

**MOBILE WEARABLE
NANO-BIO HEALTH
MONITORING
SYSTEMS WITH
SMARTPHONES AS
BASE STATIONS**

**Vijay K. Varadan and
Linfeng Chen**

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Series Editors' Preface

Biomedical and Nanomedical Technologies (B&NT)

This **concise** monograph series focuses on the implementation of various engineering principles in the conception, design, development, analysis and operation of biomedical, biotechnological and nanotechnology systems and applications. The primary objective of the series is to compile the latest research topics in biomedical and nanomedical technologies, specifically devices and materials.

Each volume comprises a collection of invited manuscripts, written in an accessible manner and of a concise and manageable length. These timely collections will provide an invaluable resource for initial enquiries about technologies, encapsulating the latest developments and applications with reference sources for further detailed information. The content and format have been specifically designed to stimulate further advances and applications of these technologies by reaching out to the non-specialist across a broad audience.

Contributions to *Biomedical and Nanomedical Technologies* will inspire interest in further research and development using these technologies and encourage other potential applications. This will foster the advancement of biomedical and nanomedical applications, ultimately improving healthcare delivery.

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Preface

Due to the rapid advances in nanotechnology, telecommunication and information technologies, efficient and reliable telemedicine (also known as remote point of care or remote healthcare), which has been a holy grail in medicine, is coming into practice. It is expected to significantly improve the quality of healthcare while reducing the costs, especially for patients with chronic illnesses, such as neurological, metabolic, and cardiovascular disorders which require constant long term untethered monitoring, as well as patients discharged after an operation or serious medical crises. It eliminates the distance barriers in medicine. Vital information about a patient, who lives far away from medical support, can be acquired by the medical staff. More importantly it saves lives in critical care and emergency situations by alerting medical staff if there is a dangerous change in patient status.

This monograph discusses the development and application of mobile wearable nano-bio health monitoring systems for telemedicine. In such a system, nanomaterials-based biosensors are used to measure physiological signals, such as electrocardiogram (ECG), electroencephalogram (EEG), electromyogram (EMG), and electrooculogram (EOG). The obtained physiological signals are filtered, amplified and transmitted to a remote storage server, utilizing Smartphones as base stations. Cloud computing resources are used for complex computations, such as feature extraction and automatic diagnosis. The information in the remote storage server can be instantly accessed by healthcare providers, and medical advice can also be sent instantly to the patient through the wireless communication system.

This monograph consists of six chapters. The first chapter starts with the evolution of health monitoring. The basic architecture of a mobile health monitoring system is discussed subsequently, followed by the applications of Smartphones for healthcare. Following this, smart textile based wearable health monitoring systems are discussed.

Chapters 2 and 3 discuss the technologies for the development of mobile wearable nano-bio health monitoring systems. Chapter 2 deals with the development of nano-bio sensors for health monitoring, which exhibit attractive advantages over the conventional physiological sensors. After introducing the typical physiological signals for health monitoring, bioelectric sensors based on carbon nanotubes and metal nanowires, respectively, are discussed, followed by cuffless blood pressure sensors. Chapter 3 discusses the telecommunication and information technologies for mobile health monitoring systems, and the discussion is concentrated on signal transmission and receiving, and the relaying of signals by Smartphones. Following this, e-Nanoflex is discussed as an example of the telecommunication and data processing system.

Chapter 4 discusses the development of smart textile based wearable health monitoring systems. After introducing the concept of smart textiles, printable electronics are discussed, followed by textile sensor technology. Subsequently, the roll-to-roll techniques for the fabrication of smart-textile based health monitoring systems are discussed.

Four case studies are given in Chapter 5. These are cardiac health monitoring, e-bra for ECG measurement for women, smart vest for ECG and blood pressure measurement for men, and diagnosis of sleep apnea.

In Chapter 6, a brief summary is made on the transformation of healthcare practices due to mobile wearable health monitoring systems, and the technical challenges for the development and application of mobile wearable health monitoring systems are discussed.

The development of mobile wearable health monitoring systems for telemedicine is an interdisciplinary field, mainly involving nanotechnology, electrical and electronic engineering, information technology, biology and medicine. The authors have many years of research experience in this field. This monograph is prepared mainly based on the authors' research results, and some of the technical details are released for the first time. Meanwhile, the major achievements and the latest progress in this area are reviewed in the monograph.

The authors greatly appreciate the contributions from Pratyush Rai, Prashanth Kumar, Sechang Oh, Hyeokjun Kwon and Nilanjan Banerjee. These people spent a lot of time and effort in the design and implementation of various types of mobile wearable health monitoring systems, and their careful comments greatly improved the contents of this monograph.

This monograph can be a textbook for a short training course on telemedicine, as well as a reference for nanotechnology courses for graduates and senior undergraduates in the fields of electrical and electronic engineering, materials sciences and engineering, physics, chemistry, biology, and medicine. Engineers and healthcare practitioners who are interested in telemedicine will also find this monograph a useful reference.

Author Biographies

Vijay K. Varadan is currently the Twenty-First Century Endowed Chair in Nano-and Bio-Technology and Medicine, and Distinguished Professor of Electrical Engineering and Distinguished Professor of Biomedical Engineering (College of Engineering) and Neurosurgery (College of Medicine) at University of Arkansas. He is also a Professor of Neurosurgery at the Pennsylvania State University College of Medicine. He also holds honorary doctorate degrees in Nano-, and Bio-Technologies and Medicine from India. He joined the University of Arkansas in January 2005 after serving on the faculty of Cornell University, Ohio State University and Pennsylvania State University for the past 39 years. He is also the Director of the Center of Excellence for Nano-, Micro-, and Neuro-Electronics, Sensors and Systems and the Director of the NSF Center for Wireless Nanosensors and Systems (WiNS). He is also a Director of the Global Institute of Nanotechnology in Engineering and Medicine (GINTEM). The purpose of this Institute is to create a global effort to solve current and future medical concerns using advanced nanotechnologies by developing Research Hospitals at selected overseas countries. Varadan has concentrated on the design and development of various electronic, acoustic and structural composites, smart materials, structures, and devices including sensors, transducers, Microelectromechanical Systems (MEMS), synthesis and large scale fabrication of carbon nanotubes, NanoElectroMechanical Systems (NEMS), microwave, acoustic and ultrasonic wave absorbers and filters. He has developed neurostimulator, wireless microsensors and systems for sensing and control of Parkinson's disease, epilepsy, glucose in the blood and Alzheimer's disease. He is also developing both silicon and organic based wireless sensor systems with RFID for human gait analysis and sleep disorders and various neurological disorders. He was a founder and the Editor-in-Chief of the Journal of Smart Materials and Structures. He was the founder and Editor-in-Chief of the Journal of Nanotechnology in Engineering and Medicine. He is currently the Editor-in-Chief of the Journal of Smart Nanosystems in Engineering and Medicine, and Editor of the Journal of Advanced Materials Research. He is an Associate Editor of the Journal of Microlithography, Microfabrication and Microsystem. He serves on the editorial board of International Journal of Computational Methods. He has published more than 500 journal papers and 15 books. He has 15 patents pertinent to conducting polymers, smart structures, smart antennas, phase shifters, carbon nanotubes, and implantable device for Parkinson's patients, MEMS accelerometers and gyroscopes. He is a fellow of SPIE, ASME, Institute of Physics, Acoustical Society of America. He has many visiting professorship appointments in leading schools overseas.

Linfeng Chen received his B. Sc. degree in modern applied physics (major) and his B.Eng. degree in machine design and manufacture (minor) from the Tsinghua University, Beijing, China, in 1991, and he received his Ph.D. degree in physics from the National University of Singapore in 2001. From 1991 to 1994, he was an assistant lecturer at the Department of Modern Applied Physics, Tsinghua University, Beijing, China. From 1994 to 1997, he was a research scholar with the Department of Physics, National University of Singapore. From 1997 to 2001, he worked at the DSO National Laboratories, Singapore, as a project engineer and later a member of technical staff. From 2001 to 2005, he was a research scientist at the Temasek Laboratories, National University of Singapore. Since 2005, he has been a member of research faculty at the Department of Electrical Engineering, University of Arkansas, Fayetteville. He is a senior member of IEEE. His research interests mainly include microwave electronics, functional nanomaterials, and energy harvesting and storage devices.

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Abstract

This monograph discusses the development and application of mobile wearable nano-bio health monitoring systems for telemedicine. In such a system, nanomaterials-based biosensors are used to measure physiological signals, such as electrocardiogram (ECG), electroencephalogram (EEG), electromyogram (EMG), and electrooculogram (EOG). The obtained physiological signals are filtered, amplified and transmitted to a remote storage server, utilizing Smartphones as base stations. Cloud computing resources are used for complex computations, such as feature extraction and automatic diagnosis. The information in the remote storage server can be instantly accessed by healthcare providers, and medical advice can also be sent instantly to the patient through the wireless communication system.

1. Introduction

1.1 Evolution of health monitoring

Continuous health monitoring is essential for recuperating patients and patients with chronic health conditions. It can be used in judging whether an individual is in a physiological state suitable for his duties, and it is also useful for people of all age groups who have possible health problems or have opted for a healthy lifestyle.

Chronic diseases can be effectively controlled if they are diagnosed at their early stages and they are regularly monitored with proper medication cares and guides [1]. For example, detection of cardiac arrhythmias from continuous electrocardiogram (ECG) recordings is an important approach that physicians use to adjust medication for post myocardial infarction patients. Common chronic neurological disorders, such as epilepsy and Alzheimer's disease, can be identified from electroencephalogram (EEG) recordings. The changes in brain function may occur several hours before any clinical manifestation in patients with progressive brain ischemia, or in patients suffering from vasospasms after a subarachnoid hemorrhage. These events are important parts of a patient's health history, and the detection and recording of these events play a key role in the risk stratification process used by physicians to plan treatments. Therefore, continuous real time monitoring is a valuable tool that can help both diagnosis and treatment planning.

Many accidents, which have frequently happened on aircraft, high-speed passenger trains, long-range highway express buses and so on, were caused by the operational errors of the pilots or drivers [2]. Most of the operational errors were due to the high mental stress or drive dozing of the pilots or drivers, and some of them were diagnosed as sleep apnea syndrome (SAS). Diseases such as SAS and sudden infant death syndrome (SIDS) mostly happen while an individual is in sleep or in an unconscious condition. These diseases are generally difficult to detect by physicians without a continuous monitoring of the change in a person's vital signs. Therefore, close and continuous monitoring is needed, which can assist healthcare providers to identify whether a patient is in a healthy condition.

The concept of continuous health monitoring can be translated as point-of-care (POC) technology for preventive/corrective medicine, and as metabolic rate estimation and regulation in healthy lifestyle. POC testing is also known as ancillary testing, near-patient testing, and bedside testing. A classical definition of POC testing is "diagnostic testing performed at or near the site of patient care", and it is also defined as "analytical patient testing activity provided within the institution but performed outside the physical facilities of the clinical laboratories" [3].

A currently available system for POC monitoring consists of wired sensors which need to be manually mounted on a patient. Such a system has

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three obvious drawbacks. First, complete health monitoring needs multiple sensors to detect various physiological signals, such as ECG, EEG, electromyogram (EMG), electroculogram (EOG), pulse oximetry, air flow pressure, and respiration effort, and wiring these sensors to one monitoring unit is cumbersome and highly intrusive. Second, these sensors use customized data transmission hardware and software that cannot be easily integrated into a patient's quotidian life, and the individual has to carry a special device for data collection. Third, the sensors used in a majority of these systems are not wearable.

A conventional POC testing usually requires the transportation of instruments to the patient's premises for data collection at certain regular intervals. This traditional approach to POC systems usually involves frequent visits by healthcare personnel to the patient's vicinity for diagnosis. During these visits, the healthcare personnel usually record the patient's vital signs and take decisions as to any changes in the treatment and address any issues that the patient may have. Obviously this involves large expense in addition to the inconvenience caused to the patient in terms of the time spent and the intervention with daily life.

A higher quality of life is now expected by patients, even when suffering from various chronic diseases. Patients generally want to be treated at home and with as little pain and discomfort as possible. Society needs to reduce the increasing cost of medicine while also improving the quality of healthcare [4]. This implies a development of alternative solutions to the traditional hospital methods for disease prevention and health monitoring. Cost-efficient access to the best care and illness prevention can empower each individual and enable him/her to have a longer and healthier life.

Remote patient monitoring (RPM) is an emerging area of telemedicine, which includes devices and technology that enable healthcare providers to remotely diagnose, treat, and advise patients. RPM systems usually monitor a patient's vital signs, which could include ECG, EEG, respiration rate, blood pressure and temperature, depending upon the condition to be monitored. Such a system can obviate the need for repeated visits to the hospital. Moreover, the continuously monitoring of human physiology by such a system can provide valuable data to prognosticate the onset of critical health problems.

Recently, the concept of body area network (BAN) was proposed [5]. It is defined as a network of independent wireless nodes that span the personal space of a user. As an ultimate objective of BAN, the independent sensors for physiological signals, such as ECG, EOG, EMG, pulse rate, blood oxygen saturation, temperature and respiration, will send data through their wireless transmitters, to a single receiving station which may be a Smartphone, a personal digital assistant (PDA), a personal computer (PC), or a custom receiver unit. Various wireless communication protocols can be used, such

as Bluetooth, ZigBee, and custom communication protocols for low power transmission of data.

A mobile wearable health monitoring system is a truest embodiment of the BAN concept [6]. Its body worn sensors (slaves) communicate with a single receiver unit (master) and transmit time synchronized data in real time. Mobile wearable health monitoring systems represent a new generation of healthcare by providing real-time unobtrusive health monitoring through the on-body sensors [7, 8].

Besides monitoring physiological parameters [9], a wearable health monitoring system can also be designed for monitoring body motions [6, 10–12]. The monitoring of human movement is important for the clinical applications of fall detection, fall risk assessment, and energy expenditure. The importance of these applications is considerable in light of the global demographic trends and the resultant rise in the occurrence of injurious falls and the decrease of physical activity [6]. The use of wearable motion sensing technology offers important advantages over conventional methods for obtaining measures of physical activity and/or physical functioning in individuals with chronic diseases. Having the capability to track human body kinematics allows clinicians to classify and analyze a stroke patient's progress which aid in the rehabilitation program. Monitoring and capturing real time body motion further permits corrective measures to be implemented for more effective rehabilitation results [11].

A considerable amount of research has been made on mobile wearable health monitoring systems, and encouraging progress has been achieved. This monograph aims to report the latest advances in the development of mobile wearable nano-bio health monitoring systems, and more information on in this field can be found in books [13, 14], reviews [10, 15–17], and numerous papers and presentations.

1.2 Architecture of a mobile health monitoring system

In this section, the e-Nanoflex platform developed by Varadan et al. [18] is used as an example for discussing the basic architecture of a mobile wearable health monitoring system. This platform is capable of monitoring the health condition of a patient wherever he/she may be and communicating the data in real time to a physician or a hospital. Unlike the conventional health monitoring systems that either are local sensor systems or rely on custom relaying devices, e-Nanoflex is a highly nonintrusive and inexpensive end-to-end cyber-physical system. Using nanostructured sensors, e-Nanoflex provides nearly invisible monitoring of physiological conditions. It relies on Smartphones to filter, compress, and relay geo-tagged data. Further, it ties to a backend cloud infrastructure for data storage, data dissemination, and abnormality detection using machine learning techniques. An e-Nanoflex is a complete system for physiological sensing and geo-tagged data dissemination to hospitals and caregivers. It is a basic platform that can support any

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nanostructure based flexible sensors for monitoring a variety of conditions such as body temperature, respiration air flow, oxygen consumption, bio-electric signals, pulse oximetry, muscle activity, and neural activity.

Advances in medical nanotechnology coupled with rapid development in Smartphones and cloud computing offer significant advantages over existing systems. Nanosensors offer the unique advantage of small size and high sensitivity that makes them ideally suited for everyday use as they bear no conspicuous presence. Additionally, a Smartphone can be used to relay health and activity monitoring data from these user worn devices to a cloud resident server. As shown in Figure 1-1, an e-Nanoflex system can seamlessly integrate nanobiosensors with Smartphone relays and backend cloud services to provide continuous health monitoring to patients.

As a basic platform, an e-Nanoflex can support a variety of sensors, such as nanostructure based flexible gas sensors, as well as carbon nanotube (CNT) based flexible strain and temperature sensors. Figure 1-2 shows an application example of an e-Nanoflex for monitoring respiration effort using a sensor incorporated in a band aid, which will be discussed further in Section 3.5. Other physiological signals, such as EOG, EEG, ECG and pulse rate, can also be monitored when corresponding sensors are used. More application examples can be found in the case studies discussed in Chapter 5.

An e-Nanoflex sensor system integrates a Bluetooth radio module, amplifier, and sensor in a compact medical plaster form. The system is easy to use and the sensors can be simply placed on the skin at appropriate positions, such as the limb lead positions for ECG. The data from the sensors are streamed to a backend cloud through a Smartphone. While initial

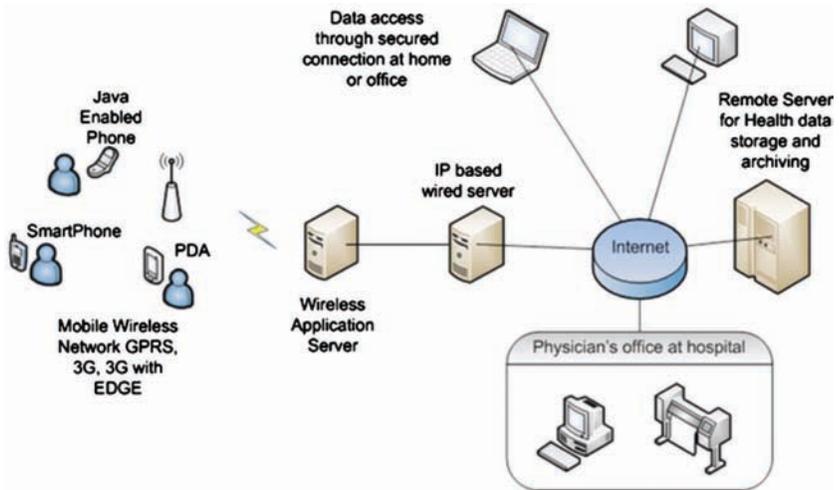


Figure 1-1 Data flow from e-Nanoflex sensors to remote storage servers.

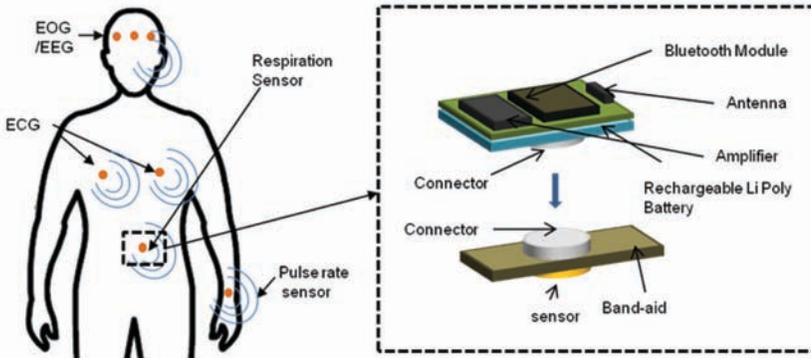


Figure 1-2 Monitoring of respiration effort using a sensor incorporated in a band aid.

filtering occurs locally at the Smartphone, most of the complex processing is delegated to the cloud. Such a partitioning approach has a two-fold advantage. First, sophisticated computationally intensive signal conditioning algorithms, such as adaptive filters, are best implemented on a server capable of cloud computing. Second, in anticipation of a large scale deployment, there will be multiple users sending data simultaneously and cloud storage is indispensable to handle such large volumes of data. Additionally, an alert message to a physician’s phone or a message to the nearest emergency response service can be sent if any anomaly is detected by the cloud server. The Smartphone can also be programmed to automatically capture a video during a cardiac episode so that paramedics can be better prepared.

The data from the e-Nanoflex sensors can be displayed on the Smartphone, as shown in Figure 1-3 (a), so that the user can check the status

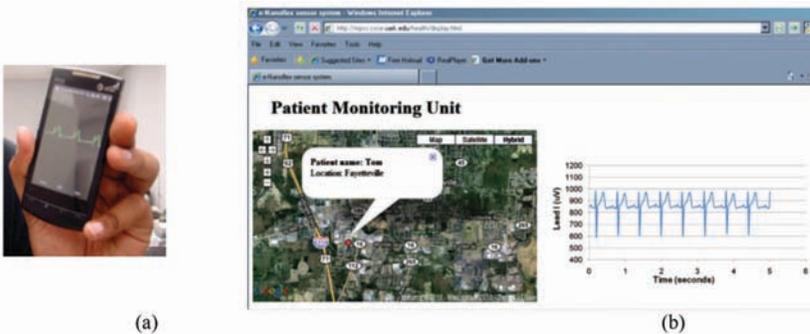


Figure 1-3 The data display, storage and recovery in an e-Nanoflex system. (a) A Smartphone displaying ECG data. (b) Snapshot of ECG data stored from a user and the corresponding location from which the data were sent.

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anytime. The data, tagged with the current GPS location and the time, are also sent to a remote server through the 3G network. In case of an emergency, a message with recorded data and current location and time can be sent to the emergency response team. As shown in Figure 1-3 (b), the location of the user and the data received from the sensor can be recovered from the server.

1.3 Smartphones for healthcare applications

In the e-Nanoflex platform discussed in Section 1.2, a Smartphone not only works as a base station, but also performs basic analysis on the raw data from the sensors.

Smartphones are mobile telephones that have computer-like functionality, which typically includes e-mail, Internet access, and increasingly, some sort of screen and keyboard that allow use of software designed for Smartphones [19]. They are actually minicomputers that have a telephone attached. The first Smartphone was the Simon, designed by IBM in 1992. The real start of the Smartphone, in terms of public exposure, occurred in 2001 with the Palm “Treo”, which had a full keyboard, wireless Web browsing, e-mail, calendar, and the ability to be synced with a computer to download third-party programs. In 2007, Apple released the iPhone, which had two primary innovations [19]. First, it used a touchscreen interface instead of a keyboard. The second significant innovation was not the device itself, but the App Store, a place where iPhone users could buy software designed specifically for the iPhone. Apple also opened the App Store to third-party designers and made a very low entry point, so small developers could participate.

Since Apple announced their mobile App Store in 2009, thousands of apps for the iPhone related to health or medicine have been developed [19]. The medically related Smartphone apps are not exclusive to the iPhone. Many companies that have developed medical applications for Smartphones are making them compatible for other brands as well, including Palm, Blackberry, Win Mobile, and Android.

Many healthcare providers are adopting Smartphones successfully in a diverse range of practices [19]. Several reasons make Smartphones attractive to healthcare providers. The primary reason is that many POC Smartphone apps have been developed. The second reason is that healthcare providers are mobile workers and a Smartphone provides a huge amount of information at their fingertips no matter where they are. Even when a healthcare provider is in his office, he is moving around a lot, not really stationed at his computer. Further, the multiple media aspects of Smartphones, along with connectivity and mobility can help a healthcare provider become more efficient. Meanwhile, patients are also getting used to accessing health information, actively participating in their own healthcare, and maintaining contact with their healthcare providers through Smartphones. In particular, chronic

conditions such as diabetes, mellitus and cardiovascular disease, are perceived as a special niche market for Smartphone apps. Therefore, Smartphones are starting a new epoch in healthcare, and there are significant opportunities to exploit the potential of Smartphones in healthcare [20].

1.4 Smart textile based wearable health monitoring systems

Due to the advances in nanotechnologies, telecommunication, low-power design, new textiles, and flexible sensors, new user-friendly devices have been developed to enhance the comfort and security of a patient. As clothes and textiles are in direct contact with about ninety percent of the skin surface, smart sensors and smart clothes with noninvasive sensors are an attractive solution for home-based and ambulatory health monitoring [4].

Although it started off as an effort to address battlefield needs, the creation of a wearable information infrastructure, in the form of a smart shirt, opened up entirely new frontiers in civilian healthcare, including monitoring of firefighters at a fire scene, patients in hospitals or at home recovering from illnesses/surgeries, infants prone to cot death or sudden infant death syndrome (SIDS), or athletes in training or competition [21].

The field of smart textile-based wearable healthcare monitoring systems has been generating a lot of interest in the research and business communities, with the aim of getting the technology into the marketplace [2, 22]. For example, Coyle et al. developed a wearable sensing system that integrates a textile-based fluid handling system for sample collection and transport with a number of sensors including the sensors for sweat rate, ECG, respiration, and blood oxygenation [23]. It can be used to monitor a number of physiological parameters together with sweat composition in real time. This has huge implications for the field of sports and human performance and opens a new field of research in the clinical setting.

Smart textile based wearable health monitoring systems can greatly enhance home healthcare and disease prevention [4]. For healthy subjects, the system will not only help the user to adopt a healthier lifestyle, but will also effectively improve personal performances due to better fitness and more effective ways of coping with stress. For individuals at risk of diseases, the system will provide adequate information on how to deal with individual risk factors like hypertension, obesity, diabetes, physical inactivity, and stress through personalized training plans. Early detection through long-term trend analysis will dramatically reduce the potential damages of severe events. For post-event patients, this system can significantly improve the rehabilitation process, and can detect possible complications at their early stages. Daily monitoring will enable new forms of personalized drug treatment and the self-administration of drug medication, according to the specific behaviors and circumstances of each individual. For chronic patients, intelligent biomedical clothes empower the user to better understand and self-manage the

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disease state. Early detection by continuous long-term monitoring is helpful for avoiding the occurrence of acute events and complications that may lead to hospitalization and extended hospital treatments.

This monograph consists of six chapters. After the introductory chapter, Chapter 2 discusses nanotechnology-based biosensors for health monitoring, and Chapter 3 discusses the telecommunication and information technologies for mobile health monitoring systems. Chapter 4 discusses the development of smart textile based wearable health monitoring systems. Four case studies are given in Chapter 5. In Chapter 6, perspectives and major technical challenges in the development and application of mobile wearable health monitoring systems are discussed.