Review

Emerging Trends in Healthcare Adoption of Wireless Body Area Networks

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Abstract
Real-time personal health monitoring is gaining new ground with advances in wireless communications. Wireless body area networks (WBANs) provide a means for low-powered sensors, affixed either on the human body or in vivo, to communicate with each other and with external telecommunication networks. The healthcare benefits of WBANs include continuous monitoring of patient vitals, measuring postacute rehabilitation time, and improving quality of medical care provided in medical emergencies. This study sought to examine emerging trends in WBAN adoption in healthcare. To that end, a systematic literature survey was undertaken against the PubMed database. The search criteria focused on peer-reviewed articles that contained the keywords “wireless body area network” and “healthcare” or “wireless body area network” and “health care.” A comprehensive review of these articles was performed to identify adoption dimensions, including underlying technology framework, healthcare subdomain, and applicable lessons-learned. This article benefits healthcare technology professionals by identifying gaps in implementation of current technology and highlighting opportunities for improving products and services.

Advances in information and communication technology have made real-time transmission of biological information a possibility. From a healthcare delivery perspective, this has opened up avenues for efficient monitoring by increasing patient mobility while also facilitating a geographically agnostic monitoring facility. From a patient perspective, the benefits include improved quality of care and cost savings.

The Institute of Electrical and Electronics Engineers (IEEE) 802.15 standard defines a body area network (BAN) as “a communication standard optimized for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics/personal entertainment and others.” Numerous definitions of WBAN have been put forth, including: “A special purpose sensor network designed to operate autonomously to connect various medical sensors and appliances, located inside and outside of the human body.” Miniature devices containing sensor nodes that monitor biological and physiological signals are affixed either on the human body or in vivo, and the resultant data are processed and transmitted wireless.

Figure 1 shows a typical configuration of a WBAN. Several sensor nodes are placed on or implanted within the human body. They monitor, capture, and transmit biometric measurements (e.g., electrocardiogram [ECG] data, blood pressure values, glucose
levels, limb movements) to an on-body “control” unit, usually termed a “body coordinator.” This device in turn assimilates and transmits data over a wireless local area network, wide area network, or the Internet to a remote healthcare monitoring facility, thus generating an end-to-end wireless communication system.

Although numerous literature reviews focus on WBAN implementations to solve a specific healthcare problem, no comprehensive literature surveys summarize WBAN applications across a breadth of healthcare domains, highlight emerging WBAN technology trends in this context, and discuss overlapping concerns. Therefore, the current article seeks to holistically educate readers on these three aspects.

Methods
The aim of this study was to survey trends in WBAN adoption within healthcare from the perspective of the healthcare domain in which it was adopted and the relevant WBAN technology framework(s) used. A systematic literature review was conducted using PubMed. The search criteria focused on peer-reviewed articles that contained the keywords “wireless body area network” and “healthcare” or “wireless body area network” and “health care.” Articles that primarily reviewed evolving WBAN technology protocols but did not emphasize its relevance in solving a healthcare problem were excluded from the review. This eliminated 20 results and reduced the review set to 63 articles. Findings from articles that met these criteria are reviewed in subsequent sections.

Results
Figure 2 shows the distribution by types of articles, and Table 1 summarizes the articles by category. Figure 3 represents key themes from the healthcare and WBAN technology context that appeared in the literature survey. Each is discussed in the next section.

Discussion
WBAN technologies are enabling advances in a broad range of healthcare domains. Trends with respect to healthcare adoption are discussed below.
Healthcare Context

Ambient Intelligence. Ambient intelligence is the paradigm of empowering people's capabilities by means of digital environments that are sensitive, adaptive, and responsive to human needs, habits, gestures, and emotions. Acampora et al. surveyed the emergence of ambient intelligence in the healthcare domain, along with the technology required to achieve this goal. They discuss the increased use of ambient intelligence in continuous behavioral monitoring of assisted-living patients, therapy and rehabilitation, and persuasive and emotional well-being monitoring. All of this is enabled through WBAN-enabled body sensors, including accelerometers, gyroscopes, humidity and temperature sensors, pulse oximetry, and carbon dioxide gas sensors.

Inferring human activities is at the core of ambient intelligence. To that end, Martínez-Pérez et al. developed the eStimating aCtivities based on Artifact's behavior aNalysis (SCAN) framework, which recognizes human activity through the handling of artifacts (i.e., items that have electronic devices embedded in them to gather information automatically). SCAN leverages a combination of accelerometers, computer vision, and radio frequency identification (RFID) technologies to recognize artifacts that are integrated with the “roaming beat” concept (i.e., capturing a set of images during a time frame when an activity is performed). This framework was implemented in a healthcare setting in Mexico to characterize caregiver activities for elders affected by Alzheimer’s disease and dementia. Data gathered over a four-month period enabled the authors to infer 74 of 81 recorded activities correctly. The activities were categorized as feeding, measuring blood pressure, hygiene, and taking medication. This work highlights the importance of using sensors that are not affixed to the human body but can be used to transmit information about the environment in an intelligent manner.

Costa et al. presented a case study of the Ambient Assisted Living for All project, the goal of which was to develop a novel ambient assisted-living environment that would provide a platform for interoperable hardware devices and software in a home environment. By incorporating artificial intelligence into the environment-software cycle that exists in typical sensor systems, the

![Figure 2. Categorization of articles included in the review](image-url)
installed networks can learn human behavior and, over time, perform desired actions without human intervention. Such systems have the potential to supplement care for the elderly or physically impaired.

**Cardiopulmonary Monitoring and Chronic Disease Management.** Zito et al.\(^{20}\) presented a novel wearable wireless interface for monitoring heart beat and breath rates. An ultrawide band radar sensor and a lower-power radio interface were embedded within a garment that detected, recorded, and transmitted data to a remote acquisition unit. Such data could potentially be transmitted over the Internet to a remote server. This intervention could prove valuable in a healthcare setting, where physicians could remotely monitor patient physiological data. Other authors have surveyed literature or developed prototypes using WBAN and complementary technology to more efficiently acquire ECG and other patient vitals, as well as integrate data with smart sensing systems, telemedicine hubs, and fourth-generation (4G) telecardiology.\(^{5,12,33,34,38}\)

Yilmaz et al.\(^{37}\) reviewed recent progress involving noninvasive monitoring technologies for managing chronic diseases such as diabetes. Impedance spectroscopy can be used to measure changes in electrical properties of blood noninvasively, which then can be translated to blood glucose readings through the use of an arm module affixed with electrode sensors.\(^{37}\) Another example is the monitoring of respiration of drivers by embedding a gauge in a seat belt. These technologies may currently lack the off-body transmission concept. The authors review complementary wireless communication protocols and antenna design, which when combined with the hitherto mentioned devices, are suitable for end-to-end WBAN applications.

**Fall Prevention and Detection.** Pannurat et al.\(^{47}\) define “fall” as “an event which results in a person coming to rest inadvertently on the ground or other lower level.” They performed an expansive review of currently available fall detection systems, categorized by sensor type used, number of distinct activities of daily living monitored, sensor placement on the human body, underlying technology and algorithms used, and the relative performance index of the technology and algorithms (several of which are enabled by WBANs).
In a related literature survey, Delahoz and Labrador stated that an estimated $43.8 billion will be invested in fall-related medical care by 2020. To minimize these costs, they emphasized the need to focus on fall prevention systems that go beyond just detection. To that end, they reviewed state-of-the-art external and wearable sensors for both fall detection and prevention. They explored the design aspects of camera-based, ambient, and wearable sensors, including those enabled by WBANs.

Felisberto et al. developed an open and distributed architecture based on a multiagent system to detect human movements, postures, and harmful activities including falls. Their prototype consisted of a custom-built sensor node that is sensitive to body movements, in conjunction with a WBAN acting as the communication medium. The experiments conducted to validate the prototype’s effectiveness to detect both hampered and unhampered falls were promising and warranted longer-term studies.

**mHealth.** Kartsakli et al. define mHealth as the use of mobile and wireless communication technologies to facilitate and improve healthcare and medical services. They conducted a comprehensive survey of machine-to-machine (M2M) communications that enable seamless device interaction without human intervention. An M2M ecosystem is described as one in which medical sensors are placed in the vicinity of or inside the human body; the sensors interface with an M2M gateway via a WBAN. The gateway collects and forwards sensory data over the Internet to remote servers for integration with other healthcare-related applications like electronic medical records. Some characteristics of WBAN sensors used in mHealth applications include deep brain simulation, hearing assistance, electromyography, and video imaging. Funded research projects for mHealth, such as HELP (Home-based Empowered Living for Parkinson’s disease patients), seek to control and/or mitigate Parkinson’s disease symptoms. The authors also review projects that aid in the recovery of patients with major depression, such as HelpMood.

Martínez-Pérez et al. reviewed the extant research literature and commercial applications for penetration of mobile applications to manage the eight most prevalent conditions published by the World Health Organization: iron-deficiency anemia, hearing loss, migraine, low vision, asthma, diabetes, osteoarthritis, and unipolar depressive disorders. In the context of using technologies like WBAN, wireless personal area networks, and RFID, they found that diabetes was the most investigated condition, followed by asthma and depression. An interesting finding was that there were far fewer literature review results than commercial application results, indicating that the current landscape for mHealth applications has more economic motivation than research motivation. Morón et al. investigated the capabilities and limitations of using smartphones in functioning as gateways between medical WBANs and remote servers.

**Managing Childhood Obesity.** The goal of the KNOWME network is to enable healthcare providers with access to real-time detection, classification, and monitoring of physical activity and other obesity-related behaviors to tailor individualized interventions. The KNOWME network includes a WBAN with a pair of tri-axial accelerometers, a heart rate monitor, and a mobile phone, forming a data collection hub that transmits data to a remote secure server. In response, the mobile phone interface can provide customized and instant text messages encouraging the patient to become more active when specific thresholds of sedentariness are reached.

Emken et al. cite reports of minority youth being at a higher risk of obesity, partly due to ethnicity. To address these challenges, they conducted a study where 20 overweight Hispanic youth aged 12 to 17 years were fitted with KNOWME networks and asked to perform a series of activities for a predetermined amount of time. Analysis of vital signs captured showed that KNOWME networks could distinguish basic movements, such as lying down, walking, and running, as well as differentiate between similar activities performed at different intensities (e.g., standing and fidgeting vs. standing and playing a computer simulation game like Nintendo Wii Tennis). Based on their findings, the authors believe that the
KNOWME networks can be trained to cater to multiple demographics, thereby delivering customized interventions.

High-Risk Infant Care. Movement recognition aims to capture and analyze relevant limb movements through computerized approaches focusing on continuous, objective, and quantitative assessment. Marcroft et al. cite challenges in detecting abnormal motor skill development in infants, including limited variation from generalized movements and limited fluency of occurrence. Detecting these subtle changes by humans alone requires considerable training. Against this backdrop, the investigators surveyed recent translational studies using movement recognition technology as a means to assess movement in high risk infants. They cited the emerging role of wearable movement sensors in measuring spontaneous movements and upper-limb acceleration and categorizing atypical movements of preterm infants, in some cases with additional complications like brain injury. While research and clinical trials in this domain are nascent, the researchers believe it holds long-term promise.

Stress Management. Wu et al. discussed the use of wearable medical devices in the applied field of psychophysiology called biofeedback, the focus of which is developing methodologies for controlling human emotions and releasing stress. To address the social problem of stress management and depression among the unemployed population, they designed a prototype biofeedback system along with a wearable sensor platform. A total of 67 participants aged between 20 and 45 years, 33 of whom were unemployed, were recruited for experimental studies. Over a period of several weeks, participants were fitted with the wearable biofeedback system and measurements recorded. Analysis of respiratory and heart rhythm patterns pre- and postexperiment validated that the cardiovascular system for unemployed participants recovered from the adverse effects of jobless stress triggered by modulation to their autonomic nervous system.

The above discussion underscores the enhanced role played by complementary wearable sensors coupled with WBAN and related technologies in delivering ubiquitous healthcare. However, it must be emphasized that several WBAN implementations cited above are in a prototype phase with lab simulation tests or limited experimental results with human subjects reported. To monetize these models for wider consumption would require the use of a formal product life cycle.

WBAN Context
While the previous section highlighted WBAN technology applications in healthcare, the following section presents emerging wireless technology paradigms that are finding prominence in use cases pertaining to healthcare.

Human Body Communication. The IEEE 802.15.6 standard recognizes human body communication (HBC) as a physical layer communication solution for the WBAN. Compared with the traditional wireless BAN, this paradigm uses the human body as the propagation medium. As a result, Nie et al.59 state concerns that need to be considered in HBC, including: 1) increased mobility, as both the sensor nodes and the data aggregation device are located either in or on the human body; 2) lower power consumption to synchronize sensor nodes, as they are separated by no more than arm-span length; 3) battery size for nodes, which must be small but at the same time have a life span of several months; and 4) the requirement for effective management of burst data in the aggregator, as a result of frequent triggering of physiological alerts.59 Considering these concerns, they have proposed a newer statistical frame-based time division multiple access (S-TDMA) protocol for use in HBC. Experimental evaluation of this protocol in relation to established protocols shows that S-TDMA demonstrates relatively lower energy consumption, has lower data latency, and a higher transmission-efficiency.

In a related study, Nie et al.53 modeled and characterized dynamic propagation channels using HBC to compare and contrast with challenges inherent in wireless propagation in WBANs due to motions of the human body. In situ experiments were conducted to investigate three HBC propagation channels (from right leg to left leg, from right hand to left hand, and from right hand to left leg)
under 33 distinct human body motion scenarios. The authors believed that this study is the first of its kind, with the results demonstrating that HBC is motion insensitive, lending itself as a reliable communication link during periods of human motions.

**Microelectromechanical Systems.** MEMS are mechanical and electromechanical elements developed through microfabrication techniques. The physical dimensions of MEMS devices range from less than 1 µm to several millimeters, making them ideal for use as body sensors in conjunction with WBANs. Acampora et al. cited increasing adoption in various sensors, including accelerometers, CO₂ gas sensors, and ECGs. More recently, MEMS is being used for developing textile-structured electrodes that can be embedded in clothing-related fabrics, making for a more comfortable and longer-term monitoring experience for patients while wearing clothes. Ciuti et al. surveyed MEMS technologies developed by Italian research centers for human-centered applications, with applications including Parkinson’s disease assessment, measurement of infant actions, management of remote patient-rehabilitation, and applications involving medical ultrasound.

**Mobile Augmented Reality.** Augmented reality is a complementary technology being integrated with WBANs for ubiquitous healthcare delivery. González et al. described augmented reality’s goal as “augment everything everywhere for everyone.” They presented an architecture for an end-to-end real-time remote heart rate monitoring system for patient care. The unique aspect of this initiative is that it provides the ability for nurses to remotely interact with digital information embedded within the patient’s physical environment. Using the prototype developed, healthcare personnel can remotely use a smartphone’s touch-screen option to access patient heart rate data. This is made possible with a combination of two- and three-dimensional computer vision and the DroidAR framework available for the Android Smartphone. This feature offers substantial value considering that the remote patient environment can be made to respond to user input, thereby enabling a two-way communication.

**Newer Prototypes, Frameworks, and Protocols.** Table 2 summarizes the technology prototypes and/or frameworks developed by authors in the literature surveyed, while Table 3 summarizes novel protocols presented.

**Overlapping Concerns**
The sensitive nature of healthcare information and inherent risks and challenges of high-quality wireless communication present a unique set of concerns, some of which have been referenced by the authors of the literature surveyed. The critical themes addressed are described below.

**Privacy and Security.** The National Committee on Vital and Health Statistics, a consultative board of the Department of Health & Human Services, offers the following definition of health information privacy: “An individual’s right to control the acquisition, uses, or disclosures of his or her identifiable health data.” This means that patients have the right to determine what healthcare data can be collected, used, and disclosed. When transmitted through a wireless channel such as WBANs linked to external networks, such data are susceptible to eavesdropping, identity threats, medical information misuse, medical fraud, and leakage. In addition to implementing advanced technological solutions to mitigate this scenario, it becomes critical to have strict laws and regulations to safeguard patient privacy in this context.

Addressing these security concerns is complicated due to the multiple data collection, access, and transmission points in the WBAN scenario. First, the on-body device nodes may be subject to compromise, as they can be apprehended by anyone in close proximity to the patient with relative ease. A network hacker with a powerful antenna can easily eavesdrop on patient vital signs being transmitted, along with coordinates to a patient’s physical location, placing them in harm’s way. An attacker might gain control of one of more nodes and initiate a host of attacks on neighboring nodes. For instance, in a Sybil attack, the compromised node assumes multiple identities when presenting itself to its neighbors, thereby collecting more data than it would otherwise. These data then could be manipulated prior to transit with an intent to...
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<th>Prototype/Framework</th>
<th>Reference No.</th>
<th>Purpose</th>
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<tr>
<td>ActiS sensor</td>
<td>3</td>
<td>A WBAN-based sensor platform to monitor heart activity</td>
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<td>WBAN motion architecture</td>
<td>4</td>
<td>WBAN architecture that recognizes human movements and postures and detects harmful activities</td>
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<td>WBAN telemedicine framework</td>
<td>5</td>
<td>Framework to integrate WBANs with telemedicine systems</td>
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<td>Accelerated ray-tracing method</td>
<td>6</td>
<td>Enhanced electromagnetic ray-tracing technique to predict effects of human body movement based on relative positions of WBAN body controller unit and wireless access point</td>
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<td>Distributed multiagent system architecture</td>
<td>7</td>
<td>A belief-, desire-, and intention-based multiagent system for recognizing human movements and harmful activities</td>
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<td>Biometric-based heart rate variability algorithm</td>
<td>8</td>
<td>A novel algorithm to generate security keys using heart rate variability readings to secure body sensor networks</td>
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<td>Knowledge-based home healthcare system</td>
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<td>A smart home healthcare monitoring system that infers knowledge from its environment</td>
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<td>BARI+ biometric-based security for WBAN</td>
<td>10</td>
<td>WBAN distributed security key management mechanism that leverage biometrics</td>
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<td>ATLAS</td>
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<td>An energy-efficient MAC framework protocol for WBAN designed to be traffic load aware</td>
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<td>Biopotential acquisition system for ubiquitous healthcare</td>
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<td>Model for frozen shoulder rehabilitation</td>
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<td>An activity recognition model to recognize six different types of exercises used in frozen shoulder therapy</td>
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<td>SCAN (eStimating aCtivities based on Artifact's behavior aNalysis) framework</td>
<td>14</td>
<td>Framework to infer human activities through one’s handling of physical artifacts embedded with electronic sensor device</td>
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<td>Three-tier security architecture for mHealth applications using WBAN</td>
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<td>Framework for wireless health monitoring</td>
<td>16</td>
<td>A framework using ZigBee technology for real-time secure health monitoring in smart homes</td>
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<td>ZIPMS (ZipBee Inpatient Monitoring System)</td>
<td>17</td>
<td>ZigBee technology enabled in-patient monitoring to support telehospital applications</td>
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<td>KNOWME-based framework for optimal sample allocation for activity detection</td>
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<td>Newer framework that optimizes transmission power for collecting biometric samples from the KNOWME WBAN-based network</td>
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<td>Prototype to evaluate functional electrical simulation (FES) algorithms</td>
<td>19</td>
<td>Novel wireless architecture that enables assistive movement in treating central nervous system lesions in humans, using a wearable FES system</td>
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<td>Ultrawide band (UWB)-based radar sensor for next-generation wearable wireless interface</td>
<td>20</td>
<td>Prototype of wearable sensor for monitoring heart and breath rates and transmitting to remote data acquisition unit, using UWB for communication</td>
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<td>Butterfly encryption scheme for securing WBANs</td>
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<td>Android smartphone-based telemonitoring system</td>
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<td>Prototype for telemonitoring system with Android smartphone acting as body controller unit coordinating on-body sensors</td>
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<td>SMTRPM (short multilevel tool for remote patient monitoring)</td>
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<td>Prototype for remote monitoring of heart rate and temperature using mobile augmented reality technology</td>
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<td>Wearable biofeedback system for stress management</td>
<td>26</td>
<td>Prototype of system for measuring stress levels of unemployed population using a combination of multi-biosensor platform with resonance frequency training technology</td>
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<td>RFID-based real-time remote monitoring of body temperature</td>
<td>27</td>
<td>Using RFID as a complementary WBAN technology for real-time remote location and monitoring of body temperature</td>
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<tr>
<td>Pulse oximeter prototype for remote patient monitoring</td>
<td>28</td>
<td>Prototype of a networked pulse oximeter and personal monitoring server for remote, continuous monitoring of patient pulse rate</td>
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Table 2. Technology prototypes and/or frameworks developed. FPDE, flexible polydimethylsiloxane dry electrode; MAC, medium access control; RFID, radio-frequency identification; WBAN, wireless body area network.
mislead remote caregivers, potentially prompting them to administer incorrect medications to patients. Worse yet, the attacker could masquerade the vulnerable node as the body coordinator, sending false messages to remote healthcare monitoring sites to the extent that the larger network becomes susceptible to denial-of-service attacks.67

To effectively address these challenges, Al Ameen et al.61 characterize three levels of healthcare wireless sensor network security: 1) administrative level (e.g., conducting security background checks of healthcare staff), 2) physical level (e.g., securing access to physical devices that interface with the WBAN), and 3) technical levels (e.g., intrusion detection and prevention techniques, encryption of healthcare data stored at the local WBAN gateways, on disks, etc.). Given that the unique characteristics of the WBAN make it different from other wireless sensor networks, Muhammad et al.10 have proposed BARI+, a novel security key management mechanism using biometric measurements. In this technology, random biometric measurements read from the human body are used to generate authentication keys. These keys are exchanged for internode communication and refreshed periodically, thus providing means for authentication, preserving confidentiality of measurements that are read and transmitted, and providing a defense mechanism against malicious attacks. Similarly, Pirbhulal et al.8 proposed a heart rate variability–based algorithm for key generation to secure body sensor networks. Sahoo7 proposed a three-tier security architecture for mHealth applications in which lightweight authentication and confidentiality protocols are used for internode WBAN communication. Kumar et al.35 surveyed state-of-the-art research in securing healthcare applications that use wireless sensor networks. They concluded that additional research is needed to address specific security aspects of wireless sensor networks for medical purposes, including public and symmetric key cryptography, secure routing, and quality of service in a security context.

Reliability. A complementary concern that needs to be addressed is reliability. In a typical hospital setting, patients can temporarily roam out of the wireless network range or might come in close physical proximity to other remotely monitored patients. This may mean that data collection is temporarily delayed or corrupted. WBANs need to effectively handle data transmissions in such real-life scenarios.

Research is underway to design distributed data-routing protocols that possess knowledge of redundant paths in a hospital network. In their novel QoS-aware peering routing protocol for delay-sensitive data (QPRD), Khan et al. developed WBAN data packets that were divided into ordinary packets (e.g., those containing patient glucose levels) and reliability-sensitive packets (e.g., those containing critical data such as patient blood pressure).68,69 QPRD prescribes a mechanism to best route each data type across the network, based on predefined reliability requirements. A body coordinator affixed to a patient first connects

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<th>Protocol</th>
<th>Reference No.</th>
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<tr>
<td>WUR (wake-up receiver for wireless health monitoring)</td>
<td>56</td>
<td>A novel health monitoring MAC protocol (WhMAC) using the wake-up receiver concept to improve energy efficiency of WBANs</td>
</tr>
<tr>
<td>E-SAP (efficient strong authentication protocol for healthcare)</td>
<td>57</td>
<td>A strong two-factor user authentication protocol for healthcare applications that use wireless medical sensor networks</td>
</tr>
<tr>
<td>CLNC-MAC (cloud-assisted MAC protocol)</td>
<td>58</td>
<td>A novel MAC layer protocol for WBANs that leverages cloud technology, enabling guaranteed delivery of data packets by coordination among sensor node relays</td>
</tr>
<tr>
<td>S-TDMA (statistical TDMA for human body communication)</td>
<td>59</td>
<td>A multiconstraint-aware (energy, delay, transmission efficiency, and emergency management) MAC layer protocol customized for human body communication at the physical signaling layer of WBAN standard stack</td>
</tr>
<tr>
<td>I-MAC (hybrid medium-access control protocol using interrupt mechanism)</td>
<td>60</td>
<td>To improve energy and time-slot utilization efficiency and data delivery delay requirements, an interrupt-MAC protocol is proposed</td>
</tr>
</tbody>
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Table 3. WBAN-related protocols developed. MAC, medium access control; TDMA, time division multiple access.
to a central nursing station coordinator to obtain information of all peer body coordi-

nators in the network. An end-to-end path reliability is first calculated for all paths from 

source to destination, and the degree of path redundancy is decided based on the type of 

data being transmitted. Doing so ensures that even if one node in the network is 

temporarily unavailable, data transmission to destination is unhindered.

Of important note, researchers have performed experimental evaluations of these 

protocols in a simulated environment and achieved promising results. However, it is the 

author’s opinion that incorporating them into commercial WBAN products requires 

considerably more verification and validation under a comprehensive set of real-hospital 

scenarios to ensure they perform at expected resiliency levels.

**Ease of Use.** Because WBAN sensor nodes are affixed to the human body, ease-of-use 

plays a key role in effective end-to-end WBAN systems. Portability, where both the 

sensor node and the on-body collector can be moved on the body with relative ease, is a 

related characteristic.

Usability features (or lack-thereof) play a critical role in adoption of WBAN, considering 

that sensors are affixed either on the human body or in vivo. In both cases, the sensor 

nodes must be unobtrusive and be comfortable for long-term use. Because sensors can be 

placed at different parts of the body, both Hughes et al.\(^33\) and Lai et al.\(^39\) emphasized the 

need for sensor designers to balance the number of nodes with wearability characteris-

tics. Lai et al. further underscored potential health hazards inherent in long-term sensor 

use, such as exposure to radio radiation and increase in thermal temperature in the areas 

where nodes are placed. As a partial solution to this problem, Yilmaz et al.\(^37\) recommended 

a strategic combination of both wired and wireless technologies based on the physiologi-

cal vital signs being monitored.

**Quality of Service.** WBANs need to meet several critical quality-of-service (QoS) 

characteristics, such as very-low-energy consumption of on-body sensor nodes, low 

network bandwidth, minimal packet transmission delay and packet loss, high reliability 

and throughput, long battery life, and minimal collision and retransmission.\(^5\) 

Depending on the function performed, they also need to support a wide range of require-

ments (e.g., support a data rate from 100 Kbps to up to 10 Mbps, as well as a network 

latency of 10 to 250 ms. Added to that, QoS can differ between periodic and urgent data transmission.\(^60\) For example, ECG and 

electromyography require higher reliability with real-time delivery; however, respiration 

monitoring sensors, while requiring higher reliability, can tolerate delays to some 

extent.\(^70\) Another important QoS is long-term patient safety. In vivo sensor nodes have the 

added constraint of heat and power dissipation that can cause thermal damage to 

human tissue inside the body.

In response, several studies have been conducted to improve QoS. Hughes et al.\(^33\) 

performed an extensive review of relatively energy-efficient WBAN protocols to optimize 

the QoS conditions mentioned above.

Monowar and Bajaber\(^29\) proposed a thermal-aware QoS routing protocol for in vivo sensor 

nodes. The Thermal-aware Localized QoS protocol aims to prevent the generation of 

highly heated in vivo nodes through the use of greedy routing algorithms. It is clear from 

these studies that designing a WBAN network to effectively and efficiently meet the 

QoS requirements is complicated.

**Cost.** It is interesting to note that none of the authors of the literature reviewed cite cost 

of WBAN as a primary adoption barrier. However, Yilmaz et al.\(^37\) compared the relative 

cost of wired versus wireless technologies for on-body sensors. In the context of leveraging 

mobile phones as a ubiquitous mechanism for collecting and transmitting physiological 

signs, Patrick et al.\(^64\) cited the severe penalties levied by mobile phone carriers when custom-

ers go over their allotted data plans as a limiting adoption factor.

**Conclusion**

This review discussed healthcare domains in which WBANs have been examined and 

implemented, as well as explicit WBAN frameworks, emerging protocols, and 

complementary technologies that have been applied in solving specific healthcare prob-

lems. In addition, it highlighted key cross-cutting concerns between the two areas
of study. This article should provide researchers a unique opportunity for contextual analysis of the topics presented relative to their progress, challenges, and opportunities. It became apparent from the literature review performed that commercialization of the technologies discussed is in its infancy. While numerous prototypes and frameworks have been cited, the author found few references to similar off-the-shelf products. Therefore, this article should provide the practitioner critical insights on how to best productize and commercialize these emerging trends, as well as make the much-needed technology available to the larger population in a cost-effective manner.

References


Sterile Processing
Knowledge, Skills, Competencies

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