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Novel Wireless Devices for Cardiac Monitoring

Joseph A. Walsh III, MD, MS; Eric J. Topol, MD; Steven R. Steinhubl, MD

The digital revolution and the rapid development of smartphones, mobile connectivity, and social networking have changed the way we live. The average American is constantly connected via high bandwidth to a vast network of data and sophisticated digital platforms, with >90% of American adults owning a cell phone and 55% having a smartphone.¹ The digital revolution has transformed virtually every industry and every facet of our personal lives but has been conspicuously absent from the world of medicine. Physicians and healthcare networks have been slow to adopt electronic medical records and to integrate medical data with the ubiquitous mobile device. Recently, however, novel devices for wireless monitoring have emerged and begun to be integrated with the care of the cardiac patient. We believe that the evolution of these wireless cardiac monitoring devices will mark a new era in medicine and a transition from population-level health care to individualized medicine in which suitable patients are equipped with advanced biosensors that, in turn, have their data processed through sophisticated algorithms to predict events before they occur. This review is meant to be a comprehensive overview of the novel wireless cardiac monitoring devices that are available, as well as the technologies that are currently under development and poised to revolutionize the way we practice cardiology. A comprehensive list of a number of devices that are currently available or under development is given in the Table for reference.

Arrhythmia Detection

Cardiac arrhythmias such as atrial fibrillation are common and can be associated with adverse outcomes such as embolic stroke. Less common but more malignant rhythm disorders such as ventricular tachycardia can herald sudden cardiac death.² The identification and management of arrhythmias in the patient with palpitations, syncope, a history of arrhythmia, or high risk for sudden cardiac death often rely on conventional Holter monitoring, event monitoring, or continuous remote telemetry.³ These technologies, although effective, are burdensome to the patient, are expensive (up to \$750), and can often miss arrhythmias if the patient does not activate the event monitor at the time of symptom onset.^{3,4} A number of new and effective technologies for wireless monitoring of arrhythmias have been developed and validated and are currently available for patient care.

Real-Time Smart Phone Monitoring

Using a novel smartphone adapter, patients are now able to capture and transmit single-lead ECG data to their healthcare

providers. The AliveCor (Figure 1) and ECG Check (Cardiac Designs) systems are US Food and Drug Administration (FDA)-approved single-lead (lead I) ECG monitoring systems that consist of a case that snaps on the back of a smartphone. Finger contact on the case of the smartphone activates ECG recording of bipolar lead I and is transmitted to the smartphone from the case using frequency modulation of an ultrasound or Bluetooth signal that is received in the speaker of the smartphone. Once captured digitally in the smartphone, it can be viewed in real-time and transmitted to a secure server for the patient's provider to review in PDF format. The system has been validated in a number of settings, including event monitoring and screening of atrial fibrillation.⁵

ECG Patch Monitoring

As opposed to the bulky and burdensome devices currently available for ambulatory ECG monitoring, the ECG patch monitor is an adhesive, single-lead ECG monitor that is applied to the left pectoral region. The typical ECG patch monitor consists of a system on a chip that converts analog ECG signals to digital format, an accelerometer to assist with artifact removal, a low-power Bluetooth low-energy processor that transmits the data, and a lithium polymer battery. There are several FDA-approved ECG patch monitoring devices currently available.

One example of this technology is the Zio Patch (iRhythm Technologies, San Francisco, CA; Figure 2), a waterproof, single-use, continuous ECG monitor that can be worn for up to 14 days. It lacks any leads or wires, and its low-profile design allows the patient to wear it with minimal interruption of daily activities. The device is mailed to the patient's home in an envelope, worn for up to 14 days, and returned in a prepaid envelope for analysis and reporting to the patient's provider. A recent trial of the 14-day Zio Patch monitor compared with conventional 24-Holter monitor showed that the Zio Patch detected 57% more (96 versus 61 events; $P<0.001$) significant clinical events than the conventional Holter.⁶ The majority of study participants (81%) preferred the Zio patch to conventional Holter monitoring; 94% said they found the device comfortable to wear compared with only 52% for the Holter. There are several limitations to this technology, however. The Zio patch offers only 1 lead as opposed to the multiple channels available with conventional Holter monitoring. This may have contributed to the Holter monitor being significantly more sensitive for the detection of events (61 events detected over 24 hours with Holter versus 52 events over 24

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Table. Comprehensive Overview of Existing Wireless Cardiac Monitoring Devices

Name	Company	Link	Brief Description
Comprehensive vital sign monitoring			Skin microblush change in capillary filling to measure heart rate and chest movement to measure respiratory rate
VitalSigns Camera	Phillips	http://www.vitalsignscamera.com/index.html	
Scout	Scanadu	http://www.scanadu.com/	Measures temperature, pulse, oximetry, ECG, heart rate variability, and pulse wave transit time
BioPatch	Zephyr	http://www.zephyranywhere.com/healthcare/biopatch/	Adhesive patch transmits wirelessly pulse, R-R interval, respiratory rate, activity, respirations, ECG, position, and posture
Hexoskin	Hexoskin Wearable Body Metrics	http://www.hexoskin.com/en?utm_campaign=Listly&utm_medium=list&utm_source=listly	Shirt measures heart rate, heart rate variability, respiratory rate and volume, and activity; also estimates $\dot{V}O_2$ max
OMSignal	OMSignal	http://www.omsignal.com/	Washable shirt that monitors 3-lead ECG, respirations, stress, and temperature
Sensor Bra	Microsoft	http://www.cs.rochester.edu/hci/pubs/pdfs/FoodMood.pdf	Sensors built into bra: heart rate, respiration, Electrodermal activity; 3-axis accelerometer; 2-axis gyroscope; designed to track emotions and study emotional eating
Intermittent ECG			
Alivecor System	Alivecor	http://www.alivecor.com/	With application able to analyze and print ECGs as PDFs; ECG data sync between the application and online ECG hub; prescription only
ECG Check	CardiacDesigns	http://cardiacdesigns.com/	With application able to analyze and print ECGs as PDFs; ECG data sync between the application and online ECG hub
EPI Mini (also EPI Life)	EPI Mobile Health Solutions	http://epimhealth.com.sg/	Separate device that transmits ECG to smartphone, which can forward it to a "health concierge" service that can send back a reading; cleared by the US Food and Drug Administration for consumer use
12-Lead ECG	MobilECG	http://mobilecg.hu/	USB-based open-source 12-lead clinical ECG
Prolonged ECG monitoring			
eMotion ECG Mobile	Mega Electronics	http://www.megaemg.com/products/emotion-ecg/	3-Lead ECG data are transmitted from the wearable ECG sensor to a mobile phone via Bluetooth; the phone forwards the data over mobile network to a server, which stores the data; the data can be monitored in real time or a specialist can investigate and analyze the stored ECG data
BodyGuardian	Preventice	http://www.preventice.com/	Patch monitor of ECG, activity, respirations, and body position
Zio XT Patch	iRhythm	http://www.irhythmtech.com/?utm_campaign=Listly&utm_medium=list&utm_source=listly	14-d continuous cardiac rhythm monitoring with a single adhesive chest wall device; once completed, it is mailed for analysis
NUVANT Mobile Cardiac Telemetry System	Corventis	http://www.corventis.com/	Automatic and patient-triggered 30-d cardiac rhythm monitoring; arrhythmia detection: the device transmits information via a wireless data transmission device, zLink, to the Corventis Monitoring Center
Ambulatory ECG	iHealth	http://ces.cnet.com/8301-35284_1-57616620/at-ces-2014-health-monitors-join-the-wearables-parade/	Sensor attaches to chest and transmits ECG to smartphone
Heart failure			
CoVa necklace	Perminova	http://www.perminova.com/sensor/	Measures heart rate, respiratory rate, fluid levels
VitaLink	vg-bio	http://www.vgbio.com/vitalink-remote-patient-monitoring/	Measures pulse, heart rate variability, transthoracic impedance, and activity via head band and chest strap
AVIVO Mobile Patient Monitoring System	Corventis	http://corventis.com/us/avivo.asp	Monitors thoracic impedance, heart rate, heart rate variability, respiration rate, posture, and heart rhythm with wireless transmission to the Corventis Monitoring Center
Telescale	Cardiocom	http://www.cardiocom.com/telescale.asp	For daily weights with automated verbal/feedback and communication to the patient and provider

(Continued)

Table. Continued

Name	Company	Link	Brief Description
Blood pressure			
ViSi Mobile	Sotera Wireless	http://www.visimobile.com	Wireless vital sign monitoring with noninvasive continuous blood pressure monitor
Wireless wrist blood pressure monitor	iHealth	http://www.ihealthlabs.com/wireless-blood-pressure-wrist-monitor-feature_33.htm	Wireless wrist blood pressure measurement and heart rate transmitted to a mobile application
iPhone-connected blood pressure cuff	Withings	http://www.withings.com/bloodpressuremonitor	Plugs into iPhone or iPad and tracks and displays all results; also available in 2014 with Bluetooth connection between the cuff and smartphone
Continuous blood pressure watch	Quanttus	http://www.technologyreview.com/news/524376/this-fitness-wristband-wants-to-play-doctor/	Continuous monitoring of blood pressure, heart rate, and respirations.
BPro radial artery pressure monitor	HealthStats	http://www.healthstats.com	Watch-like device that samples radial artery waveforms via tonometry at regular time intervals over a 24-h period; for assessment of ambulatory blood pressure
Wearable, wireless ambulatory blood pressure monitor	iHealth	http://ces.cnet.com/8301-35284_1-57616620/at-ces-2014-health-monitors-join-the-wearables-parade/	Vest-like device that allows blood pressure to be measured as frequently as every 15 min throughout the day
Ultrasound			
VScan	GE	http://www3.gehealthcare.com/en/Products/Categories/Ultrasound/Vscan	Standalone ultrasound imaging device that can download and transmit images
MobiUS SPI	Mobisante	http://www.mobisante.com/product-overview/	Smartphone-based ultrasound
Terason USmart 3200T	Terason	http://www.terason.com/index.asp	Comprehensive ultrasound
Nanomaxx	Sonosite	http://www.sonosite.com/products/nanomaxx	Standalone ultrasound imaging device that can download and transmit images.

hours with Zio; $P < 0.013$) during the 24 hours of dual monitoring. The extended duration of monitoring and comfort of use likely outweigh these limitations and make this a meaningful device for use in patients with arrhythmias.

Another example is the NUVANT Mobile Cardiac Telemetry system, which is a wireless-enabled arrhythmia event monitor. It consists of a wearable monitoring device and a portable data transmission device. Unlike the Zio Patch, which records and stores all ECG data, allowing arrhythmia detection only in retrospect, the NUVANT system performs real-time analysis and transmission. Once applied to the body, the sensor automatically activates and begins monitoring and transmitting ECGs when a select list of rhythm abnormalities is encountered (ie, 3-second pause, ventricular tachycardia).⁷ There is also a patient trigger magnet that can be used to collect and transmit symptomatic episodes. All events are transmitted to a cloud-based application where it can be analyzed by certified ECG technicians.

Injectable Loop Recorders and Device-Tailored Anticoagulation

The miniaturization of cardiac monitoring devices and advances in remote data transmission capabilities have led to the development of extremely small, injectable loop recorders and novel therapeutic strategies for anticoagulation in atrial fibrillation. Devices like the FDA-approved Medtronic REVEAL LINQ have provided clinicians with a long-term monitoring device (up to 3 years) that can be injected under the skin and is one-third the size of a AAA battery. These miniaturized loop recorders build on the utility of patch monitors and offer a long-term monitoring period for patients with

clinical conditions such as unexplained syncope and cryptogenic stroke. In fact, the recently reported Cryptogenic Stroke and Underlying Atrial Fibrillation (CRYSTAL-AF) trial⁸ randomized patients with cryptogenic stroke to monitoring with an implantable REVEAL XT device versus conventional monitoring and found a dramatic increase in the detection rate (30% versus 3%) of atrial fibrillation at 36 months.

Remote monitoring of implantable cardiac defibrillators and pacemakers is commonly used in current practice, but there is emerging interest in the use of remote atrial tachycardia monitoring for tailored anticoagulation in patients with atrial fibrillation. Data were recently released from the Randomized Trial of Anticoagulation Guided by Remote Rhythm Monitoring in Patients With Implanted Cardioverter-defibrillator and Resynchronization Devices (IMPACT) trial,⁹ which randomized participants to device-tailored anticoagulation on the basis of atrial tachycardia alerts from existing implantable cardiac defibrillators or pacemakers versus conventional office-based monitoring. Although the study did not meet its primary end point for a reduction in stroke, systemic embolism, or major bleed, it was underpowered, and there was a low rate of compliance with anticoagulation in the intervention group.

The National Institutes of Health has recently funded a novel trial using the implantable REVEAL XT monitor for device-tailored anticoagulation. The device performs daily monitoring of the patient for episodes of atrial fibrillation lasting >1 hour. The data are manually downloaded to the Internet and reviewed by the patient's healthcare provider for initiation of oral anticoagulation if needed.¹⁰ The recently approved LINQ monitor, however, will allow automated nightly downloads



Figure 1. Alivecor real-time monitoring of ECG. Finger contact on the case activates ECG recording of bipolar lead I and is transmitted to the smartphone.

and smartphone alerts to streamline the process. This type of device-tailored anticoagulation is a novel method to minimize the complications associated with anticoagulation in atrial fibrillation while maximizing its benefits. Moreover, this type of intervention is a natural translation of biosensor-driven data from a diagnostic to a therapeutic role and has the potential to transform the way we manage chronic diseases.



Figure 2. Zio Patch, an adhesive ECG patch.

Wireless Vital Sign Monitoring

Cardiac patients on the inpatient telemetry wards and intensive care units require close observation with frequent vital sign measurement and ECG monitoring. Even the most critically ill patients, however, have their complete vital signs measured and reported to their physicians only every hour in the intensive care unit and every 4 to 6 hours on the telemetry units. Recent advances in noninvasive blood pressure monitoring and wireless delivery systems have made continuous vital sign monitoring available for all inpatients in the form of a small monitor slightly larger than a wrist watch. The Sotera ViSi mobile system is a patient-worn monitor that is connected to a series of small biosensors, including a pulse oximeter, a skin temperature sensor, telemetry leads, and a noninvasive continuous blood pressure monitor that uses pulse arrival time and cuff calibration to continuously monitor the patient. The pulse arrival time, defined as the time required for the arterial pulse pressure wave to travel from the aortic valve to the periphery, can be estimated as the delay between the peak of the R wave on the ECG and the arrival of the corresponding pulse wave on pulse oximetry (photoplethysmography). It has been validated in a number of settings^{11,12} as an accurate method for noninvasive assessment of blood pressure. The Sotera system wirelessly transmits data via secure encryption through existing Wi-Fi networks to the electronic medical record and remote alarm systems allowing the physician 24/7 access to the patient's vital signs. Significant alteration in a patient's vital signs alerts the provider immediately via his or her smartphone. Further advances in predictive analytics will build on this technology by establishing algorithms for preventing clinical events such as impending circulatory disorders before they occur in the inpatient setting. Moreover, the continuous wireless monitoring of vital signs can be seamlessly translated into the outpatient setting on hospital discharge or even for use in the prevention and real-time management in appropriate individuals.

One such device designed for individual home use is the Scanadu Scout (Figure 3), which will soon enter FDA trials. It is a hockey puck-shaped device that is held between 2 fingers and directed at the patient's forehead. The device is designed to generate a complete set of vital signs, including heart rate, blood pressure, temperature, respiratory rate, and oxygen saturation, in <10 seconds and to transmit the data wirelessly to the patient's smartphone where it can be stored, tracked, analyzed, and transmitted to a provider if desired. The technology underlying devices like the Scanadu Scout is based on photoplethysmography, which relies on an infrared light source directed at the skin surface and the relationship of the backscattered light as detected by a photodetector to the variation in blood volume with each heartbeat. There are numerous applications of this technology because the reflected light can be calibrated to detect many important physiological measures such as photoelectric activity (the shift in wavelength between oxygenated and deoxygenated hemoglobin that measures oxygen saturation), cardiac output, and blood pressure. Similar but wearable devices such as watches and necklaces are also currently under development and in validation phases. Like the Scout, these wearable devices will transmit data to the patient's smartphone and continuously analyzed and interpreted, relying in large part

on machine learning. In addition to conventional vital signs, many of these wearable devices in development can monitor novel parameters like autonomic nervous system activity using heart rate variability and electrodermal tracking (using the changes in the conductance of the skin as a surrogate for sympathetic tone), as well as sleep quality measurements. This technology is still in its infancy but has the potential to revolutionize health care and to bring the doctor's office to the patient's smartphone.

Handheld Ultrasound

Echocardiography is a critical tool for the diagnosis and management of heart disease. More than 20 million echocardiographic procedures are performed each year in the United States.¹³ More than 22% of these procedures, however, are currently deemed inappropriate,¹⁴ and the rising costs of health care in the United States, coupled with the increasing complexity of cardiac patients, demand a more efficient and streamlined way to integrate echocardiography into our daily clinical practice. The recent development of high-resolution pocket mobile echocardiography (PME) devices has the potential to revolutionize bedside and outpatient management of cardiac patients and to alleviate the burden of healthcare costs associated with cardiac imaging. These small devices consist of a small phased-array probe connected to a handheld viewer the size of a smartphone. Most models easily fit into a white coat pocket and have advanced imaging capabilities with high-resolution 2-dimensional imaging, color Doppler, and measurement capabilities. Numerous studies have documented the similar diagnostic accuracy of bedside evaluation with a PME and conventional transthoracic echocardiography in clinical scenarios such as valvular heart disease assessment, ejection fraction assessment, and volume status assessment using the inferior vena cava diameter.^{15–18} Moreover, recent data suggest that PME not only has a diagnostic accuracy similar to that of conventional transthoracic echocardiography but is more cost-effective.¹⁹ Barriers to wide-scale implementation of PME in the clinical arena include the significant costs of each device (up to \$8000) and the logistics of physician reimbursement

for performing and interpreting bedside scans on daily rounds. As opposed to handheld viewing, next generations of these devices that are already available (Mobisante, Inc, Redmond, WA) consist of a simple phased-array probe that wirelessly transmits data via Wi-Fi or Bluetooth to a tablet-based tool and central electronic medical records for image storage and subsequent interpretation and advanced diagnostics. It is possible that in the future patients may be able to acquire and transmit their own images to their healthcare providers for wireless monitoring of chronic cardiac conditions such as valvular heart disease.

Heart Failure

Despite the availability of a multitude of evidence-based therapies for the treatment of heart failure, the burden of heart failure on the US population remains unacceptably high, with an estimated 1 million admissions per year.²⁰ Moreover, readmission rates for heart failure, the majority of which are for congestion,²¹ are a marker of worse prognosis and represent a significant healthcare expenditure and performance measure for payers.²² Efforts to reduce the burden of rehospitalization have been largely ineffective given the poor sensitivity and specificity of conventional markers such as weight and symptoms.^{23,24}

Multiple Parameter Testing

Although the relative sensitivity and specificity of conventional standalone markers of congestion are poor, there has been intense interest in using remote monitoring of multiple markers for the assessment of impending congestive episodes and readmission. Anand et al^{25,26} recently developed and validated an algorithm for predicting impending heart failure using a combination of physiological signals obtained from an external device adhered to the chest. The Multi-Sensor Monitoring in Congestive Heart Failure (MUSIC) trial studied this predictive algorithm using a combination of bioimpedance, heart rate, respiratory rate, activity duration, and body posture that was tailored to each participant. In that trial, 543 participants with an ejection fraction of $\leq 40\%$ and a recent admission for heart failure were remotely monitored for 90 days. The predictive algorithm had a sensitivity of 63% and a specificity of 92% for the prediction of rehospitalization in the validation cohort, numbers that far exceed conventional performance characteristics of single parameter testing, although still far from ideal. Other wearable monitoring devices such as the Perminova CoVa necklace (Figure 4) are under development for the long-term management of heart failure and have the capacity to monitor complex hemodynamics such as stroke volume and cardiac output noninvasively. The CoVa necklace, worn just a few minutes a day, measures thoracic bioimpedance and ECG waveforms to determine the patient's thoracic fluid index, heart rate, heart rate variability, and respiratory rate. Newer versions of the firmware of the device, using the same hardware, will be able to monitor stroke volume, cardiac output, and blood pressure. As the fidelity of biosensors improves and predictive analytics become more powerful, multiple parameter testing has the potential to drastically improve the management of heart failure and many other chronic conditions.



Figure 3. Scanadu Scout, a wireless vital sign monitor.



Figure 4. Perminova CoVa necklace uses thoracic bioimpedance and ECG monitoring to determine stroke volume, blood pressure, and cardiac output in patients with chronic cardiac conditions.

Breath Analysis

Breath metabolomics, the study of the complex mixture of volatile organic compounds in exhaled breath, has the potential to become a safe and noninvasive method of identifying patients with impending decompensation in a point-of-care fashion. Previous studies have demonstrated that elevated levels of acetone, pentane, and nitric oxide levels in exhaled breath are correlated with the severity of heart disease.^{27–29} A recent analysis from a group at the Cleveland Clinic demonstrated that a “breathprint” derived from a select group of volatile organic compounds could accurately discriminate between heart failure patients and control subjects (Wilks $\lambda=0.109$; $P<0.0001$).³⁰ Breath analysis platforms using Bluetooth-enabled nanosensors are already under development (Vantage) with the planned capability of transmitting breathprint data to a smartphone for analysis and upload.³¹ Breath metabolomics, a rapidly developing field, has the potential to offer patients a noninvasive diagnostic tool for complex diseases.

Wireless Invasive-Pressure Monitoring

It has been well documented that left ventricular filling pressures begin to rise in the days and weeks preceding a hospitalization for heart failure,^{24,32} independent of weight, and a number of novel implantable devices have been developed to identify and intervene on this rise in filling pressures before hospitalization. CardioMEMS (CardioMEMS, Atlanta, GA) is a passive, wireless, radiofrequency sensor implanted into the pulmonary artery that continuously monitors pulmonary artery pressure. This device was tested in the 2011 CardioMEMS Heart Sensor Allows Monitoring of Pressure to Improve Outcomes in NYHA Class III Heart Failure Patients (CHAMPION) trial³³ wherein 550 participants with class III heart failure symptoms and a previous hospitalization for heart failure were randomized to implantation with continuous monitoring versus standard of care and followed up for the 6-month end point of heart failure hospitalization. At 6 months, there were 84 heart failure–related hospitalizations in the sensor group compared with 120 in the usual care group (hazard ratio, 0.72; 95% confidence interval, 0.60–0.85;

$P<0.0002$). At 15 months, there was an impressive 39% reduction in heart failure hospitalizations in the sensor group with a significant improvement in quality of life compared with usual care. Importantly, physicians were given a standardized algorithm for the management of patients in the monitoring group, and the benefits were independent of left ventricular ejection fraction. The initial FDA review of the device in 2011 was met with concern about the detailed recommendations of study sponsor nurses for the management of pulmonary artery pressure alarms in the treatment arm. Subsequent analyses of device alerts in the absence of these detailed recommendations were met by a favorable review by the FDA advisory committee in 2013 and the device was approved by the FDA on May 28, 2014.

Coronary Artery Disease

Secondary Prevention With Continuous ST-Segment Monitoring

Acute myocardial infarction is a major cause of death and morbidity in the United States, and despite improving door-to-balloon times among US hospitals, the time from symptom onset to arrival at hospital remains 2.5 to 3 hours.^{2,34–36} This delay in treatment results in potentially irreversible myocardial infarction and lethal arrhythmias that may have been avoided if the patient had come to medical attention earlier. Continuous ST-segment monitoring is able to detect “supply-related” ST-segment shifts that occur in the absence of increased heart rates (“demand-related” shifts) and are a highly sensitive and specific marker of ischemia and impending infarction. The Angelmed Guardian implantable cardiac device is a single right ventricular lead that is currently in clinical testing among patients with a recent (<6 months) acute coronary syndrome event and at high risk for recurrence. The device detects ST-segment shifts ≥ 3 standard deviations beyond a patient’s daily ST-segment variation and alerts the patient to seek medical care. In the first-in-human trial,³⁷ 37 patients were followed for 1.5 years, and the device alerted 4 of these patients to seek medical attention, all of whom had angiographic evidence of coronary occlusion or ruptured plaques. The average alarm-to-door time was 19.5 minutes, and there were 2 false-positive findings resulting from arrhythmia.

Embedded Nanosensors

In addition to electrical markers, biological markers of impending plaque rupture are critically important for the prevention and early identification of myocardial infarction. One such biological marker currently being studied for use in the early identification of plaque rupture is circulating endothelial cells. Recent investigation has confirmed that circulating endothelial cells, identified by multiple surface markers using a fluorescence microassay, are significantly elevated in patients presenting with acute myocardial infarction compared with control subjects with an area under the curve of 0.95.³⁸ Integration of highly sensitive and endothelium-specific genomic markers with blood-embedded nanosensors has the potential to make the new diagnosis of an imminent myocardial infarction before the event has initiated, representing the true prevention capability of wireless embedded sensing technology.

Wireless Cardiac Rehabilitation

Cardiac rehabilitation is a critical component of the secondary prevention of coronary artery disease and is well established to improve outcomes in patients with coronary artery disease.^{39,40} Despite the clear benefits of cardiac rehabilitation, enrollment rates are still <30%, and there are many patients without the resources or availability to attend supervised exercise and education 3 days a week.⁴¹ Home-based programs for cardiac rehabilitation hold promise for improved compliance rates but still require monitoring by a nurse or trained technician.⁴² Home-based cardiac rehabilitation, in conjunction with wireless ECG, blood pressure and heart rate monitoring, may provide a means of improving compliance with cardiac rehabilitation. A study conducted in Korea⁴³ randomized 50 patients to conventional care versus home-based cardiac rehabilitation for 12 weeks and monitored echocardiographic measures of left ventricular function and regional wall motion abnormalities. After 12 weeks, the group in the home-based cardiac rehabilitation group showed significantly improved ejection fraction and a reduced number of regional wall motion abnormalities. This type of home-based exercise training can be further extrapolated to other chronic conditions in which exercise has shown beneficial effects such as peripheral arterial disease and congestive heart failure.

Challenges That Lie Ahead

Need for Validation, Cost-Effectiveness

The rapid development of the hardware and software involved in the new generation of wireless cardiac monitoring devices has outpaced the real-world validation, and large-scale, pragmatic studies are needed to validate the enormous amounts of data generated from these monitors. Ongoing clinical trials will be critical to determine the safety, efficacy, and cost-effectiveness of this new technology relative to conventional methods of monitoring patients. Moreover, a much greater understanding of individual variability in the acceptance, engagement, and sustainability of these technologies and the most appropriate balance of patient and provider involvement are critically important areas of study.

Data Security

Personal health information is heavily protected under the Health Insurance Portability and Accountability Act (HIPAA), and the dissemination of electronic medical data to mobile and cloud-based technology requires encrypted and secure networks. The investment in online security for the mobile monitoring devices of the future must be a major priority because a data breach could be catastrophic for the future of this industry and could expose patients to both an invasion of their privacy and the potential for personal harm.

Reimbursement and Medico-Legal Issues

The deluge of data that come from wireless cardiac monitoring devices needs to be analyzed because it is still the job of the healthcare provider to react to the information and to provide appropriate care to the patient in the appropriate turnaround time. Whereas improved data analytics with automated decision support will be a critical component of

any successful widespread implementation of home monitoring, the product of these analyses will still require provider oversight that needs to be reimbursed—directly in the fee-for-service environment or, better, indirectly through incentives to keep individuals well. Moreover, tasks such as performing a bedside echocardiographic assessment with a PME, which is financially disincentivized from multiple directions, need to become part of a sustainable system of care. This new technology demands that we re-examine how physicians are paid in the current environment, and efforts are underway in many states to reimburse physicians for electronic services such as returning emails and conducting “tele-visits.” The rapid adoption of accountable care organizations will also make wireless cardiac monitoring devices more relevant by reducing hospitalization and empowering patients and providers to focus on improving health.

Predictive Analytics, Machine Learning, Algorithms

The rapid development of hardware like biosensors has overshadowed the slower development of the software needed to manage the enormous amount of data that these biosensors can generate. Mobile technologies will go well beyond providing data physicians already know how to treat (eg, blood pressure at an office visit) and instead will provide brand new data streams (eg, continuous blood pressure during daily activities) that will require tremendous bioinformatics capabilities to eventually understand. As discussed in previous segments of this review, the capacity for technological advances in the way we are able to process large amounts of data using predictive analytics and network biology will usher in the era of personalized medicine and the ability to predict clinically significant events well before they occur.

The Cardiovascular Patient of the Future

In light of the technological advances we have reviewed here, it is likely that the cardiac patient of the future, “wired” with a personalized network of biosensors, will be extremely different from the usual patient today. These biosensors will transmit a wealth of data about the patient’s genomic, metabolomics, and clinical responses to daily stimuli to the patient’s smartphone peripheral brain. Once that information is received, the smartphone will process it using sophisticated and personalized modeling software and will direct the patient to take action, for example, to contact his or her physician, to adjust a medication, or to alert emergency medical services of an impending myocardial infarction. These devices have the potential to revolutionize medicine. The eventual integration and study of these devices in the coming years must carefully examine not only the relative safety and efficacy of this technology relative to conventional care but also the impact of this technology on changing the costs of health care by preventing rehospitalization and empowering patients.

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KEY WORDS: echocardiography ■ electrocardiography ■ heart failure