziness, laboured breathing in exercise, mental confusion
10 (7.0 litres)	Spastic muscles, inability to balance with eyes closed, general incapacity, delirium and wakefulness, swollen tongue
11 (7.7 litres)	Circulatory insufficiency, marked thickening of the blood and decreased blood volume, failing renal function

Where 'thirst threshold' is the extent of the dehydration at which the sensation of thirst first arises.

Mathematical models have attempted to estimate *hypo*-hydration by considering potentially unique combinations of symptoms or affects upon performance. However, too many confounding factors have rendered this approach unreliable and inaccurate. The ability to accurately monitor hydration status in real-time would, arguably, satisfy such a need. Furthermore, the ability to monitor the hydration status of the individual may address those fundamental questions:

"How much water is enough, and how much is too much?"

[2] Adolph EF 1947 found that the hypohydration equivalent to a loss in TBW of 3% to 4% BW during prolonged marching in the heat impaired performance and caused exhaustion and collapse.

The ability of military logistics to supply water to meet the demand is critical to operational effectiveness, but understanding how to make best use of the water may be the key to success.

3-2.4 AFFECT OF HYDRATION STATUS UPON PERFORMANCE (PHYSICAL AND COGNITIVE)

The daily volume of liquid water that an individual needs depends on the state of hydration of the human body and the rate of loss of body water (i.e., dehydration). The rate of loss of water from the body may be influenced by a number of intrinsic (e.g., cardiovascular fitness, age[3], gender, body composition, illness) and extrinsic (e.g., physical activity, environmental stress) factors. When matched for such factors, men generally require more water than women due to their higher, relative fat-free mass and comparatively greater daily energy expenditure. It has been suggested that adopting a lifestyle that exposes the body to chronic *hypo*-hydration may increase the risk of kidney stones, gall stones and some cancers. Consumption of a diet that lacks the appropriate balance of nutrients may encourage obligatory diuresis, exacerbating the risk of *hypo*-hydration and the need for water.

3-2.4.1 *Hypo*-Hydration

Water that is lost from the body must be replaced. Failure to successfully replace losses in body water results in dehydration and exposes personnel to an increased risk of heat illness. Dehydration reduces heat dissipation by reducing skin blood flow during exercise, usually resulting in an increased deep body temperature [8]. This poses a threat to thermoregulation, as it may limit the body's most effective natural means of losing excess body heat (i.e., evaporation of sweat from the skin[4]) [4]. Both physical and cognitive performances are impaired proportionally to the magnitude of body water loss incurred (see Table 3-2.3).

[3] Old age may diminish the sensation of thirst, as well as the ability to concentrate the urine.

[4] Approximately 675 W of excess body heat is lost with each litre of sweat that is evaporated from the skin. In the absence of sweating, the body could over-heat within 40-minutes of light work.

Table 3-2.3: The Influence of Hypohydration (and Heat Stress) upon Human Performance

Performance Construct	**Performance during Hypohydration [5] *v.* Euhydration (*Without* Added Heat Stress)** *Range*		**Performance during Hypohydration [5] *with* Heat Exposure *v.* Euhydration** *Range*	
	From: Least Change Reported (%)	*To:* Greatest Change Reported (%)	*From:* Least Change Reported (%)	*To:* Greatest Change Reported (%)
Maximal aerobic power	0.0 (Houston et al. 1981)	-6.5 (Below et al. 1995)	-4.0 (Caldwell et al. 1984)	-27.0 (Craig and Cummings 1966)
Submaximal aerobic endurance	+1.7 (Robinson et al. 1995)	-48.0 (McConell et al. 1997)	7.0 (Below et al. 1995)	-31.0 (Walsh et al. 1994)
Maximal anaerobic power	0.0 (Houston et al. 1981)	-18.0 (Nielsen et al. 1981	0.0 (Jacobs et al. 1980)	-35.0 (Nielsen et al. 1981
Maximum muscle strength	0.0 (Greenleaf et al. 1966)	-11.0 (Bosco et al. 1968)	0.0 (Saltin 1964)	-5.0 (Webster et al. 1990)
Maximum muscle endurance	0.0 (Serfass et al. 1984)	-9.0 (Bosco et al. 1974)	0.0 (Greiwe et al. 1998)	-31.0 (Torranin et al. 1979)
Target shooting	*n/a*	*n/a*	Reduced speed and accuracy (Epstein et al. 1980)	
Choice reaction time	*n/a*	*n/a*	Faster response time to peripheral stimuli (Leibowski et al. 1972)	
Visual-motor tracking, attention and arithmetic efficiency	*n/a*	*n/a*	Tracking was impaired (Gopinathan et al. 1988)	
Short-term memory	*n/a*	*n/a*	Short-term memory was impaired (Cian et al. 2000, Gopinathan et al. 1988)	
Long-term memory	*n/a*	*n/a*	Recall was impaired (following exercise) (Cian et al. 2000)	

Adapted from Sawka 2005 (Chapter 4: Water) [5], where the full references for the citations in the above table can be obtained.

[5] *Hypo*-hydration was equivalent to a loss in total body water of >2% total body weight.

However, even small losses of body water (1.2% BW) have a detrimental impact on physical work and negatively impact human thermoregulation [5]. Accordingly, dehydration may be the greatest non-adversary threat to military operations.

Incomplete fluid replacement decreases TBW and, as a consequence of fluid exchange, affects each fluid space. Nose et al. 1983 [10] concluded that dehydration results in water distribution largely from the intra- and extracellular fluid compartments of muscle and skin [4]. Water is lost first from the extracellular space. Next, a proportionately greater percentage of water comes from the intracellular fluid compartment. Costill et al. 1976 [11] found that when subjects lost 6% BW due to dehydration, approximately 50% of the water that was lost came from intracellular fluid. Thus muscle cells, which are 70% water, are depleted of the water necessary to maintain metabolic functions. This is one reason why dehydration negatively impacts exercise performance. One study [12] showed that moderate exercise (50% $\dot{V}O_2max$) in cool environmental temperatures (14.4°C [60°F]) without prior dehydration resulted in most of the fluid losses coming from the extracellular interstitial fluid. However, when subjects repeated the same protocol in a hot environment (36.2°C or [97°F]), 23% of the fluid losses came from the intracellular compartment. Thus, progressive dehydration in originally euhydrated individuals performing moderate exercise primarily depletes extracellular fluid. However, when the heat stress is combined with *hypo*-hydration, fluid is drawn from the intracellular compartment. Therefore, technology that is intended to monitor the hydration status of the human body must understand the dynamic pattern of activity both within and between the body's fluid compartments in order to correctly estimate TBW.

Heat acclimatization affords efficient thermoregulation by promoting an earlier onset and scale of sweating under heat stress, but it increases the requirement for water. The benefit of heat acclimatization is lost when the body becomes dehydrated. The body cannot adapt to dehydration, and it can only survive for a few days without water. Even mild dehydration[6] degrades performance (see Table 3-2.3), and it may occur in any environment (e.g., hot, cold, hypo-/hyper-baric). However, since 1990, military operations have increasingly been undertaken in hot environments where sweat losses are likely to be highest. Combining the high heat stress typically encountered during military operations with dehydration has been found to exacerbate impairment during complex cognitive and mental tasks (see Table 3-2.3), thereby increasing the likelihood of human error and degrading operational effectiveness.

3-2.4.2 *Hyper*-Hydration

The normal homeostatic response by the human body to the ingestion of fluids that produce a temporary state of *hyper*-hydration would be diuresis (excretion of the excess body water as urine). However, achieving a mild state of *hyper*-hydration prior to performing physical exercise may delay the onset of *hypo*-hydration and its associated performance decrements. Consumption of water containing glycerol has been found to increase the retention of water within the body[7] while decreasing urine output [13]. Retention of excess water, or hypotonic fluid, within the body may dilute essential electrolytes (e.g., hyponatraemia), thereby increasing the risk of injury (compared with euhydration), as well as threatening performance, health and even life as the severity of the condition worsens.

3-2.4.3 Water Intoxication (Hyponatraemia)

An imbalance in the body's electrolytes (see Figure 3-2.2) can occur when large quantities of very salty sweat are replaced by drinking only *plain* water at a time when the daily diet contains too little sodium (from salt) to replace the losses. The symptoms of hyponatraemia are similar to those associated with *hypo*-hydration and include mental confusion, weakness and fainting. During the first 6-months of

[6] Aerobic performance may be reduced by as much as 20% or 30% when only 2% to 4% of total body water is lost.

[7] Glycerol solutions appear to have a greater effect in expanding TBW and ICF than equal volumes of water.

coalition operations in Iraq (2003), hyponatraemia accounted for 6% of all reported heat illnesses[8] among UK Armed Forces. The US Army has demonstrated how promulgation of *guidelines for effective fluid replacement* has successfully reduced the incidence of hyponatraemia in their deployed personnel.

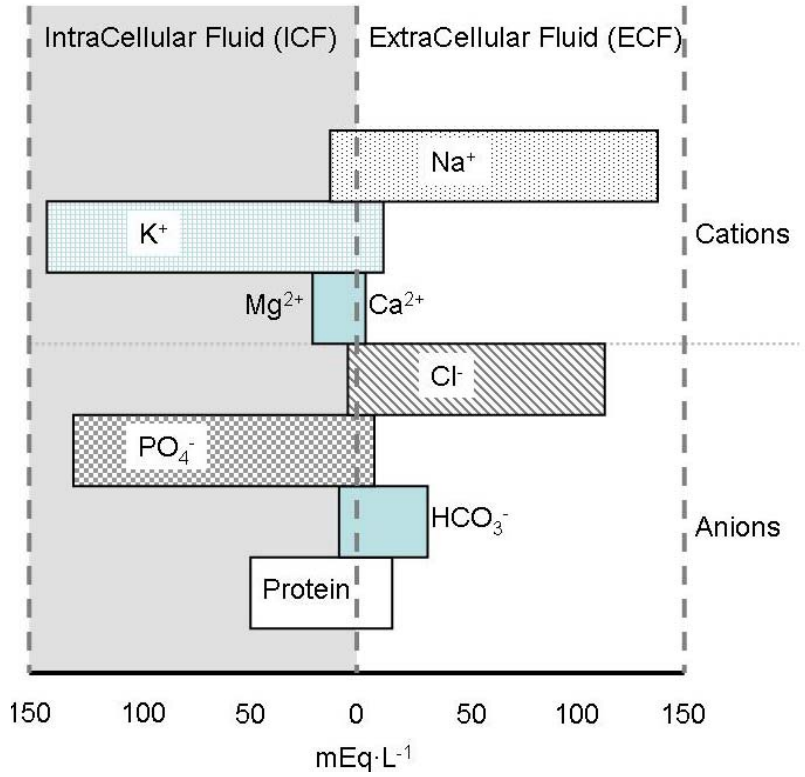

Figure 3-2.2: The Concentration (mEq·L^{-1}) of Major Electrolytes (cations and anions) within the Extracellular and Intracellular Fluid Compartments of the Human Body [5] [9].

3-2.5 STRATEGIES ADOPTED WITHIN THE ARMED FORCES OF NATO TO REDUCE THE RISK OF *HYPO*-/*HYPER*-HYDRATION

In order to determine the need for real-time monitoring of hydration status, it is necessary to appreciate the merits and limitations of the existing tactics, techniques and procedures that have been used within NATO to mitigate the risk (to health and performance) of *hypo*-hydration.

Note: Much of the information within this section has been taken from the excellent review articles by Cheuvront 2004b [15] and the National Academies Press [4].

3-2.5.1 Consumption of Water Ad Libitum (Supplying Water to Theatre)

Provision of potable fluids to personnel in sufficient and timely supply during military operations continues to be a challenge to military logistics. Defence doctrine affords guidance concerning the quantity of water to deliver to theatre, and the mode of storage of potable water (Joint Warfare publication [4-01.1], 2005), and if achieved it may be considered to lessen the need to monitor hydration status. However, in the absence of potable water, *hypo*-hydration during military operations cannot be avoided.

[8] During the first 6 months of military operations in Iraq during 2003, there were 849 reported cases of heat illness among UK Armed Forces, of which 766 cases required hospital attention, and 161 were returned to the UK for treatment [14].

Under such circumstances the deployment of technology to accurately assess the hydration status of military personnel in real-time could not be used to avoid *hypo*-hydration, and alerting the individual to their progressively degrading state of hydration would reduce morale and compromise operational readiness. During the first 6-months of Op TELIC (2003)[9] the UK's defence catering group were able to supply[10] military personnel with a water allowance equivalent to 6.0 L·person-1·day-1. However, such an allowance had been considered by Joint Service Publication (JSP) 539 to be sufficient to replace the sweat losses expected during only low intensity physical work lasting 12 hours at 20°C (Wet Bulb Globe Temperature [WBGT])[11] or 8 hours at 25°C (WBGT), and the environmental heat stress during Op TELIC (2003) had exceeded 35°C WBGT[12] when the physical demands were high. Defence Council Instruction JS 59 (1996) had previously recommended a daily water allocation as high as 15 L·person-1·day-1 for such military duty in hot desert environments[13]. Provision of such a large quantity of water could have been supplied to only 11,200 personnel of the 35,000 UK Armed Forces that had been deployed[14] during the initial 6-months of Op TELIC. A number of questions were raised:

> *"How much water is actually needed? If the right quantity can be supplied, how should the water be used?, and what are the consequences of getting it wrong?"*

3-2.5.2 Access to (or Carriage of) Potable Water

It cannot be assumed that military personnel deployed to the front-line during military operations will have access to bottled water. Furthermore, the benefit of applying any system that may accurately determine hydration status and provide appropriate advice concerning fluid intake can only be realised in the presence of sufficient water to consume. Military personnel must ensure that they carry potable water or have unrestricted access to potable water as required. The capacity of the standard, black water canteen used by British Armed Forces is 1-litre. To consume water from such a container requires the user to remove the canteen from the 'webbing pouch' (worn about the waist), unscrew the lid and place it to the mouth. Sweat losses may occur at a rate that exceeds 1.5 L·hour-1 during military operations in hot environments (requiring almost 2 full canteens to be consumed each hour). Forbes-Ewan et al. 1999 [16] investigated the use of a portable bladder/tube system (e.g., CamelBak® with a capacity of 2 to 3 litres) as the source of potable water for dismounted troops. They reported a slight positive effect on hydration status when compared with use of the standard canteen. However, the 'bladder/tube' system was unanimously preferred by its military users as the primary means of water carriage. They concluded that the portable bladder/tube system offered operational advantages over water bottles when considering the effect on hydration status.

3-2.5.3 Use of Work : Rest Schedules

Physical activity associated with work that is undertaken during military training and operations adds heat to the body. Evaporation of sweat from the skin is the prime mechanism by which the excess body heat may be dissipated. However, dissipation of body heat in this way increases the need to replace the water that is lost as sweat. A common approach within the Armed Forces of NATO to managing the threat of

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[9] Op TELIC was the code name for the deployment of British Armed Forces to Iraq during the military campaign of 2003.

[10] Delivered by DCG at a rate of 1,176,000 litres·week^{-1} within 784,000 bottles (i.e., 234 pallets·day^{-1}).

[11] WBGT: Wet Bulb Globe Temperature.

[12] Under these conditions, the human gains heat from the environment and, in the absence of any aid to promote cooling, it relies on its ability to evaporate sweat from the skin in order to survive (an increase in body temperature of only 3°C may result in irreparable heat injury and death).

[13] This concurs with the JWP 4-01.1 guidelines regarding the provision of water during the *'emergency phase'* of operations.

[14] Op TELIC: 46,000 UK Armed Forces personnel were deployed at the 'peak' of major combat operations (March/April 2003), but this figure had reduced to 18,000 personnel by the end of May 2003.

dehydration has been the development of work : rest schedules. In the UK, the Joint Service Publication 539 entitled '*Climatic Injuries in the Armed Forces: Prevention and Treatment'* provides guidance to military commanders concerning the use of work: rest tables for specific threshold levels of environmental heat stress. However, adherence to such schedules is not always practical. Estimating hydration status by means of monitoring an individual's compliance with such work : rest schedules, as the only measure, is unreliable and not advised. Use of micro-climate conditioning garments may be valuable in conserving body water that would otherwise be lost as sweat, but insensible losses must be accounted for and the body water deficit replaced in order to reduce the risk of hypo-hydration.

3-2.5.4 Drinking Strategies: Monitoring the Intake of Beverage

The bladder/tube system for carrying potable water that was described earlier in this section has since been further developed to enable it to be rapidly re-filled, and to filter the water of contaminants. However, carrying sufficient water is one consideration; another important issue affecting hydration status concerns the timely consumption of the water. Although Nevola et al. 2003 [17] demonstrated that it was possible to manually record fluid intake and urine output during a 194-kilometre unsupported desert march, the procedure remained impractical and inappropriate for military operations. USARIEM has developed and tested their adaptation of the bladder/tube system known as the 'Drink-o-meter' or 'Fluid Intake Monitor (FIM)' [18]. Inclusion of a flow meter in series with the drinking tube enables a micro-processor to determine the rate of fluid drawn through the tube (and assumed to be ingested). The micro-processor uses information from the USARIEM heat strain model to predict sweat loss based upon the individual's physical work rate and the environmental stress to which they are exposed. A series of light emitting diodes (LEDs) arranged in a traffic light system (i.e., red, amber, green) provides bio-feedback to the user (red: signifies insufficient rate of fluid intake; amber: signifies that the rate of fluid intake matches the predicted sweat loss; and green: signifies consumption of fluid at a rate that exceeds predicted sweat loss) and aims to promote optimal hydration status.

Civilian and military scientific organisations (e.g., the American College of Sports Medicine, USARIEM, UK Defence Science and Technology Laboratory [14]) have provided guidelines concerning drinking strategy prior to, during and following physical exercise in a hot environment. However, compliance with such guidelines cannot assume the maintenance of euhydration. Monitoring fluid intake must be considered in combination with other factors that may explain fluid balance if hydration status is to be monitored with an acceptable level of accuracy. Figure 3-2.3 illustrates the use of mathematical models to predict water requirements when working in particular environments (of known heat stress [WBGT °C]) and terrain.

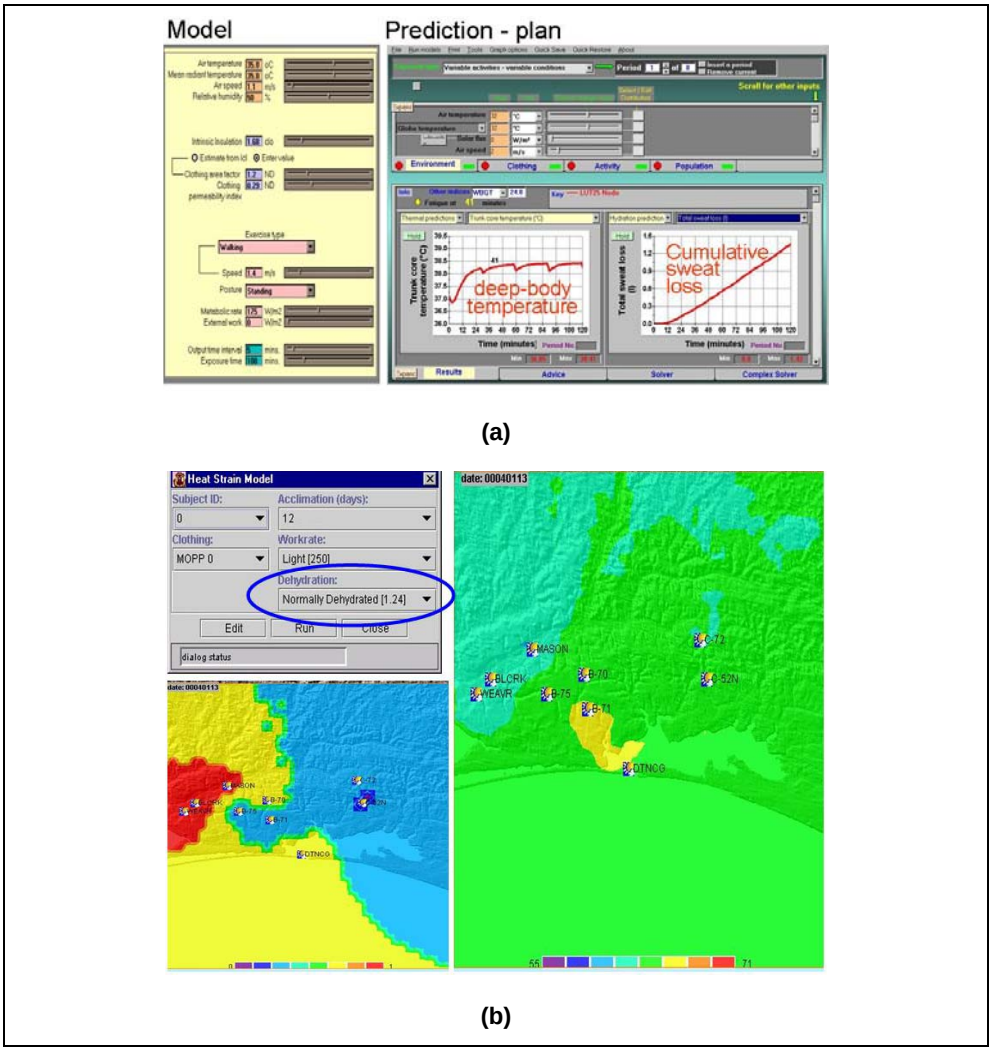

Figure 3-2.3: (a) The UK's Human Limits Prediction System is Used to Predict Sweat Loss for a Particular *Work : Rest* Regime; and (b) USARIEM's OMEGA Heat Strain Model is Used to Predict Hourly Fluid Intake Requirements Based upon the Environmental Heat Stress, Microclimate (Clothing Worn) and Expected Metabolic Load (i.e., Physical Work).

3-2.6 METHODS OF ASSESSING HYDRATION STATUS (MARKERS OF HYDRATION STATUS)

The need to maintain euhydration to support good health and optimal performance is well documented [19], [20]. However, the methods that have been used by scientists and employers to assess the state of hydration of the human body are less well-established. The accuracy with which TBW (i.e., hydration status) can be determined is confounded by numerous factors (both intrinsic and extrinsic in nature). Despite the need, there is presently no consensus governing the recommended mode for the assessment of hydration status. No single method of assessing TBW can presently be administered with the same level of accuracy and precision in all conditions within which military personnel may be exposed. Table 3-2.4 has summarised many of the techniques that have been used to estimate TBW and highlighted those methods that may currently be used to monitor hydration status (of the human body) in real-time and during free-living. When considered in isolation, clinical signs and symptoms such as thirst, dizziness, headache, and tachycardia are far too generalised (and too imprecise) to reliably differentiate dehydration (or to determine subsequent *hypo*-hydration) from other possible causes.

Table 3-2.4: Methods to Estimate the Hydration Status of the Human Body (as Reported Within the Open Literature)

Target Analyte / Sample or Measurement	**Method of Analysis** [criteria used to differentiate, euhydration from *hypo*-hydration]	**Can the Method be used in the Field?** (**Y**es / **N**o)	**Can this Method be Used for *Real-Time Monitoring* of Hydration Status?** (**Y**es accurately / Yes but **U**nreliable / **N**ot currently)	**Technology Readiness** (**R**eady now / **U**nder development / **C**oncept stage)	**Component of Total Body Water Used to Estimate Hydration Status** (**Y**es)				***Example of Existing Technology***
					TBW	*ICF*	*ECF*	*PV*	
Individual opinion	Sensory perception (signs and symptoms) [Thirst stimulus may indicate *hypo*-hydration]	Y	U *(e.g., thirst stimulus)*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*Subjective rating scales.*
Urine and saliva	Isotope (tracer) dilution to estimate total body water (e.g., deuterium oxide, tritium oxide and antipyrine).	Y	N	R	**Y**	*n/a*	*n/a*	*n/a*	*Mass spectrometry (e.g., SF-ICP-MS Element, Thermo Finnigan MAT).*
Total body mass	Acute change in body mass (excluding urine or faeces) is assumed to be due to a change in total body water	Y	N	R	**Y**	*n/a*	*n/a*	*n/a*	*It may be possible (e.g., assessing the force under-foot using compression load-cells).*
Total body water	Bioelectrical impedance	Y	N	R	**Y**	**Y**	**Y**	*n/a*	*Bodystat® QuadScan 4000. The multi-frequency systems (5 kHz to 200 kHz) are more accurate than single-frequency systems. Dualscan 2005 system (Bodystat®, Douglas, Isle of Man).*
	Dual-energy X-ray absorptiometry	N	N	R	**Y**	*n/a*	*n/a*	*n/a*	*Lunar DPX, Hologic QDR 1000/W (estimated using fat mass : fat free mass)*
	Radiofrequency absorptiometry	N	N	U	**Y**	*n/a*	*n/a*	*n/a*	*Wavetek 2002A signal generator operating at 13 dBm output, with two antennas (transmission and reception, 1/8 λ at 916 MHz, a power sensor Bontoon 51013). See Moran et al. 2004 [30].*
	Near infrared interactance	Y	N	R	**Y**	*n/a*	*n/a*	*n/a*	*Futrex 5000. However, it has been considered to be unreliable when estimating TBW (Sarhill et al. 2005).*
Breath (expired air)	Water content within expired air (Humidity)	*n/a*	N	C	*n/a*	*n/a*	**Y**	*n/a*	*n/a*
Saliva	Osmolality [>77 mOsmol·kg^{-1} may reflect *hypo*-hydration, as it exceeds the 'normal' euhydrated value] [Sawinski et al. 1966]	Y	N	R	*n/a*	*n/a*	**Y**	*n/a*	*Osmometry (freezing point depression osmometer: Advanced Instruments, MA, USA; and Mechrolab vapour pressure osmometer Model 301). See Oliver et al. 2007 [33], Walsh et al. 2004 [34].*

Target Analyte / Sample or Measurement	**Method of Analysis** [criteria used to differentiate, euhydration from *hypo*-hydration]	**Can the Method be used in the Field?** (**Y**es / **N**o)	**Can this Method be Used for *Real-Time Monitoring* of Hydration Status?** (**Y**es accurately / Yes but **U**nreliable / **N**ot currently)	**Technology Readiness** (**R**eady now / **U**nder development / **C**oncept stage)	**Component of Total Body Water Used to Estimate Hydration Status** (**Y**es)				***Example of Existing Technology***
					TBW	*ICF*	*ECF*	*PV*	
	Specific gravity [>1.0 may reflect *hypo*-hydration] [35] [36]	Y	N	R	*n/a*	*n/a*	**Y**	*n/a*	*Hydrometry and reagent strip technologies.*
	Volume	Y	N	U	*n/a*	*n/a*	**Y**	*n/a*	*Estimated using flow meters implanted on the lingual aspect of the 2nd molar (tooth).*
	Salivary flow rate [<~200 µL·minute^{-1} may reflect *hypo*-hydration] [34]	Y	Y	U	*n/a*	*n/a*	**Y**	*n/a*	
Urine	Colour (U_{col}) [U_{col}</= 3 reflects euhydration; U_{col}>/= 7 was evident in *hypo*-hydration] [23]	Y	N	R	**Y**	*n/a*	*n/a*	*n/a*	*Urine colour chart (see Armstrong et al. 1994)* [23]
	Osmolality [>800 mOsmol·kg^{-1} may reflect *hypo*-hydration] [4]	Y	N	R	**Y**	*n/a*	*n/a*	*n/a*	*Freezing point depression osmometry.*
	Volume [<1 L·day^{-1} may indicate *hypo*-hydration] [37]	Y	N	U	**Y**	*n/a*	*n/a*	*n/a*	*Reabsorption of urea is inversely related to urine flow rate (see Blood Urea Nitrogen).*
	Frequency of voids [zero voids in 24 hours would be indicative of dehydration] [4]	Y	N	U	**Y**	*n/a*	*n/a*	*n/a*	
	Specific gravity [USG > 1.020 [15] represents a state of *hypo*-hydration (Armstrong et al.. 1994)] [4]	Y	N	R	**Y**	*n/a*	*n/a*	*n/a*	*Bayer™ GP multistix (reagent strip)*
	Odour [a strong odour may indicate *hypo*-hydration] [37]	Y	N	U	**Y**	*n/a*	*n/a*	*n/a*	*n/a*

[15] However, Armstrong 2000 [37] stated that hypo-hydration was evident when USG > 1.030.

Target Analyte / Sample or Measurement	**Method of Analysis** [criteria used to differentiate, euhydration from *hypo*-hydration]	**Can the Method be used in the Field?** (**Y**es / **N**o)	**Can this Method be Used for *Real-Time Monitoring* of Hydration Status?** (**Y**es accurately / Yes but **U**nreliable / **N**ot currently)	**Technology Readiness** (**R**eady now / **U**nder development / **C**oncept stage)	**Component of Total Body Water Used to Estimate Hydration Status** (**Y**es)				***Example of Existing Technology***
					TBW	*ICF*	*ECF*	*PV*	
Blood (plasma, serum or whole)	Osmolality [>295 mOsmol·kg^{-1} may reflect *hypo*-hydration] [34]	Y	N	R	*n/a*	*n/a*	**Y**	**Y**	*Osmometry (freezing point depression osmometer: Advanced Instruments, MA, USA).*
	Bromide dilution to estimate Extracellular fluid (ECF)	Y	N	R	*n/a*	*n/a*	**Y**	*n/a*	*Ionics (e.g., 82Br, 35SO4, chloride isotopes)* *Crystalloids (e.g., Inulin, mannitol)*
	Azo dye (e.g., Evan's blue (or T1824) (and radioactive Iodine-131 labelled human serum albumin [RISA])	N	N	R	*n/a*	*n/a*	*n/a*	**Y**	*The tracers bind Radioactive Iodine-131 labelled human Serum Albumin (RISA): The 364-keV gamma rays emerging from the RISA can be measured with a NaI detector, placed in a flat-field lead-lined collimator mounted on an articulating mobile stand.*
	Sodium concentration (salinity and osmotic pressure) to estimate ECF [>155 mOsmol·kg^{-1} may reflect *hypo*-hydration] [9]	Y	N	R	*n/a*	*n/a*	**Y**	**Y**	*i-STAT® 1 handheld system* (spectrophotometry).
	Haematocrit and haemoglobin	Y	N	R	*n/a*	*n/a*	*n/a*	**Y**	*Changes in PV can be estimated using the Dill and Costill, 1974 formula. Hemacue can be used.*
	Blood Urea Nitrogen (BUN) [>20 mg·dL^{-1} may be indicative of *hypo*-hydration] [16]	N	N	U	*n/a*	*n/a*	**Y**	*n/a*	*Most accurately measured by a colorimetric process. It can also be measured by the diacetylmonoxime method, but the test results are less accurate*
	Biochemical regulators of fluid balance (homeostasis)	N	N	R	*n/a*	*n/a*	**Y**	**Y**	*Aldosterone, arginine, vasopressin, ACE*
Heart	Heart rate variability (HRV) (electrical activity) and pulse pressure.	Y	U	R	*n/a*	*n/a*	*n/a*	*n/a*	*Hidalgo Ltd ECG monitors (algorithms for HRV require further development). See Cooke et al. 2006 [38] and Kanjilal et al. 2004 [39] (concerning HRV) and Convertino et al. 2006 [40] (concerning pulse pressure).*
Skin	Turgor (pinch test)	Y	U	*n/a*	*n/a*	**Y**	**Y**	*n/a*	*n/a*

[16] The threshold for hypo-hydration using blood urea nitrogen was provided by the American Society of Health-System Pharmacists, Inc., 1998.

Target Analyte / Sample or Measurement	**Method of Analysis** [criteria used to differentiate, euhydration from *hypo*-hydration]	**Can the Method be used in the Field?** (**Y**es / **N**o)	**Can this Method be Used for *Real-Time Monitoring* of Hydration Status?** (**Y**es accurately / Yes but **U**nreliable / **N**ot currently)	**Technology Readiness** (**R**eady now / **U**nder development / **C**oncept stage)	**Component of Total Body Water Used to Estimate Hydration Status** (**Y**es)				***Example of Existing Technology***
					TBW	*ICF*	*ECF*	*PV*	
Body	Anthropometry	Y	N	R	**Y**	*n/a*	*n/a*	*n/a*	*This has limited application to real-time monitoring, as the formulae used to estimate TBW (Watson formula, Hume formula and Chertow formula) are limited to using changes in body weight when considering acute changes in body water.*
Fluid consumption	Comparing fluid intake with the expected fluid requirement.	Y	U	R	**Y**	*n/a*	*n/a*	*n/a*	*Drink-o-meter (US Army).* [17]
Sweat from the skin	Collection of sweat at several sites on the body.	Y	N	R	**Y**	*n/a*	*n/a*	*n/a*	*Sweat patches to estimate the body water lost as sweat. (see Allan JR and Wilson CG 1971) [41]*
Physical activity	Mathematical algorithms to estimate sweat losses.	Y	N	U	**Y**	*n/a*	*n/a*	*n/a*	*Models include the Physical limits prediction system (UK) and technology to assess physical activity has been developed using triaxial accelerometers (e.g., 3dNXTM model [BioTel Ltd., Bristol, UK]). See Fudge et al. 2007.*

[17] Volume Sensing Collapsible Bladder Canteen (Provisional Patent, in process), Montain, Scott J. and Hoyt, Reed W., Attorney Docket Number RIEM 05-18; and Gear Flowmeter Drink-O-Meter (Provisional Patent) USPTO # 60/721,530, Hoyt, Reed W., Montain, Scott J., Wollowitz, Michael and Hickox, Matthew, Attorney Docket Number RIEM 05-25.

Table 3-2.4 describes the most common methods of assessing the state of hydration of the human body that have been reported in the open literature. Further details to describe those more popular techniques from Table 3-2.4 have been provided within the following paragraphs (the techniques have been listed in alphabetical order below).

3-2.6.1 Acute Change in Total Body Mass (BM)

When the mean value for an individual's euhydrated total body mass[18] has been established (from measurements taken at the same time each day over several consecutive mornings), a basic estimate of hydration status may be based upon the assumption that a rapid change in BM may reflect an acute, 'size-matched' change in TBW (where 1.0 kg BM = 1.0 L TBW). First morning BM as an index of euhydration assumes that 1 ml of sweat loss is equivalent to a loss of 1 g BM and that there is caloric balance. BM is limited as a tool for long-term assessment of hydration status, since it cannot dissociate changes in body composition, which are also reflected as gross changes in BM. Clearly, BM is most useful to detect acute changes in hydration status, but it can compliment long-term hydration status monitoring if used in combination with another hydration assessment technique. Casa et al. 2000 [20] and Cheuvront et al. 2004b [21] found that the euhydrated total BM demonstrated a daily variance equivalent to ± 1.0% BM (when procedures were taken to reduce the influence attributed to diurnal variation) [4]. The stability of daily BM allows acute mass changes to be correctly attributed to body water loss. Failure to correct for carbon exchange produces minimal error, but semi-nude or nude measurements must be made to eliminate the potentially large underestimation of losses that result when sweat is retained in clothing. Use of BM in this way has been shown to provide the simplest, least expensive and most popular technique for obtaining a quick estimate of any acute change in TBW and, hence, the state of hydration of the human body [22].

3-2.6.2 Bioelectrical Impedance Analysis (BIA)

This is a non-invasive technique that can be used to measure TBW. A low ampere current (single or multiple frequency) is passed between several skin electrodes that have been placed on the wrist and ankle. The basic assumption is that the resistance (impedance) to the electrical current varies inversely with the water and electrolyte content of the body's tissues. Under controlled laboratory conditions (for euhydrated individuals), determination of TBW by means of BIA has been found to compare favourably with the isotope dilution method (r = 0.87 to 0.98 [23], [24]). Although BIA is sensitive to detecting tonic *hypo*-hydration, it significantly underestimates the level of absolute fluid losses and is independently altered by changes in body fluid volume and tonicity [24], [25]. Acute shifts in body fluid, sweating, rehydration, and other variables common to physical work during military operations also confound its accuracy. Fluid and electrolyte concentrations may have independent effects on bioimpedance, thus providing grossly misleading values regarding the extent of *hypo*-hydration [24]. BIA with a 0/∞ kHz parallel (Cole-Cole) multi-frequency model may improve the accuracy and precision with which to assess acute changes in hydration status (of the human body) following corrections for changes in plasma protein concentration. The multi-frequency device measures Impedance values at 5, 50, 100 and 200 kHz (e.g., Bodystat® QuadScan 4000). In a healthy, euhydrated subject, at a low frequency of 5 kHz, the impedance (or the electrical resistance) will be high, as the signal cannot penetrate the cell membrane (it measures, therefore, only the extra-cellular fluid [ECF]). However, at the higher frequencies such as 200 kHz, the signal penetrates the cell membrane as reflected by a low impedance value (believed to be indicative of the TBW). However, Bartok et al. 2004 [26] found that even this system was insensitive to hypertonic dehydration. O'Brien et al. 2002 [24] concluded that BIA was not a valid tool for monitoring hydration status.

[18] Where, for simplicity, total body mass (kg) and total body weight (kg) are assumed to be the same (equal).

3-2.6.3 Blood Borne Biochemical Markers

Under controlled conditions the use of plasma markers to estimate hydration status have been considered to be reliable despite plasma volume being readily confounded [27]. Plasma osmolality has been shown to be tightly controlled about a euhydration set-point of ~285 mOsmol·kg^{-1} [10]. Popowski et al. 2001 [28] demonstrated that this narrow range of values increases by ~5.0 mOsmol·kg^{-1} for every 1.0% to 2.0% loss in total body weight attributed to exercise *hypo*-hydration. Plasma osmolality was also found to be sensitive to rehydration. Plasma sodium has been considered to be indicative of plasma osmolality [28], although Senay 1979 [29] disputed the efficacy of this technique. Although fluid regulatory hormones, such as arginine vasopressin and aldosterone, generally respond predictably to volume and osmotic changes, they are altered by exercise [31] and heat acclimation [32] and require more expensive and complicated analysis techniques. Plasma osmolality is thus the simplest, most accurate and reliable plasma marker for tracking hydration changes over hours or days [4]. Sodium is the primary cation of the ECF (see Figure 3-2.2).

The concentration of sodium within ECF has been found to increase with the decrease in TBW. However, only a poor correlation has been reported ($r = –0.46$, $p = 0.14$ [4]) between plasma sodium and acute loss in TBW (i.e., *hypo*-hydration). The blood urea nitrogen (BUN) test is a measurement of the amount of urea that has been passively absorbed into the vascular system. The majority of urea is synthesized from ammonia by the liver during the hepatic urea cycle. Urea is freely filtered by the glomeruli and partially passively reabsorbed as filtrate transverses the renal tubules. The kidneys excrete the majority of urea. Reabsorption of urea is inversely related to urine flow rate. Although the level of Blood Urea Nitrogen (BUN) is usually considered to be indicative of kidney function, it has also been used in clinical practices to determine *hypo*-hydration. The pattern of high BUN (normal range 8 to 25 mg·dL^{-1}) and otherwise normal renal function (e.g., normal creatinine or creatinine clearance) is considered to be an indicator of hypovolemia (a reduction in plasma or blood volume). However, BUN is also directly related to protein intake. Therefore, BUN can be used to estimate hydration status for individuals who demonstrate normal renal function.

3-2.6.4 Pulse Pressure and Heart Rate Variability

Pulse pressure (calculated as the difference between systolic and diastolic blood pressure) has been found to improve the sensitivity of the early detection of hypovolaemia [42]. Fourier analysis of the electrical activity of the heart has been used to explain how high frequency (HF) power (0.15 – 0.40 Hz) was representative of autonomic parasympathetic activity, whilst low frequency (LF) power was more likened to sympathetic activity. The ratio of HF/LF was shown to be sufficiently sensitive to act as a marker of central blood loss [37]. However, this ratio may also reflect hypovolaemia attributed to *hypo*-hydration occurring as a result of physical activity or exercise. While exercise heat stress and hydration status are known to independently influence heart rate variability (HRV), Carter et al. 2005 [43] found that HRV decreased by both *hypo*-hydration and exercise heat stress.

3-2.6.5 Radio Frequency (RF) Absorptiometry

Moran et al. 2004 [30] investigated the acute loss in total body weight (attributed to a matched loss in TBW) with the change in the pattern of absorption of radio-waves that was evident in the participants of their study. Detectable changes in radio frequency absorptiometry were found to account for a significant proportion of the variance with the acute change in total body weight ($r^2 = 0.734$) for the same individuals (when *hypo*-hydrated and euhydrated). Further work is presently being conducted to establish the reproducibility and validity of the RF method for estimating hydration status (considering the influence of associated with gender, age and health status upon TBW).

3-2.6.6 Salivary Markers Associated with *Hypo*-Hydration

Adolph and Wills 1947 [44] showed that the rate of flow of saliva was reduced with levels of *hypo*-hydration which exceeded 2.0% BW. However, the variability in this response was quite large when

the extent of the *hypo*-hydration exceeded 3% BW. Such high variance with progressively more severe dehydration serves to limit the confidence with which the rate of flow of saliva may resolve subsequent loss in total body water. Salivary flow rate was found to be too insensitive to detect moderate levels of *hypo*-hydration following 24-hours of restricted (inadequate) fluid intake [45]. The osmolality of saliva for an individual who has incurred a level of *hypo*-hydration equivalent to a loss of 2.9% BW during exercise in a hot environment was found to be significantly greater than the osmolality during euhydration [34]. Saliva osmolality and total protein appear to be as sensitive as urine osmolality when attempting to track changes in hydration status during hypertonic-hypovolemia. Walsh et al. 2004 [34] suggested that dehydration had a greater influence upon the decrease in the rate of flow of saliva during prolonged exercise than did markers of neuroendocrine regulation. The United States Army Medical Research and Materiel Command has developed a micro-electronic (micro-fluid, intra-oral hydration sensor) package for the basic intra-oral sensor platform suitable for field deployment. This package includes a sensor small enough in size that it can be etched and bonded onto a tooth. The sensor includes a micro osmometer to estimate hydration status (by means of salivary osmolality), and it contains the circuitry to send the data, first to a short range transmitter located extra-orally on the user and subsequently to a remote monitor 1 – 2 miles away.

3-2.6.7 Skin Turgor

This is a very basic field test for severe *hypo*-hydration that could be used to confirm the results from a more reliable method of determining hydration status. The pinch test is unable to resolve the extent to which dehydration has occurred, as the subjective assessment of the elastic recoil of the skin following a 'pinch' may only serve as a threshold between conditions of *'apparently euhydrated' v. 'severe hypo-hydration'*. The principle behind the pinch test assumes that the speed with which the skin returns to its original position following a pinch (i.e., elastic recoil) is determined by the turgidity of the cells (i.e., ICF), which underpin the elastic compliance of the skin [14].

3-2.6.8 Stable Isotope Dilution (Biochemical Tracers)

The use of safe, stable isotopes (with a half-life of several days or weeks) as biochemical tracers has been considered to be the gold standard field-method for assessing TBW and its constituent body fluid compartments. TBW is assessed by calculating the quantity of isotope that is retained by the body following equilibration with a known dose (volume and enriched concentration) of a specific tracer isotope (most commonly, deuterium oxide, tritium oxide or antipyrine, whilst bromide-82 dilution has been used to estimate ECF). Analysis of background water, urine and/or saliva samples using a mass spectrometer enables the retention of the tracer isotope to be identified and the TBW to be estimated. Results are accurate and reproducible to within 1%. For a 75 kg man with 50 L (TBW), this precision would allow detection of changes in body water of > 0.65 L or < 1% change in body mass. Before assessing changes in fluid balance with such biochemical tracers, an additional method of assessing hydration status (TBW) must be conducted in order to confirm that the TBW volume is "normal" (i.e., the individual is initially euhydrated). TBW is often used in combination with body mass measurements to ascertain acute (or hourly), graded fluctuations in fluid balance [25], but it is most valid for assessing chronic (over several days), free-living, patterns in TBW (i.e., hydration status).

3-2.6.9 Sweat

Evaporation of sweat from the skin is a key mechanism underpinning the effectiveness of human thermoregulation during heat exposure or exercise. Sweat accounts for the largest proportion of TBW loss during heat exposure in apparently healthy, heat acclimatised adults. Technology (i.e., 'sweat patches') to trap samples of sweat at specific sites on the body surface in order to estimate sweat loss and to identify the composition of sweat has been available for almost 40 years (Allan JR and Wilson CG, 1971 [41]). However, more practical 'patches' have been developed and validated in recent years [6], [37]. Despite the reported developments, this technique remains unable to monitor sweat losses in real time.

3-2.6.10 Thirst

Thirst is the intrinsic stimulus that promotes the desire to consume beverages (i.e., fluid intake). However, when an individual experiences the sensation of thirst, the human body may have already incurred a deficit in TBW equivalent to 0.5% to 1.0% BW. Use of thirst alone as the method for determining the requirement for fluid intake (possibly acting as a monitor of the individual's hydration status) has been shown to effectively replace only ~50% to 66% of the fluid that would be necessary to restore and maintain euhydration. This progressive shortfall in fluid intake has been described as 'voluntary dehydration' [6].

3-2.6.11 Urinary Markers Associated with *Hypo*-Hydration

Dehydration (and the resulting *hypo*-hydration) has been found to affect urine volume, urine specific gravity (USG), urine osmolality (U_{Osm}) and urine colour (U_{Col}). The concentration of urine varies inversely with its volume, which is reduced during *hypo*-hydration. Although it is possible to measure the volume of each void of urine on a daily basis [17], it is impractical. The quantitative (USG, U_{Osm}) or qualitative (U_{Col}) assessment of urine concentration is more readily achieved. Urine volume is difficult and impractical to track, but it may corroborate other measures of dehydration. If urine colour cannot be measured, then urine volume may be the only field indicator of hydration level available. Active individuals should drink enough fluid to produce 1 to 2 L of urine per day. Voids per day are also difficult to track under field situations, but few or no voids are corroborative of dehydration. As a screening tool to differentiate euhydration from *hypo*-hydration, urine concentration (USG, U_{Osm}, U_{Col}) has been shown to be reliable [37], [17] with reasonably definable thresholds. Urine becomes more concentrated during dehydration. Urine specific gravity and urine osmolality increase with dehydration and are strongly correlated (r = 0.82 to 0.97) with each other [14], [8]. However, these measures correlate poorly with plasma osmolality and fail to reliably track documented changes in total body weight corresponding to acute *hypo*-hydration and rehydration [28]. It is likely that drink composition influences the endocrine regulation of renal water and electrolyte reabsorption, as Shirreffs and Maughan 1996 [46] demonstrated, and that oral consumption of large volumes of hypotonic fluids resulted in the copious production of urine in the absence of euhydration. Use of the first morning void following an overnight fast minimizes the effect of diet upon urine concentration and maximizes measurement reliability [10], [17], [24]. It is concluded that USG, U_{Osm}, and U_{Col} are best used (collectively) to determine diurnal changes in hydration status. Urine colour and urine odour are a more subjective assessment and, therefore, are not ideal for determining *hypo*-hydration, but a darker urine colour or strong odour can confirm *hypo*-hydration (as determined by a more empirical method). During dehydration urine tends to be dark in colour or possess a strong odour when compared with voids whilst euhydrated from the same individual. Urine colour may be a better field indicator of dehydration than urine volume [23].

3-2.7 EMERGING TECHNOLOGIES (THE FUTURE)

Continued advances in technology may ensure the delivery of novel methods to evaluate changes in human hydration status in the future (adding to or improving those methods that have already been identified within Table 3-2.4). For example, muscle water content has been shown to be reduced proportionally to the reduction in TBW [47], and it may be possible, in the future, to conduct non-invasive measurements of muscle water by microfluid technologies, such as capillary electrophoresis. Both ultrasound and nuclear magnetic resonance imaging may also detect muscle tissue hydration changes [4]. Minimally invasive sub-dermal electrolyte sensors could be developed to improve the reliability and sensitivity of techniques that employ measures of electrical impedance to estimate whole body hydration status. The text entitled 'Monitoring Metabolic Status' by the National Academies Press [4] described interest in developing methods for the automatic monitoring of urinary excretion rates and solute concentrations as a means of determining TBW and, hence, monitoring hydration status. Application of Dual energy X-ray Absorptiometry (DXA), as well as fibre-optic sensors in methods of monitoring hydration status, may be possible in the future.

3-2.8 CONCLUSIONS

Water is the most abundant nutrient in the human body, and arguably the most important, as it is essential to sustain performance (physical and cognitive), health and life. The body maintains water within extracellular and intracellular compartments, which collectively describe the TBW (accounting for approximately 60% of the total body mass of an adult man). The state of hydration of the human body is determined by the level of TBW and, as such, technology that seeks to monitor hydration status must attempt to estimate TBW by either direct or indirect methods. In general, the first morning measurement of body weight conducted in combination with an assessment of urine concentration (urine specific gravity, urine osmolality, and urine colour) affords sufficient sensitivity with which to detect diurnal deviations from euhydration. Plasma osmolality, isotope dilution, and body mass changes can provide more reliable information regarding acute changes in hydration status when greater precision is required. Although less practical, day-to-day, plasma osmolality and isotope dilution can also track changes in the state of hydration of the human body with reasonable accuracy over prolonged periods. Plasma sodium and fluid regulatory hormones are easily confounded and bioelectrical impedance is not a reliable measure of TBW when hydration is altered, and the method has limited utility with which to assess hydration status in the field. Real-time monitoring of hydration status in the field has been the challenge of military scientists throughout the NATO nations. Salivary osmolality and the rate of flow of saliva have enabled sensors mounted on the second molar (tooth) to monitor hydration status in real-time. It is possible that future technological advances may allow evaluation of other measures (e.g., muscle water content) that hold promise as indices of hydration status.

3-2.9 REFERENCES

[1] Marriott, B.M. (Editor), Committee on Military Nutrition Research, Food and Nutrition Board. (1994). Food Components to Enhance Performance: An Evaluation of Potential Performance-Enhancing Food Components for Operational Rations. Institute of Medicine of the National Academies, The National Academies Press, Washington, D.C., www.nap.edu.

[2] Tharion, W.J., Lieberman, H.R., Montain, S.J., Young, A.J., Baker-Fulco, C.J., Delany, J.P. and Hoyt, R.W., (2005). Energy requirements of military personnel. Appetite, 44(1):4765.

[3] Mudambo, K.S., Scrimgeour, C.M. and Rennie, M.J., (1997). Adequacy of food rations in solders during exercise in hot, day-time conditions assessed by doubly labelled water and energy balance methods. Eur J Appl Physiol Occup Physiol, 76 (4):346-351.

[4] Committee on Metabolic Monitoring for Military Field Applications, (2005). Monitoring metabolic status (predicting decrements in physiological and cognitive performance). Standing Committee on Military Nutrition Research, Food and Nutrition Board. Institute of Medicine of the National Academies, The National Academies Press, Washington, D.C., www.nap.edu.

[5] Sawka, M.N., (2005). Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate: Chapter 4, Water. Panel on Dietary Reference Intakes for Electrolytes and Water Standing Committee on the Scientific Evaluation of Dietary Reference Intakes, Food and Nutrition Board. Institute of Medicine of the National Academies, The National Academies Press, Washington, D.C., www.nap.edu.

[6] NATO Research and Technology Organization Neuilly-Sur-Seine, FRANCE (Corporate author). (2004). NATO Maintaining Hydration: Issues, Guidelines, and Delivery. Proceedings from the RTO Human Factors and Medicine Panel (HFM) Specialists' Meeting held in Boston, USA, 10-11 December 2003. RTO-MP-HFM-086, AC/323(HFM-086)TP/54, www.rta.nato.int.

[7] Hoyt, R.W. and Honig, A., (1996). Environmental influences on body fluid balance during exercise: altitude. In: Body Fluid Balance, Buskirk, E.R. and Puhl, S.M., Eds. CRC Press, Boca Raton, pp. 183-196.

[8] Gonzalez-Alonso, J., Mora-Rodriguez, R., Below, P.R. and Coyle, E.F., (1995). Dehydration reduces cardiac output and increases systemic and cutaneous vascular resistance during exercise. J Appl Physiol, 79:1487-1496.

[9] Greenleaf, J.E. and Fink, W.J., (1982). The body's need for water. In: Nutrition and Athletic Performance: Proceedings of the Conference on Nutritional Determinants in Athletic Performance, San Francisco, CA, 24-25 September 1981, Haskell, W., Skala, J. and Whitman, J. (Eds.). Bull Publishing, Co., Palo Alto, CA.

[10] Nose, H., Morimoto, T. and Ogura, K., (1983). Distribution of water losses among fluid compartments of tissues under thermal dehydration in the rat. Jpn J Physiol, 33:1019-1029.

[11] Costill, D.L., Cote, R. and Fink, W., (1976). Muscle water and electrolytes following varied levels of dehydration in man. J Appl Physiol, 40:6-11.

[12] Maw, G.J., Mackenzie, I.L. and Taylor, N.A., (1998). Human body-fluid distribution during exercise in hot, temperate and cool environments. Acta Physiol Scand, 163:297-304.

[13] Freund, B.J., Montain, S.J., Young, A.J., Sawka, M.N., DeLuca, J.P., Pandolf, K.B. and Valeri, C.R., (1995). Glycerol hyperhydration: hormonal, renal, and vascular fluid responses. J Appl Physiol, 79:2069-2077.

[14] Nevola, V.R., Stearck, J. and Harrison, M.H., (2005). Commanders' guide: Fluid intake during military operations in the heat. Defence Science and Technology Laboratory report published by the Expert Panel on Armed Forces Feeding on behalf of the Ministry of Defence, UK.

[15] Cheuvront, S.N., (2004b). Assessing hydration status: Laboratory and field. Proceedings of the Round Table on Hydration and Physical Activity, American College of Sports Medicine, 9 December 2003, Boston, MA, USA.

[16] Forbes-Ewan, C.H., Cotter, J.D., Amos, D. and Lau, W., (1999). Comparison of Two Systems of Water Delivery for Use on Military Operations. DSTO Scientific and Technical Report DSTO-TR-0787, http://www.dsto.defence.gov.au/publications/2119/?print=true.

[17] Nevola, V.R., Stroud, M.A., Turner, J.J. and Withey, W.R., (2003). Water intake and urine output during a 194-kilometre unsupported desert march. Proceedings from the RTO Human Factors and Medicine Panel (HFM) Specialists' Meeting held in Boston, USA, 10-11 December 2003. RTO-MP-HFM-086, AC/323(HFM-086)TP/54, www.rta.nato.int/.

[18] Frykman, P.N., (2002). Tracking physiologic strain in free-living subjects. Colloquium presentation, 1 June, The American College of Sports Medicine, AGM, USA.

[19] American College of Sports Medicine position stand, (1996). Exercise and fluid replacement. Med Sci Sports Exerc, 28(1):i-vii.

[20] Casa, D.J., Armstrong, L.E., Hillman, S.K., Montain, S.J., Reiff, R.V., Rich, B.S.E., Roberts, W.O. and Stone, J.A., (2000). National Athletic Trainers' Association position statement: fluid replacement for athletes. Journal of Athletic Training, 35(2):212-224.

[21] Cheuvront, S.N., Carter, R., Montain, S.J. and Sawka, M.N., (2004a). Daily body mass variability and stability in active men undergoing exercise-heat stress. Int J Sport Nutr Exerc Metab, October, 14(5):532-40.

[22] Cheuvront, S.N., Haymes, E.M. and Sawka, M.N., (2002). Comparison of sweat loss estimates for women during prolonged high-intensity running. Med Sci Sports Exerc, 34(8):1344-1350.

[23] Armstrong, L.E., Maresh, C.M., Castellani, J.W., Bergeron, M.F., Kenefick, R.W., LaGasse, K.E. and Riebe, D., (1994). Urinary indices of hydration status. Inter J Sport Nutr, 4:265-279.

[24] O'Brien, C., Young, A.J. and Sawka, M.N., (2002). Bioelectrical impedance to estimate changes in hydration status. Int J Sports Med, 23:361-366.

[25] O'Brien, C., Baker-Fulco, C.J., Young, A.J. and Sawka, M.N., (1999). Bioimpedance assessment of hypohydration. Med Sci Sports Exerc, 31(10):1466-1471.

[26] Bartok, C., Schoeller, D.A., Sullivan, J.C., Clark, R.R. and Landry, G.L., (2004). Hydration testing in collegiate wrestlers undergoing hypertonic dehydration. Med Sci Sports Exerc, March, 36(3):510-7.

[27] Sawka, M.N. and Coyle, E.F., (1999). Influence of body water and blood volume on thermoregulation and exercise performance in the heat. Exerc Sports Sci Rev, 27:167-218.

[28] Popowski, L.A., Oppliger, R.A., Lambert, G.P., Johnson, R.F., Johnson, A.K. and Gisolfi, C.V., (2001). Blood and urinary measures of hydration during progressive acute dehydration. Med Sci Sports Exerc, 33(5):747-753.

[29] Senay, L.C., Jr., (1979). Effects of exercise in the heat on body fluid distribution. Med Sci Sports Exerc, 11(1):42-48.

[30] Moran, D.S., Heled, Y., Yanovitch, R., Margaliot, M. and Shapiro, Y., (2004). Hypohydration measurements by radio frequency. Paper #17: NATO Maintaining Hydration: Issues, Guidelines, and Delivery. Proceedings from the RTO Human Factors and Medicine Panel (HFM) Specialists' Meeting held in Boston, USA, 10-11 December 2003. RTO-MP-HFM-086, AC/323(HFM-086)TP/54, www.rta.nato.int.

[31] Montain, S.J., Laird, J.E., Latzka, W.A. and Sawka, M.N., (1997). Aldosterone and vasopressin responses in the heat: hydration level and exercise intensity effects. Med Sci Sports Exerc, 29(5):661-668.

[32] Francesconi, R.P., Sawka, M.N. and Pandolf, K.B., (1983). Hypohydration and heat acclimation: plasma rennin and aldosterone during exercise. J Appl Physiol, 55:1790-1794.

[33] Oliver, S.J., Laing, S.J., Wilson, S., Bilzon, J.L., Walters, R. and Walsh, N.P., (2007). Salivary immunoglobulin A response at rest and after exercise following a 48 h period of fluid and/or energy restriction. Br J Nutr, March, 7:1-8.

[34] Walsh, N.P., Laing, S.J., Oliver, S.J., Montague, J.C., Walters, R. and Bilzon, J.L., (2004). Saliva parameters as potential indices of hydration status during acute dehydration. Med Sci Sports Exerc, September, 36(9):1535-42.

[35] Banderas-Tarabay, J.A., Gonzalez-Begne, M., Sanchez-Garduno, M., Millan-Cortez, E., Lopez-Rodriguez, A. and Vilchis-Velazquez, A., (1997). The flow and concentration of proteins in human whole saliva. Salud Publica Mex, 39:433-441 (translated from Spanish).

[36] Shannon, I.L., (1973). Reference for human parotid saliva collected at varying levels of exogenous stimulation. J Dent Res, 52:1157.

[37] Armstrong, L.E., (2000). Performing in Extreme Environments. Human Kinetics, Champaign, IL, USA.

[38] Cooke, W.H., Salinas, J., Convertino, V.A., Ludwig, D.A., Denise, R.N., Duke, J.H., Moore, F.A. and Holcomb, J.B., (2006). Heart rate variability and its association with mortality in prehospital trauma patients. J Trauma Injury Infection and Critical Care, February, 60(2):363-370.

[39] Kanjilal, P.P., Hoyt, R.W. and Gonzalez, R.R., (2004). Hypohydration and exercise-induced shifts in the scaling property of heart beat interval series. Paper #15: NATO Maintaining Hydration: Issues, Guidelines, and Delivery. Proceedings from the RTO Human Factors and Medicine Panel (HFM) Specialists' Meeting held in Boston, USA, 10-11 December 2003. RTO-MP-HFM-086, AC/323(HFM-086)TP/54, www.rta.nato.int/.

[40] Convertino, V.A., Cooke, W.H. and Holcomb, J.B., (2006). Arterial pulse pressure and its association with reduced stroke volume during progressive central hypovolemia. J Trauma, 61(3):629-634.

[41] Allan, J.R. and Wilson, C.G., (1971). Influence of acclimatization on sweat sodium concentration. J Appl Physiol, 30:708-712.

[42] Cooke, W.H., Ryan, K.L. and Convertino, V.A., (2004). Lower body negative pressure as a model to study progression to acute hemorrhagic shock in humans. J Appl Physiol, 96:1249-1261.

[43] Carter III, R., Cheuvront, S.N., Wray, D.W., Kolka, M.A., Stephenson, L.A. and Sawka, M.N., (2005). The influence of hydration status on heart rate variability after exercise-heat stress. J Therm Biol, 30(7):495-502.

[44] Adolph, E.F. and Wills, J.H., (1947). Thirst, Chapter 15. In: Physiology of Man in the Desert. Visscher, M.B., Bronk, D.W., Landsi, E.M. and Ivy, A.C. (Eds.). Interscience Publishers, Inc., New York, USA, pp. 241-253.

[45] Ship, J.A. and Fischer, D.J., (1999). Metabolic indicators of hydration status in the prediction of parotid salivary-gland function. Arch Oral Biol, 44(4):343-350.

[46] Shirreffs, S.M. and Maughan, R.J., (1996). Post-exercise rehydration in man: effects of volume consumed and drink sodium content. Med Sci Sports Exerc, 28(10):1260-1271.

[47] Wallace, W.M., Goldstein, K., Taylor, A. and Teree, T.M., (1970). Thermal dehydration of the rat: distribution of losses among tissues. Am J Physiol, 219(6):1544-1548.

Chapter 3-3 – HYPOXIA

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3-3.1 BACKGROUND

This paper outlines procedures for operational detection of disturbances of acclimatization to high altitudes. In this way, it summarizes the present state-of-the-art possibilities of ***prediction of susceptibility to disturbances in the acclimatization process*** to hypobaric hypoxic environment conditions resulting in altitude sickness, and the possibilities of ***online monitoring of the acclimatization status*** under operational conditions at high altitude.

The term "altitude acclimatization" describes a series of complex physiological responses in which lowlanders adjust to the reduced partial pressure of oxygen (PO_2) in the inspired air to minimize the effects of resulting hypoxemia and to maintain cellular function. It comprises a number of responses by nearly every organ system and is characterized by considerable variation in the time course, speed and extent of the acclimatization process in individuals. In case of complete acclimatization and successful compensation, no or only few medical problems develop. An incomplete or disturbed acclimatization process may, however, result in various pathophysiological states and clinical conditions that are summarized under the term "***altitude illness or sickness***". It commonly affects lowlanders who ascend rapidly.

In general, a difference is made between several forms of altitude illness that sometimes have fatal consequences: Acute mountain sickness (AMS) is a ***self-limiting process*** termed ***simple*** or ***benign AMS***. In contrast to that, the two other forms of AMS (HACE = high-altitude cerebral edema and HAPE = high-altitude pulmonary edema) are termed ***malignant AMS*** because they are ***not self-limiting conditions*** and are even rapidly potentially lethal.

The best way to prevent disturbances in terms of altitude illness would be to allow time for acclimatization. A graded ascent (one rest day every 600 – 1200 m) and a slow ascent rate (maximum 600 m/d) should reduce the risk of all types of high-altitude illness [17]. However, especially in military missions, the time needed to achieve acclimatization is often overridden by needs of operational scenarios and military mission goals. Problems of coping with environmental conditions, performance decrements and casualties due to hypoxia-induced altitude illness or even mission failure could be the consequence. In addition, there are suggestions that even when allowing time for acclimatization, there are altitude limits in this process that vary for different individuals.

3-3.2 ACUTE MOUNTAIN SICKNESS

AMS is a complex of symptoms in the context of recent gain in altitude. It was defined by the *Lake Louise Consensus Group* as the presence of ***headache*** in an unacclimatized person who has recently arrived at an altitude above 2500 m ***plus*** the presence of one or more of the following symptoms: anorexia, nausea or vomiting, insomnia, dizziness, and lassitude or fatigue [45]. Oliguria is often preceding. Disturbed sleep with periodic breathing with recurrent apneic periods is usually but not necessarily present. Usually, AMS is a benign and self-limiting complex of symptoms, which primarily occurs during stays at altitudes above

2,500 m, but it has been reported to occur at altitudes as low as 2,000 m. Frequently, AMS appears with a latency period of between 3 to 12 (24) hours, reaching maximum severity after 1 to 3 days, to disappear by day 5 in hitherto healthy and able-bodied individuals during excessively rapid ascent, i.e., under insufficient acclimatization.

The underlying pathophysiological processes are the object of intense discussion [[2], [3], [6], [7], [9], [19], [22], [30], [39], [40], [64]]. Whether AMS is due to cerebral vasodilation or its effectors, such as NO (Nitric oxide), or due to mild cerebral edema induced by hypoxia is unclear. Most likely these effects produce the headache that causes other symptoms like nausea and malaise. There is experimental evidence of the significant role of brain swelling in the pathophysiology of AMS.

The importance of understanding AMS for military missions is due to the fact that it weakens affected Soldiers up to and including total incapacitation at least transitorily.

3-3.2.1 Incidence of Benign AMS

Benign AMS depends on individual parameters such as a prior history of high-altitude illness, preacclimatization, sleeping altitude, and exertion, constitutional parameters such as a low hypoxic ventilatory drive; and on variables typical of each ascent, like rate and pattern of ascent, the maximum altitude reached, and the length of exposure. In general, the following applies: the faster the ascent, the higher the incidence. This explains the wide range of incidence rates reported in the literature, reaching from 20% – 25% at about 2500 m to 40% – 50% in persons climbing to 4,000 m, increasing again to over 90% when the ascent occurs within hours rather than days [[4], [17], [18], [22], [25], [37], [41], [53], [62]]. The lowest altitude at which AMS was observed was as low as 1,800 m.

AMS is almost universal among persons flying directly to destinations above 3,800 m. For military deployments, 2% of cases of complete incapacitation within 3 days of deployment to altitudes between 2,000 and 2,500 m and about 8% at altitudes between 3,350 and 5,500 m have been documented [44].

3-3.2.2 Susceptibility to AMS

Benign AMS occurs in almost all subjects, the only prerequisite being a rapid ascent to a sufficient altitude. Surprising, however, is the great variability in individual susceptibility for any given altitude/time profile. Members of younger age groups are probably at greater risk than those of older age groups (> 50 years). With respect to gender, no group seems to be immune to AMS.

3-3.3 HIGH-ALTITUDE CEREBRAL EDEMA (HACE)

HACE is rare but potentially fatal if untreated. Its importance to the military results from the fact that it often occurs in Soldiers with AMS who continue to ascend. Since it is usually preceded by AMS characterized by the same symptoms of headache, malaise, fatigue, etc., that, however, progress to ataxia and/or altered consciousness with hallucinations, disorientation and confusion, it is considered to be the final stage of severe AMS. Associated findings are papilledema and retinal hemorrhage, and occasionally, cranial-nerve palsy. It may develop over a few hours and may be accompanied by high-altitude pulmonary edema (HAPE).

The mechanism is poorly understood. Consensus exists, however, with respect to the vasogenic origin of the edema. Hemodynamic factors such as sustained vasodilation, impaired cerebral autoregulation, elevated cerebral capillary pressure and an increase in the permeability of the blood-brain barrier most likely contribute to the edema [[3], [9], [17], [22], [23], [48], [51], [64]]. The vascular endothelial growth factor, NO synthase, and bradykinin are discussed as possible mediators.

3-3.3.1 Incidence of HACE

HACE occurs relatively rarely. Its incidence is estimated to be 0.01% at about 2,500 m and 1% – 2% in people ascending to altitudes beyond 4,000 m, and is therefore lower than for HAPE [[17], [18], [25], [27], [55]]. Often, signs and symptoms of both HAPE and HACE occur. Like AMS, the incidence of HACE depends on the speed of ascent and the altitude reached.

3-3.3.2 Susceptibility to HACE

All age and sex groups seem to be susceptible; however, younger males may be more at risk. It is still unknown why certain individuals are susceptible to HACE and other forms of AMS, whereas others are not. One possible factor taken into account is the relative proportion of brain to cranial cavity size. In a review of etiology, Hackett (1998) discusses this “tight fit” hypothesis: for a given increase in fluid volume in the brain, those with a tight-fit brain in the cranial cavity will have a greater rise in pressure, whereas those with looser brains are less susceptible. The shrinking of the brain with aging could explain why older people are less susceptible to AMS and HACE.

3-3.4 HIGH-ALTITUDE PULMONARY EDEMA (HAPE)

Usually, HAPE starts with the known symptoms of benign AMS. Within only a few hours, however, the condition deteriorates. Affected persons become shorter of breath and develop chest pain, a dry cough and, eventually, bloody sputum and respiratory distress. Cyanosis and bubbling respiration occur, lastly progressing to coma and death very rapidly (< 24 hours). HAPE accounts for most deaths from high-altitude sickness [22]. In about 14% of the cases with HAPE, also HACE develops. Thus, cerebral symptoms are also common [27].

It is non-cardiogenic in origin and associated with excessive pulmonary hypertension and elevated capillary pressure due to exaggerated non-uniform hypoxic pulmonary vasoconstriction with overperfusion in less constricted areas, resulting in capillary leakage. At present, it is assumed to be a high-permeability-type lung edema in the absence of inflammation. Moreover, endothelial dysfunction, reduced NO availability, and greater hypoxemia resulting from a poor ventilatory response to hypoxia are discussed as playing a role [[3], [8], [9], [17], [22], [27], [35], [64]].

Because of its serious prognosis and the need for immediate descent and accompaniment for the indisposed person, the impact of HAPE, especially on small military units, can be significant.

3-3.4.1 Incidence of HAPE

As in AMS, the incidence of HAPE also increases with altitude and speed of ascent. Other critical determinants include age, gender, health status, previous experience at high altitude, and genetic inheritance. While HAPE shows a prevalence of 2% to 6% at 4,500 m and of 2% to 15% at 5,500 m, lethality is reported to be up to 24% [[5], [8], [18], [54]].

3-3.4.2 Susceptibility to HAPE

There are studies that support the idea that susceptibility to HAPE is of genetic origin [[5], [26]]. Many people suffering from HAPE develop this condition on subsequent altitude exposures and are found to have an exaggerated hypoxic-pressure response in their pulmonary circulation. In HAPE-susceptible persons, a genetic difference in the amiloride-sensitive sodium channel could be demonstrated. Often, impaired endothelial function with overexpression of constrictors (endothelin-1) or underexpression of vasodilators (NO), or both, may be present [[12], [28]]. A higher incidence of HLA-DR6 and HLA-DQ4

antigens found in persons susceptible to high-altitude pulmonary edema emphasizes an immunogenetic basis for susceptibility.

3-3.5 CURRENT STATUS/LIMITATIONS

In the military arena, the speed of ascent is, in most cases, required to be high. This explains the high incidence of altitude sickness in Soldier populations.

Limited physical capacity and psychological resilience at high altitudes, as well as the usefulness of acclimatization, are subjects Soldiers, medics and commanders have to deal with. The great importance of high-altitude illness to the military, in particular of HAPE and HACE, which may occur at altitudes below 2,500 m (lowest documented altitude of 1,800 m), is the fact that not only affected Soldiers become casualties, but that large numbers of personnel become tied up with the immediate and passive transportation to lower altitudes. To achieve this, each HAPE or HACE case requires at least 2 personnel in simple terrain; usually, however, it requires 4 personnel, and in difficult terrain, even more. This is why, especially for military missions, advanced identification of Soldiers particularly ***susceptible*** and/or, even better, ***particularly resistant to altitude sickness*** would be a dramatic advantage and not only desirable, but of great importance, in particular, for deployments of small groups (SOF detachments), since they can "afford" casualties only to a limited extent.

So far, a lot of data has been accumulated and different methods have been tested in order to identify those persons "at risk" for altitude sickness [[6], [16], [38], [49], [53], [56], [60], [62]] or to improve high-altitude performance [42]. Efforts to find a predictive parameter for susceptibility to high-altitude illness have been manifold. There are a lot of data regarding the responses of ***ventilatory*** (HVR, HCVR, PCO_2, PO_2, minute ventilation, nocturnal periodic breathing) and ***pulmonary vascular parameters*** (HPVR), as well as of ***other physiological parameters*** such as cerebral blood flow, cerebral autoregulation index, body temperature, and the responses of ***different biomarkers for altitude illness to hypoxia*** (urinary leukotrienes, nitric oxide, endothelin-1, free oxygen radicals, C-reactive protein, proinflammatory cytokines like interleukin 6 and interleukin 1, VEGF and soluble VEGF receptor-1, asymetric dimethylarginin (ADMA), ACE I/D gene polymorphism, renin-angiotensin-aldosteron system, cortisol, ADH, and ANP) [[6], [12], [14], [15], [24], [26], [33], [34], [36], [38], [43], [46], [59], [63]]. However, these results are only of value to a limited extent because:

1) None of those parameters mentioned above shows a correlation to susceptibility to high-altitude sickness that is strong enough to create a test on this basis;
2) Findings are highly contradictory; or
3) Most important and aggravating is that most of the candidate parameters to reliably detect impending AMS are difficult to measure accurately under the operational conditions.

Soldiers are confronted with, and practical advice is often overridden by military requirements for special missions.

Thus, apart from the history of acclimatization, there are, at present, no good and reliable predictors for susceptibility to altitude illness, acclimatization status, as well as for future performance at high altitude [[17], [43], [62]], and also no progress has been achieved in the ***early diagnosis of individuals "at risk".*** Thus, the potential is minimal for identification of those persons at risk for problems of acclimatization and poor performance at high altitude. Of all data accumulated until now and different methods tested so far in order to identify those persons "at risk" for altitude sickness or to improve high-altitude performance ***online-monitoring of oxygen saturation,*** using pulse oximetry currently seems to be most promising in terms of prediction of subsequent AMS (a low $psaO_2$ on arrival at altitude being a good predictor for the

later development of AMS [[10], [13], [20], [47], [57], [58], [61], [62]] and is possibly practicable even under numerous imaginable operational conditions.

3-3.6 OXYGEN SATURATION – PRESENT STATUS

The method using pulse oximetry for determining arterial oxygen saturation was developed by Takuo Aoyagi in 1972. It is non-invasive, continuous and instantaneous, imposes only a minor burden on the patient and is simple to operate. The first commercially marketed pulse oximeters appeared in the early eighties.

In order to determine arterial oxygen saturation, absorption is measured at wavelengths at which the absorption characteristics of oxyhemoglobin and desoxyhemoglobin are markedly different. This is the case at around 660 nm and beyond 900 nm. Hence, ordinary pulse oximeters are units that emit two wavelengths that radiate through the tissue with red and infrared light, while a photosensor measures the amount of light absorbed. The amount of light absorbed then allows for determining the amount of oxygen saturation that is defined as the ***proportion of oxygenated hemoglobin to the entire concentration of hemoglobin***.

Even though measuring arterial oxygen saturation using ***pulse oximetry*** has become a routine method in a clinical environment, in particular in intensive-care medicine, due to certain technological as well as physiological limitations on the accuracy and availability of data, there is no simple and reliable method to assess oxygen saturation by using a network-enabled Soldier-wearable sensor in a field setting so far [1], [11], [29], [50], [52]]. Thus, detectable plethysmographic pulsations are necessary to enable an oximeter to distinguish between light absorption by arterial blood and the background absorption associated with venous blood and tissue constituents. Thus, failures occur during hypotension, hypothermia, or in cases of extreme systemic vascular resistance, resulting in reduced peripheral arterial pulsations with inadequate pulsatile flow. Improper function can be observed whenever their signal to noise ratio falls below certain limits. Very important for operational settings is also the fact that they are susceptible to motion artifacts.

3-3.6.1 Sensors

As far as the sensors are concerned, a difference in terms of the type of measurement is made between the so-called transmission sensors and reflectance sensors.

3-3.6.1.1 Transmission Sensors

For sensors using the ***transmission method***, the tissue studied is irradiated with the light of a predefined wavelength, while the light source and the detector must be located opposite each other. Usually, measurements are taken using a clip at a finger, an ear lobe or a toe.

Transmission sensors are used more often in clinical environments than reflectance sensors. However, the measurement points, such as the Soldier's finger or ear lobe, are not always readily accessible during missions.

3-3.6.1.2 Reflectance Sensors

Thus, the use of **reflectance sensors** is of particular interest on this field of military operations. For this method, the light source and the detector are applied **next to each other** on a skin region where the **reflected** intensity of light is analyzed.

Previous investigations of our group in the altitude climatic simulation chamber could prove that a forehead sensor using the reflectance principle is ***basically suitable for use as an early-warning system*** for arterial

hypoxia [31]. Its only disadvantage was a slightly higher reading compared with the gold standard: the bloody measurement. Further studies concentrating especially on the influence of vibrations and motion on the signal quality of this forehead sensor, in general, could show that in healthy subjects, this type of sensor was capable of providing satisfactory signal quality under both simulated and real-world helicopter flight conditions, in particular due to the vibrations involved [32]. Even physical workload such as running, cycling and inline skating gave good readings, with a mean failure rate no higher than 3% – 4%. Looking at the sensor signal quality of the photoplethysmogram during centrifuge drives with up to 9 Gz also revealed satisfactory pulse waves. These results are most promising with respect to the application of a pulse oximeter sensor using the reflectance principle under operational conditions.

3-3.6.2 Future Trends

Pulse oximetry as a young field of clinical monitoring is developing rapidly. Nowadays, oximeters are on the market, operating at multiple wavelengths, enabling them to detect dyshemoglobins. Several manufacturers have significantly upgraded their software, as well as their hardware, thus improving the performance of oximeters tremendously. Thus, it is within sight, that in the nearer future pulse oximetry would be applicable even under operational conditions.

3-3.7 WAY FORWARD

We are on the horizon to having the real key element for the prediction of altitude illness susceptibility. At present, ***monitoring of oxygen saturation*** seems to meet our requirements best. However, to suit different mission needs, a variety of problems still needs to be solved.

On the subject side, further studies are necessary to evaluate the application of pulse oximetry as a screening tool, including the ***establishment of predictive cut-off values*** specific for different points and modes of measurement, as well as for different ascent/time altitude exposure profiles. In order to determine those "at risk", it is also necessary to sufficiently establish specificity and sensitivity of such a test.

On the sensor side, existing advanced wearable biosensors with the ability to track SaO_2 in real time have to be improved, especially with respect to noise due to motion artifacts. This includes the improvement of both soft- and hardware. For military missions, sensors using the reflectance principle seem to be preferred above all.

Furthermore, the attempt should be made to ***integrate suitable reflectance sensors*** into the Warfighter Physiological Status Monitoring – Initial Capability (WPSM-IC) device to ensure reliable, continuous measurements of arterial oxygen saturation that are robust enough even under field conditions, to enable Soldiers, medics and commanders to monitor those "at risk" for altitude-related disturbances of the acclimatization process in order to be able to initiate effective countermeasures. Even if oxygen saturation proved not to be the ideal parameter for the prediction of altitude illness, the ability to measure it under field conditions would allow estimations of the course of altitude illness and/or the success of a potential therapy. Thus, trying to integrate it into the WPSM-IC would be worth the attempt.

3-3.8 SUMMARY

In military operations, Soldiers are exposed to a wide range of environmental extremes, including high-altitude locations. Of all factors combined with high terrestrial elevations, the lack of oxygen is most dangerous, since for other factors, coexisting with high-altitude environments, such as cold, winds, and solar radiation, appropriate protection strategies have already been developed.

Usually, hypoxia-induced medical problems at altitude are related to disturbances of the acclimatization process itself and are divided into three main diseases: AMS, HACE and HAPE, that sometimes have fatal

consequences. Since all of these conditions usually coincide with disordered sleep, as well as with physical and cognitive performance decrements which, in the case of military operations can question the mission's success, the advance identification of Soldiers who are particularly susceptible or resistant to altitude sickness would be of tremendous importance under military operational high-altitude conditions, and especially in missions with small groups (SOF detachments) in high-altitude areas, since they can "afford" casualties only to a limited extent. The possibility to predict medical problems likely to be encountered by Soldiers exposed to high terrestrial elevations would be very useful to estimate high-altitude sickness casualty rates associated with different ascent/time profiles on the one hand, and to approximate the troop strength necessary to fulfil a certain mission on the other, and at least for the outcome of military mountain operations as a whole.

Until now, however, there is no simple and reliable method to make valid predictions with respect to the susceptibility to and early on-site diagnosis of high-altitude sickness, as well as to the acclimatization status and future performance at high altitude.

Of all methods tested in this context, besides the history of previous exposures, ***online monitoring of oxygen saturation*** currently seems to be most promising in terms of prediction of subsequent AMS (a low $psaO_2$ on arrival at altitude being a good predictor for the later development of mountain sickness) under operational conditions, even if the overall correlation between symptoms and pulse oximetry values is weak. It is, with certain limitations, easily accessible and could be principally integrated into a real-time ambulatory system, even working under operational conditions, and offers the advantage of not only making predictive statements, but also of allowing to estimate the course of disease and/or the success of a potential therapy, at least in the nearer future. In this context, even with the limitations mentioned, it could provide helpful information to commanders and medics by enabling them to initiate effective countermeasures at an early stage and could help to improve AMS case management and ascent planning.

However, much work is still to be done to develop advanced wearable biosensors that have the capability to track $psaO_2$ in real time, and that are reliable and robust enough under field conditions. In addition, further studies are necessary to evaluate the application of pulse oximetry as a screening tool for large groups at risk of developing altitude sickness, including sufficient establishment of specificity and sensitivity of such a test.

Any other methods for the prediction of susceptibility to high-altitude illness tested so far, such as responses of multiple diverse physiological parameters of ventilation, cerebral circulation and thermoregulation to hypoxia, as well as the determination of different potential biomarkers for altitude illness, are suitable only to a limited extent. This is because the correlation with susceptibility to high-altitude sickness is weak, results are contradictory, there are no early markers of the development of altitude sickness, or online monitoring during military operations is not possible, at least not at present.

3-3.9 REFERENCES

[1] Alexander, C.M., Teller, L.E. and Groos, J.B., (1989). Principles of pulse oximetry: Theoretical and practical considerations. Anesth Analg, 68:368-376.

[2] Bailey, D.M., Kleger, G.-R., Holzgraefe, M., Ballmer, P.E. and Bärtsch, P., (2004). Pathophysiological significance of peroxidative stress, neuronal damage, and membrane permeability in acute mountain sickness. J Appl Physiol, 96:1459-1463.

[3] Barry, P.W. and Pollard, A.J., (2003). Altitude illness. Clinical review. BMJ, 326:915-919.

[4] Bärtsch, P., (1992). Wer wird bergkrank? Schweiz med Wschr, 122(9):307-314.

[5] Bärtsch, P., (1999). High altitude pulmonary edema. Med Sci Sports Exerc, 31(1 suppl):S23-27.

[6] Bärtsch, P., Swenson, E.R., Paul, A., Jülg, B. and Hohenhaus, E., (2002). Hypoxic ventilatory response, ventilation, gas exchange, and fluid balance in acute mountain sickness. High Alt Med Biol, 3:361-376.

[7] Bärtsch, P., Bailey, D.M., Berger, M.M., Knauth, M. and Baumgartner, R.W., (2004). Acute Mountain Sickness: Controversies and advances. High Alt Med Biol, 5:110-124.

[8] Bärtsch, P., Maibaurl, H., Maggiorini, M. and Swenson, E.R., (2005). Physiological aspects of high-altitude pulmonary edema. J Appl Physiol, 98:1101-1110.

[9] Basnyat, B. and Murdoch, D.R., (2003). High-altitude illness. Lancet, 361:1967-1974.

[10] Bircher, H.P., Eichenberger, U., Maggiorini, M., Oelz, O. and Bärtsch, P., (1993). Relationship of mountain sickness to physical fitness and exercise intensity during ascent. J Wild Med, 5:302-311.

[11] Bowes, W.A., Corke, B.C. and Hulka, J., (1989). Pulse oximetry: A review of theory, accuracy, and clinical applications. Obstet Gynecol, 74:541-546.

[12] Busch, T., Bärtsch, P., Pappert, D., Grünig, E., Hildebrandt, W., Elser, H., Falke, K.J. and Swenson, E.R., (2001). Hypoxia decreases exhaled nitric oxide in mountaineers susceptible to high-altitude pulmonary edema. Am J Respir Crit Care Med, 163:368-373.

[13] Compte-Torrero, L., Botella de Maglia, J., de Diego-Damia, A., Gomez-Perez, L., Ramirez-Galleymore, P. and Perpina-Tordera, M., (2005). Changes in spirometric parameters and arterial oxygen saturation during a mountain ascent to over 3000 meters. Arch Bronconeumol, 41(10):547-552.

[14] Dehnert, C., Weymann, J., Montgomery, H.E., Woods, D., Maggiorine, M., Scherrer, U., Gibbs, J.S.R. and Bärtsch, P., (2002). No association between high-altitude tolerance and the ACE I/D gene polymorphism. Med Sci Sports Exerc, 34(12):1928-1933.

[15] Dehnert, C., Grunig, E., Mereles, D., von Lennep, N. and Bärtsch, P., (2005). Identification of individuals susceptible to high-altitude pulmonary oedema at low altitude. Eur Respir J, 25:545-551.

[16] Eichenberger, U., Weiss, E., Riemann, D., Oelz, O. and Bärtsch, P., (1996). Nocturnal periodic breathing and the development of acute high illness. Am J Respir Crit Care Med, 154:1748-1754.

[17] Gallagher, S.A. and Hackett, P.H., (2004). High altitude illness. Emerg Med Clin N Am, 22:329-355.

[18] Hackett, P.H. and Rennie, D., (1976). The incidence, importance and prophylaxis of acute mountain sickness. Lancet, 2:1149-1154.

[19] Hackett, P.H., Rennie, D., Hofmeister, S.E., Gover, R.F., Grover, E.B. and Reeves, J.T., (1982). Fluid retention and relative hypoventilation in acute mountain sickness. Respiration, 43:321-329.

[20] Hackett, P.H., Roach, R.C., Hollingshead, K.F., Schoene, R.B. and Mills, W.J., (1987). Arterial saturation during ascent predicts subsequent acute mountain sickness. Hypoxia and cold: Proceedings. Praeger, New York, p. 544.

[21] Hackett, P.H., Yarnell, P.R., Hill, R., et al., (1998). High-altitude cerebral edema evaluated with magnetic resonance imaging. JAMA, 280:1920-5.

[22] Hackett, P.H. and Roach, R.C., (2001). Current Concepts. High-altitude illness. N Engl J Med, 345(2):107-114.

[23] Hackett, P.H. and Roach, R.C., (2004). High altitude cerebral edema. High Alt Med Biol, 5:136-146.

[24] Hohenhaus, E., Paul, A., McCullough, R.E., Kücherer, H., Bärtsch, P., (1995). Ventilatory and pulmonary vascular response to hypoxia and susceptibility to high altitude pulmonary oedema. Eur Respir J, 8:1825-1833.

[25] Honigman, B., Thesis, M.K., Koziol-McLain, J., et al., (1993). Acute mountain sickness in a general tourist population at moderate altitude. Ann Intern Med, 118: 587-592.

[26] Hotta, J., Hanaoka, M., Droma, Y., Katsuyama, Y., Ota, M., and Kobayashi, T., (2004). Polymorphisms of renin-angiotensin system genes with high-altitude pulmonary edema in Japanese subjects. Chest, 126:825-830.

[27] Hultgren, H.N., (1996). High-altitude pulmonary edema: current concepts. Annu Rev Med, 47:267-284.

[28] Kanazawa, F., Nakanishi, K., Osada, H., Kanamaru, Y., Ohrui, N., Uenoyama, M., et al., (2005). Expression of endothelin-1 in the brain and lung of rats exposed to permanent hypobaric hypoxia. Brain Res, 1036:145-154.

[29] Kelleher, J.F., (1989). Pulse oximetry. J Clin Monit, 5:37-62.

[30] King, A.B. and Robinson, S.M., (1972). Ventilation response to hypoxia and acute mountain sickness. Aerospace Med, 43:419-421.

[31] Ledderhos, C., Krimmer, I., Schneider, A., Gens, A., Miosga, J., Rall, G. und Knitza, R., (2005). Untersuchungen zur Entwicklung eines SpO_2-Frühwarnsensors zur Erkennung eines plötzlichen und unerwartet auftretenden Sauerstoffmangels bei Luftfahrzeug-Führern. Abstracts of the 43rd Annual Meeting of the German Association for Aviation and Space Medicine 33.

[32] Ledderhos, C., Gens, A., Hofmeister, K,, von Blücher, A., Knitza, R. and Rall, G., (2007). Studies on the basic operational capability of a reflexion pulse oximeter for the detection of oxygen deficiency during helicopter operations. Aviat Space Environ Med, 78(3):241.

[33] Loeppky, J.A., Icenogle, M.V., Maes, D., Riboni, K., Scotto, P. and Roach, R.C., (2003). Body temperature, autonomic responses, and acute mountain sickness. High Alt Med Biol, 4:367-373.

[34] Loeppky, J.A., Icenogle, M.V., Maes, D., Riboni, K., Hinghofer-Szalkay, H., and Roach, R.C., (2005). Early fluid retention and severe acute mountain sickness. J. Appl. Physiol, 98:591-597.

[35] Maggiorini, M., Melot, C., Pierre, S., Pfeiffer, F., Greve, I., Sartori, C., Lepori, M., Hauser, M., Scherrer, U. and Naeije, R., (2001). High-altitude pulmonary edema is initially caused by an increase in capillary pressure. Circulation, 103:2078-2083.

[36] Maggiorini, M., Bärtsch, P. and Oelz, O., (1997). Association between raised body temperature and acute mountain sickness: cross sectional study. BMJ, 315:403-404.

[37] Maggiorini, M., Muller, A., Hofstetter, D., Bärtsch, P. and Oelz, O., (1998). Assessment of acute mountain sickness by different score protocols in the Swiss Alps. Aviat Space Environ Med, 69(12):186-92.

[38] Milledge, J.S., Thomas, P.S., Beeley, J.M. and English, J.S.C., (1988). Hypoxic ventilatory response and acute mountain sickness. Eur Respir J, 1:948-951.

[39] Milledge, J.S., Besley, J.M., Broome, J., Luft, N., Pelling, M. and Smith, D., (1991). Acute mountain sickness susceptibility, fitness and hypoxic ventilatory response. Eur Respir J, 4:1000-1003.

[40] Moore, L.G., Harrison, G.L., McCullogh, R.E., et al., (1986). Low acute hypoxic ventilatory response and hypoxic depression in acute altitude sickness. J Appl Physiol, 60:1407-12.

[41] Murdoch, D., (1995). Altitude illness among tourists flying to 3740 meters elevation in the Nepal Himalayas. J Travel Med, 2:255-256.

[42] Muza, S.R., Rock, P.B., Zupan, M.F., Miller, J.C., Tomas, W.R. and Cymerman, A., (2004). Residence at moderate altitude improves ventilatory response to high altitude. Aviat Space Environ Med, 75:1042-1048.

[43] Pesce, C., Leal, C., Pinto, H., Gonzalez, G., Maggiorini, M., Schneider, M. and Bärtsch, P., (2005). Determinants of acute mountain sickness and success on Mount Aconcagua (6962 m). High Alt Med Biol, 6:158-166.

[44] Pigman, E.C. and Karakla, D.W., (1990). Acute mountain sickness at intermediate altitude military mountainous training. Am J Emerg Med, 8:7-10.

[45] Roach, R.C., Bärtsch, P., Oelz, O. and Hackett, P., (1993). Lake Louise AMS Scoring Consensus Committee: the Lake Louise acute mountain sickness scoring system. In: Hypoxia and Molecular Medicine, Sutton, J.R., Houston, C.S. and No Coates, G., (Eds.). Charles, S. Houston, Burlington, VT, pp. 272-274.

[46] Roach, R.C., Muza, S.R., Rock, P.B., Lyons, T.P., Lilly, C.M., Drazen, J.M. and Cymerman, A., (1996). Urinary leukotriene E_4 levels increase upon exposure to hypobaric hypoxia. Chest, 110:946-951.

[47] Roach, R.C., Greene, E.R., Schoene, R.B. and Hackett, P.H., (1998). Arterial oxygen saturation for prediction of acute mountain sickness. Aviat Space Environ Med, 69(12):1182-1185.

[48] Roach, R.C. and Hackett, P.H., (2001). Frontiers of hypoxia research: acute mountain sickness. J Exp Biol, 204:3161-3170.

[49] Savourey, G., Moirant, C., Eterradossi, J. and Bittel, J., (1995). Acute mountain sickness relates to sea-level partial pressure of oxygen. Eur J Appl Physiol, 70:469-476.

[50] Severinghaus, J.W., (1993). History and recent developments in pulse oximetry. Scand J Clin Lab Invest, 53 (Suppl 214):105-111.

[51] Severinghaus, J.W., (1995). Hypothetical role of angiogenesis, osmotic swelling, and ischemia in high-altitude cerebral edema. J Appl Physiol, 79 (2):375-379.

[52] Severinghaus, J.W. and Spellmann, M.J., (1990). Pulse oximeter failure thresholds in hypotension and vasoconstriction. Anesthesiology, 73:532-537.

[53] Schneider, M., Bernasch, D., Weymann, J., Holle, R. and Bärtsch, P., (2002). Acute mountain sickness: influence of susceptibility, preexposure, and ascent rate. Med Sci Sports Exerc, 34(129):1886-1891.

[54] Singh, I., Kapila, C.C., Khanna, P.K., Nanda, R.B. and Rao, B.D., (1965). High altitude pulmonary oedema. Lancet, 1:229-234.

[55] Singh, I., Khanna, P. and Srivastava, M., (1969). Acute mountain sickness. N Engl J Med, 280:175-184.

[56] Sutton, J.R., Bryan, A.C., Gray, G.W., et al., (1976). Pulmonary gas exchange in acute mountain sickness. Aviat Space Environ Med, 47:1032-1037.

[57] Tannheimer, M., Thomas, A. and Gerngross, H., (2003). Eignet sich die Sauerstoffsättigung zur Objektivierung der Höhensymptomatik? Erfahrungen einer militärisch-zivilen Forschungsexpedition zum Broad Peak (8047 m). Wehrmed Mschr, 47:34-41.

[58] Tannheimer, M., Thomas, A. and Gerngross, H., (2002). Oxygen saturation course and altitude symptomatology during an expedition to broad peak (8047 m). Int J Sports Med, 23:329-335.

[59] Tissot van Patot, M.C., Leadbetter, G., Keyes, L.E., Bendrick-Peart, J., Beckey, V.E., Christians, U. and Hackett, P., (2005). Greater free plasma VEGF and lower soluble VEGF receptor-1 in acute mountain sickness. J Appl Physiol, 98:1626-1629.

[60] Vann, R.D., Pollock, N.W., Pieper, C.F., Murdoch, D.R., Muza, S.R., Natoll, M.J. and Wang, L.Y., (2005). Statistical models of acute mountain sickness. High Alt Med Biol, 6:32-42.

[61] Van Osta, A., Moraine, J.J., Melot, C., Maibäurl, H., Maggiorini, M. and Naeije, R., (2005). Effects of high altitude exposure on cerebral hemodynamics in normal subjects. Stroke, 36:557-560.

[62] Ward, M.P., Milledge, J.S. and West, J.B., (2000). High Altitude Medicine and Physiology, 3rd edition. Arnold, London.

[63] Windle, C.M., Slaven, G.M. and Macleod, M.A., (1998). Cerebral perfusion and psychometric testing after exposure to high altitude in the mountains. J R Nav Med Serv, 84:24-29.

[64] West, J.B., (2004). The physiologic basis of high-altitude diseases. Ann Intern Med, 141:789-800.

Chapter 3-4 – PSYCHO-PHYSIOLOGICAL CONSIDERATIONS

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3-4.1 BACKGROUND

Today's military operations are characterized by round the clock deployment of personnel. Moreover, military actions might last days or even weeks, and such continuous operations require many Soldiers, navy personnel, and pilots to sustain performance for long periods with mostly inadequate rest or rest facilities. Another consequence of this operational military strategy is that military personnel have to perform during night when the body clock dictates sleep. So, besides important factors as amount and quality of sleep, the timing of sleep is affected due to the requirements of the mission.

Circadian disruptions, inappropriate sleep and sleep deprivation are significant factors that lead to both physical and mental fatigue. The following sections will address sleep and the effects of inadequate sleep on cognitive performance. Finally, three different types of sleep monitoring will be discussed.

3-4.2 SLEEP

Sleep is a fundamental requirement for humans. The average amount of sleep is around 7 to 8 hours per 24 hours, although there is large inter-individual variability. Sleep onset normally occurs in the late evening, at a time when three factors promoting sleep act in concert: the falling phases of the circadian rhythms of core temperature and plasma adrenalin, the rise of plasma melatonin secreted by the pineal, and the rise in fatigue due to time awake [1]. Waking normally occurs in the morning due to the rising phases of the circadian rhythms of core temperature and plasma adrenalin, increasing light and its suppression of melatonin secretion, and the recuperative role of sleep having decreased sleep pressure [2]. Normally, the environment is conducive to such timing, being quiet and dark (non-alerting) at night and noisier and lighter (more active) in the daytime. However, even though changes in lifestyle can alter the times when individuals are forced to sleep (during night-work, for example), the lack of adjustment of the circadian rhythms reduces the length of daytime sleep, and the desire to sleep at night remains [3]. The importance of circadian rhythmicity is indicated by the observation that these results have been reproduced in sleep laboratories, in which external factors such as noise or light can be maintained constant. Another implication of the importance of circadian rhythms is that returning to sleep after waking is easier during the middle of the night than during the daytime or at the end of a nocturnal sleep.

Relevant to this issue are those studies in which sleep has been curtailed (partial sleep loss). Such studies indicate that losses of 2 h or less have little effect upon some tests of mental performance, but are associated with increased subjective sleepiness and a decreased subjective estimate of the ability to concentrate in the daytime. Successive occasions of partial sleep loss of this magnitude cause a progressive rise in the sensation of daytime fatigue but without a progressive deterioration in mental performance at some tasks (logical reasoning, for example). However, other tests of mental performance, such as vigilance tasks, do show a decrement.

Partial sleep deprivation, by delaying the time of sleep or curtailing it, has the effect of reducing the amount of sleep stages 1 and 2 that are normally the main constituents of the last part of sleep. This raises again the question as to the roles of the different stages of sleep, an issue that has not been resolved. It also

raises the concept of “obligatory” (recuperative) versus “facultative” sleep. This concept places greater weight upon the earlier part of sleep, the obligatory part, with more SWS and REM sleep, and tends to place less stress upon the value of the later stages of sleep, which are richer in stages 1 and 2. However, continual awakenings due to external disturbances will affect all sleep stages, including SWS and REM sleep. In practice, there is a “rebound” phenomenon, by which subjects tend to return to the interrupted sleep stage. However, it takes time to pass through sleep stages 1 and 2 before regaining SWS. In these circumstances, SWS and REM sleep are found throughout a larger proportion of the interrupted sleep than is the case when sleep is not interrupted.

In summary, sleep fractionation has been shown to change the sleep stage profile, to cause deterioration in mood, and to decrease sleep latency in the Multiple Sleep Latency Test [4]. Its effect upon mental performance is less clear, but this might be a reflection of the wide range of tasks that “mental performance” covers, and indicate the need to choose tests of mental performance that are appropriate and sensitive enough for a particular circumstance.

3-4.3 THE EFFECTS OF SLEEP DEPRIVATION/CIRCADIAN DISRUPTIONS ON COGNITIVE PERFORMANCE

Mental fatigue is typically associated with tasks demanding intense concentration, rapid or complex information processing, and other high level cognitive skills. Alternatively, mental fatigue may arise from prolonged activity, particularly those requiring sustained alertness.

Insufficient sleep represents a potential source of fatigue and sleep deprived individuals are more likely to become drowsy or even those off on the job. However, lack of sleep can also affect performance in a number of additional, less drastic ways.

3-4.3.1 Vigilance

Tasks requiring sustained attention and rapid reaction time are particularly sensitive to the effects of inadequate sleep [5]. In fact, tests involving these skills have often been used as a general marker for diminished response capacity in sleepy individuals [6].

Many military jobs require continuous monitoring for several hours and the performance on these tasks is rapidly affected. Performance is becoming less efficient progressively when auditory or visual stimuli have to be detected [7]. This ‘impaired vigilance’ is characterized by a drop in correct responses and an increase in target reaction time.

3-4.3.2 Lapsing

The particular sensitivity of vigilance tasks to sleep loss may be largely explained by the phenomenon of ‘blocks’ or ‘lapses’. These are transient, intermittent episodes marked by a complete loss of awareness and failure to respond to external stimuli. They are also referred to as ‘microsleeps’ [8]. Microsleeps may be as brief as one to ten seconds in length, but generally increase in number and duration as sleep deprivation continues [9].

With respect to critical jobs and tasks in the military environment, even a brief loss of awareness may have serious consequences. Lapsing may even make the difference between success and failure in certain operations requiring sustained vigilance.

3-4.3.3 Cognitive Slowing

A typical effect of sleep deficit is a greater variability in performance. In most areas of performance sleep deprivation tends to have a more marked effect on speed than on accuracy. This has been observed in a

wide variety of tasks. The speed/accuracy trade-off has sometimes been interpreted in terms of a deliberate strategy on the part of the person performing the task [10]. However, an exception to this pattern occurs when the nature of the task is such that the individual has no way of slowing down: then, errors begin to increase, or items are missed entirely (work paced tasks [11]).

3-4.3.4 Memory

Sleep loss also appears to have negative effects on memory. Short term memory problems have been linked to lapsing during encoding [12] and attention deficit during memorization [13].

Memory problems occur mostly when an individual has remained continuously awake for more than 30 hours [10]. What one can expect from more chronic sleep deficit, where sleep is curtailed over a period of days, and the effects on memory is not so clear.

3-4.3.5 Time on Task

Task duration is one factor that influence fatigue levels generally, even in people who are not short of sleep. There is a tendency for performance to deteriorate the longer a task is performed. Under sleep deprivation this effect becomes more pronounced. Although the sleep deprived individual may be able to sustain normal levels of performance for brief periods, deterioration sets in faster than it would in a well-rested person. The amount of time required for this to occur depends on many factors (task complexity, predictability, task familiarity, etc.). The nature of the task is also significant: while some kinds of vigilance tasks may be maintained for an hour, performance involving sustained attention and frequent reactions may deteriorate within a few minutes [14].

3-4.4 METHODS TO ASSESS SLEEP

3-4.4.1 Polysomnography (PSG)

The use of PSG (EEG + EOG + EMG), coupled with the scoring system of Rechtschaffen and Kales, has become the standard way of describing the sleep profile. Several measures can be derived from the polysomnogram, a plot of the sleep stages during the course of the time spent in bed. These measures describe the length of sleep, its consolidation, and the amounts and distributions of the different sleep stages. It is not clear, however, which, if any, of these measures is associated with the various roles that have been ascribed to sleep.

3-4.4.2 Questionnaires

The main disadvantages of using PSG to describe sleep are its cost, the technical expertise required, the degree of compliance required by the subjects, and the inconvenience. As a result, more convenient (to the investigator and subject) alternatives have been sought. They are sleep questionnaires and actigraphy.

Several sleep questionnaires have been developed. They generally require the respondent to assess the value of the sleep (“how refreshing was it?”) as well as to estimate sleep latency, time of sleep onset, number of awakenings, and time of sleep offset. Proponents of the sleep questionnaire argue that it successfully identifies gross changes in the sleep pattern – a long sleep latency or an early awakening – but estimates of the actual times of sleep onset and offset, and of the number of awakenings during the sleep, do not seem to be estimated accurately. However, the questionnaire can lead to information about the perception of the sleep in terms of how refreshing it has been, and this cannot yet be inferred from the measures derived from PSG.

3-4.4.3 Actigraphy

The actimeter is a small device similar to a wristwatch that is generally worn on the non-dominant wrist. It records and stores the number of occasions that the device is accelerated by an amount greater than some threshold setting. The actigraph is a record of the amount of activity plotted against time.

The actigraphy record has been used to assess aspects of the quality of sleep, as well as sleep length and latency. These assessments have included sleep efficiency and sleep fragmentation [15], [16], [17]. In some cases, it has also been used to estimate SWS, this being equated with periods of minimum activity in the actogram. In all these measures, there is some disagreement in the literature with regard to the value of actigraphy as a substitute for PSG. The general view seems to be that the strength of actigraphy is more as an objective record of the sleep-wake cycle as a whole, and that it is valuable in this regard, both in experimental and in clinical circumstances (see reviews cited above).

One factor to bear in mind when interpreting the actigraphy record is that most activity counts are very low at night (during sleeping); indeed, it is generally the case that most of the time intervals during sleep show an activity count of zero. This jeopardizes attempts to assess sleep stages from the activity record, and also necessitates a different way of assessing the sleep actigraphy record for disturbances.

3-4.5 CONCLUSIONS

Polysomnography is the established objective method of assessing sleep quality, but its relationship with subjectively experienced sleep quality is ambiguous. It is difficult to use in the field, due its cost, the technical expertise required, the degree of compliance required by the subjects, and the inconvenience.

Sleep questionnaires are practical and may identify gross changes in the sleep pattern, such as a long sleep latency or an early awakening, but subjective estimates of the actual times of sleep onset and offset, and of the number of awakenings during the sleep, are often unreliable. However, the questionnaire can provide information about the perception of the sleep in terms of how refreshing it has been, and this cannot yet be inferred from the measures derived from the PSG.

Actigraphy is a useful method, due to its low cost and convenience. It is an objective method that reliably records sleep-wake cycles over time. However, this method has not been validated as yet for measurement of sleep quality variables, such as arousals, brief awakenings, and deep sleep. Moreover, the sleep latency measured by actigraphy depends on the investigator’s definition of exactly when sleep starts.

In summary, all the above mentioned methods have their specific advantages and disadvantages when assessing sleep. Actigraphy seems most promising, but will be limited to predicting sleep duration. Combining actigraphy data with subjective data will improve reliability. In future, efforts should be made to develop a wearable sleep monitoring system based on a multi-parameter approach.

3-4.6 REFERENCES

[1] Dijk, D.J. and Czeisler, C., (1995). Contribution of the circadian pacemaker and the sleep homeostat to sleep propensity, sleep structure, electroencephalographic slow waves, and spindle activity in humans. J Neurosci, 15:3526-3538.

[2] Akerstedt, T. and Gillberg, T., (1981). The circadian variation of experimentally displaced sleep. Sleep, 4:159-169.

[3] Akerstedt, T., (1995). Work hours, sleepiness and the underlying mechanisms. J Sleep Res, 4(Suppl. 2):15-22.

[4] Mitler, M.M., Carskadon, M.A. and Hirshkowitz, M., (2000). Evaluating sleepiness. In: Principles and Practice of Sleep Medicine, Kryger, M.H., Roth, T.R. and Dement, W.C. (Eds.). PUBLISHER? Philadelphia, USA.

[5] Horne, J., (1988). Why We Sleep. Oxford University Press, New York.

[6] Pivik, R.T., The several qualities of sleepiness: psychophysiological considerations. In: Monk, T.H., ed. Sleep, sleepiness and performance. Chichester, UK: John Wiley & Sons; 1991:3-38.

[7] Warm, J.S., (Ed.), (1984). Sustained Attention in Human Performance. John Wiley & Sons, New York.

[8] Murray, E.J., (1965). Sleep, Dreams, and Arousal. Appleton-Century Crofts, New York.

[9] Williams, H.L., Lubin, A. and Goodnow, J.J., (1959) Impaired performance with acute sleep loss. Psychological Monogr.: Gen and Appl, 73:1-26.

[10] Dinges, D.F. and Kribbs, N.B., (1991). Performing while sleepy: effects of experimentally-induced sleepiness. In: Sleep, Sleepiness, and Performance, T.H. Monk (Ed.). John Wiley & Sons, New York.

[11] Willimas, H.L. and Lubin, A., (1967). Speeded addition and sleep loss. J Exp Psychol, 73:3313-7.

[12] Polzella, D.J., (1975). Effects of sleep deprivation on short-term recognition memory. J Exp Psychol, 104:194-200.

[13] Elkin, A.J. and Murray, D.J., (1974). The effects of sleep loss on short-term recognition memory. Can J Psychol, 2:23-36.

[14] Tilley, A.J. and Wilkinson, R.T., (1984). The effects of a restricted sleep regime on the composition of sleep and performance. Psychophysiology, 21:406-12.

[15] Garfinkel, D., Laudon, M., Nof, D. and Zisapel, N., (1995). Improvement of sleep quality in elderly people by controlled-release melatonin. Lancet, 346:541-544.

[16] Sadeh, A., Hauri, P.J., Kripke, D.F. and Lavie, P., (1995). The role of actigraphy in the evaluation of sleep disorders. An American Sleep Disorders Association Review. Sleep, 18:288-302.

[17] Lowden, A. and Akerstedt, T., (1998). Sleep and wake patterns in aircrew on a 2-day layover on westward long distance flights. Aviat Space Environ Med, 69:596-602.

Chapter 3-5 – MONITORING OF HEART RATE VARIABILITY FOR ASSESSMENT OF FATIGUE AND RESTORATION DURING SLEEP

(Heart Rate Variability and Restoration during Sleep)

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3-5.1 BACKGROUND

Several different forms of fatigue are recognized in human factors research on performance degradation [1], [2]. Physical fatigue is caused by prolonged or intensive physical work limiting physical tolerance. Fatigue associated with sustained task performance and cognitive demands is usually referred to as mental fatigue. It is thought that the limiting condition for tolerance of physical fatigue is not muscular strain but a loss of cognitive control. Sleep disruptions may also be caused by both physical and mental work. In some cases we may also distinguish emotional fatigue associated specifically with emotional overload.

In this context physical, mental and sleep-based fatigue are the most relevant problems. It is important to consider their joint effects as the pathophysiological mechanisms involved. Multiple stressors such as physical overexertion, psychoemotional stress and sleep deprivation have strong impact on autonomic control of body physiological systems. It is generally agreed that all activities followed by increased sympathetic influence involve an increase of heart rate (HR) frequency and a decrease of HR variability. Central nervous and cardiovascular systems during continuous work are mainly responsible for optimal body functioning, which is limited by fatigue and the need for rest and sleep. In this aspect, sleep has a restorative function, which is realized during the modifications in the central and autonomous nervous system. Autonomic HR control, measured by means of HR variability, might be seen as characteristic of cardiovascular function, responsible for energetic supply of any activities, such as physical, mental, or emotional, as well as during fatigue and sleep [3], [4].

Furthermore, HR variability might be used in assessment of human states during sleep-wake cycles. Night sleep with modifications in functional state of autonomic nervous system changes autonomic HR control and hemodynamics over individual sleep stages and, in this way, might have a restorative function towards cardiovascular function. Because of this, night sleep might be used as a natural situation for cardiovascular testing without exercise involvement in order to assess a restoration of cardiovascular function. HR spectral analysis during sleep indicated that HR variability modifications during sleep are related to individual sleep stages and depend on the baseline autonomic HR control level [3], [5]. Not only mental effort but also the adaptability of cardiovascular function during the fatigue-restoration cycle can be assessed by HR variability.

3-5.2 METHODOLOGY OF HEART RATE VARIABILITY ANALYSIS

3-5.2.1 Requirements for Sensors

The information obtained from sensors detecting electrocardiosignal should be analyzed using advanced methodologies allowing to detect, to assess and to evaluate the different human states, as well as pathological aberrations. From this point of view, the most valuable seems HR variability analysis.

Most cardiovascular signals can be easily measured by the use of electrocardiography (ECG) and provide objective information about human state while the person is at rest or engaged in a variety of activities. HR variability is strongly affected by artefacts that arise due to poor quality of the signal related to the sensors' bad contact to the skin during body movements, or to incomplete heart beats such as extra systoles. Both types of artefacts can artificially increase HR variability in a significant way. Therefore, segments in which artefacts in the ECG signal occur should be corrected using special "correction algorithms," or should not be included in the assessment of HR variability [6].

3-5.2.2 HR and HR Spectral Analysis

A common way to measure HR variability is to use frequency spectra, which are often divided into several ranges. HR variability at rest in stationary situation can be assessed by spectral analysis of RR interval sequence using Fast Fourier (non-parametric method) or autoregression function (parametric method) [7]. Four oscillatory ranges in power spectrum are distinguished: ultra low frequency component (ULFC; ≤ 0.003 Hz), very low frequency component (VLFC; 0.003 – 0.04 Hz), low frequency component (LFC, 0.04 – 0.15 Hz) and high frequency component (HFC; 0.15 – 0.40 Hz). Power spectral density analysis of HR provides the basic information of how power (variance) distributes as a function of frequency. Power spectral density analysis might be performed either on short- or long-term RR interval recordings.

Short-term recordings allow frequencies to be analyzed at least above 0.04 Hz. Measurement of the different frequency components is usually made in absolute values of power (ms2), but strongly recommended to be measured in relative values (e.g., to total power) or normalized units (n.u.), which represent relative value of each power component in proportion to the total power minus the VLFC. The representation of LFC and HFC in n.u. emphasizes the controlled and balanced behaviour of the two branches of autonomic nervous system, sympathetic and parasympathetic, respectively. Nevertheless, relative values or n.u. should always be quoted with total spectral power and absolute values of individual components in order to describe, in total, the distribution of power in each spectral component.

Long-term recordings in the entire 24-h period might be used for HR spectral analysis, as well. The result then includes ULFC, in addition to VLFC, LFC, and HFC. The slope of the 24-h spectrum can also be assessed on a log-log scale by linear-fitting the spectral values. The problem of "stationarity" is discussed with long-term RR-interval recordings. If mechanisms responsible for RR-interval modulations of a certain frequency remain unchanged during the whole period of recording, the corresponding frequency component of HR variability may be used as a measure of these modulations. If the modulations are not stable, the interpretation of the results of frequency analysis is less defined. In particular, physiological mechanisms of RR-interval modulations responsible for LFC and HFC cannot be considered stationary during 24-h period. More detailed information about autonomic modulation of RR intervals is available in shorter recordings preserving "stationarity" of the process. It should be remembered that individual oscillatory components provide measurements of the degree of autonomic modulations rather than the level of autonomic tone.

The analyzed ECG signal should satisfy several requirements in order to obtain a reliable HR variability calculation and spectral estimation. The sampling rate for correct detection of R wave of ECG should be at least 500 Hz [8]. If ectopic beats, arrhythmic events, missing data and noise effects interrupts "stationarity" of HR recording, proper interpolation (or linear regression or similar algorithms) on preceding/successive beats on HR signal or on its autoregression function should be used reducing this error. The relative number and relative duration of RR intervals, which were omitted or interpolated, should also be quoted.

3-5.2.3 HR Analysis Using Poincare Plot of RR Intervals

The HR might yield a specific pattern of the Poincare plot depending on the test type (active orthostatic test, physical load, wakefulness, sleep stages) and the autonomic control level [6], [9]. A sinus rhythm analysis, after the elimination and interpolation of ectopic or error values, was performed as follows (Figure 3-5.1):

1) The maximal HR variability or tonic control level (ΔRR_t), measured as the maximal distance between the two points on two parallel lines tangential to the cluster at the peak value level of HR variability, was assessed;
2) The average HR response to respiration (V) was measured additionally in order to improve evaluation of n.vagus impact;
3) The maximal HR response or reflex control level (ΔRR_r) reflected by diagonal of square (corresponding to 99.9% level of the histogram ($p \leq 0.001$)) was measured as the distance between the minimal (RR_{min}) and the maximal (RR_{max}) values on the diagonal of the plot; and
4) The general HR variability as the plot of all square (P, ms2) involving both, tonic and reflex control components [9].

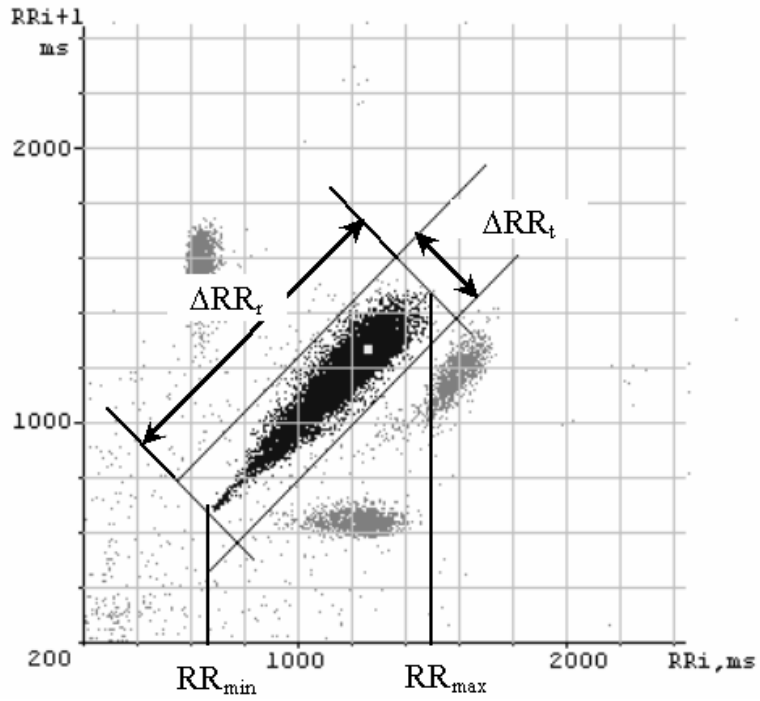

Figure 3-5.1: Quantitative Analysis of HR Variability by Poincare Plot (RR_{min}, Minimal Value of RR Interval; RR_{max}, Maximal Value of RR Interval; ΔRR_r, Maximal HR Response; ΔRR_t, Maximal HR Variability).

3-5.3 HEART RATE AND HEART RATE VARIABILITY AS A MEASURE OF FUNCTIONAL STATUS

3-5.3.1 Heart Rate and Heart Rate Variability as a Measure of Physical Fitness

During physical activity the body requires more oxygen, the heart pumps more powerfully and the HR increases [10]. HR begins to increase within one second of the onset of isometric exercise. Initial HR responses to exercise are mediated by abrupt parasympathetic withdrawal, while increases of sympathetic activity begin about 30 to 60 seconds after the onset of exercise and then gradually increase with increasing work load and depend on muscle mass involved in exercise. An increase in HR because of diminishing parasympathetic and increasing sympathetic activation results in a gradual decrease of HR variability, which mainly depends on parasympathetic control. Because of this, HR responses to exercise are more informative than modifications in HR variability.

There is a general relationship between HR and oxygen consumption, and thus, an indirect assessment of physical activity or energy expenditure may be attempted using HR. This relationship provides a basis for the monitoring of physical activity by recording HR, being the most precise at high levels of energy expenditure reaching 50% – 90% of maximum oxygen intake. An increase in HR due to a decrease in parasympathetic control is an immediate response of the cardiovascular system to exercise. This increase in HR is followed by an increase in sympathetic control to the heart and systematic blood vessels. During exercise, HR increases linearly with workload and VO_2. During mild work at a constant work rate, HR reaches steady state within several minutes. As workload increases, the time necessary for HR to stabilize will progressively lengthen. Recovery of HR after exercise is dependent on the baseline level of fitness of the subject. Relatively rapid HR during mild exercise or recovery could be due to deconditioning. The HR response to exercise and the recovery time after exercise depend on the baseline level of autonomic HR control, which is strongly related to the subject's fitness.

Well-trained sportsmen and very well fitted subjects are characterized by expressed bradycardia and very low HR variability due to maximal influence of parasympathetic HR control at rest, as well as by marked HR responses to exercise due to withdrawal of parasympathetic and increase of sympathetic activity [3]. Thus, HR response to exercise can be used for evaluation of reflex HR control and adaptability level of the cardiovascular system.

3-5.3.2 Heart Rate Variability as a Measure of Mental Workload

The use of HR variability in both laboratory and field settings is valued not only because of its usefulness as a measure of mental effort, but also because of application where continuous recording is required. In laboratory studies, HR variability has consistently responded to changes from rest to task conditions and to a range of between-task manipulations [11]. In operational contexts, HR variability has seen increased use as an indicator of the extent of task engagement in information processing requiring significant mental effort, particularly in flight-related studies [12], [13], [14]. HR variability has been reported to respond rapidly to changes in user workload and strategies, usually within seconds [11]. Thus, HR variability has been able to detect rapid transient shifts in mental workload [12].

In a recent study involving the level of user control and changes in HR variability during simulated flight maintenance, the demands of dynamic monitoring and fault diagnosis for 11 trainee flight engineers were examined in relation to changes in HR variability [15]. HR variability was found sensitive to the different phases of the work environment; in particular, the frequency 0.07 – 0.14 Hz range was suppressed during the mentally demanding problem-solving mode. The findings of this study support both the use of HR variability as a physiological index of mental effort and its value in operational contexts.

3-5.3.3 Heart Rate Variability as a Measure of Cardiovascular Function During Sleep

Human functional status might be assessed by HR variability modifications during sleep-wake cycle. Studies on long-term acclimation of cardiac rhythm to microgravity in astronauts have shown that more pronounced decrease of HR observed in non-REM sleep was produced by an increase of parasympathetic activity [16]. HR spectral analysis during sleep indicated that HR variability modifications during sleep have been related to individual sleep stages and depend on baseline autonomic HR control level [17], [18]. Adaptability of cardiovascular function during fatigue-restoration cycle can be assessed by HR variability [4].

Usually in healthy subjects, a decrease in HR and its variability from wakefulness before sleep to Stage 4 was seen with a parallel increase in respiratory arrhythmia depending on the diminution of sympathetic and the augmentation of parasympathetic control. In REM sleep, an increase in HR and its variability with a parallel decrease in respiratory arrhythmia was observed, mainly depending on the withdrawal of parasympathetic control, and a slight increase in a sympathetic one [17]. Both behaviors were confirmed by the HR power spectrum analysis [18]. The absolute values for each oscillatory component of the HR power

spectrum were equal during wakefulness. A decrease in the total spectral power, largely accountable for by VLFC, was observed during non-REM sleep. In REM sleep an increase was observed in the total spectral power, largely accounted for by a marked prevalence of VLFC due to a small contribution of LFC and HFC. Those changes confirm that the HR modification during non-REM sleep is dependent on an increase in parasympathetic input and a decrease in a sympathetic one; while the HR changes during REM sleep are more dependent on the withdrawal of parasympathetic input rather than on an increase in sympathetic one [17].

HR Poincare plots might be seen as an easy and informative method for visual presentation of HR variability changes during time-course of sleep. As shown in Figure 3-5.2 the HR changes over sleep stages were followed by the modifications of HR variability, reflecting autonomic control [9]. The dots concentrated in a well-formed circle reflect the lowest HR (longest RR interval) depending on maximal influence of parasympathetic control during Stages 3 and 4. In REM sleep the dots are scattered in a larger area representing bigger RR interval responses (ΔRR_r,) and more expressed maximal HR variability (ΔRR_t,). In principal, HR variability pattern during sleep might be used for assessment of functional state (i.e., sleep state).

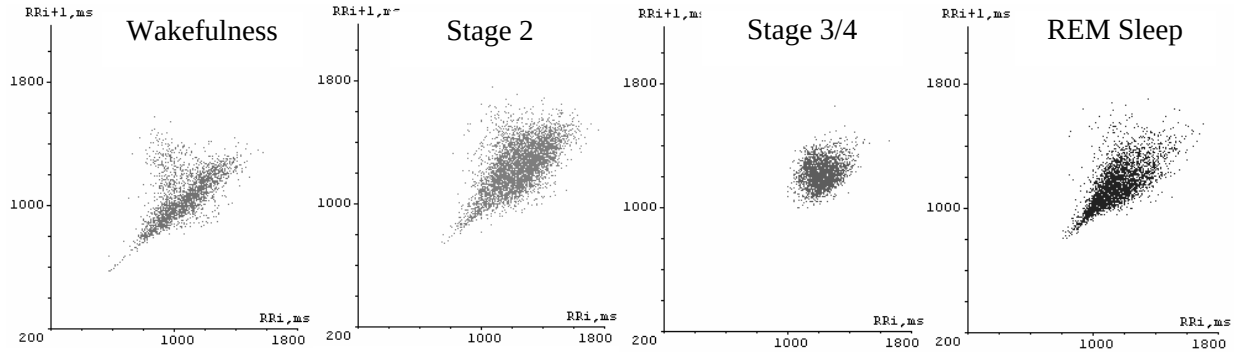

Figure 3-5.2: Poincare Plots of RR Interval During Different Sleep Stages.

Some specific differences of the HR restoration during sleep are demonstrated in Figure 3-5.3. The square of RR intervals in Poincare plot collected during sleep time is more expressed in subject showing autonomic HR control restoration in sleep, as compared with subject demonstrating inability to restore. In subject with restorative sleep (top row), HR response to AOT at morning-time, as compared with evening-time, was increased demonstrating restoration of autonomic HR control. However, in subject with non-restorative sleep, a square in Poincare plot representing RR intervals during sleep (bottom row) is less expressed demonstrating more decreased HR variability and HR frequency responses in sleep. HR responses to AOT at evening-time and at morning-time were expressed at the same level showing inability to restore cardiovascular function during sleep. HR responses to AOT and exercise test depend on the level of autonomic control. In subject with restorative sleep demonstrating higher HR variability during sleep, the HR responses to AOT and exercise test are more expressed, as in subject with non-restorative sleep. The clear relation among HR variability level, functional cardiovascular reserve and sleep is evident [6], [9].

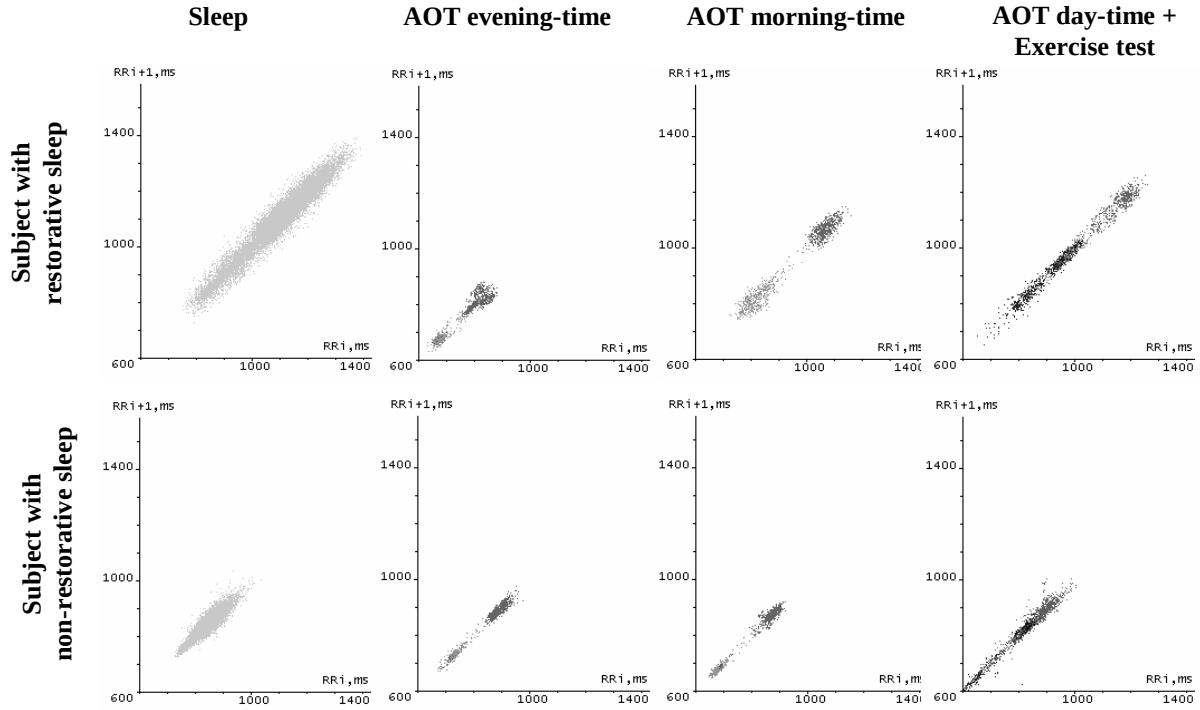

Figure 3-5.3: HR Variability During Different Testing Conditions.

Thus, evaluation of adaptability of cardiovascular function, while measured as total HR responses during sleep and exercise, should provide important information about the functional reserve of investigated persons. While measured separately during night sleep and functional tests at waking state, Poincare plot might dispose supplementary information about which branch, sympathetic or parasympathetic, of HR control was more involved in the process of adaptation. The HR variability reflects a huge amount of vital physiological and psychophysiological issues: autonomous nervous system and its different control mechanisms, restoration from fatigue, mental workload, sleep efficiency, and others. Analyses of the HR rate variability provide important information on exercise training effects on human fitness; that is, the HR variability was shown to be significantly higher in physically active compared to non-physically active healthy humans.

HR parameters, drawn from HR Poincare plots mentioned in methodology, during different sleep stages (Figure 3-5.3), like the parameters drawn from HR power spectrum, enabled to have nearly similar information about tonic and reflex HR control. The HR testing during night sleep demonstrated better reflection of parasympathetic HR control, while exercise testing showed a more sympathetic one. Active orthostatic test (AOT) at morning just after sleep enabled to evaluate aspects, tonic and reflex control, their restoration after sleep, particularly sympathetic and parasympathetic aspects of HR response. Poincare plot of HR with its quantification, being a simple and visually effective method of analysis, might be informative for evaluation of functional status (Figure 3-5.3).

Poincare plots reflect maximal level of HR frequency changes during shifts of sleep stages, which might be used as a measure of adaptability of cardiovascular system. It was much more expressed for trained sportsmen, as compared with healthy subject. For healthy subject, its total level of adaptability was lower, HR being less low at minimal level during slow wave sleep and less high at maximal level during REM sleep or arousals. Thus, a decrease of HR maximal response might be related to reduction of HR control from both sides, parasympathetic and sympathetic control depression; however, more so from the parasympathetic.

A well-trained sportsman, as compared with non-trained healthy subject, is characterized by a more expressed square of dots on Poincare plots constructed from RR intervals at sleep and orthostatic tests, as well as the bigger reflex (ΔRR_r) and tonic (ΔRR_t) component of HR variability measured by Poincare plot.

Poincare plot reflects maximal level of HR frequency changes during shifts of sleep stages, which might be used as a measure of adaptability of cardiovascular system. It was much more expressed for trained sportsmen, as compared with healthy subject. For healthy subject its total level of adaptability was lower, HR being less low at minimal level during slow wave sleep and less high at maximal one during REM sleep or arousals. Thus, a decrease of HR maximal response might be related to reduction of HR control from both sides, parasympathetic and sympathetic control depression; however, more so from the parasympathetic.

The baseline level of autonomic HR control and balance of sympathetic-parasympathetic inputs might be measured by means of analysis of HR power spectrum components, while adaptability of cardiovascular function and fatigue–restoration cycle might be assessed by means of very simple methodology – an analysis of HR Poincare maps, constructed from consecutive RR intervals, recorded during sleep, AOT, or exercise [9], [19]. All tests together enable to evaluate a total level of adaptation reserve of cardiovascular function, using HR responses to all tests. Particular restoration of adaptability might be evaluated using HR analysis during repetitive AOT, performed just before and after sleep.

In the cases of fatigue developing during disturbed wake-sleep cycle or overtraining situation in high physical or emotional overcrowding, there might be some differences in HR control restoration during sleep. If cardiovascular function was not able to restore, a fatigue might be increasing during the rest of the day. Such situations might be seen in sportsmen during their training sessions when overtrained [20]. Because of that, HR responses to AOT might be used for evaluation of restoration of their functional status after night sleep.

3-5.4 SLEEP QUALITY AND RESTORATION OF CARDIOVASCULAR SYSTEM

Night sleep with modifications in functional state of autonomic nervous system during shifts of sleep stages and cycles is responsible for modification of HR variability and its periodical structure, reflecting particular domination of sympathetic or parasympathetic control at individual sleep stage [21], [22]. On the other hand, normal sleep is responsible for a restoration of functional state of nervous system, regulating all organism functions, particularly cardiovascular function, after their activation or exhaustion during daily activities or mission action.

The sleep quality has a positive impact on cardiovascular function during sleep [21], [22]. The main characteristics of night sleep quality in three groups of persons, distributed according to ability of restoration of their reflex HR control, are presented in Table 3-5.1 [23]. The best situation of sleep quality was in Group 1, while Group 2 demonstrated significantly lower sleep efficiency, higher wakefulness level at sleep, and lower level of deep non-REM sleep. Group 3 demonstrated lower sleep efficiency and shorter total sleep time, more wakefulness after sleep onset, as well as less slow wave sleep, as compared with Group 2. REM sleep decreased, as well, if compared with Groups 1 and 2. Thus, disturbed sleep, total sleep time and sleep architecture might be seen as having negative impact on restoration of autonomic control in sleep.

Table 3-5.1: Sleep Quality (Polysomnographic and Pittsburgh Sleep Quality Index (PSQI) Data) in Subject Groups Distributed According to the Restoration of HR Control During Sleep

	Restoration of HR Reflex Control during Sleep		
	Complete	Incomplete	No Restoration
TST; min.	320.9	318.7	308.2*I
SE, %	87.0	85.8*I	84.1*I
REM lat., min.	92.5	94.4	90.2
WASO, %	13.0	14.2*I	15.9*I
REM Sleep, %	12.7	12.1	10.6*I, II
S1, %	9.1	9.7	10.4
S2, %	52.7	53.4	53.7
S3, %	7.9	6.7*I	5.6*I
S4, %	1.9	1.1*I	1.0*II
BM, %	2.7	2.7	2.8
PSQI	7.6	7.9	7.9

* $p<.05$

Our data demonstrate that there might be two aspects of cardiovascular function control's restoration after sleep:

i) An increase of reflex HR control due to both increased sympathetic and parasympathetic impact during sleep, followed by a decrease of the vessel tone; and

ii) An increase of adrenergic neurohumoral control with a relative decrease of parasympathetic impact to HR variability, following an increase of adrenergic activity after awakening after few episodes of REM sleep, to which such pattern of spectral components is characteristic.

3-5.5 CONCLUSIONS

Heart rate (HR) has been the most popular psychophysiological measure to monitor the human functional status, because HR has been found to be very sensitive to different functional states. HR increases due to physical and mental activities and decreases during relaxation or sleep. It is very easy to monitor HR from electrocardiogram recording in laboratory and field settings. The average HR can be obtained easily by means of ECG recorders; however, to assess HR variability, the accuracy of the HR measurement must be high and more sophisticated techniques are required, which reduces the ease of use.

HR and HR variability for assessment of human functional status could be based on inter- and intra-variables of cardiovascular parameters of individual. Assessment could be performed during baseline condition (reference point) using measurement during quiet supine (or sitting) wakefulness and different testing conditions (including sleep stage shifts), as well as during operational mission. The range of HR and HR variability responses might be used as a characteristic determining cardiovascular functional reserve (adaptability) and is closely related to general functional status.

Night sleep with modifications in functional state of autonomic nervous system is changing autonomic HR control over individual sleep stages. Because of that, HR variability might be used in assessment of human states during sleep-wake cycles. HR spectral analysis during sleep indicated that HR variability modifications during sleep are related to individual sleep stages and depend on the baseline autonomic HR control level.

3-5.6 REFERENCES

[1] Fried, K., (2007). Fatigue and military operation. NATO RTA HFM-151/Workshop on "Operational Fatigue", Paris.

[2] Wilson, G., Fraser, W., Beaumont, M., Grandt, M., Varoneckas, G., Veltman, H., Svensson, E., Burov, A., Hockey, B., Edgar, G., Stone, H., Balkin, T., Gilliland, K., Schlegel, R.E. and Van Orden, K., (2004). Operator Functional State Assessment. NATO RTO Technical Report 2004, RTO-TR-HFM-104 http://www.rta.nato.int/Pubs/RDP.asp?RDP=RTO-TR-HFM-104.

[3] Varoneckas, G., (2003). Heart rate variability in the evaluation of functional status during training. Operator Functional State: The Assessment and Prediction of Human Performance Degradation in Complex Tasks. Robert, G. and Hockey, J., (Eds.). NATO Science Series I: Life and Behavioural Sciences. IOS Press, Burke, VA, 355:90-106.

[4] Varoneckas, G., (2000). Analysis of heart rate variability during sleep as a tool for assessment of cardiovascular adaptability and fatigue in sleep-wake cycle. Individual differences in the adaptability to irregular rest-work rhythms. Status of the use of drugs in sleep-wakefulness management. RTO Meeting Proceedings 31. RTO Human Factors and Medicine Panel (HFM) Workshop, Venice, Italy, 3-4 June, 1999. Canada, pp. 22-1 – 22-7.

[5] Angus, R.G., Heslegrave, R.J. and Miles, W.S., (1985). Effects of prolonged sleep deprivation, with and without chronic physical exercise, on mood and performance. Psychophysiology, 22:276-282.

[6] Varoneckas, G. and Zemaityte, D., (2002). Quantitative evaluation of autonomic heart rate control during sleep stages using Poincare plots. EMBEC'02 IFMBE Proceedings, 3(2):1318-1319.

[7] Sayers, B.M., (1973). Analysis of heart rate variability. Ergonomics, 16:17-37.

[8] Malik, M., Bigger, J.T., Camm, A.J., Kleiger, R.E., Malliani, A., Moss, A.J. and Schwartz, P.J., (1996). Guidelines heart rate variability: Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Eur Heart J, 17:354-381.

[9] Zemaityte, D., Varoneckas, G., Ozeraitis, E. and Podlipskyte, A., (2001). Autonomic heart rate control evaluation by means of heart rate Poincare plots analysis. Biomedicine, 1:27-35.

[10] Falls, H.B., (1968). Physiology of Exercise. Academic Press, New York.

[11] Aasman, J., Mulder, G. and Mulder, L.J.M., (1987). Operator effort and the measurement of heart rate variability. Hum Factors, 29:161-170.

[12] Kramer, A.F., (1991). Physiological metrics of mental workload: A review of recent progress. In: Multiple-task Performance, Damos, D. (Ed.). Taylor and Francis, London, pp. 279-328.

[13] Wilson, G.F., (1993). Air-to-ground training missions: A psychophysiological workload analysis. Ergonomics, 36:1071-1087.

[14] Wilson, G.F. and Eggemeier, F.T., (1991). Physiological measures of workload in multi-task environments. In: Multiple-task Performance, Damos, D. (Ed.). Taylor and Francis, London, pp. 329-360.

[15] Tattersall, A. and Hockey, G., (1995). Level of operator control and changes in heart rate variability during simulated flight maintenance. Hum Factors, 37(4):682-698.

[16] Gundel, A., Drescher, J., Spatenko, Y.A. and Polyakov, V.V., (1999). Heart period and heart period variability during sleep on the MIR space station. J Sleep Res, 8:37-43.

[17] Zemaityte, D., Varoneckas, G. and Sokolov, E., (1984). Heart rhythm control during sleep. Psychophysiology, 4:279-289.

[18] Zemaityte, D., Varoneckas, G., Plauska, K. and Kaukenas, J., (1986). Components of the heart rhythm power spectrum in wakefulness and individual sleep stages. Int J Psychophysiol, 4:129-141.

[19] Pivik, R.T., Busby, K.A., Gill, E., et al., (1996). Heart rate variations during sleep in preadolescents. Sleep, 19(2):117-135.

[20] Kepezenas, A. and Zemaityte, D., (1983). Relationship between heart rate structure and physical fitness in sportsmen (Rus). Fiziologija Cheloveka, 9(5):729-739.

[21] Parmeggiani, P.L., (1994). The autonomic nervous system in sleep. In: Principals and Practice of Sleep Medicine, 2nd edition, Kryger, M.H., Roth, T. and Dement, W.C., (Eds.). WB Saunders, Philadelphia, pp. 194-203.

[22] Varoneckas, G. and Zemaityte, D., (1997). Restoration of cardiovascular function during night sleep in relation to physical fitness in CAD patients with congestive heart failure. XXIV International Congress on Electrocardiology. Abstracts. Bratislava, Slovak Republic, 24-28 June 1997.

[23] Varoneckas, G., (2007). Restorative function of sleep and fatigue. NATO RTA HFM-151/Workshop on “Operational Fatigue”, Paris.

Chapter 3-6 – PHYSIOLOGICAL MONITORING COMBAT CASUALTY CARE

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ABSTRACT

A primary objective of the research program in Combat Casualty Care is to develop and demonstrate a semi-automated capability that provides critical casualty information remotely for trauma triage and to improve patient management at higher echelons of care. When this goal is met, the medic will possess a greater decision-support based on continuous information about live/dead status, and severity and progression of the injury and which injuries require rapid interventions. Since hemorrhagic shock remains a leading cause of potentially preventable death on the battlefield, research activities for advanced capabilities for remote triage, en route, and in-hospital care focus on the identification and care of wounded Soldiers with severe hemorrhage. This research is founded on the fundamental premise that meeting this goal will save lives on the battlefield. The purpose of this paper is to review past and current status of physiologic monitoring for combat casualty care, and to describe future research plans that will lead to advanced diagnosis and triage capabilities for combat medics by developing improved algorithms for clinical assessment of wounded Soldiers.

3-6.1 BACKGROUND

The US combat experience has demonstrated that acute hemorrhage and subsequent hemodynamic decompensation (shock) account for about 50% of the deaths on the battlefield and the forward operating table, a statistic that has remained relatively unchanged since World War I [1]. In addition, hemorrhage is the primary cause of death in about 30% of the injured Soldiers who die from wounds. Likewise, uncontrolled hemorrhage accounts for up to 82% of the early operative deaths from trauma in the civilian arena. However, the mortality rate in combat casualties drops to between 2% and 4% if the trauma patient is stabilized through surgery [1], [2]. It is therefore clear that the ability to significantly reduce the mortality and morbidity associated with hemorrhagic shock on the battlefield will depend heavily on improving the capability of combat medical personnel to quickly diagnose the requirement for clinical intervention and/or early evacuation.

Hemorrhagic shock is typically identified by the degree of hypotension and non-specific signs and subjective symptoms such as cold, clammy skin; pallor; weak thready pulse; unstable vital signs; and diminished mental status that develop as a result of blood loss [3]. Of the several vital sign measurements associated with circulatory shock and subsequent poor outcome, the battlefield medic is currently limited to the physical

assessment of mental status, pulse character, and pulse rate measurements for diagnosis of wounded Soldiers. In special operation forces, it is rare that standard blood pressure (BP) and pulse oximetry may be available. In all cases, these capabilities require exposure of the medic to the life-threatening situation of hostile fire. Thus, providing a physiological monitoring capability for remote triage decision-support would reduce the risk to combat medics and provide them, as well as unit leaders, situation understanding regarding the immediate health status of their warfighters and prioritization of care and evacuation.

3-6.2 CURRENT STATUS/LIMITATIONS

The challenge in determining hemorrhagic shock is that although it is easily diagnosed in late stages when therapy may be less effective, it is difficult to obtain an early diagnosis. The solution to this dilemma is to identify the physiologic signal(s) that provide the best *early* indicators of blood volume loss and impending hemodynamic decompensation.

Currently there is no accurate and easy method to assess the magnitude of hemorrhage (blood loss) in an operational environment. In addition, current medical care during military trauma casualty transport fails to provide advanced decision-support capabilities for treatment with resuscitation fluids and oxygen. Although significant reductions in BP and oxygen carrying capacity of the blood (SpO_2) are routinely provided by standard clinical monitoring, compensatory mechanisms that buffer against changes in BP and SpO_2 make these measurements poor indicators for *early* assessment of shock [4], [5]. This notion was supported by preliminary data from our laboratory demonstrating that BP and SpO_2 change very little (Figure 3-6.1, Panels A and B) during significant (as much as 2 liters) progressive reduction in central blood volume in humans despite dramatic reductions in stroke volume (SV) and cardiac output (Figure 3-6.1, Panels D and E). Thus, the appearance of hypotension and other signs and symptoms of shock represent a point in time when it may be too late to introduce effective intervention(s). Some recent research has identified several parameters that seem to provide early indicators of impending circulatory collapse.

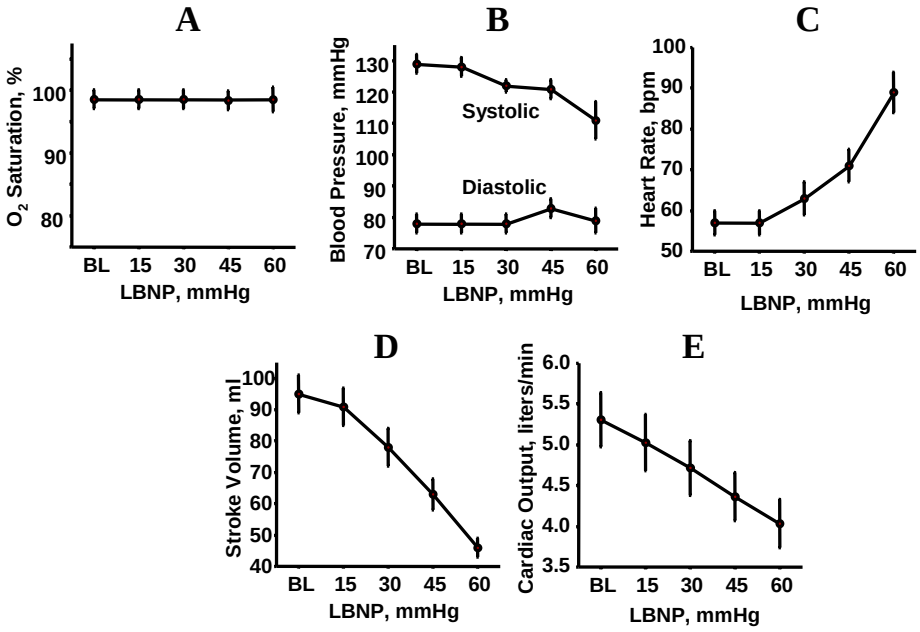

Figure 3-6.1: Hemodynamic and Arterial O_2 Saturation Responses During Progressive Reductions in Central Blood Volume in Humans. Lower body negative pressure (LBNP) was used to transiently redistribute blood away from the heart; i.e., higher LBNP equates to greater loss of central blood volume. Values are mean ± 1 standard error.

3-6.3 POTENTIAL KEY PARAMETERS

3-6.3.1 Heart Period Variability

A linear relationship exists between changes in central blood volume and sympathetic nerve activity [6]. This relationship indicates that any index of sympathetic nerve activity could act as an effective marker for early detection of blood loss. Power spectral analysis generated from application of fast Fourier transform on R-R interval data obtained from the electrocardiogram (ECG) waveform can provide a non-invasive assessment of the balance between sympathetic and parasympathetic nervous activity [7]. We subsequently analyzed R-R interval data obtained from trauma patients who sustained head, blunt, or penetrating injuries leading to hemorrhage [8]. Patients who died had statistically lower low frequency power spectrum (LF) and greater high frequency power spectrum (HF) and HF/LF ratio than those who lived, suggesting that early parasympathetic predominance marked by suppression of sympathetic activity with high vagal tone may be an early signal of mortality. Subsequent investigations have indicated that non-linear frequency analyses (i.e., HR complexity) may also provide a non-invasive distinguisher between patients who live and die or receive life saving interventions (LSI). The calculation of some index associated with heart period variability to assess blood volume status of combat casualties is attractive, since it can, with some processing, be calculated from an ECG trace. However, recent analyses have revealed that heart period variability has high inter- and intra-individual variability that may limit its practical use in clinical assessment of casualties. Thus, the viability of heart period variability as a decision support tool for early assessment of blood loss and identification for the need of a LSI awaits further research.

3-6.3.2 Pulse Pressure (PP)

Any physiological response that tracks alterations in SV should provide an effective indicator for early detection of blood loss and the need for fluid resuscitation. Vital sign data collected from trauma patients who sustained blunt or penetrating injuries leading to severe hemorrhage revealed that patients who died had statistically lower pulse pressure (PP) at the time of emergency medical personnel arrival than those who lived, even when there were no differences in systolic blood pressure (SBP), heart rate (HR), or SpO_2 [8]. When we performed continuous measurements of PP with SV, BP, and SpO_2 in human volunteers who underwent progressive central hypovolemia, PP proved to be a significantly earlier indicator of central blood volume reduction than mean arterial pressure (MAP) or SpO_2 because of its ability to track SV [9]. Thus, both trauma patients and laboratory experimental data obtained from hypovolemic humans suggest that a reduction in PP may provide an indicator of fluid resuscitation requirements before BP begins to decrease. This approach is particularly attractive since PP can be easily calculated from measurements available on current monitors (SBP minus DBP). The use of PP as part of an algorithm for decision-support of treatment of battlefield casualties or closed-loop resuscitation is limited to the presence of monitors placed in military transport vehicles with capabilities to measure BP.

3-6.3.3 Electrocardiogram Waveforms

Recent human laboratory experiments have provided evidence that R-wave amplitude measured from lead II ECG waveforms increases linearly with progressive reduction of central blood volume [10]. The amalgamated correlation (R^2) between average SV and average R-wave amplitude was 0.989. These results indicate that changes of R-wave amplitudes occur prior to changes in BP and, therefore, amplitude monitoring may allow for early detection for the need of fluid resuscitation or other interventions. Although perhaps not practical during transport of patients, Emergency Department (ED) or Intensive Care Unit (ICU) monitors that provide stable ECG waveforms could support analysis of R-wave amplitude as part of an algorithm for controlling closed-loop resuscitation and other decision-support.

3-6.3.4 Cardiac Baroreflex Sensitivity (BRS)

The cardiac baroreflex sensitivity (BRS) reflects vagal reflex responses and can be assessed by calculating the ratio of the change in HR to the change in mean arterial pressure (ΔHR/ΔMAP). BRS is altered as a linear inverse function of reduced central blood volume and provides earlier indication for the need of intervention than BP, which remains constant [11]. Accurate BRS measurement was independent of breathing rate and, therefore, shows promise as a tool to assist in the assessment of changing blood volume status. As this method of calculating BRS assesses the changes in both HR and MAP, it would be necessary to temporally track these parameters. However, this calculation could be easily achieved with the currently available measures of HR and BP on standard medical monitors. It is therefore possible that changes in autonomic vagal activity reflected by altered BRS could serve as an important adjunct to monitoring HR, HF/LF, and BP, track progression to hemodynamic instability in bleeding patients, and assist in the early assessment casualty status.

The techniques suggested here show promise in their ability to identify hemorrhagic shock at a stage where meaningful interventions could save lives. However, translating these techniques to wearable sensors on a warfighter is currently extremely challenging. In the US's Warfighter Physiological Status Monitoring (WPSM) program, a phased approach has been adopted. Initially the system was developed to provide a presence or absence of vital signs, but the sensors have been developed with a view to applying more complex remote triage algorithms as technology and better understanding of the signals advances.

3-6.4 CURRENT SENSORS/PARAMETERS THAT CAN BE ASSESSED

3-6.4.1 Vital Sign Detection System

The current US WPSM includes a Vital Sign Detection System (VSDS) (Hidalgo Ltd., Swavesey, Cambridgeshire, UK). The VSDS monitors HR, respiration rate, activity, body posture/position, and skin temperature, and uses information from these sensors in several algorithms to determine whether there is a presence or absence of vital signs. The system also has a number of self checks to ensure that the device is being worn, that electrodes are in contact with a warfighter, and that the device is working correctly. In order to provide more confident results, the system uses two redundant independent channels for measuring both HR and respiration rate. For HR, one technique is the measurement and analysis of two channels of ECG waveform data. The ECG channels are sampled at 256 Hz and, under moderate exercise, appear stable enough to consider implementing various indices of heart period variability. Figure 3-6.2 shows a prototype VSDS device. Other manufacturers are beginning to develop ECG-enabled ambulatory chest sensors allowing competition in the market place (e.g., Foster Miller, Inc., Waltham, MA).

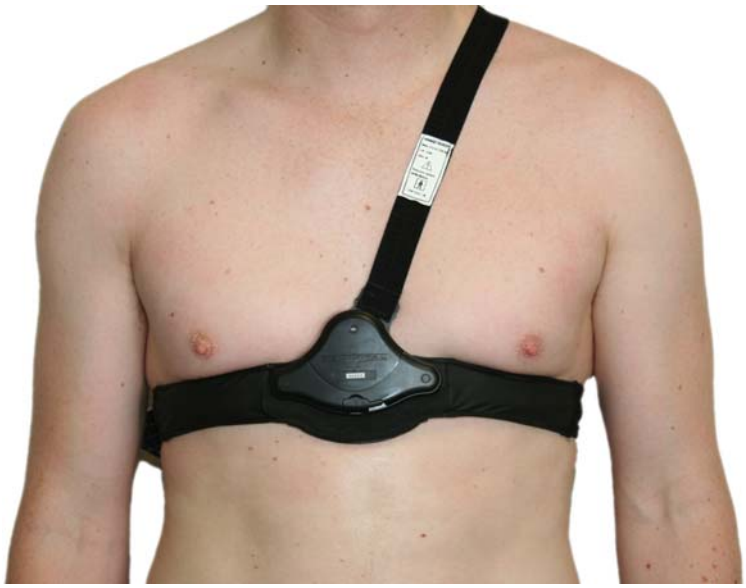

Figure 3-6.2: Vital Sign Detection System (US – WPSM, Hidalgo, Swavesey, Cambridgeshire, UK).

3-6.4.2 Ballistic Impact Detection System

In the current design of the US's WPSM system, an analog acoustic sensor array is used to capture an initial high frequency shock wave and lower frequency skin deformation to identify a ballistic impact. To meet aggressive power requirements, the current Ballistic Impact Detection System (BIDS) (Quasar Inc., San Diego, CA) was designed as an analog-thresholding circuit that only provides a ballistic impact trigger/threshold signal and left, right, or center location information. A more advanced digital BIDS system is under development that will allow the recording of ballistic impact signatures above or close to the impact threshold. Figure 3-6.3 demonstrates the components of the ballistic impact signature used by the analog and digital BIDS.

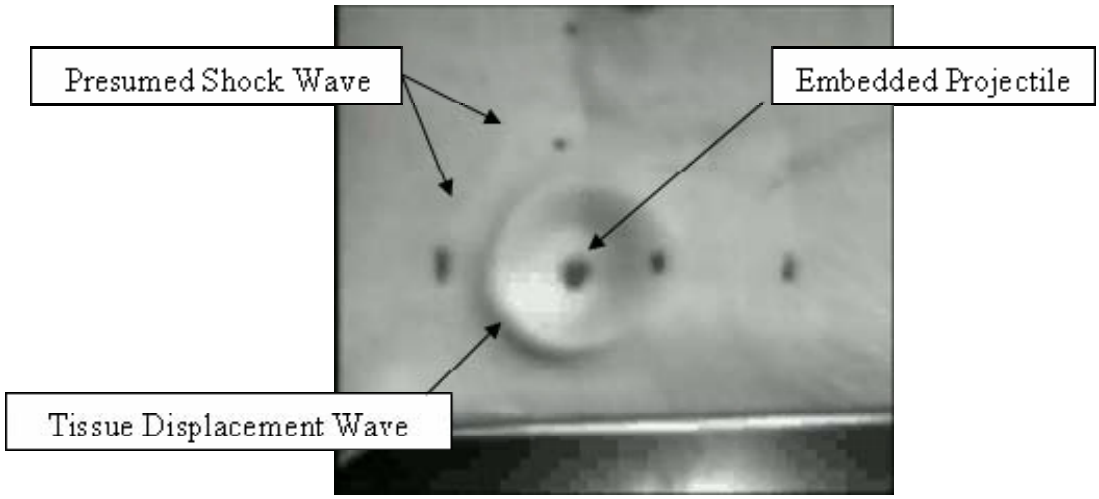

Figure 3-6.3: Ballistic Impact to the Left Lateral Chest of an Animal Model. This image was captured from a high-speed (4500 frames/sec) video recording for a representative animal experiment. The analog voltage response from the sensor elements were digitized at 20,000 samples per second and digitally recorded.

3-6.5 MODELS AND ALGORITHMS

3-6.5.1 Presence or Absence of Vital Signs

The US's WPSM system uses a simple algorithm to determine the presence or absence of vital signs. The algorithm for an expectant casualty is defined as the absence of HR, respiration rate, and activity for more than 5 minutes. The algorithm demands that devices that measure these parameters also conduct a series of self checks to ensure that an absence is truly an absence rather than the device being removed or malfunctioning.

3-6.5.2 Remote Triage Decision Support

Unfortunately, elevated HR (Figure 3-6.1, Panel C) in a wounded Soldier may be impossible to accurately interpret since "fight-or-flight" responses are a natural consequence of battle. This notion is best supported by the observations that the HR of pre-hospital trauma patients who go on to die are not always statistically distinguishable from the HR of patients who survive trauma injury [8], [12]. Thus, other sensor or contextual information may help distinguish wounding from high stress. For example, the BIDS may provide evidence of a ballistic impact on the Soldier; the VSDS (with 3 dimensional accelerometry) will identify if the warfighter has fallen to the ground; and more complex information from ECG measurements such as the addition of the heart period variability to the VSDS may begin to provide future algorithms with the ability to conduct remote triage support. Incorporating some form of cognitive assessment may also help to improve the medics' ability to assess health state. A cognitive assessment could be as simple as the medic calling the warfighter on the radio or initiating a stimulus and response through the VSDS. The VSDS can vibrate in a similar fashion to a mobile phone stimulus, and detect a pattern of taps from the warfighter as a response. Such a cognitive tool would represent a surrogate for the sensitivity and specificity of assessing patient status provided by the motor response of the Glasgow Coma Score (GCS) [13].

3-6.6 THE WAY FORWARD (E.G., REQUIREMENTS FOR THE FUTURE)

3-6.6.1 Remote Physiological Monitoring for Combat Casualty Care

A decreasing heart period variability may provide an early and sensitive indicator of mortality. On the other hand, a decreasing heart period variability can be observed in trauma patients with severe hemorrhage and in individuals who are undergoing physical activity. Therefore, more information is required in order to apply R-R interval variability to remote physiological monitoring of combat casualties. Since GCS motor scores are important indicators of the need for intervention [13], advanced development of remote sensing for combat casualty care will include an algorithm with continuous assessment of heart period variability, an indication of pulse pressure, communication capability between the medic and casualty, body movement, and body position. Figure 3-6.4 depicts such a multi-factor decision-tree algorithm for remote triage [14].

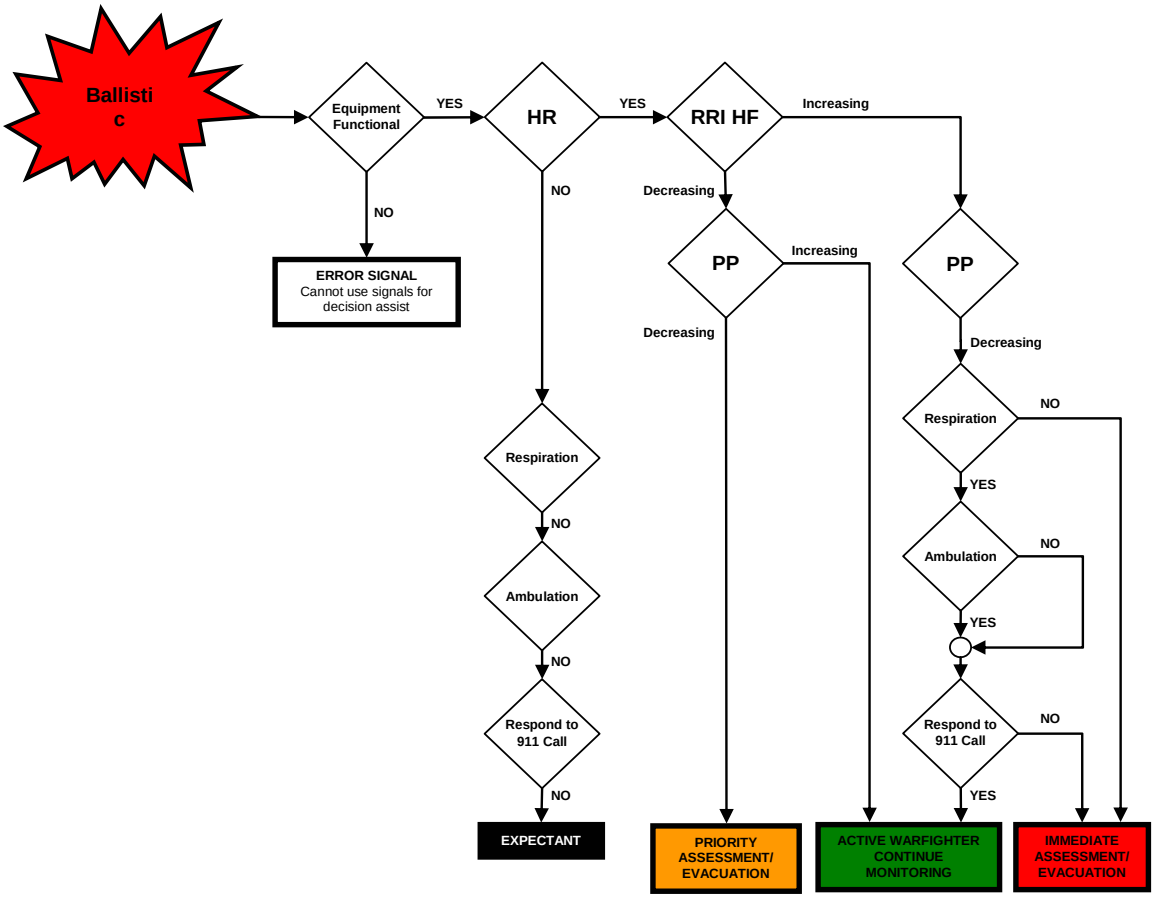

Figure 3-6.4: Schematic Representation of a Decision-Support Algorithm for the Triage of Military Casualties: Injured and Decompensating, Requiring Immediate, High Priority Evacuation; Injured and Compensating Appropriately, Requiring Priority Evacuation; not Injured, no Evacuation Required; or, Expectant, Requiring Very Low Priority Evacuation. HR, heart rate; RRI HR, high frequency RRI variability; PP, pulse pressure. Figure adopted from Rickards et al. [14].

3-6.7 ADVANCED MEDICAL MONITORS FOR EN ROUTE AND IN-HOSPITAL CARE

3-6.7.1 Integration of Derived Vital Signs Currently Available on Standard Monitors

New prototypes of medical monitors with capabilities for calculation of heart period variability, PP, and BRS could provide an important tool for earlier detection of severe blood loss and a requirement for fluid resuscitation during in-hospital care, and a potential component to an algorithm for closed-loop resuscitation during medical evacuation. Perhaps equally important will be future testing and analysis of combined markers such as changes in heart period variability and PP (e.g., ΔPP /ΔHRV) that may provide more sensitive indicators of blood loss in wounded casualties.

3-6.7.2 Continuous Measurement of Arterial Blood Pressure

The current process of combat casualty care can be greatly improved by providing appropriate continuous vital sign observations. New technologies such as infrared photoplethysmography on a peripheral digit (e.g., finger) can provide for non-invasive measurement of continuous arterial BP. The significance of

such technology lies in the observation that loss of central blood volume causes increases in arterial pressure oscillations that cannot be measured with the use of standard medical monitors that require a minimum of 30 seconds to detect systolic and diastolic Korotkoff sounds [5]. Consequently, arterial pressure oscillations increase proportionately to progressive reduction in central blood volume when mean arterial BP can remain unchanged [5]. These patterns suggest that measurement of arterial pressure oscillations with infrared photoplethysmography technology could provide an earlier control input for closed-loop fluid resuscitation currently obtained from standard BP measurements.

3-6.7.3 Measurements for Monitoring Oxygen Delivery

Early recognition of the need for oxygen under conditions of tissue hypoperfusion is widely believed to improve outcome and decrease the progression to multi-system organ failure by virtue of maintaining end-organ perfusion. Routine clinical parameters such as SpO_2, blood pH and blood base deficit [15]-[17] are often late indicators of the true extent of metabolic derangement during hemorrhagic shock [5]. Additionally, pH and base deficit measurements require invasive blood sampling, which provides intermittent rather than continuous monitoring capability and may be accompanied by delays in obtaining test results. Clearly, these measures are inadequate for a truly autonomous closed-loop system. Since muscle oxygen tension (PmO_2) and tissue oxygen saturation (StO_2) decreases during tissue hypoperfusion before changes in tissue and blood pH [18]], PmO_2 and StO_2 were measured using near infrared spectroscopy (NIRS), and compared to standard hemodynamic parameters and SpO_2 in ten healthy human volunteers who were exposed to progressive central hypovolemia [19], [20]. All subjects demonstrated a decline in PmO_2 and SmO_2 that paralleled the progressive reduction in central blood volume, while SBP, and SpO_2, were unchanged until the time of hemodynamic decompensation when SBP decreased precipitously [19], [20]. Both PmO_2 and StO_2 were also inversely correlated with total peripheral resistance suggesting that PmO_2 and StO_2 are early indicators of reduced oxygen delivery through vasoconstriction. Blood pH and base deficit were not altered during the early phases of central blood loss when PmO_2 and StO_2 were decreasing [5]. These results suggest that PmO_2 and StO_2 measurements with NIRS technology added to current monitors could provide an earlier control input for closed-loop oxygen delivery than SpO_2 currently obtained from pulse oximetry.

3-6.7.4 Development of Models and Algorithms for New Sensor (Monitoring) Systems

Realizing the limits of current diagnosis and treatment capabilities on the battlefield, an algorithm that facilitates remote triage, medical evacuation, and in-hospital care of combat casualties is one of the primary objectives of current Combat Casualty Care research. Such a reliably predictive algorithm does not currently exist but is critically needed. Optimal management designed to prevent the onset of circulatory shock requires a recognition and integration of multiple complex physiological responses with varying time courses. Such a capability could be provided with development of computer models and algorithms designed to provide medical personnel with automated trending and decision support software designed to identify the *best early* predictors of impending hemodynamic decompensation. Significant early indicators of hemodynamic decompensation obtained from human experiments will be identified using correlation coefficients, multiple logistic regression, Reed-Muench analysis, Kaplan-Meier survival analysis, cluster analysis, and discriminate analysis to develop multifactorial decision-support algorithms.

3-6.7.5 Device Transition for Battlefield Use

The resulting algorithm for early prediction of hemodynamic decompensation will inherently identify the specificity and frequency of physiologic measures to be used to direct decisions regarding development or identification of new medical monitoring devices or technologies that can be worn by the Soldier or placed in medical transport vehicles or Combat Support Hospitals. For example, a small computer that includes the algorithm could be part of the monitoring system worn by the Soldier. A personal digital assistant (PDA) device carried by battlefield medics could provide a simple visual code (green, yellow, red) of the

Soldier's medical status that can be transmitted via global-positioning satellites. If integrated into the proposed system, combat mortalities could be reduced by enabling medical personnel to:

1) Commence triage within moments after a Soldier is wounded;
2) Receive more accurate information of wound severity and progression to shock; and
3) Optimize available treatment and evacuation.

Since the killed-in-action rate for US battlefield medics has been reported to be as high as double that of infantryman [14], the advanced diagnosis system could be instrumental in reducing battlefield mortality of medics by providing early identification of dead Soldiers.

3-6.8 SUMMARY

A primary objective for improved monitoring in combat casualty care is to develop and demonstrate a semi-automated capability that provides critical information remotely to support trauma triage decisions, and to improve patient management at higher echelons of care. This goal will be accomplished with new sensor systems that provide continuous data acquisition of numerous non-invasive physiological signals (measurements) that provide the basis for new algorithms predictive of clinical outcome and the need for clinical intervention. Not only will this approach be utilized to direct the future of combat casualty care monitoring systems, but they will facilitate rational decisions concerning bandwidth requirements. The resulting algorithm(s) will enhance the diagnosis and acute treatment of hemorrhagic wounds. It is in this manner that our approach will produce an enhanced human capability for advanced diagnosis and treatment of combat casualties and will ultimately be able to improve survivability of combat wounds.

3-6.9 REFERENCES

[1] Bellamy, R.F., (1984). The causes of death in conventional land warfare: Implications for combat casualty care research. Mil Med, 149:55-62.

[2] Zajtchuk, R. and Sullivan, G.R., (1995). Battlefield trauma care: focus on advanced technology. Mil Med, 160:1-7.

[3] Orlinsky, M., Shoemaker, W., Reis, E.D. and Kerstein, M.D., (2001). Current controversies in shock and resuscitation. Surg Clin North Am, 81:1217-1262.

[4] Wo, C.J., Shoemaker, W.C., Appel, P.L., et al., (1993). Unreliability of blood pressure and heart rate to evaluate cardiac output in emergency resuscitation and critical illness. Crit Care Med, 21:218-223.

[5] Convertino, V.A., Ryan, K.L., Rickards, C.A., et al., (2008). Physiological and medical monitoring for en route of combat casualties. J Trauma, 64:S342-353.

[6] Convertino, V.A., Ludwig, D.A. and Cooke, W.H., (2004). Stroke volume and sympathetic responses to lower-body negative pressure reveal new insight into circulatory shock in humans. Auto Neurosci, 111:127-134.

[7] Malliani, A., Pagani, M., Lombardi, F., et al., (1991). Cardiovascular neural regulation explored in the frequency domain. Circulation, 84:482-492.

[8] Cooke, W.H., Salinas, J., Convertino, V.A., et al., (2006). Heart rate variability and its association with mortality in prehospital trauma patients. J Trauma, 60:363-370; discussion 370.

[9] Convertino, V.A., Cooke, W.H. and Holcomb, J.B., (2006). Arterial pulse pressure and its association with reduced stroke volume during progressive central hypovolemia. J Trauma, 61:629-634.

[10] McManus, J.G., Convertino, V.A., Cooke, W.H., et al., (2006). R-wave amplitude in lead II of an electrocardiogram correlates with central hypovolemia in humans. Acad Emerg Med, 13:1003-1010.

[11] Cooke, W.H. and Convertino, V.A., (2005). Heart rate variability and spontaneous baroreflex sequences: implications for autonomic monitoring during hemorrhage. J Trauma, 58:798-805.

[12] Cooke, W.H., Salinas, J., McManus, J.G., et al., (2006). Heart period variability in trauma patients may predict mortality and allow remote triage. Aviat Space Environ Med, 77:1107-1112.

[13] Holcomb, J.B., Niles, S.E., Miller, C.C., et al., (2005). Prehospital physiologic data and lifesaving interventions in trauma patients. Mil Med, 170:7-13.

[14] Rickards, C.A., Romero, S.A., Ryan, K.L., et al., (2008). Combat stress or hemorrhage? Evidence for a decision-assist algorithm for remote triage. Aviat Space Environ Med, 79:670-676.

[15] Martini, W.Z., Chinkes, D.L., Sondeen, J. and Dubick, M.A., (2006). Effects of hemorrhage and lactated Ringer's resuscitation on coagulation and fibrinogen metabolism in swine. Shock, 26:396-401.

[16] Kvarstein, G., Mirtaheri, P. and Tonnessen, T.I., (2003). Detection of organ ischemia during hemorrhagic shock. Acta Anesthesiol Scand, 47:675-686.

[17] Schlinchting, E. and Lyberg, T., (1995). Monitoring of tissue oxygenation in shock: an experimental study in pigs. Crit Care Med, 23:1703-1710.

[18] Soller, B.R., Heard, S.O., Cingo, N.A., et al., (2001). Application of fiberoptic sensors for the study of hepatic dysoxia in swine hemorrhagic shock. Crit Care Med, 29:1438-1444.

[19] Soller, B.R., Ryan, K.L., Rickards, C.A., et al., (2008). Tissue oxygen saturation is not an early indicator of central hypovolemia in humans. Crit Care Med, 36:176-182, 2008.

[20] Soller, B.R., Soyemi, O.O., Yang, Y., et al., (2008). Non-invasively measured muscle oxygen saturation is an early indicator of central hypovolemia in humans. J Appl Physiol 104:475-481.

Chapter 4 – AN EXAMPLE OF A PHYSIOLOGICAL MONITORING SYSTEM (DESCRIPTION OF THE WORK IN THE CZECH REPUBLIC)

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The prototype of the small, lightweight and robust system for monitoring and analyzing, continuously and in real time, the physiological data of the human body is presented. The system intended for the Czech Army is body-worn, non-obtrusive, non-invasive and easy to use. It focuses on complex monitoring of physiological and environmental data of a Soldier during training or combat activity and is supposed to be used mainly for military applications, particularly for monitoring combat casualties.

4.1 INTRODUCTION

In recent years there are several activities in developing mobile, small, lightweight and robust systems for monitoring and analyzing, continuously and in real time, the physiological data of the human body. The system must be body-worn, non-obtrusive, non-invasive and easy to use. It must monitor the vital data of the human body and transmit it in real-time using secure wireless technology. The implication and potential of these wearable health monitoring instruments are widespread (e.g., in aircraft, sport, in-home care, clinical monitoring, cardiac monitoring, patient transport and emergency worker monitoring). Of paramount importance is the use of such devices in military for monitoring combat casualties, which requires the rugged devices capable of daily use in extreme environments, such as temperature, humidity, vibration, radiation and other environmental factors.

4.2 SYSTEM OVERVIEW

In this report the progress in developing above-mentioned systems for monitoring human body physiological data in Czech Republic is disclosed. It is supposed that these systems will be used mainly for military applications, particularly for monitoring the combat casualties.

A prototype of a system for complex monitoring of physiological and environmental data of a Soldier during the training or combat activity is being developed [2], [6]. In addition, the use of the system as a mobile wireless alternative to an intensive care unit in a military mobile hospital in case of large-scale accidents is

taken into consideration. In such a way, all the problems in the health protection of Soldiers and other persons will be solved.

The developed system for monitoring physiological and environmental parameters is called BioSuperVisor. It will make possible the increase of effective utilization of Soldiers in training or combat activities in accordance with their actual health conditions. In addition, it can prevent personal injuries due to overload. The mobile wireless intensive care unit may be used subsequently after an injury of a Soldier or other person. It will increase medical security in the field, particularly by obtaining important personal health status information leading to easier vital function stabilization. The system allows monitoring of the vital functions of the person during transport to the place where medical care is provided. The system is designed to operate in extreme environmental conditions, such as temperature, humidity, vibration, radiation and other environmental factors.

The system will be beneficial in the following situations:

- Monitoring important physiological data [12], [17], [19] of Soldiers during combat or training activities (i.e., heart rate, body temperature, accepted liquid, partial blood gases, pO_2, pCO_2, sleep time).
- Fast localization of places where injured Soldiers are situated.
- Easy and considerate triage of injured Soldiers and their transport from combat field, from trench and building ruins to places where the medical care is provided.
- Stabilization of vital functions and their monitoring during transport to the field hospital.

4.3 MONITORING SYSTEM IN DETAILS

The system intended for the Czech Army is designed as a multifunctional device composed of several components:

- The system for monitoring physiological and environmental values during combat or training activities is called BioSuperVisor.
- The mobile system for advanced monitoring of physiological parameters, applicable in the field, for monitoring during transport and immediately after transport of the injured Soldier. This system is called Mobile wireless intensive care unit (ICU).
- The system for finding the injured Soldiers, their remote triage and transfer.

Technical solution is developed to be complex and consists of connectable modules. The system is easy to service, should not inconvenience the Soldier and is verified to be reliable. Potential disturbances from the environment were carefully analyzed, and solid protection was implemented.

4.3.1 BioSuperVisor – Mobile Wireless Telemetric System

The system is designated for complex monitoring of physiological and environmental data of Soldiers during training or combat activity. System schematics is available in Figure 4-1. The commander has full overview of the physiological data of the Soldier (i.e., actual physical load), environmental data around the person and expected stress level [15], [22], [23], [24]. The simple algorithm for the physical load estimation and stress level estimation is based on composition of four signals [3], [8], [9], [10]: actual heart rate (derived from ECG in real time), body temperature (fast thermometric sensor placed on body, typically in chest belt), body position and body activity (both derived from the accelerometer signals). The algorithm is able to estimate with certain probability the level of the physical and mental load and generate alarms when the individual threshold in any computed parameter is reached. Also long term variations in heart rate are used for the

estimation of the actual sympatho-vagal balance. It is possible visualization of history and trends in all computed parameters for off-line analysis and additional research purposes. Set of these parameters will improve security of the persons on the team; take a preventive measure in case of person overload or body injury. The commander has knowledge of the heart rate, body temperature, body position (lie, stand), body physical activity or other physiological data. Emergency button is available for emergency cases. This system being developed; currently, a functional prototype is being tested in the Czech Army and the Fire Brigade. Figure 4-2 shows screenshot with software description. The whole system package is illustrated in Figure 4-3.

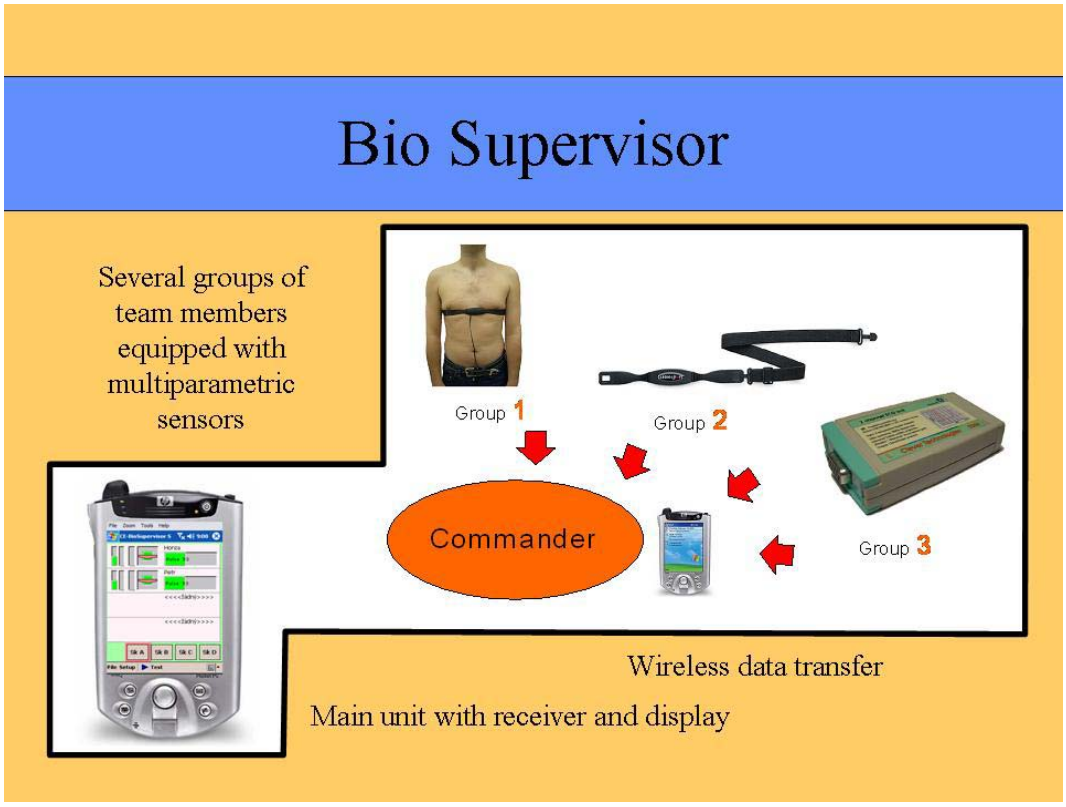

Figure 4-1: System Schematics – Groups of Team Members, Wireless Data Transfer and Main Unit.

Figure 4-2: Detailed View of the Main Unit and Software Features Description.

Figure 4-3: System Package Containing Main Unit, Sensors and Other Accessories.

The system consists of personal units attached to each member of the combat team. The personal unit has input sensors connected to the communication interface. The data are measured and transmitted via secure wireless technology to the central monitoring station. A modern PDA platform is used for maximal mobile and flexible system solution [11], [13], [18]. Connection to the stationary PC or TabletPC for data monitoring is also available. In order to remove artifacts, digital data filtering and processing is implemented. ECG artifacts or EMI distortions are thus reduced. Wearable sensors are going to be developed and implemented. Localization of body injury will then be easily detectable. Localization of the injured person with the help of satellite navigation will be discussed. The system is ready to be certified according to EU standards ISO 9001, ISO 13485, and military standards NATO AQAP 2110, STANAG 4107.

4.3.2 Mobile Wireless ICU

Mobile wireless ICU will be used for injured Soldiers or other person. It will increase medical security in the field, particularly by obtaining important personal health status information leading to easier vital function stabilization. The system allows vital function monitoring during the transport of the injured person and monitoring in the place where medical care is provided. The system is easily transportable and will allow fast installation in the field. Further research activities will probably influence specification of the new sensors.

The patient unit is battery powered and contains wireless interface for data transmitting to the main monitoring unit. This main unit allows for an easy and well-arranged summary of patient data, data trends, and online alarms and data alarm history. Two configurations of the system will be available: First, wireless monitoring of several patients will be possible at one location, and the central unit will be medical PC and will be more rugged. The second configuration of the system may be used for monitoring the injured Soldier during transport. A report including a log of the treatment given during transport will be available.

Mobile ICU is compatible with BioSuperVisor. In certain situations, it will be possible to substitute them.

4.3.3 Remote Triage

This system is in the phase of concept development. The aim is to analyze and classify assumed wound and injuries, possible situations and the environment of the emergency. Means of transport of wounded and injured people will be resolved afterwards. Configuration of necessary tools, instruments and other devices for support during remote triage and transport will be carried out. Methods and relevant tasks will be designed according to specific needs of remote triage.

4.3.4 Mobile Wireless Telemetric System Components

The system consists of several components, as described below. System schematics and body sensor placement is clear from the figure.

Commander Unit:

- Main unit:
  - PDA, Tablet PC, Notebook;
  - SW tool for data processing, data storage;
  - Display real-time data;
  - Physiological data trends;
  - Report, protocol print; and
  - Personalized records.

- Wireless receiver.
- One-look data evaluation.

Soldier Unit:

- Multiparametric sensor:
  - Heart rate, ECG;
  - Body temperature;
  - Body position: lying, standing; and
  - 6Body activity.
- Wireless transmitter;
- Soldier unit may include GPS navigation system and emergency button.

4.4 KEY PHYSIOLOGICAL PARAMETERS TO BE MONITORED

Preliminary sets of parameters, both physiological and environmental, that are to be considered (for example [1], [4], [5], [14], [16]) were selected in field application. The list of parameters follows:

- Electroencephalogram (EEG);
- Electrocardiogram (ECG);
- Electrooculogram (EOG);
- Breath curve;
- Body temperature;
- Myopotentials;
- Blood oxygenation;
- Analysis of breath gasses;
- Galvanic skin resistance;
- Bioimpedance;
- Actigraphy – body physical activity in 3D;
- Glucose blood;
- Biochemical analysis, namely urine; and
- Environmental temperature, illumination, pressure, noise, atmospheric gases analysis.

When selecting applications, several conditions need to be considered:

- Several attributes to keep in mind: “One touch button control,” “Plug and Play,” and “Absolutely Idiot Proof.” No further detailed setting in the field and during application is possible.
- Easy sensor application. Sensor has to be resistant to technical and movement artifacts.
- Non-invasivity of the measuring method. Sensor may not disturb Soldier’s body and may not limit his movements and combat activities.
- Signal has to be diagnostically applicable and robust from artifacts caused by field environment.

- High importance of diagnostic information. Selected parameters and computed trends need to be precise and need to specify the vital and psycho-physiological state of the monitored person.
- Signal evaluation needs to be automated and transparent. Continuous and reproducible measurement needs to be applied to display even the fast variations of psycho-physiological status.

4.4.1 Current Sensors

When applying selected criteria from Section 4 and on the basis of the know-how in biological signal processing in the field environment, the sensors and parameters to be monitored can be reduced. In actuality, field conditions are implemented in only several sensors and parameters: ECG, heart rate, body temperature and actigraphy. Sensors are placed in the chest belt.

4.4.2 Physiological Assessment

Prototype of the system allows continual monitoring of the parameters listed in Section 4.1. In the main unit the evaluation of data [7], [20], [21] is carried out by real-time processing, and signals are distinguished as follows:

- Vital functions monitoring of the person – ECG, heart rate, breath curve;
- Psycho-physiological state of monitored person – heart rate, symphatovagal balance based on HR analysis; and
- Body physical load estimation – 3D actigraphy, body movements and body position monitoring, intensity of movement.

4.5 RESULTS AND SUGGESTIONS FOR FURTHER WORK

The technology platform has been developed, and first field trials have been performed. The system will be modified according to the experience gained from the collected data. It is required to modify parameters of the sensors, algorithms and SW tools in order to comply with the suggested extensions. Selection of key physiological parameters for the system was carried out, based on know-how, experience, and consultations with field teams, with respect to criteria presented in Section 4. The first prototype of the sensor met only the parameters described in Section 4.2, and the following significant parameters should be included in the future:

- Myopotentials;
- Blood oxygenation;
- Bioimpedance;
- Galvanic skin resistance; and
- Environmental temperature, illumination, gas pressure, noise, atmospheric gases analysis.

Further parameters to be monitored will be taken into account. We hope that the biochemical sensors based on bio-nanotechnology will bring further improvement. The system is designed to be modular for connection of further sensor modules.

4.6 SUMMARY

Commander or Medic Require:

- Real-time physiological status of the Soldier;
- Ready state information about the Soldier;

- Health status monitoring;
- Prevention or reduction casualties;
- Rapid identification and decision on the battlefield;
- Status of the Soldier with respect for the security of the Soldier's team;
- Effective coordination of the action;
- Monitoring the level of Soldier stress due to the training or other stimulus; and
- Monitoring of the reaction speed of the team member in a defined situation.

BioSuperVisor System Provides:

- Remote monitoring of personnel status via several sensors attached to a Soldier;
- Sensors communicate with a Soldier unit; the unit processes the information and communicates wirelessly with the remote monitor;
- Life-sign detection based on measurements of heart rate and body activity, body orientation, body temperature;
- Lightweight design;
- Information on fitness for duty and real-time probabilities of judgment and decision-making;
- Information about stressful environment;
- Status monitoring during performance of critical missions;
- Thresholds can be set to trigger a yellow or red alert on selected monitored parameters;
- Ability to monitor Soldier sleep status – activity monitoring to measure the number of hours of sleep; and
- Easy one-look data and trend evaluation.

Basic modules of the measuring system were tested with hopeful results. Further development is going to be oriented to the following areas:

- Optimalization of sensor hardware for field conditions; certification of device according to European and NATO standards.
- Design and adaptation of methods for system implementation; modification of the method, according to Army legislative regulations.
- Improvement of system ergonomics; improvement of sensor design; advanced field trials.
- Implementation of interoperability with existing military systems. Integration of wireless interface into the military communication system, together with data security.
- Optimalization of communication algorithms and tools that facilitate decision making. This will ensure robust data processing, automatic and semi-automatic evaluation of the Soldiers, and state classification. This is an important and key feature of the system that will increase system utilization.

All the steps mentioned before are expensive and time consuming, but real implementation of such a system is going to be an important part of modern military application.

4.7 REFERENCES

[1] Ahuja, N.D., Agarwal, A.K., Mahajan, N.M., Mehta, N.H. and Kapadia, H.N., GSR and HRV – its application in clinical diagnosis. Computer-Based Medical Systems, 2003 Proceedings of the 16th IEEE Symposium, 26-27 June 2003: 279-283.

[2] Bittner, R., Smrcka, P., Vysoky, P., Hana, K., Pousek, L. and Schreib, P., Detecting of fatigue states of a car driver. 1st international symposium on medical data analysis, ISMDA 2000, Springer Verlag, Berlin Heidelberg 2000, ISBN 3-540-41089-9: 260-273.

[3] Dosel, P., Hanousek, J., Petricek, J., Cmiral, J. and Cettl, L., Testing method of plus and minus Gz tolerance at Czech Air Force pilots. Journal of Gravitational Physiology, 11, 2004, 2, ISSN 1077-9248: 239-240.

[4] Fowles, D.C. and Christie, J., et al., Recommendations for electrodermal measurements. Journal of Psychophysiology. 18 (1981): 232-239.

[5] Gang, Y. and Malik, Heart rate variability analysis in general medicine. Indian Pacing Electrophysiol. Journal, 2003; 3(1):34.

[6] Hana, K., Fiala, R., Kaspar, J., Smrcka, P. and Brada, J., Modular measuring system "ADVANCED PDA" designated for support of the medical and biomedical engineering research. Proceedings of the 3rd European Medical & Biological Engineering Conference EMBEC'05 & IFMBE, Prague 2005, ISSN 1727-1983: 2101/1-6.

[7] Hana, K., Smrcka, P., Kaspar, J. and Fiala, R., Software component for GSR processing. [Technical report, Authorized software]. Prague: CTU in Prague, Faculty of biomedical engineering, 2007.

[8] Hanousek, J., Petricek, J., Cmiral, J. and Dosel, P., Cockpit physiological signal acquisition system. Proceedings of the 14th international conference BIOSIGNAL '98, Brno 1998, ISSN 1211-412X, ISBN 80-214-1169-4: 148-150.

[9] Hanousek, J., Petricek, J., Cmiral, J. and Dosel, P., Comparison of Pilot's Physiological Responses to the LBNP, Flight and Centrifuge Load. Proceedings of the European Medical & Biological Engineering Conference, Vienna 1999, ISSN 01400118: I/458-459.

[10] Hanousek, J., Dosel, P., Cmiral, J., Petricek, J. and Cettl, L., Pilot's physiological measurement in plus and minus Gz load changes. Proceedings of the 2nd European Medical & Biological Engineering Conference, Vienna 2002, ISSN 1680-0737, ISBN 3-901351-62-0: II/1298-1299.

[11] Jaap, C., et al., Bluetooth – a new low power radio interface providing short-range connectivity. Proceedings of the IEEE, Vol.88: 1651-1661.

[12] Kneppo, P., Rosik, V., Tysler, M., Karas, S., Hana, K., Smrcka, P. and Juleny, A., High resolution ECG mapping system for non-invasive cardiac diagnostics. Proceedings of the World Congress on Medical Physics and Biomedical Engineering 2006, Seoul, 2006, Springer-Verlag Berlin Heildelberg 2006, ISSN 1727-1983, ISBN 3-540-36839-6: 3371/1-4.

[13] Led, S., Serrano, L. and Galarraga, M., Wearable wireless monitoring system based on Bluetooth technology. Proceedings of the 3rd European Medical & Biological Engineering Conference EMBEC'05 & IFMBE, Prague 2005, ISSN 1727-1983: 1619/1-6.

[14] Madden, K. and Savard, G.K., Effects of mental state on heart rate and blood pressure variability in men and women, Clin Physiol. 1995, 15(6): 557-569.

[15] Malik, et al., Heart rate variability – standards of measurement, physiological interpretation and clinical use. European Heart Journal, 19: 354-381.

[16] Nishida, Y., and Hori, T., Non-invasive and unrestrained monitoring of human respiratory system by sensorized environment. Proceedings of the 1st IEEE international Conference on Sensors (Sensor 2002), 2002: 62.4/1-6).

[17] Patil, A.A. and Patil, A.G., Wireless R-R interval data acquisition and analysis system for study of heart rate variability. Proceedings of the 3rd WACBE World Congress on Bioengineering 2007, Bangkok, Thailand, 2007, Biomedical Engineering Society, Singapore 2007, ISBN 978-81-904262-8-2: 5.2-2/1-4.

[18] Ping, F., et al., Towards e-health with integrated wearable telemetric system for cardio-pulmonary signal measurement. Proceedings of the 3rd WACBE World Congress on Bioengineering 2007, Bangkok, Thailand, 2007, Biomedical Engineering Society, Singapore 2007, ISBN 978-81-904262-8-2: 10.4-3/1-4.

[19] Smrcka, P., Hana, K., Kaspar, J., Brada, R. and Fiala, R., Multifractal analysis of heart rate variability in sleep deprivation and alcohol intoxication. Proceedings of the 3rd European Medical & Biological Engineering Conference EMBEC'05 & IFMBE, Prague 2005, ISSN 1727-1983: 2120/1-6.

[20] Smrcka, P., Hana, K., Kaspar, J., Fiala, R. and Brada, J., Software for HRV computing (WinXP/ Linux platform). [Technical report, Authorized software]. Prague: CTU in Prague, Faculty of biomedical engineering, 2007.

[21] Smrcka, P., Hana, K., Kaspar, J. and Fiala, R., Software component for processing and evaluation of breath signal. [Technical report, Authorized software]. Prague: CTU in Prague, Faculty of biomedical engineering, 2007.

[22] Tikkanen, et al., Characterization and application of analysis methods for ECG and time interval variability data. [Research report]. Faculty of Physical Science, Division of Biophysics, University of Oulu, 2000.

[23] Zefferino, R., et al., Assessment of heart rate variability (HRV) as a stress index in an emergency team of urban police. G. Ital. Med. Lav. Ergon. 2003, 25 Suppl(3):167-169.

[24] Zhai, J. and Barreto, A., Stress detection in computer users through non-invasive monitoring of physiological signals. Electrical and Computer Engineering Department, Biomedical Engineering Department; Florida International University.

Chapter 5 – CONCLUSIONS AND RECOMMENDATIONS

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Ambulatory physiological monitoring technologies are being actively developed for a wide variety of applications, including commercial products for sports (e.g., heart rate monitors), clinical products to assess and manage patients (e.g., Holter monitors, external or implantable cardiac monitors, sleep apnea system), research tools to capture data for post hoc analysis (e.g., recording pedometers, accelerometer-based activity monitors), and technologies to monitor Soldiers.

Commercial chest sensor systems come in a variety of forms, from simple commercial heart rate monitors (e.g., Polar, Finland), to electro-textile sensor-shirts (e.g., Watchdog Tactical Vest, http://www.fostermiller.com/literature/documents/DS07-023-WatchdogTactical.pdf Foster-Miller, Waltham, MA), to multi-sensor chest belts (e.g., Bioharness, http://www.zephyrtech.co.nz/products/professional/bioharness, Zephyr, Auckland) and FDA-certified medical-grade thoracic sensor systems (e.g., Equivital, Hidalgo Ltd., Cambridge, UK; http://www.hidalgo.co.uk/toplevel.htm?whatwedo_equivital.htm). The Hidalgo chest sensor system measures electrocardiogram and heart rate, respiration rate, core body temperature (via radio thermometer pill), chest skin temperature, body orientation and activity patterns. These latter two systems illustrate the trend towards having multiple sensors housed at a given sensor location on the body. These types of systems can be used to assess human physiological status (e.g., thermal-work strain, activity/inactivity, and vital sign detection). This information can be stored for later analysis, or transmitted off-body for combat casualty care remote monitoring, work/rest management or safety oversight of personnel engaged in higher risk activities.

Monitoring the physiological status of a Soldier is particularly challenging from both a scientific and technological point of view. Systems must be scalable and readily adapt to new requirements and applications related to mission preparation (e.g., physical training, mission planning), mission support (e.g., thermal strain monitoring and management; hydration management; sleep management; casualty care including life sign detection, remote triage), and after mission review. Environmental conditions are often extreme (heat, cold, water, dust, vibration/shock); the ability to recharge or replace batteries can be limited; system volume, weight, power requirements, and cost must be minimized; and all body-worn technologies must be acceptable to the individual Soldier. Making sense of the physiological data collected from the wearable system may require synthesis with other data types such as geo-location and environmental data (e.g., weather). Models and algorithms are needed to predict physiological status and provide some metric of statistical confidence. Finally, the data management and data communication challenges are significant, given the prevalence of motion artifact, intermittent connectivity, and the difficulty in designing effective graphical user interfaces (information displays).

The authors of this report have reviewed their varied experiences and approaches to meeting many of these challenges. Mr. Buller provided an overview of typical physiological monitoring system architectures from both hardware and software points of view. The discussion touched on various issues including methods for managing artifacts in sensor data, extracting thresholds, trends and features from data streams, applying algorithms and models to the data, and defining physiological state with an accompanying metric of data confidence. The chapter by Dr. Gunga reviewed thermal strain assessment methodologies, including the innovative “double sensor” for estimating core temperature [1]. Although body core temperature (Tcore) is obviously an important physiological parameter, measuring Tcore with

radio pills is expensive (~$50/pill). A less precise but non-invasive and inexpensive way to estimate core temperature is the "double sensor" [1]. The double sensor estimates core temperature from skin temperature and heat flux. Estimating thermal state using surrogate measures of Tcore, such as those provided by the double sensor algorithms, will continue to be challenging in that the Tcore estimates may be accurate on average (i.e., at a small group level), but may not always provide sufficiently precise estimates of thermal state for individuals.

Dr. Nevola provided a broad review of human hydration, including the importance and physiology of hydration, the consequences of under- and over-hydration, and markers and methods of assessing hydration state. He culminated with the vision of sensors capable of measuring muscle hydration directly. Hydration requirements, both in terms of sensors and algorithms, is an area where work remains to be done. Practical ambulatory methods of estimating tissue hydration are not yet available. Methods of estimating fluid intake using flow estimations of consumption (e.g., Hydracoach, http://www.sportline.com/hydracoach.php) are potentially useful, but making such measurements reliable can be difficult due to technical issues such as imprecise or unreliable turbine sensors. Furthermore, knowing fluid intake alone is insufficient when one has no estimate of sweat output or the adequacy of urine output. This leads to the use of predictive models, such as the empirical heat strain decision aid (HSDA) [2], providing a more systematic basis for estimating water requirements. However, more accurate and precise rational, first-principles models are needed to make these predictions.

Dr. Ledderhos has provided a practical discussion of altitude illness, from Acute Mountain Sickness (AMS) to High Altitude Pulmonary and cerebral edema (HAPE/HACE). In addition, a review of the value, applications, and limitations of oximetry in detecting disturbances of acclimatization to high altitudes were discussed, as well as the possibility of near real-time monitoring of acclimatization status under operational conditions at high altitude.

Dr. Valk reviewed the importance of sleep, and how circadian disruptions and sleep deprivation can lead to physical and mental fatigue and degraded cognitive performance. He also discussed the various methodologies for assessing sleep status (EEG, electroencephalography; EOG, electrooculography; EMG, electromyography; actigraphy). Wrist actigraphy has classically been used to estimate apparent sleep (i.e., activity/inactivity patterns). Existing systems store data for post hoc analysis, a time consuming process. New systems are envisioned where data streams wirelessly with on-the-fly analysis and presentation over mobile ad hoc data networks. From an algorithmic point of view, the state of technical readiness or maturity varies by the area of interest. For example, sleep performance modeling [3] is at a point where the models provide the apparent equivalent of "subject matter expertise" to be used to optimize mission and work schedule planning. However, the reliability and generalizability of these predictive models is not known [4]. Dr. Varoneckas reviewed the relationship of heart rate variability and fatigue, focusing on how heart rate variability might be used to assess human states during sleep-wake cycles.

Dr. Convertino reviewed the use of ambulatory physiologic monitoring for combat casualty care, and described plans to develop improved algorithms that will enable medics to clinically assess wounded Soldiers. A long-standing dream of those engaged in combat casualty care is remote vital signs detection. The technical challenges are complex. For example, advanced triage using ECG features such as R-to-R intervals is complex and has implementation issues in real time associated with performing Fast Fourier transforms on a Micro Processor, and collecting ECG data where very accurate inter-beat intervals can be determined with no over- or under-counting of beats. An additional and significant challenge is making a vital signs detection system that is light and unobtrusive enough, or has other utility, such that Soldiers would routinely wear the system. Current systems are too obtrusive for continuous monitoring to be practical.

Finally, Mr. Smrcka and co-workers provided an example of an integrated prototype physiological monitoring system that can be used to monitor and analyze real-time physiological responses of military

personnel. Complete end-to-end systems, such as the example from the Czechs, have been demonstrated with limited success. Another complete system is the Land Warrior system, which incorporates the Warfighter Physiological Status Monitoring system. A lower technical readiness level naturally accompanies efforts to develop complete systems. For example, the U.S. Land Warrior often relies on sensor communication via hard-wired cable connections to avoid the issues of wireless links broadcasting their position.

In conclusion, real-time ambulatory physiological and psycho-physiological status monitoring has been demonstrated for a number of health state indicators. Technology maturity and the ability to move that technology to an operational setting is dependent upon the health state area. While miniature low power sensor technology has made great strides in recent years, the dearth in high resolution data in operational settings has made the validation and development of real-time state algorithms challenging. By combining the emerging sensor systems with both rational and empirical models, on-the-fly health state determinations will be possible. For true remote monitoring, tactical radios or beacons need to be issued to each warfighter to allow health state information to be passed to medics, the commander, or other critical personnel.

5.1 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

1) Progress towards a real-time physiological status monitoring system for military personnel has come from identifying the minimal requirements for a system, recognizing that each group of Soldiers has unique needs, and maintaining flexibility by utilizing technologic approaches that can easily be adapted to meet new needs.

2) Future research might explore ways to maintain the data security without imposing overly heavy encryption requirements on lightweight wearable systems. Information that is only transiently sensitive could be secured with lighter weight methods than would otherwise be needed, avoiding burdensome encryption techniques that can disable wearable systems. To date, most of the research with physiological monitoring has focused on the health of the warfighter, whether for use in combat casualty care or in preventing illnesses and injuries. Future research may focus more attention on providing the commander with information regarding warfighters' readiness to fight based on real-time continuous ambulatory physiological and psycho-physiological measurements.

3) Establish practical test-bed venues, such as those offered by military training sites, to develop, acquire, test, and validate new ambulatory physiological monitoring sensor systems. These venues can offer realistic point of insertion for new technologies by allowing the use of commercial off-the-shelf (COTS) radios to transmit data, and by offering structured training routines and the opportunity to gather important contextual information (i.e., subject, clothing, mission, geo-location, meteorological characteristics). Ensure that comprehensive data sets are collected that can be used for predictive modeling. Use a modular technical architecture so the removal of old technologies and the integration of new sensors and algorithms can be done with minimal disruption. Establish databases that can be used to develop and test new predictive algorithms. Validate new algorithms against new data sets collected during rigorous training missions in different environments requiring varied protective clothing ensembles. Leverage international partnerships by sharing data, overcoming the combinatorial explosion of conditions that makes it impractical for one nation to run experiments on every combination of conditions.

5.2 REFERENCES

[1] Gunga, H.C., Sandsund, M., Reinertsen, R.E., Sattler, F. and Koch, J., (2008). A non-invasive device to continuously determine heat strain in humans. J Therm Biol, 33:297-307.

[2] Matthew, W.T., Berglund, L.G., Santee, W.R. and Gonzalez, R.R., (2003). USARIEM Heat Strain Model: New Algorithms Incorporating Effect of High Terrestrial Altitude. USARIEM, Natick, MA, Technical Report T03-9.

[3] Proceedings of the Fatigue and Performance Modeling Workshop, June 13-14, 2002, Seattle, WA (2004). Aviat Space Environ Med, March, 75 (Suppl. 1, March 2004), A1-A199. http://www.ingentaconnect.com/content/asma/asem/2004/00000075/a00103s1.

[4] Friedl, K.E., Mallis, M.M., Ahlers, S.T., Popkin, S.M. and Larkin, W., (2004), Research requirements for operational decision-making using models of fatigue and performance. Aviat Space Environ Med, 75 (Suppl. 1, March 2004):A192-9.

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14. Abstract

Dismounted warfighting groups are increasingly recognizing the benefits of knowing the medical status information that body-worn computerized physiological sensor systems can provide. This report on real-time physiological and psycho-physiological status monitoring reviews: a) Physiological monitoring system architectures, methods for managing noisy sensor data, and algorithms and models used to define physiological state; b) Thermal strain assessment methodologies, including an innovative method for estimating core temperature; c) Human hydration, and markers and methods of assessing hydration state; d) Altitude illness, from Acute Mountain Sickness (AMS) to High Altitude Pulmonary and Cerebral Edema (HAPE/HACE), and the possibility of monitoring acclimatization status under operational conditions at high altitude; e) Sleep, and how circadian disruptions and sleep deprivation can lead to physical and mental fatigue and degraded cognitive performance; f) The relationship of heart rate variability and fatigue; and g) The use of ambulatory physiologic monitoring for combat casualty care. In addition, a prototype physiological monitoring system is described. Future research should: i) Explore simple data security methods suited to lightweight wearable systems; ii) Focus on practical militarily-relevant applications of ambulatory physiological and cognitive state measurements; and iii) Seek to establish practical test-bed venues to develop new ambulatory physiological monitoring capabilities.

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