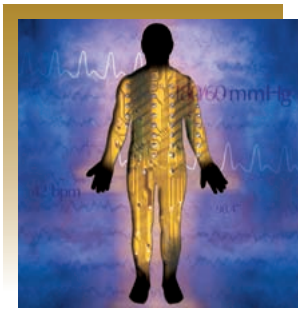

Enhancing the Quality of Life Through Wearable Technology

The Role of a Personalized Wearable Intelligent Information Infrastructure in Addressing the Challenges of Healthcare

SUNGMEE PARK AND SUNDARESAN JAYARAMAN

It is hard to place a price tag either on human life or on the quality of life. This has become starkly evident since the attack on the World Trade Center on September 11, 2001. A new "normal" has emerged for people around the world and our "way of life," as we have known it, has been changed forever. There is a similar, yet silent, crisis that is dramatically affecting the quality of life for individuals—lack of access to affordable and high-quality healthcare.

Technology is the key to enhancing the *quality* of life for everyone in the *continuum of life* from newborns to senior citizens—whether it is the safe delivery and care of undernourished premature babies or extending the life of a senior citizen through exploratory treatments and procedures. Technology is indeed the catalyst that can rapidly transform healthcare and the practice of medicine. So, any technology to minimize the loss of human life and/or enhance the quality of life has a *value* that is priceless. Moreover, the healthcare industry must meet the challenge of balancing cost containment with maintenance of desired patient outcomes, and this can be accomplished through the adoption of technology.

An overview of the key challenges facing the practice of medicine today is presented in this article along with the need for technological solutions that can "prevent" problems. Then, the development of the Wearable Motherboard™ as a "platform" for sensors and monitoring devices that can unobtrusively monitor the health and well being of individuals (directly and/or remotely) is described. This is followed by a discussion of the applications and impact of this technology in the continuum of life—from preventing SIDS to facilitating independent living for senior citizens. Finally, the future advancements in the area of wearable, yet comfortable, systems that can continue the transformation of healthcare—all aimed at enhancing the quality of life for humans—are presented.

The Role of Technology in Improving Healthcare

The Healthcare Challenge

Consider the following facts:

- In a recent report, the Institute of Medicine concluded "The U.S. healthcare delivery system does not provide consistent, high-quality medical care to all people" [1].
- Experts estimate that as many as 98,000 people die in any given year from medical errors that occur in hospitals. That's more than die from motor vehicle accidents, breast cancer, or AIDS (acquired immune deficiency syndrome)—three causes that receive far more public attention. Indeed, more people die annually from medication errors than from workplace injuries. Add the financial cost to the human tragedy, and medical error easily rises to the top ranks of urgent, widespread public problems [2].
- Healthcare spending in the U.S. soared to US$1.42 trillion in 2001, as across-the-board increases fueled the fastest annual growth in a decade [3]. In 2000, healthcare spending totaled US$1.31 trillion.
- As a percentage of GDP, healthcare spending increased from 13.3% in 2000 to 14.1% in 2001 [3].
- Seven major diseases accounted for 80% of deaths in the United States in 1990: heart disease, cancer, diabetes, arthritis, chronic bronchitis, influenza, and asthma [4]. For many of these health conditions, *early, systematic intervention* would be highly beneficial.
- With universal access to information (e.g., through the Web), today's healthcare consumer is demanding more options and taking control in determining the course of healthcare.

Thus, the healthcare industry is facing a set of significant challenges on several fronts, viz., availability (or access), quality, and cost. At the same time, there is a real opportunity for the healthcare industry: According to Andy Grove, the Chairman of Intel Corp., the healthcare industry is facing an Internet-driven "strategic inflection point" or a time in which extreme change forever alters the competitive landscape of an industry, creating new opportunities and challenges [5].

Responding to the Healthcare Challenge

To respond successfully to the set of challenges, the healthcare industry must:

- reduce healthcare costs while maintaining the high quality of care
- provide access to care for as many people as possible
- provide easy access to specialized professionals *anywhere* and at *anytime*
- shift the focus of healthcare expenditures from *treatment* to *prevention* through wellness programs
- control length of hospital stay and *decentralize* the provision of healthcare

The principal advantage of the Smart Shirt is that it provides, for the first time, a very systematic way of monitoring the vital signs of humans in an unobtrusive manner.

- address the increase in the aging population and caring for chronically ill patients.

Thus, the healthcare industry must meet the challenge of balancing cost containment with maintenance of desired patient outcomes.

The Need for Improvement and Change: Role of Technology

To meet this set of growing challenges, healthcare professionals are trying to provide patient care more efficiently and, whenever possible, in the least expensive setting, throughout the *continuum of care*—be that an ICU (intensive care unit), a hospital general care unit, a skilled nursing facility, an outpatient clinic, or a patient's home. This has created a demand for portable, versatile medical devices that can be moved easily from the ICU all the way to a homecare setting [6]. Also, there is a critical need to enhance the physician's abilities to successfully address even the most seemingly desperate of situations, whether it is the safe delivery and care of undernourished premature babies or extending the life of a senior citizen through exploratory treatments and procedures.

Six Aims for Improving Healthcare

The Institute of Medicine has underscored the need for a "national statement of purpose" for the healthcare system as a whole and has identified six key aims for the improvement of healthcare. These include a healthcare system that is *safe*, *effective*, *patient-centered*, and provides *timely*, *efficient*, and *equitable* care that does not vary in quality across the nation [1]. The healthcare industry must respond, and respond soon, to this call for action to improve the healthcare system in the nation.

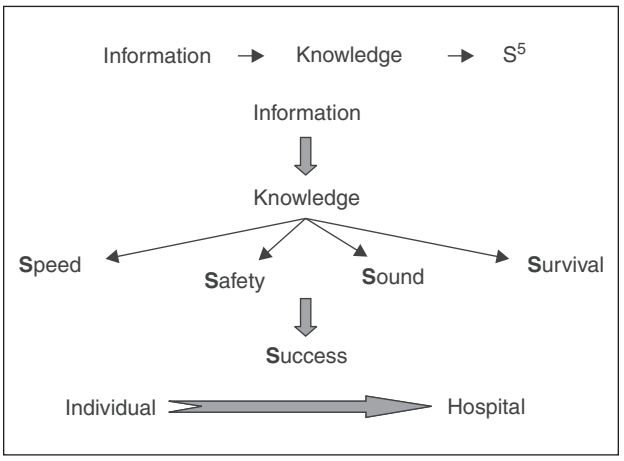

Fig. 1. The information-knowledge-S^5 framework.

Role of Technology

Technology is the key to enhancing the *quality* of life for everyone in the *continuum of life* from newborns to senior citizens. Technology is indeed the catalyst that can rapidly transform healthcare and the practice of medicine. Moreover, technology is essential for the healthcare industry to meet its challenges discussed earlier. Therefore, any technology to minimize the loss of human life and/or enhance the quality of life has a *value* that is priceless.

Information is at the heart of a successful healthcare system. As shown in Figure 1, information leads to "knowledge" which, in turn, leads to S^5 (speed, safety, sound, survival, and success). Armed with the right information, the doctor can provide *speedy* and *safe* treatment that is based on *sound* decision making, which can ensure the *survival* of the patient, thereby creating a *successful* healthcare delivery system. Moreover, to realize a healthcare system with the six key aims identified by the Institute of Medicine, there is a need for an effective and mobile information infrastructure or monitoring system that can be tailored to the individual's requirements to take advantage of the advancements in telemedicine and information processing. And, if this information infrastructure can be realized in the form of a *wearable garment* that can collect, process, store, and transmit (and receive) information about the wearer (e.g., body vital signs, to (and from) any remote location, say via the Internet) it would go a long way toward:

- addressing the healthcare challenge
- realizing the healthcare system called for by the National Institute of Medicine
- enhancing the quality of life for everyone in the continuum of life throughout the continuum of care.

The remainder of this article provides details of the Wearable Motherboard (Smart Shirt) developed at Georgia Tech, which represents the first attempt at realizing an unobtrusive, mobile, and easy-to-use vital signs monitoring system; presents the key applications of the Smart Shirt technology along with its impact on the practice of medicine; and covers key opportunities to create the next generation of truly "adaptive and responsive" medical systems.

The Wearable Motherboard (Smart Shirt) Technology

Research at Georgia Tech—funded initially in October 1996 by DARPA through the U.S. Department of the Navy—has led to the realization of the world's first Wearable Motherboard or an "intelligent" garment for the 21st Century [7]. The Georgia Tech Wearable Motherboard (GTWM), or the Smart Shirt, uses optical fibers to detect bullet wounds and special sensors and interconnects to monitor the body's vital signs during combat conditions. However, as the research

progressed, new vistas emerged for the deployment of the resulting technology including civilian medical applications and the new paradigm of personalized mobile information processing using the flexible information infrastructure, and that led to the concept of a "wearable motherboard." Just as special-purpose chips and processors can be plugged into a computer motherboard to obtain the desired information processing capability, the Smart Shirt provides an extremely versatile framework for the incorporation of sensing, monitoring, and information processing devices. The principal advantage of the Smart Shirt is that it provides, for the first time, a very systematic way of monitoring the vital signs of humans in an *unobtrusive* manner.

An Overview of the Smart Shirt Technology

Figure 2 shows the key user requirements identified during the Smart Shirt design and development process. The details of the design methodology can be found elsewhere [8]. Several versions of the Wearable Motherboard (Smart Shirt) have been produced, and with each succeeding version, the garment has been continually enhanced from all perspectives—functionality, capabilities, comfort, ease of use, and aesthetics.

Figure 3 shows the architecture of the Wearable Motherboard intended for medical applications. The comfort or base fabric (woven, knitted, nonwoven, etc.) provides the necessary physical infrastructure for the Wearable Motherboard. The base fabric is made from typical textile fibers (e.g., cotton, polyester, blends) where the choice of fibers is dictated by the intended application. The developed interconnection technology has been used to create a flexible and wearable framework to plug in sensors for monitoring a variety of vital signs including heart rate, respiration rate, electrocardiogram (EKG), body temperature, and pulse oximetry (SpO_2). In addition, by plugging in a microphone into the Smart Shirt, voice can be recorded.

These sensors can be positioned in desired locations on the body and will plug into the Smart Shirt. The flexible data *bus* integrated into the structure transmits the information from the suite of sensors to the multifunction processor known as the Smart Shirt Controller. This Controller, in turn, processes the signals and transmits them wirelessly (using an appropriate communication protocol such as Bluetooth, 802.11b) to desired locations (e.g., doctor's office, hospital, battlefield triage station). The *bus* also serves

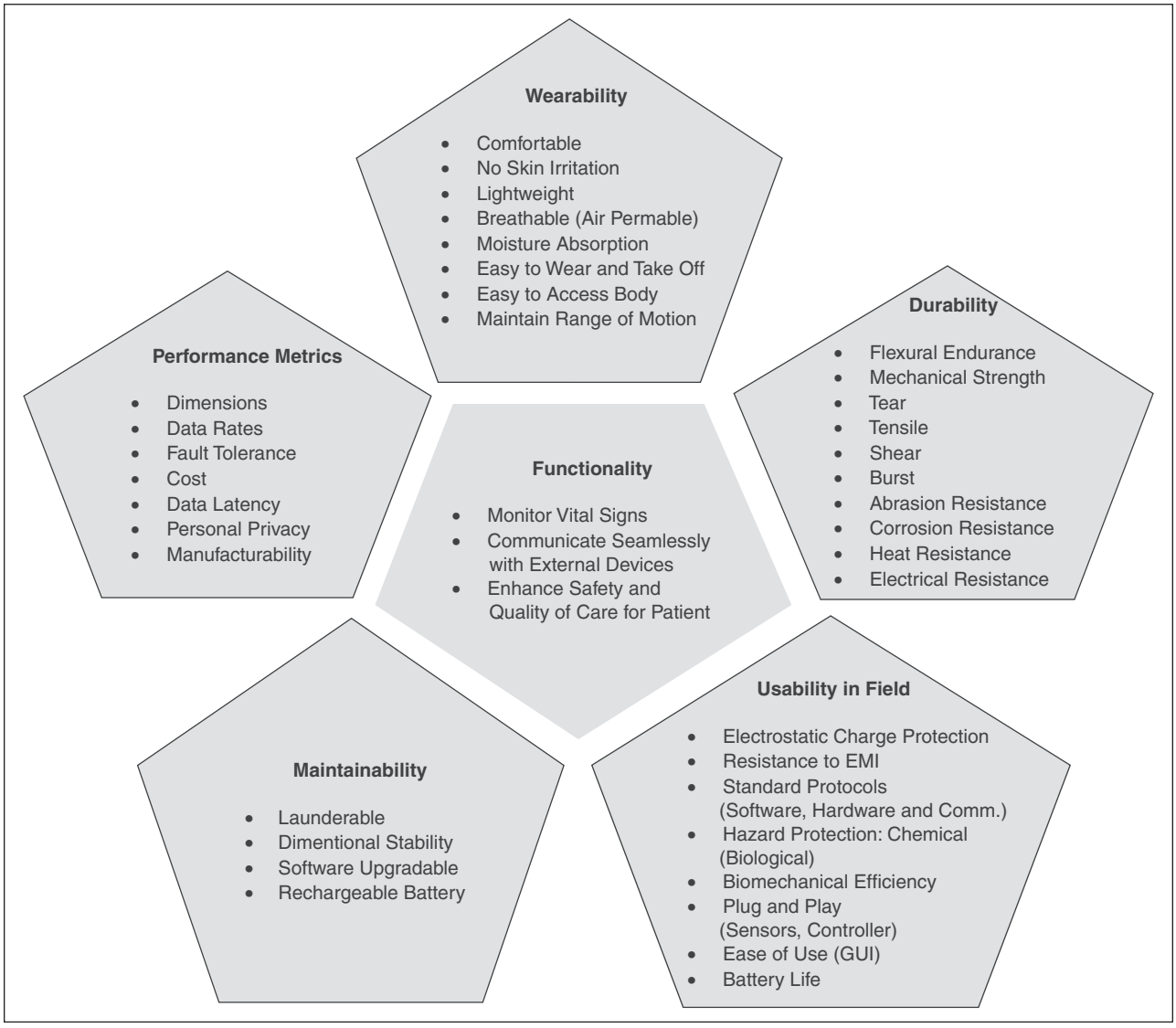

Fig. 2. Smart Shirt system: User requirements analysis.

to transmit information *to* the sensors (and hence, the wearer) from external sources, thus making the Smart Shirt a valuable information infrastructure.

The motherboard or "plug and play" concept means other sensors can be easily integrated into the structure. For instance, a sensor to detect oxygen levels or hazardous gases can be integrated into a variation of the Smart Shirt that will be used by firefighters. This information along with the vital signs can be transmitted to the command center or fire station where personnel can continuously monitor the firefighter's condition and provide appropriate instructions, including ordering the individual to evacuate the scene, if necessary.

Testing of the Smart Shirt

The vital signs monitoring capability has been tested by a subject wearing the garment and measuring the heart rate, respiration rate, electrocardiogram (EKG), and body temperature using commercial off-the-shelf sensors that "plug" into the Smart Shirt. The data is wirelessly transmitted to a personal computer. Figure 4 shows the display of the key vital signs including the EKG waveform on the computer illustrating the successful realization of the Wearable Motherboard concept. The garment is also comfortable and easy to wear and take off similar to a typical undershirt. For monitoring acutely ill patients who may not be able to wear the garment over the head (like a typical undershirt), Velcro® and zipper fasteners are used to attach the front and back of the garment creating a garment with full monitoring functionality that is also easy to use.

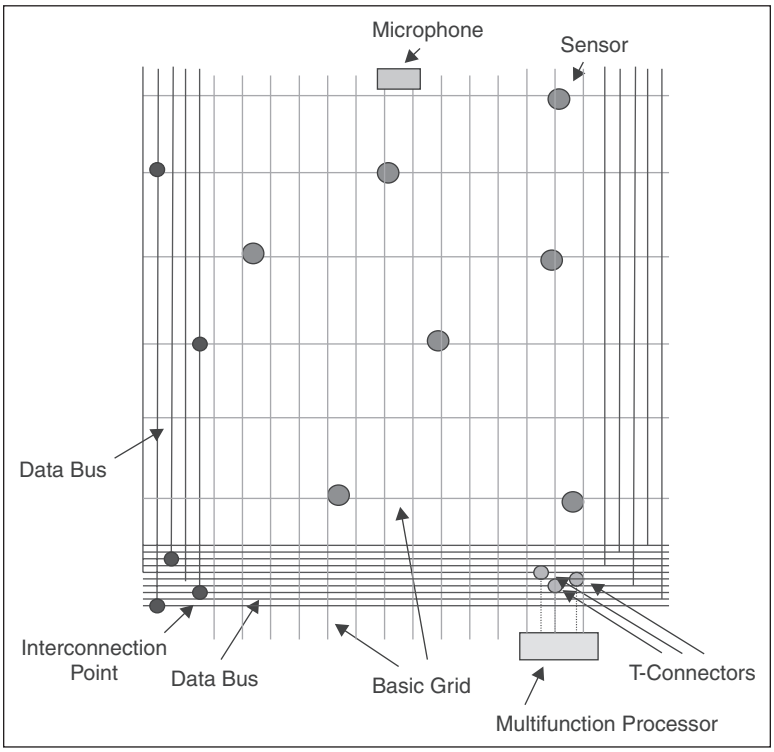

Fig. 3. The wearable motherboard architecture.

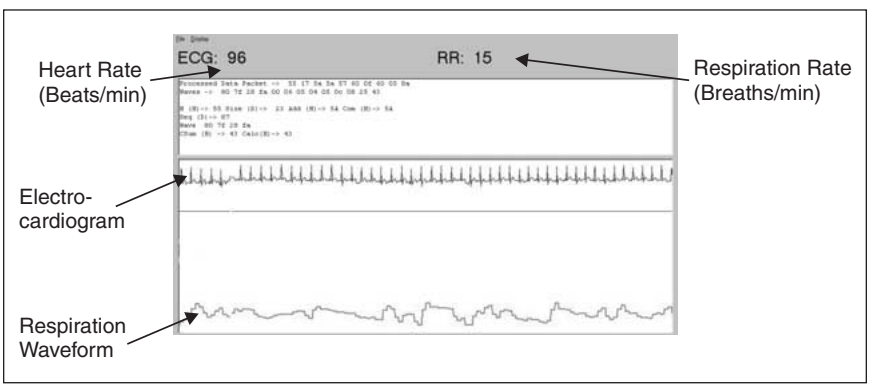

Fig. 4. The display of key vital signs from the Smart Shirt.

Applications and Impact of the Smart Shirt

This research on the design and development of the Smart Shirt has opened up new frontiers in personalized information processing, healthcare and telemedicine, and space exploration, to name a few [9]. Until now, it has not been possible to create a personal information processor that was customizable, wearable, and comfortable; neither has there been a garment that could be used for unobtrusive monitoring of the vital signs of humans on earth or in space.

Applications of the Smart Shirt

Figure 5 illustrates the use of the Smart Shirt in a variety of applications—battlefield, public safety, health monitoring, sports and fitness, among others. The vital signs information gathered by the various sensors on the body travels through the Smart Shirt to the Smart Shirt Controller for processing; from there, the computed vital signs are wirelessly transmitted using the "communications information infrastructure" in place in that application (e.g., the firefighters' communications system, the battlefield communications infrastructure, the hospital network, the wireless-fidelity (Wi-Fi) network at home) to the respective monitoring station. There, the back-end Data Display and Management System—with a built-in knowledge-based decision support system—can receive this vital signs data in real-time and provide the right response to the situation.

Table 1 summarizes the broad range of applications of the Smart Shirt technology [6]. The table also shows the application type and the target population that can utilize the technology.

Impact of the Smart Shirt

The Smart Shirt will have a significant impact on the practice of medicine since it fulfills the critical need for a technology that can enhance the quality of life while reducing healthcare costs across the continuum of life, i.e., from newborns to senior citizens, and across the continuum of medical care, i.e., from homes to hospitals and everywhere in between, as shown in Figure 6. The six aims for an improved healthcare system identified by the Institute of Medicine are also shown in the outer ring of the figure and illustrate the potential of the Smart Shirt technology in facilitating the realization of the desired healthcare system.

Clothing, the most universal of interfaces, is probably the only "constant" that is an integral part of the individual throughout the twin continua shown in the figure. By having a technology that is not only ubiquitous but also has the ability and intelligence to respond to the changes in the needs of the wearer, the quality of preventive care can be significantly enhanced, thus reinforcing the paradigm that "investment in prevention is significantly less than the cost of treatment." For instance, when an infant version of the Smart Shirt is used for monitoring babies prone to SIDS (sudden infant death syndrome), it can shift the focus from the treatment of infants who have suffered brain damage due to apnea to the prevention of the damage in the first place. The relative costs of the two scenarios (prevention versus treatment) are only too well known to be elaborated upon here.

The Smart Shirt can contribute to reductions in healthcare costs while enhancing the quality of life. For instance, patients could wear the Smart Shirt at home and be monitored by a monitoring station (similar to home security monitoring companies), thereby avoiding hospital stay costs and reducing the overall cost of healthcare. At the same time, a home setting can contribute to faster recovery. For example, if the patient recovering at home from heart surgery is wearing the Smart Shirt, the EKG can be transmitted wirelessly (through a mobile phone, Internet, etc.) to the hospital on a regular basis. This monitoring will help the patient feel more "secure" and will facilitate the recuperation while simultaneously reducing the cost and time associated with recovery. Moreover, in the event of an emergency, the doctor can be notified instantaneously. Using the online medical records (available over the Web), the physician can administer the *right* treatment at the *right* time at the *right* cost and indeed save a life, thereby realizing the full potential of the Smart Shirt technology!

Furthermore, persons who have known disorders can wear the Smart Shirt and be under *constant* monitoring of their physical conditions by medical personnel. For example, it can be used to monitor mentally ill patients (e.g., those suffering from manic depression) or even kids suspected of ADD (attention deficit disorder) on a regular basis to gain a better understanding of the relationship between their vital signs and their behavioral patterns so that their treatments (e.g., medication) could be suitably modified. Other potential applications include the treatment of anxieties and phobias. Such medical monitoring of individuals is critical for the successful practice of telemedicine that is becoming economically viable in the context of advancements in computing and telecommunications, especially the Internet.

Yet another potential impact of the Smart Shirt technology is the eventual disappearance of geographical/physical boundaries as barriers for individuals seeking the best in healthcare worldwide. For example, patients in remote/rural areas served by general family practitioners can have conve-

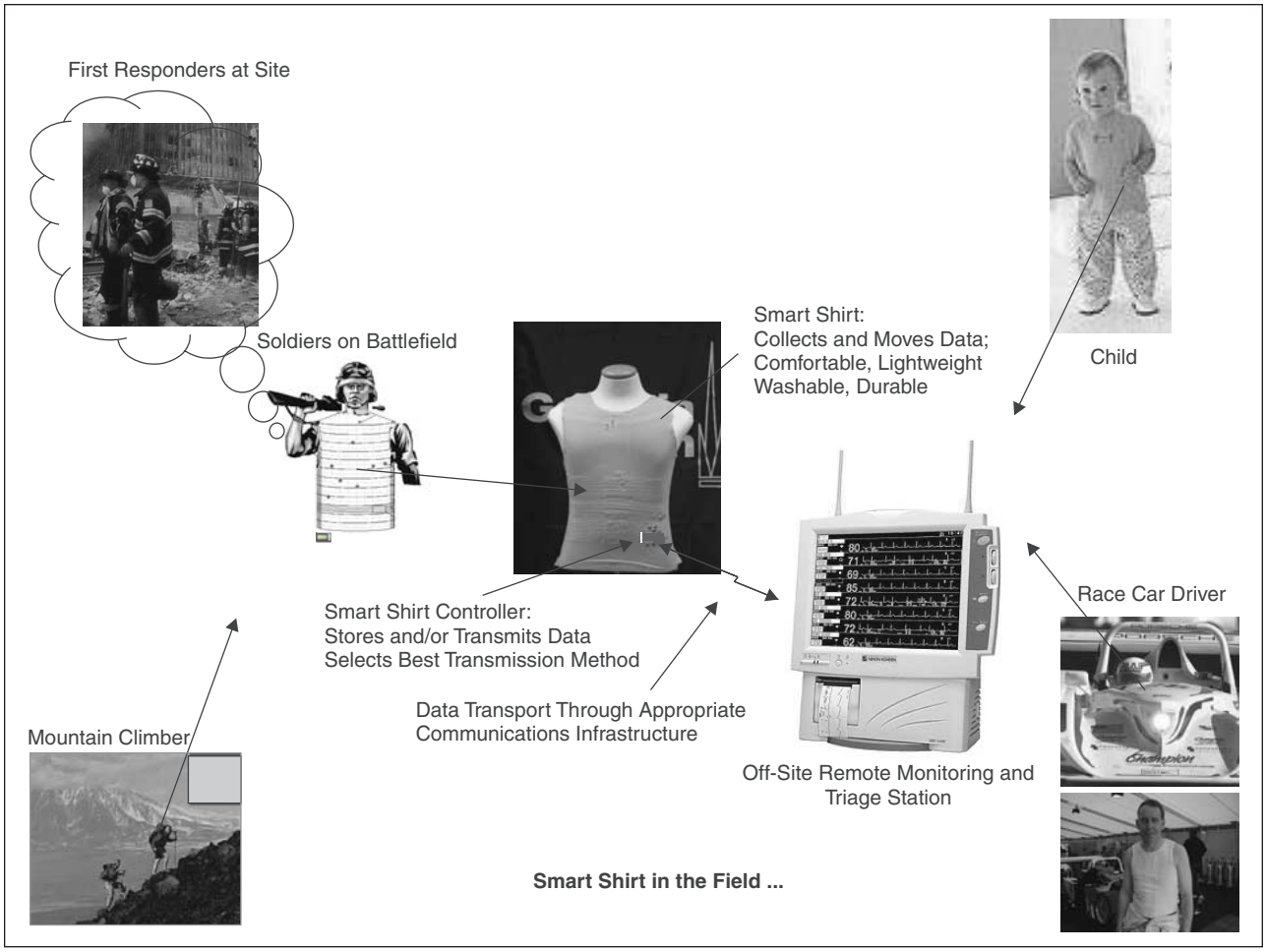

Fig. 5. Smart Shirt in various fields of application.

nient and easy access to healthcare specialists without having to travel, thereby minimizing overall healthcare costs. In the future, the physical boundaries and distances that limit a specialist's healing area could potentially disappear and patients can indeed access *any* specialist they desire in *any* part of the world. In fact, taken one step further, this approach could potentially lead to a network of "specialty" centers around the world where each hospital could focus on a particular area of medicine rather than attempt to excel in *all* the specialties—a new paradigm of medicine and healthcare delivery.

The Smart Shirt technology has the means to provide unobtrusive monitoring for individuals and can therefore play a critical role in disease management for the large numbers of individuals at risk for high blood pressure, heart disease, diabetes, chronic bronchitis, and depression by enabling *early, systematic intervention*.

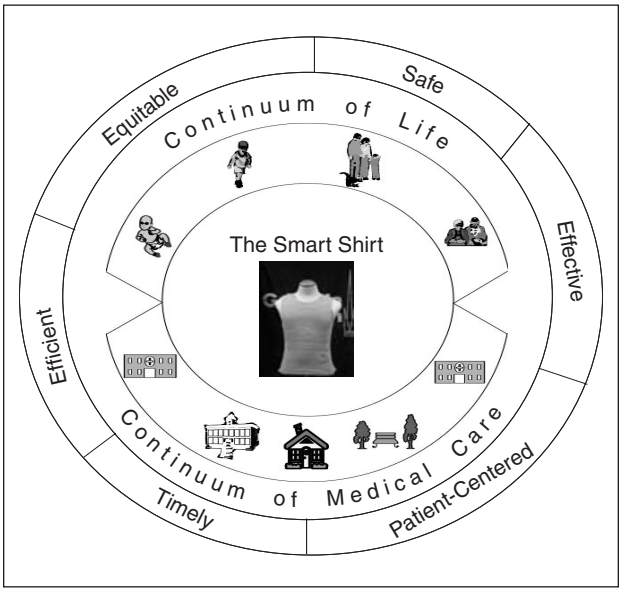

Fig. 6. Six aims for improvement in healthcare and the twin continua of life and medical care.

From: xxxxxxx@aol.com
Date: Sat, 19 Feb 2000 12:57:39 EST
Subject: Heart monitor t-shirt
To: sundaresan.jayaraman@textiles.gatech.edu
X-Mailer: AOL 5.0 for Windows sub 47

Dr. Jayaraman,

Hello. I recently read about your heart rate and breathing monitor t-shirt and wanted more information about it.

Will it be possible to purchase this equipment this Spring. We lost a son to SIDS and are expecting a second child near May. We have been told that the monitors available have a high false alarm rate and are not effective when the baby becomes mobile. We are petrified that we will not have a reliable system to monitor our second child to catch her in time to administer CPR.

We also wanted to know is the shirt adjustable? Will it grow with the baby. Our son was 10 months old, much older than the projected SIDS rate. Obviously the newborn shirt would not fit an older infant. Finally, how is it cleaned?

Thank you for your time. Your immediate response would be greatly appreciated.

Sincerely,
Mrs. xxxxxxxxx
xxxxxxx@aol.com

Fig. 7. The "value" of technology and quality of life.

Value of Technology

Figure 7 shows an example of a letter received from a parent that underscores the need for the Smart Shirt technology for medical applications such as SIDS. This indeed is the "value" that the technology provides. It is extremely hard to "quantify" this value. However, this type of response is not only gratifying to the authors but also serves as an impetus to make further contributions aimed at enhancing the quality of life for individuals.

Smart Shirt Technology and the Six Aims of the Healthcare System

The Smart Shirt technology can facilitate the realization of the six key aims for a healthcare system identified by the Institute of Medicine (see Figure 6). By focusing on the human or individual as an "information node," the Smart Shirt technology creates a "*patient-centered*" environment while collecting information from the wearer in a *timely* (and unobtrusive) manner; this information can be used to administer a treatment regimen that is *effective*, and the whole diagnosis-treatment-recover process will be more *efficient*—cost- and time-wise. By making the Smart Shirt technology easy to use and affordable, the healthcare system can indeed be made *equitable*. In other words, the Smart Shirt is a valuable information infrastructure that can facilitate the transformation of *information* to *knowledge* leading up to S^5 (Figure 1) and enhancing the quality of life for everyone.

Looking Ahead: Adaptive And Responsive Systems

By providing a "platform" for a suite of sensors that can be utilized to monitor an individual unobtrusively, the First Generation Smart Shirt technology opens up exciting opportunities to develop "adaptive and responsive" systems that can "think" and "act" based on the user's condition, stimuli, and environment [10]. Thus, the rich vital signs data stream (and resulting knowledge) from the Smart Shirt can be used to design and implement "real-time" feedback mechanisms (as part of the Smart Shirt System) to enhance the quality of care for the individual by providing appropriate and timely medical "intervention."

The Smart Shirt and Integrated Feedback Systems

Certain individuals are susceptible to *anaphylaxis* reaction (an allergic reaction) when stung by a bee or spider and need a shot of *epinephrine* (adrenaline) immediately to prevent serious illness or even fatalities. By applying advancements in MEMS (microelectromechanical systems) technology, a feedback system—including a drug delivery system—can be integrated into the Smart Shirt. Of course, mechanisms to guard against inadvertent administration of the drug can be built as part of the control system.

Likewise, the Smart Shirt's data acquisition capabilities can be used to detect the condition when an individual is lapsing into a diabetes shock and the integrated feedback mechanism can provide the appropriate response to prevent a fatality. Thus, the Smart Shirt represents yet another significant milestone in the endeavor to save and enhance the quality of human life through the use of advanced technologies.

Smart Shirt, Knowledge Banks, and Personal Privacy

As with any advanced information technology, invasion of personal privacy becomes a very big concern and the Smart Shirt is no exception. However, since the technology is in the form of a "garment," the user (or the caregiver, in the event the user is unable to make the choice due to age or mental incapacitation) must make the "deliberate" choice to put on the garment, and only then can the data be monitored [11]. In other words, the user has *control* over personal privacy. Advances in telecommunications technology are addressing other across-the-board issues such as data integrity, data latency, and data security, and these will not be unique to the use of the Smart Shirt technology. The user (i.e., the patient) will have the right to grant access to the appropriate individuals such as physicians, hospitals, and insurance companies.

The ease with which personal data can be collected in real time using the Smart Shirt will result in the creation of "knowledge banks" of human performance; this knowledge base can be used in clinical and pharmaceutical research potentially leading to new treatments, drugs, and drug delivery systems. These benefits should be weighed in the context of potential invasion of personal privacy. Similar issues arise with the Human Genome project. Therefore, there is a critical need for a major initiative that brings together experts from the medical, insurance, and legal communities to address this important facet of advanced technologies so that society can harness the benefits from technological advancements and enhance the quality of life without sacrificing an individual's most prized possession; i.e., personal privacy.

Concluding Remarks

The Smart Shirt is an effective, comfortable, and mobile information infrastructure that can be *tailored* to the individual's requirements to take advantage of the advancements in telemedicine and information processing. Just as special-purpose chips and processors can be plugged into a computer motherboard to obtain the required information processing capability,

TABLE 1. The Wearable Motherboard/Smart Shirt: Potential applications.

Segment	Application Type	Target Audience
Military	Combat Casualty Care	Soldiers and Support Personnel in Battlefield
Civilian	Medical Monitoring	Patients: Surgical Recovery, Psychiatric Care
		Senior Citizens: Geriatric Care, Nursing Homes
		Infants: SIDS prevention
		Teaching Hospitals and Medical Research Institutions
	Sports/Performance Monitoring	Athletes, Individuals
		Scuba Diving, Mountaineering, Hiking
Space	Space Experiments	Astronauts
Specialized	Mission Critical/Hazardous Applications	Mining, Mass Transportation
Public Safety	Fire-fighting	Firefighters
	Law Enforcement	Police
Universal	Wearable Mobile Information Infrastructure	All Information Processing Applications

the Smart Shirt is an information infrastructure into which the wearer can "plug in" the desired sensors and devices, thereby creating a system for monitoring vital signs in an efficient and cost-effective manner with the "universal" interface of clothing. This "fabric is the computer" paradigm—exemplified by the Smart Shirt—demonstrates the feasibility of realizing personalized mobile information processing (PMIP) and sets the stage for transforming healthcare in this new millennium.

Advanced technologies such as the Smart Shirt have the potential to dramatically alter the landscape of healthcare delivery and the practice of medicine as we know them today. By enhancing the quality of life, minimizing "medical" errors, and reducing healthcare costs, the patient-centric wearable information infrastructure can play a critical role in realizing the future healthcare system envisioned by the Institute of Medicine. Just as the spreadsheet pioneered the field of information processing that brought "computing to the masses," it is anticipated that the Smart Shirt will bring personalized and affordable healthcare monitoring to the population-at-large, thus leading to the realization of "Affordable Healthcare, Anyplace, Anytime, Anyone."

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Sungmee Park is a research associate in the School of Textile and Fiber Engineering at the Georgia Institute of Technology in Atlanta, Georgia. Park received an M.S. degree from Georgia Tech in 1995 for her work on the comfort properties of fabrics and joined the School as a research associate. In 1993, she received an M.F.A. (Master of Fine Arts) from Georgia State University in Atlanta, Georgia. At Georgia Tech, she has been working on product design and development projects including specialty fabrics for the Atlanta Ballet and the Smart Shirt. The fabric produced for the Atlanta Ballet has been premiered in productions of the Ballet. Park's other significant contribution has been to the realization of the world's first Wearable Motherboard™. also known as the "Smart Shirt." This invention was featured in a special issue of *Life Magazine* titled "Medical Miracles for the New Millennium" (Fall 1998) as "One of the 21 Breakthroughs that Could Change Your Life in the 21st Century." In November 2001, *Time Magazine* named the Smart Shirt one of the "Best Inventions of the Year 2001." Park's publications include journal articles, book chapters, and patents. She also received "Honorable Mention" in the upholstery fabric design competition organized by the Carnegie Foundation in 1992.

Sundaresan Jayaraman is a professor of textile engineering at the Georgia Institute of Technology in Atlanta, Georgia. He and his research students have made significant contributions in the following areas: i) enterprise architecture and modeling methodologies for information systems; ii) engineering design of intelligent textile structures and processes; iii) design and development of knowledge-based systems (KBS) for textiles and apparel; and iv) multimedia educational systems. His group's research has led to the realization of the world's first Wearable Motherboard™ – the "Smart Shirt." He holds the Ph.D. degree from North Carolina State University and the M.Tech and B.Tech degrees from the University of Madras, India. He was involved in the design and development of TK!Solver, the first equation-solving program from Software Arts, Inc., Cambridge, Massachusetts. Dr. Jayaraman worked as a product manager at Software Arts, Inc., and at Lotus Development Corporation, Cambridge, Massachusetts, before joining Georgia Tech in the fall of 1985. He is a recipient of the 1989 Presidential Young Investigator Award from NSF for his research in the area of computer-aided manufacturing and enterprise architecture. In October 2000, Professor Jayaraman received the Georgia Technology Research Leader Award from the state of Georgia.

Address for Correspondence: Sundaresan Jayaraman, Georgia Institute of Technology, Textile Information Systems Research Laboratory, School of Textile and Fiber Engineering, Atlanta, GA 30332-0295 USA. Tel: +1 404 894 2490. Fax: +1 404 894 8780. Web: http://www.smartshirt.gatech.edu.

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