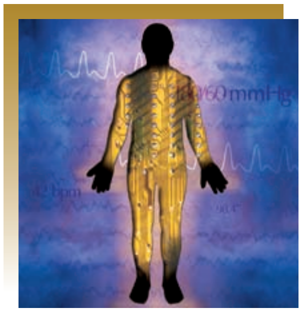

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# Stress Monitoring Using a Distributed Wireless Intelligent Sensor System

## Quantifying Stress Levels Based on Measures of Heart-Rate Variability (HRV) Using Reliable, High-Precision Instrumentation and Synchronized Measurements

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Because stress is a leading cause of illness and disease and is so pervasive, there is an inherent need to be able to monitor stress in real time over extended periods. A real-time personal stress monitor would benefit individuals by providing continuous feedback about their stress levels and by helping their physicians to objectively evaluate stress exposure between visits.

We are developing personal health monitors based on a wireless body area network (BAN) of intelligent sensors [1]. Individual monitors will be integrated into a distributed wireless system for synchronized monitoring of a group of subjects. This system could be used during the selection process and as part of a psychophysiological evaluation of military members undergoing intense training. We use measures of heart-rate variability (HRV) to quantify stress level prior to and during training as well as to predict stress resistance. This task requires reliable, high-precision instrumentation and synchronized measurements from a group of individuals over prolonged periods (days of training).

Our preliminary results indicate that individuals who have better stress tolerance also exhibit significantly different patterns of HRV, both before and during stress exposure. These baseline differences in HRV are predictive of actual military and cognitive neuropsychological test performance scores assessed during and after stress exposure [1], [2]. During our preliminary investigations, we used a stressful component of aviation water survival training, the 9D5 Multi-place Underwater Egress Trainer, as our event for the whole group. The 9D5 is a reasonably realistic representation of a helicopter conducting an emergency landing, turning upside down, and sinking. Trainees report the 9D5 session as the most stressful training event during water survival training.

### Wireless Personal Monitors

Traditionally, personal medical monitors have been used only to perform data acquisition. Typical examples are holter monitors that are routinely used for ECG and EEG monitoring. Recent developments of wireless and mobile technology [3] have laid a foundation for the new generation of wireless intelligent sensors [4], [5]. This same technology has made the implementation of intelligent medical monitors that can provide real-time feedback to the patient feasible, either as a warning of impending medical emergency or as a monitoring aid during exercise. Intelligent medical monitors can significantly decrease the number of hospitalizations and nursing visits [6] by acting as a personal "guardian angel" that can warn the user of a medical emergency or contact a specialized medical response service.

Historically, the development of patient monitors has been progressing toward larger patient mobility and physiological sensor independence. The first step involved connecting monitoring equipment to the hospital information system (HIS) to support data acquisition and archiving. With wider acceptance of the Internet, the HIS was connected to the Internet, paving the way for telemedical health applications. This step allowed remote access to the personal medical record (PMR) stored on a remote telemedical server. Patient mobility within the hospital became possible with the introduction of wireless local area network (LAN) connectivity between patient monitors and static gateways to the HIS. However, in this type of system, individual sensors are still wired to the personal monitor using a BAN. A wearable health-monitoring device using a personal area network (PAN) or BAN can be integrated into a user's clothing [7], [8]. This system organization, however, is unsuitable for lengthy, continuous monitoring, particularly during normal activity, such as intensive training or computer-assisted rehabilitation [9]. On a larger scale, wireless wide area network (WAN) connectivity allows patient monitoring outside the hospital using satellite and cell phone links.

The most recent step in patient mobility and unobstructed use came with the introduction of intelligent and implanted sensors. Wired sensor connections are a huge obstacle to the wide acceptance of these systems for prolonged monitoring. Technological advances in low power microprocessors/microcontrollers, application-specific integrated circuits (ASICs), battery capacity, and wireless technology made possible the increased intelligence of personal health monitors. As a result, wireless connectivity of individual intelligent sensors has emerged as the main research trend. This type of system features extremely low power consumption at the expense of lower communication range and bandwidth. Ultimate examples include implanted sensors and drug pumps, where battery recharging or replacement is very limited or impossible.

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**We are developing a distributed wireless system to evaluate stress resistance during stressful training using synchronized measurements of HRV within the monitored group.**

Therefore, it is necessary to enable multiyear functionality or power the sensors externally.

There is a number of active research and commercial projects in the field of portable monitoring. A typical research project is *Warfighter Physiological Status Monitoring (WPSM)*, led by the U.S. Army Research Institute of Environmental Medicine (USARIEM) and the U.S. Army Medical Research and Materiel Command (USAMMRC) [10]. This experimental prototype consists of sensors for heart rate, metabolic energy cost of walking, core and skin temperatures, GPS location, and activity/inactivity. One of the goals of the project is to provide medics with valuable information about wounded soldiers, but the final system is expected to be able to predict the critical aspects of performance under extreme conditions. Scientists at the d'Arbeloff Laboratory for Information Systems and Technology at MIT have developed a "ring sensor" that continuously monitors heartbeat rate using a photoplethysmograph (PPG) signal and sends data wirelessly to a host computer [11]. Researchers at Kansas State University are developing a wearable, Bluetooth-enabled portable health monitoring system [12]. The overall goal of this initiative is to provide affordable systems by utilizing plug-and-play sensor units that comply with the common industry standard. Commercial systems include *Digital Angel*, which is designed to provide phone and e-mail alerts whenever a person changes condition or position, and the *Symphony Diabetes Management System,* from Sontra Medical Corporation, which performs continuous noninvasive sensing of glucose and other analyses.

Implantable sensors could solve many problems in the monitoring of chronically ill patients, such as diabetic patients [13]. Design of intelligent implanted sensors must take into account a number of different considerations, such as size, power consumption, and power-efficient wireless communication. The choice of a communication frequency will dictate the size of the antenna and hence the overall size of the sensor system. In addi-

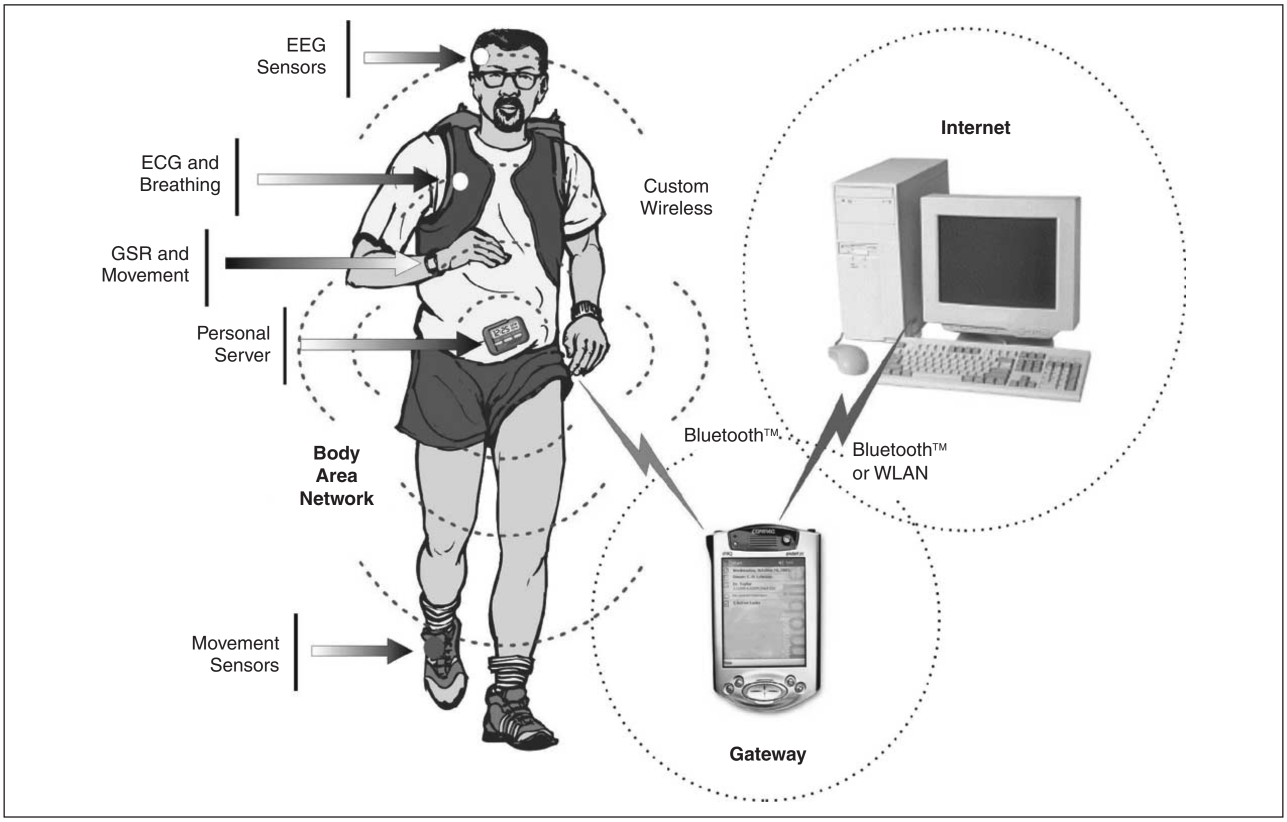


**Fig. 1.** Wireless body area network of intelligent sensors in the telemedical environment.

**Wireless intelligent sensors have made possible a new generation of noninvasive, unobtrusive personal medical monitors applicable during normal activity.**

tion, reliable transfer of data from the implanted sensors is one of the most important tasks researchers are facing.

Other ongoing projects/systems include a miniature implantable microcomputer developed by researchers from the University of Washington, Caltech, and Case Western Reserve University [14]. This sensor is capable of recording nerve and muscle signals from animals during their normal activity. Researchers at the Center for Wireless Integrated Microsystems at the University of Michigan developed the BiCMOS wireless stimulator chip [15] that will be used in conjunction with micromachined passive stimulating microprobes. Given Imaging offers a commercially available endoscopy system, the *Given Diagnostic System*, which uses a disposable imaging capsule (M2A, 11×26 mm) that passes through the gastrointestinal tract and wirelessly streams video images to the receiver that is worn on a belt. The signal is received through an array of antennas, which are also used to determine the exact location of the capsule.

Researchers at the Biomechanics-Laboratory of the Orthopaedic Hospital of the Free University of Berlin developed an inductively powered implantable device that measures hip joint forces and temperatures for the hip joint prosthesis [16].

## Wireless BAN of Intelligent Sensors (WISE)

We have integrated a BAN of wireless intelligent sensors (WISE) as a development environment for research in the field of mobile health monitoring applications [17]-[19], represented in Figure 1. WISE are microcontroller-based, intelligent physiological sensors that are responsible for data acquisition and low-level real-time signal processing tasks. Our BAN is organized as a client-server network with a single personal server (PS) and multiple WISE clients. It is a part of a telemedical system for hierarchical signal processing [20]. Individual WISE sensors are controlled by, and communicate with, the PS using a custom wireless protocol [21]. In addition to its responsibilities as a communication server, the PS also provides synergy of information through data aggregation and higher-level signal processing. For example, accelerometer-based movement sensors [17], [22] could provide the information of user activity in the case of increased heart-beat rate or changes in ST segment morphology for monitors of silent myocardical ischemia [23].

We are introducing the concept of a mobile gateway (MOGUL) to reduce power consumption of the wireless transceiver on the PS and to avoid the need to interrupt normal user activities when uploading data [1], [2]. MOGUL is a PDA-based device that can establish wireless communication with a personal server and download collected data. Because the new generation of PDA devices has significant processing capabilities, they could also be used for high-level processing. Connection between the PS and MOGUL is naturally implemented using a standard wireless PAN technology, such as Bluetooth. However, we still use standard 900 MHz RF modules because the available Bluetooth technology requires three to five times greater power consumption. In addition, we reduce power consumption by using a custom, power-efficient communication protocol [21].

Finally, the highest level of hierarchy in our architecture is the telemedical workstation on the Internet. Connection between the MOGUL gateway and the Internet is implemented using Bluetooth, IEEE 802.11, IR, or a USB via cradle. The telemedical workstation is responsible for long-term analysis of physiological signals, data presentation, and archiving.

The core of our wireless intelligent sensor (WISE) consists of a low-power Texas Instruments microcontroller (MPS430F149). The controller features a 16-bit architecture, ultra-low power consumption (less than 1 mA in active mode and ~1 µA in standby mode), 60-KB on-chip flash memory, 2-KB RAM, 12-bit A/D converter, and dual UART. Internal microcontroller analog channels monitor battery voltage and temperature. Therefore, WISE is capable of reporting the battery status and temperature to the upper level in the system hierarchy.

We developed WISE sensors for ECG/EEG monitoring [1], [2], [17], [18], portable computer-assisted physical rehabilitation [24], prolonged monitoring of breathing [19], and future generation human-computer interfaces [25] with possible applications to affective computing [26]. Our experience with system development indicates that the largest obstacle to wide acceptance and convenience of its use is the physical imple-

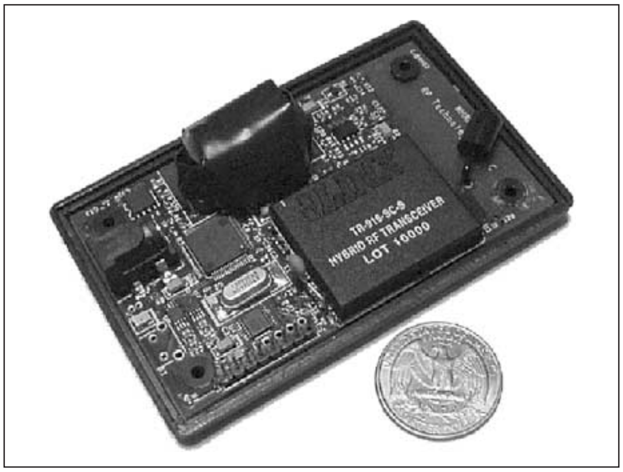


**Fig. 2.** Wireless heart rate monitor (WHRM).

mentation of physiological sensors. For example, initially we used standard wet electrodes for the ECG sensor. The result was excellent signal quality and relative immunity to noise and movement artifacts. However, this approach is not applicable for intensive training, particularly during prolonged monitoring. Fortunately, a new generation of recreational heart-monitoring devices, such as Polar [27], offers a wireless link between the HRV sensor in the chest belt and a watch-type data acquisition unit. This type of device is very convenient for heart monitoring during normal activity, exercise, and training. Therefore, we decided to use the Polar sensor for our HRV monitoring device. Because the Polar data acquisition device supports only an IR interface and has limited storage, we developed a custom data acquisition device that could be integrated into a wireless PAN of intelligent sensors.

We had to slightly change the architecture of our BAN network for this particular project. Because we are using an off-the-shelf heart-monitoring sensor (Polar chest belt), we had to separate sensing from processing. Thus, we created a WHRM monitoring device that serves as a PS and wirelessly communicates with the HRV sensor (Figure 2). The wireless heart monitor device has been developed in collaboration with *RP* Technologies (Huntsville, Alabama).

To keep the system power consumption low and to increase security, we are purposely designing our system to use short-range communication. Increased device intelligence allows data compression and transmission of results only, avoiding continuous signal transmission that is the characteristic of most telemetric systems. This is particularly important in the case of sensor networks. Without the sensor intelligence, the system must have multiple communication channels, or employ complex transmission protocols with collision control mechanisms. Another important design issue is the protection from eavesdropping [28]. Our sensors are able to support strong encryption due to the sensor's intelligence, preventing disclosure of a user's health condition [29].

### Distributed Wireless System for Stress Monitoring

Most monitoring applications are patient-centered, requiring synchronization among sensors on the same subject only. In some setups it is necessary to evaluate individual performance of subjects within the group during specific events. That requires synchronization of measurements of individual monitors within the sampling interval of the monitored physiological parameter. Monitored subjects can include patients, soldiers, firefighters, police officers, athletes, meeting participants, etc. We are developing a distributed wireless system to evaluate stress resistance during stressful training using synchronized measurements of HRV within the monitored group. This feature is not, to the best of our knowledge, available in the present generation of intelligent monitors.

User John Smith
UserID 29
PhysID 914
Num of packets 132
Good packets 762
Wrong packets 4
Tr Session 001
User 29
Comm Sess 06
Retransm 3
Time-out 2
Wrong CS 1
Rcvd CS 70

**Fig. 3.** Monitoring application running on mobile gateway (MOGUL).

Our preliminary results indicate a very good correlation between the HRV and stress level/resistance. In our preliminary investigations, we are validating the applicability of HRV measurements by correlating the various HRV parameters and psychological evaluations and hormone tests. Depending on the type of subjects being evaluated, we expect to assess both stress level and stress resistance.

### *System Description*

The Wireless Distributed Data Acquisition System uses the Polar chest belt as a HRV physiological sensor, WHRM as the personal server, and an iPAQ PDA as the mobile gateway (MOGUL) as represented in Figure 1. Our prototype system features custom wireless interfaces for both sensor to WHRM and WHRM to MOGUL connections.

Data acquisition systems that are currently in use at NAMRL require inconvenient data uploading using an infrared link to a PC. Due to limited memory storage, acquired data should be uploaded to the server for offline analysis every two to three hours. It is necessary to interrupt regular activity (or even to wake up the soldier), connect the wearable unit to the computer, and upload stored information.

The WHRM can store up to 60 hours of HRV data in nonvolatile onboard memory. An operator carrying a MOGUL periodically visits the group under the test and downloads data wirelessly without interrupting the subject's normal activity. After upload, WHRM will free its local memory for new measurements.

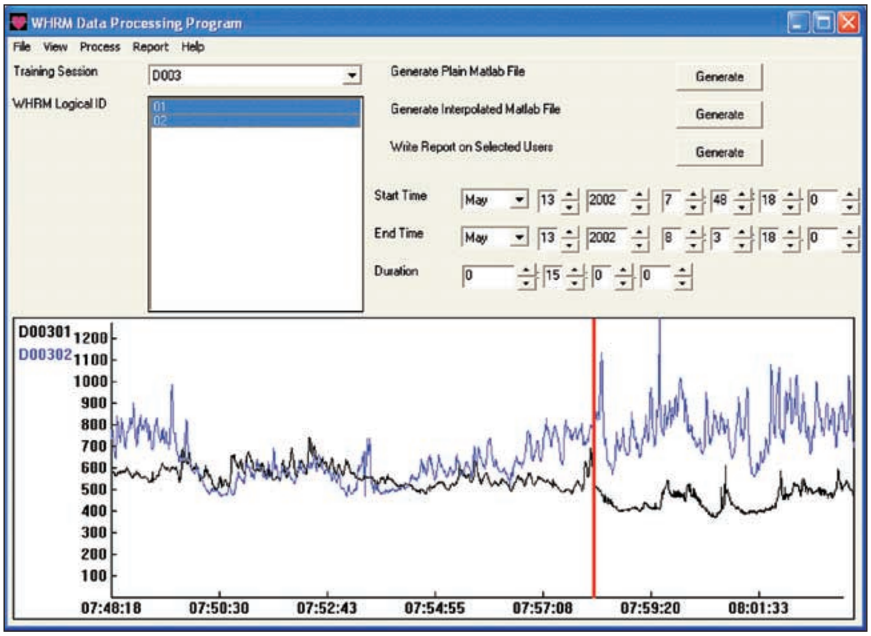
We use an iPAQ PDA with a custom wireless interface as a mobile gateway. The choice of a data acquisition platform is critical for device acceptance and ease of use. Although a laptop PC represents the best platform for software development and application environment, it would be difficult to collect data from soldiers undergoing intense training because of size and weight limitations. The main features of the iPAQ PDA computing platform include significant processing power (200-400 MHz RISC processors), excellent screen resolution and brightness, a standard program development environment, and system support for data synchronization. Generated files can be automatically transferred to a PC as soon as the PDA is returned to its cradle for recharging.

The system is organized in a master-slave configuration with the MOGUL acting as a master. Periodic visits to the training facility with the handheld MOGUL device allow uploading of collected data from individual WISE sensors. A person holding the MOGUL will move through the training area in order to establish wireless contact with all of the WISE devices in the system. Whenever the MOGUL is able to talk to the WISE devices it downloads and catalogs the data collected since the last visit.

Because the gateway is synchronized with all the other sensors, the user can conveniently (via voice recording and GUI) enter the exact start time of the training exercise, time and a description of other events, unexpected changes in the plan and schedule, etc. Some of the existing systems support *event switches*. However, this interferes with training, and very often users (particularly in stressful situations) forget to press the switch.

The system features 1-ms resolution HRV measurements, very low power consumption, and reliable data transmission based on error detection and retransmissions. Very low power consumption is achieved through short-range transmissions thanks to gateway mobility. In addition, device intelligence significantly reduces the amount of data and length of wireless transmission (more than 100 times compared to wireless telemetry systems in the case of HRV monitoring). Power consumption is further reduced due to the fact that the WHRM is idle most of the time and scans for MOGUL presence only periodically.

The system supports multiple gateways. In each contact with the individual monitoring device, the gateway creates a separate communication session file containing data downloaded from the device. A custom-made wireless interface device is connected to the iPAQ serial port and controlled by a dedicated PDA application. The same application is responsible for communication protocol implementation, data collection, file creation, data consistency checking, automatic repeat requests, and graphical user interface. A screen shot of a development version of the application is given in Figure 3. In addition to data collection, this application also monitors characteristics and the quality of the wireless channel (number of retransmissions, bit error rate, number of loss packets, etc.). We want to use that data to further improve the wireless communication protocol and to decrease power consumption of the personal monitors. All communication session files from multiple gateways are aggregated into a training session file on a central workstation that has established partnerships with all gateway PDAs. A screen shot of a program used for data aggregation, processing, and archiving is given in Figure 4.



Training Session D003

WHRM Logical ID 01 02

Start Time May 13 2002 7 48 18 0

End Time May 13 2002 8 3 18 0

Duration 0 15 0 0

**Fig. 4.** HRV processing application.

### *Methods and Preliminary Results*

We collected HRV data from the military personnel during several days of training to determine baseline HRV parameters, as well as HRV changes immediately before, during, and after stress exposure. Prolonged monitoring also facilitates assessment of stress recovery.

The 9D5 Multi-place Underwater Egress Trainer was selected as the stressor stimulus for our investigations; the 9D5 is a reasonably realistic representation of a helicopter conducting an emergency landing, turning upside, down, and sinking (Figure 5). Exposure of the trainees to the 9D5 is a mandatory training evolution during the Naval Aviation Survival Training Program at aviation preflight indoctrination. Each student receives the same instructions and training prior to the experience. Each student is subjected to the device at least three times, with each egress increasing in complexity. For example, students must wear light-filtering goggles for the third egress to simulate nighttime conditions. Students often report that this is the most stressful API training event (LCDR Lords, Head, Aviation Water Survival Training Department, NOMI Detachment Central, personal communication).

Salivary hormone responses and cognitive and psychological functioning are additionally assessed prior to, during, and after stress exposure. Circulating levels of hormones that are involved in the human response to threat have been shown to predict military performance [30]. These measures will be used to further validate the usefulness of HRV parameters as a prediction tool for military performance.

An example from our preliminary work is displayed in Figure 4, with the red line representing the beginning of the stress event. Two students simultaneously encountering 9D5 training were seen to exhibit visibly differing HRV patterns. There were differences between these two students on psychological cognitive measures as well. Student 1 reported more trait anxiety on a standardized anxiety questionnaire [31] than student 2. During training, Student 1 preformed poorly and had to be remediated. Immediately following 9D5 training, both students were admin-

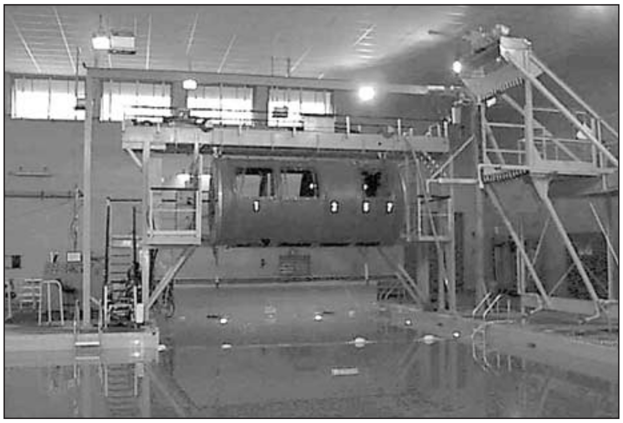


**Fig. 5.** The 9D5 Multi-Place Underwater Egress Trainer [Courtesy of U.S. Navy].

> **Our distributed wireless intelligent sensor system is convenient for prolonged stress monitoring during stressful training and normal activity.**

istered a standardized measure of visuospatial and organizational skills requiring delayed recall [32]. Student 1 exhibited much poorer performance on the delayed recall task than student 2. Although no definite conclusions can be drawn from preliminary data from so few cases, the differences between these students is striking. Upon completion of the entire study, details of the tasks administered and their relationship to HRV and hormone levels will be analyzed and submitted for publication.

## Discussion

Wireless intelligent sensors have made possible a new generation of noninvasive, unobtrusive personal medical monitors applicable during normal activity. Sensor intelligence allows implementation of real-time processing and sophisticated encryption algorithms. On-sensor data processing decreases the amount of energy spent on communication and allows implementation of power-efficient communication protocols. Decreased power consumption will significantly increase battery life and even enable externally powered intelligent sensors. The current technological trend will allow wider use of wireless intelligent sensors, lower power consumption, and smaller sensor sizes. The ultimate goal is to have a single-chip, externally powered, intelligent MEMS sensor, as proposed by NASA's Jet Propulsion Laboratory [33]. This device could be disposable and comparable in size to an ordinary adhesive bandage.

Our preliminary results indicate that HRV may represent an inexpensive methodology for the objective assessment of human reactions under stress. Our distributed wireless intelligent sensor system is convenient for prolonged stress monitoring during stressful training and normal activity. We plan to develop a more compact and efficient system for evaluation of the psychophysiological state of individual subjects as well as the relative state of the subject within the group (soldiers in the battlefield, firefighters, police officers, athletes, meeting participants, etc.).

MOGUL can be wirelessly connected to the Internet, using add-in PDA cards for WAN connectivity, creating a true real-time telemedical system. Increased device intelligence will change a whole paradigm of personal monitoring in m-Health systems [10], [17], [34] and human computer interfaces in ubiquitous computing [25], [26].

## Acknowledgments

The WISE project has been partially supported by the University of Alabama in Huntsville, grant 87716. The WHRM project has been partially funded by USAMRMC (ERMS#01145005) as a part of "The Warfighter's Stress Response: Telemetric and Noninvasive Assessment" project. We would like to thank Andy Morgan, Yale University School of Medicine, and Brent Priddy, University of Alabama in Huntsville, for all their help during implementation of this project.

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## References

[1] E. Jovanov, D. Raskovic, A.O. Lords, P. Cox, R. Adhami, and F. Andrasik, "Synchronized physiological monitoring using a distributed wireless intelligent sensor system," submitted to IEEE Engineering in Medicine and Biology Conference, Cancun, Mexico, 2003

[2] E. Jovanov, A. O'Donnell, A. Morgan, B. Priddy, and R. Hormigo, "Prolonged telemetric monitoring of heart rate variability using wireless intelligent sensors and a mobile gateway," in *2nd Joint EMBS-BMES*, Houston, TX, Oct. 2002, pp. 1875-1876.

[3] D.P. Agrawal and Q. Zeng, *Introduction to Wireless and Mobile Systems.* Pacific Grove, CA: Brooks/Cole, 2003.

[4] DARPA Sensor Information Technology. Available: http://dtsn.darpa.mil/ixo/sensit.asp, Jan. 2003.

[5] NIST SmartSpaces. Available: http://www.nist.gov/Smartspace/SmartSpaces, Jan. 2003.

[6] P. Heidenreich, C. Ruggerio, and B. Massie, "Effect of a home monitoring system on hospitalization and resource use for patients with heart failure," *Amer. Heart J.*, vol. 138, no. 4, pp. 633-640, 1999.

[7] S. Park and S. Jayaraman, "Enhancing the quality of life through wearable technology," *IEEE Eng. Med. Biol. Mag.*, vol. 22, pp. 41-48, May/June 2003.

[8] M. Gorlick, "Electric suspenders: A fabric power bus and data network for wearable digital devices," in *Proc. 3rd Intern. Symp. Wearable Comput.*, San Francisco, CA, Oct. 1999, pp. 114-121.

[9] J. Winters, Y. Wang, and J.M. Winters, "Wearable sensors and telerehabilitation," *IEEE Eng. Med. Biol. Mag.*, vol. 22, pp. 56-65, May/June 2003.

[10] R.W. Hoyt, J. Reifman, T.S. Coster, and M.J. Buller, "Combat medical informatics: Present and future," in *Biomedical Informatics: One Discipline*, I.S. Kohane, Ed. Bethesda, MD: AMIA, 2002.

[11] H. Asada, P. Shaltis, A. Reisner, S. Rhee, and R.C. Hutchinson, "Mobile monitoring with wearable photoplethysmographic sensors," *IEEE Eng. Med. Biol. Mag. (Special Issue on Wearable Sensors/Systems and Their Impact on Biomedical Engineering),* vol. 22, pp. 28-40, May/June 2003.

[12] G.E. Barnes and S. Warren, "A wearable, Bluetooth-enabled system for home health care," in *Proc. 2nd Joint EMBS/BMES Conf.*, Houston, TX, Oct. 23-26, 2002, pp. 1879-1880.

[13] G. Asada, M. Dong, T.S. Lin, F. Newberg, G. Pottie, and W.J. Kaiser, "Wireless integrated network sensors: Low power systems on a chip," in *Proc. 1998 European Solid State Circuits Conf.*, The Hague, The Netherlands, Sept. 1998, pp. 9-16.

[14] C. Diorio and J. Mavoori, "Computer electronics meet animal brains," *IEEE Computer,* vol. 38, pp. 69-75, Jan. 2003.

[15] M. Ghovanloo and K. Najafi, "A BiCMOS wireless stimulator chip for micromachined stimulating microprobes," in *Proc. 2nd Joint EMBS/BMES Conf.*, Houston, TX, Oct. 23-26, 2002, pp. 2113-2114.

[16] F. Graichen, G. Bergmann, and A. Rohlmann, "Implantable telemetry system for measurement of hip joint force and temperature," in *Biotelemetry 15: Proc. 15th Int. Symp. Biotelemetry,* Juneau, AK, 2000, pp. 661-669.

[17] E. Jovanov, J. Price, D. Raskovic, K. Kavi, T. Martin, and R. Adhami, "Wireless personal area networks in telemedical environment," in *Proc. 3rd Int. Conf. Inf. Technol. Biomed. (ITAB-ITIS2000)*, Arlington, VA, Nov. 2000, pp. 22-27.

[18] E. Jovanov, D. Raskovic, J. Price, A. Moore, J. Chapman, and A. Krishnamurthy, "Patient monitoring using personal area networks of wireless intelligent sensors," in *Proc. 38th Annu. Rocky Mountain Bioengineering Symp., RMBS 2001*, Copper Mountain, CO, Apr. 2001, pp. 373-378.

[19] E. Jovanov, D. Raskovic, and R. Hormigo, "Thermistor-based breathing sensor for circadian rhythm evaluation," in *Proc. 38th Annu. Rocky Mountain Bioengineering Symp., RMBS 2001,* Copper Mountain, CO, Apr. 2001, pp. 493-497.

[20] D. Raskovic, E. Jovanov, and K. Kavi, "Hierarchical digital signal processing," in *Proc. 2001 IEEE Int. Symp. Intelligent Signal Processing and Communication Systems, ISPACS 2001*, Nashville, TN, Nov. 20-23, 2001, pp. 18-21.

[21] J. Price, "An implementation of wireless network of intelligent sensors WISE," M.S. thesis, Electrical and Computer Engineering Department, Univ. of Alabama Huntsville, Huntsville, AL, 2002.

[22] Analog Devices. Available: http://www.analog.com/industry/iMEMS/index.html, Jan. 2003.

[23] B. Wheelock, "Autonomous real-time detection of silent ischemia," M.S. thesis, Univ. of Alabama in Huntsville, Huntsville, AL, 1999.

[24] M. Milenkovic, E. Jovanov, J. Chapman, D. Raskovic, and J. Price, "An accelerometer-based physical rehabilitation system," *34th Southeastern Symp. System Theory (SSST2002)*, Huntsville, AL, 2002, pp. 57-60.

[25] L. Collier and E. Jovanov, "A prototype emotion-sensing human-computer interface device for PDAs," *Int. J. Psychophysiol.*, vol. 45, no. 1-2, pp. 91, July 2002.

[26] R.W. Picard, *Affective Computing.* Cambridge, MA: MIT Press, 1997.

[27] POLAR. Available: http://www.polar.fi

[28] T. Martin, E. Jovanov, and D. Raskovic, "Issues in wearable computing for medical monitoring applications: A case study of a wearable ECG monitoring device," *Int. Symp. Wearable Computers ISWC 2000*, Atlanta, GA, Oct. 2000, pp. 43-50.

[29] Y. Kanamori, "Reliability and security in wireless body area network of intelligent sensors," M.S. thesis, Univ. of Alabama in Huntsville, Huntsville, AL, 2002.

[30] C.A. Morgan III, S. Wang, G. Hazlett, A. Rasmusson, G.A. Anderson, D.S. Charney, "Relationships among Cortiso Catecholamines, Neuropeptide Y and human performance during uncontrollable stress," *Psychosomatic Med.,* vol. 63, no. 3, pp. 412-422, 2001.

[31] C.D. Spielberger, R.L. Gorsuch, R. Lushene, P.R. Vagg, and G.A. Jacobs, *Manual for the State-Trait Anxiety Inventory (Form Y)*. Palo Alto, CA: Consulting Psychologists Press, 1983.

[32] D.E. Fujii, H.A. Lloyd, and K. Miyamoto, "The salience of visuospatial and organizational skills ion reproducing the Rey-Osterreith complex figure in subjects with high and low IQs," *Clin. Neuropsychologist*, vol. 14, no. 4, pp. 551-554, 2000.

[33] NASA's Jet Propulsion Laboratory. Available: http://www.nasatech.com/Briefs/Feb00/NPO20651.html, Jan. 2003.

[34] D. Starcevic, Z. Obrenovic, E. Jovanov, and V. Radivojevic, "Implementation of virtual medical devices in internet and wireless cellular networks," *1st IFIP Workshop Internet Technologies, Applications and Societal Impact*, Wroclaw, Poland, Oct. 2002, pp. 229-242.