Combat Medical Informatics: Present and Future

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ABSTRACT

In this paper, we describe a U.S. Army concept to monitor soldier physiologic status and provide computer-based medical support to increase the likelihood of soldier survival on the battlefield. Supported by an underlying platform of complex wearable computerized systems, the "Warfighter Physiological Status Monitoring" (WPSM) concept consists of an array of biosensors embedded in the soldier's uniform integrated with a database management system and a decision support system that will provide assistance in casualty prevention and casualty management. We discuss the main components of the WPSM, its present status, key requirements and outstanding challenges, and near- and far-term research directions.

INTRODUCTION

Historic advances in medicine and dramatic progress in medical informatics over the last decade have not yet translated into predictive algorithms to be used for health care of soldiers on or off the battlefield–be it in casualty prevention or in casualty management. For example, although small in number, soldiers still succumb to debilitating and costly thermal injuries[1,2] as medical decision support tools are not available to automatically monitor and predict the onset of irreversible physiologic damage. In addition, current methods for triage and diagnosis of wounded soldiers in the battlefield make minimal, if any, use of automated monitoring and medical informatics tools.

The health care of the soldier of the future, however, is expected to rely much more heavily on medical informatics technologies. The uniform and equipment of the modern dismounted soldier is being completely redesigned with an underlying platform based on complex wearable computerized systems. These emerging systems, called "Land Warrior" and "Objective Force Warrior," will integrate a wide range of new and advanced technologies. This includes a biosensor network to provide medical support and increase the probability of soldier survival on the battlefield. The increased likelihood of soldiers being widely dispersed during combat operations makes the remote collection and analysis of physiological information particularly important.

A U.S. Army program termed "Warfighter Physiological Status Monitoring" (WPSM) seeks to gather and use biosensor information for two primary purposes. First, to reduce casualties due to environmental factors, such as heat stress and altitude sickness. By having access to physiological status indicators, commanders at various levels will be better able to assess their troops and improve physical and mental performance through appropriate interventions. Second, to improve the likelihood of survival of wounded soldiers. By having remote access to physiological data and availability of computerized diagnostic and treatment decision tools at the point of care, combat medics will be able to more quickly assess, triage and more affectively manage life-threatening casualties, which may be scattered over a large area. Data suggests that certain casualties could be saved if promptly treated with effective interventions within the first hour of injury.[3]

The WPSM consists of the three main elements, (1) a suite of biosensors integrated in a personal area network (PAN), (2) a decision support software, and (3) a database management system (DBMS), depicted in Fig. 1, which would be integrated with other systems, including a global positioning system and secure communications. A suite of biosensors, built with an open architecture to allow for time-phased development and insertion of intended capabilities, will continually monitor and transmit data to a DBMS and a decision support system. A decision software system will support operational medicine by monitoring the biosensors and inferring current and predicting future soldier physiological status. It will support casualty management by enabling remote triage and providing guidance for diagnosis, treatment, and prognosis. A DBMS will contain soldier medical records as well as streaming and historic physiologic time-series data to support applications for the decision support system and ad-hoc queries. The following sections describe the requirements, challenges, present status, and future needs of the three main elements of the WPSM.

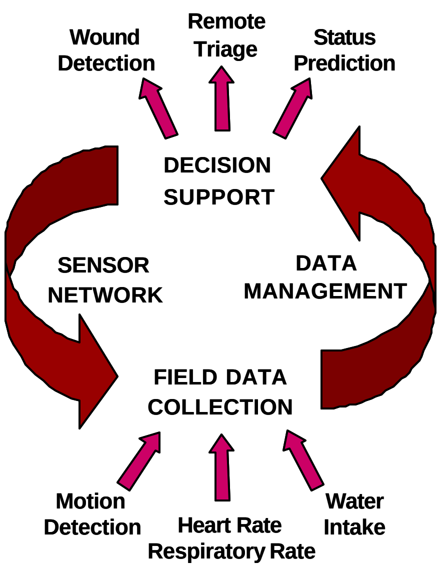

Figure 1. Elements of the Warfighter Physiological Status Monitoring concept

BIOSENSOR PERSONAL AREA NETWORK

The development of a robust, nearly undetectable wireless network of sensors is a critical part of achieving the goal of using ambulatory physiological data to improve the health, performance, and casualty management of soldiers. In this approach, a "plug-and-play" array of mission-specific biosensors, connected to an open architecture PAN, permits continual monitoring of soldier physiologic status. Physiologic data streams are then captured and stored in a DBMS for later analysis and/or monitored in near real time by triggers and other software agents to identify abnormal events.

Typical field experiments involve collecting and storing sensor data, and retrieving and analyzing the data post hoc. In contrast, operational use of ambulatory biosensor data to meet soldier's needs involves monitoring and analyzing streaming biosensor data subject to time constraints. That is, there is a distinct flip from a "human active/system passive" approach, where large amounts of data are stored and humans are heavily engaged in off-line data analysis, to a "system active/human passive" paradigm, where triggering events, such as physiologic crisis and medic request, initiate data gathering, reduction, and transmission in near real-time over a PAN to a hub, or central data collection point, where data fusion (integration) and analysis occur. This sea change involves a switch from storing large amounts of data to storing only selected snippets and routinely discarding uninformative data. Clearly, software and database systems are needed that can handle large amounts of streaming time-series data in real time and that can also support analysis and management of stored time-series data (see the DBMS section below).

To date, we have conducted a series of field experiments in which we have collected and stored physiologic data for post-hoc studies. In one such study, of a simulated attack at the McKenna Military Operations in Urban Terrain facility at the Dismounted Battlespace Battle Lab, Ft. Benning, Georgia, we also transmitted, reduced and displayed the data in real-time. Meteorologic conditions were monitored, core temperature was measured by ingested radio telemetry pill, and heart rate was measured electrocardiographically using a chest strap. Data from these ambulatory sensors were transmitted through a wireless PAN to a control facility where the physiological strain index[4] (PSI) of each soldier was displayed during the two hour simulated attack. The PSI is derived from heart rate and core temperature and is used to monitor thermal/work strain. The data were captured and stored in an XML-based database for later analysis (see the DBMS section below). Clearly, real-time PSI has potential value in military operations where heat strain is a significant risk.

In these experiments, we learned that better sensors, more dependable PAN hardware/

firmware/software, and better data management and modeling tools are needed before the collection and use of physiologic information is practical for the foot soldier. The need for novel system software and new time-series data management tools are driven by the highly constrained, harsh, changeable, and imperfect world of wearable biosensor networks. User acceptability, power, weight, and bandwidth are limited; vibration, shock, immersion, and thermal extremes are common; user needs, sensor number and capabilities change, and sensors fail. Consequently, sensor redundancy is rare, sensor capabilities are often less than ideal, and system software and time-series data management become vitally important.

Missing, degraded or corrupted sensor information is difficult to detect and correct without sensor redundancy. Poor sensor data has the potential to severely affect the usefulness of downstream decision support systems. Thus, new algorithms are needed to provide timely and reliable indication of the health of the biosensors, detect and identify individual faulty sensors, and provide analytically generated estimates of the sensor signal as a temporary substitute for the erroneous signal.[5]

New data management strategies and software will help insure intelligent use of bandwidth and scalability to accommodate many sensors and users. Furthermore, system reliability and low false-positive rates are needed, even in the face of sensor failure and untimely data delivery. Generalized solutions to streaming data will certainly follow solutions to more constrained problems, such as those surrounding the collection and use of biosensor data. Nevertheless, any system software and data management tool that is developed need to be adaptable, reconfigurable, and open.

DECISION SUPPORT SYSTEMS

The WPSM concept relies on a wide range of computer-based systems that provide decision support to reduce casualties due to environmental factors and to improve the likelihood of survival of wounded soldiers. A large body of medical decision support systems has been developed for the civilian setting with mixed results. However, most are inapplicable to the battlefield environment and its unique requirements where the needed functionalities are different from the civilian applications, the working conditions are unknown in advance, and resources are limited. Therefore, customized systems will need to be developed to address the specific military requirements.

Our initial focus is on casualty management, and in particular, in remote triage. Morbidity and mortality of wounded soldiers would be reduced due to the rapid ability to alert the medic of a wounding event and provide first-responder care. The capability to expeditiously triage casualties will be particularly important due to the increased likelihood of soldiers being widely dispersed during combat operations. In addition, by providing remote triage there will be a reduction in the number of medics killed- and wounded-in action as many are injured when attending victims that cannot be resuscitated.

As a first step, we are planning field trials of remote triage devices that will provide: life-sign detection and wound detection. These devices will have an integrated suite of physiological sensors and decision support software. The suite of physiological sensors, including ECG, inductance plethysmography, actigraphy and acoustic sensors, has dual use in providing remote triage now and operational medicine capabilities in the future.

The decision support software will interpret data from the suite of wearable sensors to automatically infer if the soldier is alive, dead, or in an unknown physiologic state due to lack of information or corrupted data. The inference shall incorporate as part of the decision-making process both clinical uncertainty—due to contradictory evidence and temporal evolution from injury onset—and data uncertainty—due to sensor/data transmission fault and sensor dislodgment. To meet these requirements and provide a probabilistically based measure of the reliability of the inference, we propose two possible approaches. The first, is to modify probabilistic risk assessment tools,[6] such as event trees, decision trees, and fault trees, which can be directly employed to assess sensor/data transmission reliability, to incorporate clinical decisions and their associated uncertainties.

Another approach, involves the use of Bayesian belief networks (BBNs) and related technologies used in Decision Theory. BBNs have a probabilistic foundation and provide the mathematical formalism whereby medical judgment may be expressed as the degree of belief in an outcome given a set of observations.

Employing Bayesian probabilistic theory, it is possible to represent clinical knowledge about the dependencies between variables and to propagate consistently and quantitatively the impact of evidence for diagnosing the current state of an individual.

We are also pursuing the development of decision support systems for treatment and prognosis of combat casualties. However, the lack of consensus as to which physiologic parameters are predictive of clinical outcome of traumatic brain injury and hemorrhage, which account for most of battlefield mortality, drove us to first answer this more fundamental question. Hence, currently, studies are underway to collect continuous physiologic data from non-invasive prehospital monitoring of trauma victims and combine these data with clinical information and outcome. These data will then be mined to determine markers of resuscitation and prognostic indicators. A DBMS is being developed (see following paragraphs) to support this effort.

DATABASE MANAGEMENT SYSTEM

Distinct database functionalities are necessary to support research applications, such as the identification of key physiologic parameters predictive of clinical outcome discussed above, and to support on-line field monitoring of soldiers in the battlefield. The following paragraphs describe our ongoing efforts to develop DBMSs that support research applications and present the envisioned requirements to support future field (operational) applications.

Research Applications

Two separate but complementary DBMSs are being developed to support basic WPSM research. The first system, which supports operational medicine research, consists of a native XML (extensible markup language) database on a local area network, an XML query server, and a set of customized tools for feature extraction and data visualization.[7] The system enables automation of WPSM data collection of soldier field experiments and provides a simple, flexible and extensible architecture to warehouse a varied array of data types dominated by time-series data. The system was employed in the three field experiments discussed above to collect, store, and analyze physiologic, meteorologic, and other data types with sampling rate ranging from minutes to days. Although this architecture has proved useful, it has limitations. XML does not provide an efficient, compact mechanism to represent time-series data collected at high sampling rates and, depending on the manner in which the query system is implemented, computer memory may limit the size and time resolution of the time-series data.

The second DBMS, which supports casualty management research focused on civilian prehospital physiologic trauma data and related animal experiments,[8] is under early stages of development. An assessment phase has been completed where functional and data requirements were identified along with potential technology solutions. The DBMS will be needed to: (a) manage text data and large amounts of time-series data with sampling rate at high as 1 msec; (b) support accurate context descriptions so that researchers can analyze data generated by others; (c) allow for remote user access to both data input and data retrieval and query; and (d) provide a user-friendly interface permitting ad-hoc query and 2D data visualization with data annotation and data cleansing capabilities. It is envisioned that the system will be supported by a relational database, with a time-series data management capability, in a client/server Web-enabled architecture supported by a browser interface. The database will be XML-enabled, permitting the warehousing of XML-encoded WPSM data from field experiments.

Field Applications

In field applications, monitoring of large arrays of physiologic sensors will require decision management infrastructures that efficiently handle large amounts of streaming and historical time-series data. Sensors continually monitoring soldier status will generate intermittent, asynchronous streams of ordered sensor values. Hence, applications for decision support systems must have the capability to monitor and process streaming time-series data, as well as to retrieve archived time-series data in near real time. Ad-hoc queries for data mining applications will require the combined use of streaming data and historical time-series data to determine, for example, the physiologic patterns of soldiers exposed to extreme environmental conditions over last few hours or for clinical comparison between current and baseline physiologic parameters. Many applications will require real-time performance.

Traditional DBMSs are incapable of handling time-series data efficiently as they were not built with this objective. Their storage structure is not tuned to effectively handle ordered data, simple time-series operations are not supported and processing is not directed at real-time requirements. New (non-relational) data structures designed from the ground up to efficiently deal with streaming time-series data as well as large amounts of historical data in a timely manner are needed to monitor and mine data from tens of thousands, if not millions, of sensors in real time.

CONCLUSIONS

In this status report paper, we describe ongoing efforts and near- and far-term research needs of the ambitious U.S. Army concept to deploy medical informatics technologies to increase the likelihood of soldier survival on the battlefield. As a first step, intended primarily to better understand the challenges ahead and to provide a means for data collection, we tested a hardware/software system that collects physiologic data from sensors attached to the soldier's body, stores the data in a native XML database for post-hoc analysis, and transmits information through a wireless personal area network to a command facility for real-time display.

Efforts are underway to develop a prototype system for remote triage, i.e., remote identification of life signs, of battlefield casualties. It consists of an array of a few biosensors and a computer-based decision support system that incorporates sensor information with clinical and data uncertainty to provide a mathematically sound, statistically based estimate of the soldier clinical state.

Many challenges remain. In particular, there is a need to identify the key physiologic parameters that are predictive of clinical outcome of trauma victims. There is a need to enhance the reliability and security of wireless personal area networks while minimizing compromising electronic emissions and optimizing bandwidth usage. Furthermore, sophisticated data management strategies will be required to handle missing, degraded, and corrupted information from asynchronous data streams consisting of large amounts of time-series data subject to real-time performance requirements.

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DISCLAIMER

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense.

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