Seamless Monitoring of Physiological Information in Daily Life: Retrospectives and Perspectives

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Abstract This paper reviews endeavors over the past decades to achieve seamless monitoring of various types of physiological information by a variety of high user-affinity approaches applicable to the daily life environment. Developments in academic research and commercialization from the early period are reviewed. The latest outcomes are briefly investigated and roughly categorized into three main models: miniature portable monitors for ambulatory application, functional fabric-based wearable monitors for better comfort, and unobtrusively deployed invisible monitors for optimum usability. Monitors for seamless monitoring of physiological information in the daily life environment differ from conventional devices that are hospital-centered and aimed at short-term use in clinics. Through scrutinizing the current systems and examining their various pros and cons, we identify existing common concerns, provide insight into problem determinants, and suggest research topics for further study. In the near future, we envision that the home will be transformed into an intelligent hub for lifelong healthcare through seamless monitoring of the human body in the daily life environment, which will foster the development of a new discipline “Metrology of Health” or “Healthology” based on a holistic view of health.

Keywords: Aging in place, seamless monitoring, unobtrusive monitoring, invisible monitoring, ubiquitous monitoring, wearable monitoring, portable monitoring, home healthcare, Metrology of Health, Healthology.

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1. Introduction

With the advent of information and communication technology (ICT), and its pervasive application in medical and healthcare domains, life expectancy at birth in 35 countries worldwide has extended into the 80s for both females and males [1]. During the first half of the 21st century, the proportion of the population aged 60 years and over will double from about 11% to 22%, representing an increase in number from 605 million to 2 billion [2]. One of the greatest concerns in the aged population is the increase in chronic conditions that account for 60% of total deaths [3]. The decline in health due to aging results in a decrease in personal quality of life and poses a huge burden in terms of global financial expenditure. Healthy aging is therefore of paramount importance.

Global action for healthy aging has been undertaken at different levels. National campaigns for health promotion and disease prevention have been implemented in Australia [4], Canada [5], China [6], the EU [7], Japan [8], Korea [9], the UK [10], USA [11], and many other countries. Such nationwide campaigns aim to promote the health condition of citizens through a total package program from national law to personal daily activities, and are sustained for several decades.

At the institutional level, a community-based social service

“aging in place” initiative known as NORC-SSP (Naturally Occurring Retirement Communities-Supportive Services Program) in the mid-1980s was designed to promote healthy aging and healthcare management in New York [12]. Since the early 1990s, a government-sponsored municipal project, “Challenge to 100 years of age,” was pioneered in West Aizu Village in northern Japan [13]. The fundamental goal is to live longer independently with better quality of life by providing a total care solution to villagers and encouraging them to practice a healthier lifestyle.

To support “aging in place” and “daily health promotion,” accurate detection and early warning of changes in health condition are indispensable. Seamless monitoring of physiological information in various living scenarios over long periods without disturbing daily activities can significantly enhance caregivers’ ability to deliver evidence-based care. A study on congestive heart failure (CHF) patients showed that use of telehealth technology decreased overall utilization of healthcare resources by 41%; physician office visits decreased by 43%, emergency department visits by 33%, and hospitalizations by 29% [14].

For seamless monitoring of multifaceted physiological information in the daily life environment, many academic goals have been addressed and a variety of technological problems have been experienced over the past several decades. Research and development have gone through different approaches to enhance several aspects such as miniaturization, comfort, and concealment, to achieve better user affinity in different application scenarios. Miniaturization technology helps implement smaller and lighter portable monitors for ambulatory application. Wearable monitors target pervasive application in daily activities without discomfort. Invisible methods are usually achieved by concealing sensors or transducers in furniture and appliances for indoor applications. Some of these technologies have matured and have been commercialized for use in daily settings, but some have yet to be achieved and further studies are required.

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This paper presents a review of the latest developments and various commercial products, discusses their appealing features and available applications, and outlines some topics for future exploration. Finally, we expect that in the future, the home will become a hub for seamless monitoring of various physiological information for lifelong healthcare.

2. Current Achievements

Noninvasive electrocardiography (ECG) was first developed in 1901 by Willem Einthoven [15] who used a string galvanometer that required water-cooling and five operators and weighed some 270 kg. However, the latest ECG devices are pocket-sized, 9 mm thick, and weigh only 13 g [16]. Various modalities for ECG measurement have been developed and can fit into our clothing, mobile phones, and indoor furniture such as beds [17–20], chairs [21], bathtubs [22, 23], and even in the shower room [24]. In addition to ECG, increasing amounts of physiological information can be monitored conveniently using a range of modalities based on various engineering principles.

With the development of micro-electromechanical systems (MEMS), integrated circuits (IC), nano, and material technologies, monitoring devices suitable for daily application have evolved along many different lines over the past several decades. Nevertheless, they can be roughly classified into three categories: portable, wearable, and invisible.

Portable monitors have been developed mainly for ambulatory usage. The early stages of development focused on miniaturization, improvement of usability, and prevention of artifacts. Advances in IC and MEMS technologies have made it possible to reduce both their size and weight. These devices can be used to obtain multiple types of physiological information, such as ECG, blood pressure, body temperature, calorie consumption, and physical activity.

Wearable monitors are usually embedded into a garment or accessory, and worn by the user as part of their clothes without the need to carry extra items. They are unobtrusive, comfortable, esthetic, and functional without affecting daily activities. Some common examples are underwear [25, 26], brassiere [27], adhesive plaster [28], shoes [29], hat, eyeglasses [30], belt, watch, bracelet, and hairpin.

Invisible monitors are usually concealed in home utilities such as furniture, electrical appliances, and sanitary equipment. They are noncontact and invisible to the user, and can function in a fully unobtrusive and automatic manner at a fixed indoor site, without requiring any intervention from the user.

As the pervasive use of ICT has provided a common gateway with connection to the Internet, all of these monitors can be linked to a mobile phone platform. Therefore, a network connection can be maintained indoors or outdoors.

The following sections present some examples of these types of equipment.

2.1 Portable Monitors

A portable monitor for continuously monitoring ECG was introduced by N.J. Holter more than 50 years ago [31]. It consisted of an 85-pound (38.6 kg) radio transceiver and could record 24 h or more of ECG. Despite requiring the same time as recording to interpret the measured ECG, the importance of the Holter portable device was recognized immediately by the medical communi-

Fig. 1 Cordless ECG monitors: (a) Cardy 303 pico+, (b) ZU-110P, (c) Zio Patch, (d) myBeat, (e) RF-ECG, (f) eHeart. (All reproduced with permissions).

ty following a large number of clinical findings in arrhythmia, silent myocardial ischemia, sudden death syndrome, and pacemaker follow-up, because such data were difficult to capture during occasional clinic visits due to their transient nature. This led to the widespread acceptance of the device as a routine clinical technique for ECG monitoring without markedly affecting daily activity.

Over the following five decades, a great deal of effort was invested toward achieving better usability, longer recording time, faster interpretation speed, smaller size, lighter weight, higher digitized resolution, more channels, and more functions. As a result, many similar products were developed.

The devices became smaller and lighter and yet more functional. In addition to ECG, these devices can simultaneously monitor multiple types of information such as activity and body temperature. The “Cardy 303 pico+” is waterproof and can be used during bathing, is only 9 mm thick, and weighs 13 g. A three-axis acceleration sensor is built-in for monitoring gestures and activities, as shown in **Fig. 1(a)** [16].

Different clinical purposes may require different electrode schemes. One problem with the traditional Holter device is the so-called cord spaghetti syndrome. A pilot study on a cordless ECG monitor aimed at mitigating the spaghetti syndrome and improving usability was conducted in the early 1990s [32]. An electrode pad was adhered directly to the body surface to measure two channels of ECG continuously over 24 h. Measured ECG was transmitted from the pad to a tape recorder real-time and without wire. Several devices such as ZU-110P (**Fig. 1(b)**) [33] and Zio Patch (**Fig. 1(c)**) have been commercially available since the early 2000s. The Zio Patch is an adhesive patch-type monitor for continuous ambulatory recording of single-lead ECG. In comparison with conventional Holter monitors that usually function for only 1 day, a pilot study involving 146 cardiac patients indicated that the Zio Patch could remain attached for as long as 14 days and detect arrhythmia more accurately without missing too many events [34–37].

Real-time processing, network connectivity, and more parameters are bundled into a compact size. The “myBeat WHS-2” (**Fig. 1(d)**) [38] and “RF-ECG” (**Fig. 1(e)**) [39] measure not only ECG but also body temperature and three-axis acceleration. The

Fig. 2 Home-oriented portable monitors by Omron: (reproduced with permission).

former is 13.7 g in weight and 10 mm in thickness, can function for 20 h using a rechargeable lithium ion button battery, and uses Bluetooth Smart communications for data exchange. Its application programming interface (API) is provided free of charge and is open to partners.

One significant derivative is an event monitor that can promptly capture emergent events such as transient arrhythmia and related symptoms, while reducing the redundancy of data recording through real-time interpretation of the ECG signal, thereby making it possible to reduce the size of the device, similar to a wristwatch [40]. The “eHeart” is a pocket-sized portable ECG recorder that can record 12 events each of 24-s duration, as shown in **Fig. 1(f)** [41].

In outdoor applications, a portable monitor usually makes use of a mobile phone for data transmission. In indoor applications, a portable monitor often has more flexible options such as Bluetooth, infrared, camera, and near-field communication (NFC) for data transmission to a base station, which relays the data to remote servers.

In addition to ECG, many other types of information such as SpO₂, glucose, blood pressure, respiratory functions, breath gas, body temperature, body fat, body weight, and motion have been integrated in a set of home-oriented portable devices. Most of these are directed toward both general wellness as well as chronic conditions such as congestive heart failure, chronic obstructive pulmonary disorder, asthma, hypertension, diabetes, obesity, and sleep disorders. Commercial products include MedStar [42], TeleHealthcare Network [43], Tiered Platforms [44], CardioBlips [45], LifeStar [46], MedicalLINK [47], HealthPlanet [48], Sentry Telemonitor [49], Health Buddy System [50], Be-Close [51], e-neighbor system [52], Care Innovations Connect Platform [53], GrandCare Com [54], Philips’ Telestation [55] Omron Wellness Link [56] and Sotera Wireless Visi Mobile System [57]. **Figure 2** shows a typical example of these systems.

The Visi Mobile includes noninvasive beat-to-beat blood pressure measurement that is either cuff-based or cuffless. Using the cuff module, blood pressure is measured and then the pulse transit time is continuously monitor to estimate the blood pressure [57]. The FDA approved cuffless, non-invasive, continuous blood pressure monitoring in 2013.

Fig. 3 Representative wearable monitors (a) Smart Shirt (provided by Sundaresan Jayaraman/Georgia Institute of Technology, reproduced with permission) (b) PEDOT-PSS (left=interior, right=exterior) (provided by NTT), (c) Wearable Wellness System (reproduced with permission), (d) Adhesive flexible plaster (reproduced with permission).

2.2 Wearable Monitors

Clothing is a good candidate for a more natural means of seamless monitoring of physiological information indoors or outdoors. Articles typically worn in daily life, such as accessories, hats, wrist watches, shirts, shoes, finger rings, bracelets, brassieres, barrettes, and belts can be used.

Sensing technology can be incorporated in traditional fabrics, or the textile itself can be made functional [58].

In the mid-1990s, the “Smart Shirt,” which integrated conductive fibers and a host of vital sign sensors, was developed to monitor the wearer’s heart rate, ECG, respiration, temperature, and voice [25], as shown in **Fig. 3(a)**.

Most functional textiles are made primarily of metallic or optical fibers that are fragile and uncomfortable to wear, and they also corrode and are non-washable. Alternatively, coating silk fibers with the conductive polymer PEDOT-PSS improves tensile strength and functionality without any adverse effects on biocompatibility, hydrophilicity, or flexibility [59], as shown in **Fig. 3(b)**. A similar product, the Wearable Wellness System (WWS) that uses yarns with built-in sensors can acquire ECG, respiratory signals, and tri-directional body movements, and extract several parameters such as heart rate, respiration rate, signal quality index, posture, activity, and energy expenditure [26], as shown in **Fig. 3(c)**. The WWS was developed as a part of the EU-funded “MyHeart” project, which aimed at continuous monitoring of vital signs to gain information regarding the health status of an individual in a natural environment [60]. They were designed to be more similar to a piece of clothing and less like a medical device.

By alternately dipping normal cotton yarn into a solution of conductive carbon nanotubes in water and a solution of special sticky polymer in ethanol several times, the yarn becomes highly conductive but remains pliable and soft [61, 62]. Moreover, addition of, for example, an anti-albumin antibody to the carbon nanotube solution results in a reaction with albumin in blood, leading to a significant increase in conductivity of the fabric. Any antibody can be incorporated into the yarn and used to detect other biomolecules and proteins.

Fig. 4 Accessories and female items as wearable monitors. (a) Fitbit, (b) finger ring (reproduced with permission), (c) e-brassiere (provided by Kwangsuk Park, reproduced with permission), (d) Karada Fit. (reproduced with permission).

Industrial exploitation of functional textiles is still in its infancy, but the number of technological implementations is increasing. A thorough investigation reviewed many of the latest advances in this area [63]. Clevertex aims to develop a strategic plan for the transformation of traditional textiles and clothing into a knowledge-driven industrial sector by 2015.

Epidermal electronics can be used to develop flexible and stretchable stamp-sized patches that can be attached to the skin to monitor electrical activity [64]. A flexible patch that integrates nano-scale sensors and drug delivery components onto a stretchable polymer substrate is used not only as a monitor but also as a therapeutic device [28, 65]. The patch can measure EMG data and perform real-time processing to determine the proper timing for delivery of medicine through the skin, as shown in **Fig. 3(d)**.

Accessories such as watches, bracelets, and finger rings are useful devices for daily monitoring. **Figure 4(a)** shows a bracelet that serves as an activity and sleep monitor when worn day and night. Multiple measurements such as photoplethysmogram, pulse rate variability, SpO_2 , and blood pressure can be performed by a finger ring, as shown in **Fig. 4(b)** [66].

More options are available for women, such as a brassiere with embedded gold nanowires as electrodes for monitoring ECG in daily life [27, 67]. This was further developed to make evidence-based decision to automatically unlock the brassiere in the presence of a lover by real-time processing of heart rate variability, as shown in **Fig. 4(c)**. “Karada Fit MTN-200” is similar in appearance to a hair holder but can measure activity and connect to a mobile phone via NFC [68], as shown in **Fig. 4(d)**.

Movements are often the source of motion artifacts in physiological measurement for ambulatory applications. Various algorithms and instruments have been deliberated to achieve reliable measurement and higher signal quality by removing the movement signals [69]. Nevertheless, one man’s trash may be another man’s treasure. The movement signal is a useful indicator in evaluating human activity. More than 20 activity monitors are available commercially [70].

When a shoe is embedded with an insole pressure sensor and an accelerometer, as shown in **Fig. 5(a)**, movement can be an important signal for monitoring daily activities, such as energy expenditure and major postures [71]. The “SenseWear” arm-

Fig. 5 Activity monitors. (a) Shoes with insole pressure sensor and accelerometer (reproduced with permission), (b) SenseWear, (c) Misfit Shine (reproduced with permission).

Fig. 6 Mobile-phone-based monitors. (a) Multiple functions, (b) sphygmomanometer, (c) ultrasound image (Photographs provided by David Kilper/WUSTL, reproduced with permission).

band [72, 73] acts as a versatile monitor of daily physical activity and sleep behaviors in a free-living environment, as shown in **Fig. 5(b)**. The “Misfit Shine” is a clasp and can track activities on land and in water, running or swimming, when clipped onto clothing [74], as shown in **Fig. 5(c)**. It weighs less than 10 g and uses a coin battery that provides power for 4 months of use.

In addition to clothing and accessories, mobile phones are now integrated into our daily life and are becoming indispensable. A mobile phone can be used to monitor falls [75]. A mobile phone may be fitted with integrated sensors for monitoring respiration gas, body fat, activity, calorie consumption, and photoplethysmogram [76], as shown in **Fig. 6(a)**. A mobile phone can also be transformed as a satisfactory platform to serve as a sphygmomanometer [77], as shown in **Fig. 6(b)**, or an ultrasound imaging monitor [78], as shown in **Fig. 6(c)**. The potential of mobile phones in application of healthcare domain remain to be further excavated [79]. The wellness paradigm of mobile phones will facilitate daily healthcare wherever there is mobile network coverage.

Wearable monitors are evolving toward increased comfort, functionality, mobility, affinity, and esthetics, and will finally merge into daily personal items without sharp demarcation.

2.3 Invisible Monitors

Although wearable monitors can be used both indoors and outdoors without marked disturbance of daily life, some are in direct contact with the human body, and therefore may be associated with problems such as unpleasant or allergic reactions. When application is limited to indoor use only, many types of physiological information can be monitored by noncontact means, where sensors are concealed and invisible to the user. Various sensors can be embedded into a wide variety of fixed home appliances such as beds, toilets, and bathtubs, or even in moving objects such

Fig. 7 Bed monitors for various vital signs. (a) Body temperature distribution map, (reproduced with permission) (b) electrocardiogram and respiratory rate, (c) ballistocardiogram.

Fig. 8 Commercial sleep monitors. (a) Sleep Design HSL-101, (b) Installed image of Sleep Scan SL-504, (c) Sleep EYE GD700, (d) Sleep Recorder SD-101 (All reproduced with permissions).

as cars. Over the past three decades, many academic studies have been conducted and some of their outcomes have been developed commercially.

Figure 7 shows bed monitors for various vital signs, such as (a) body temperature mapped by a 16×32 thermal sensor array [80], (b) ECG by two electroconductive textile sheets at the head and feet [81] and respiratory rate at the thorax and abdomen sheets [82], and (c) ballistocardiogram and respiration by a piezo-electric pressure sensor installed beneath the pillow or the mattress [83].

Many sleep monitors are commercially available as screening tools for sleep apnea and other sleep disorders. These devices usually monitor heart rate, respiration rhythm, and body movement by various engineering principles, and derive sleep parameters such as sleep efficiency, sleep latency, and sleep stage. **Figure 8** shows (a) a noncontact monitor based on Doppler radar [84–87], (b) a sensor board filled with water for sensing body pressure/vibrations [88], and (c) a thin sheet with multiple pressure-sensitive cells [89–91].

Various sensors can be embedded into sanitary facilities such as bathtubs and toilets without interfering with their utilization. **Figure 9** shows some examples: (a) a bathtub monitor that can measure ECG via stainless steel electrodes on the bathtub wall [23]; (b) the shower head and the ground constitute two electrodes for ECG measurement during shower [92–94]; (c) ECG is measured when the thighs contact two electrodes attached to the toilet seat, and body weight, urinary volume and flow rate, and sugar level are analyzed simultaneously [81,95]; (d) “Thermo

Fig. 9 Sanitary-facility-based monitors embedded into a (a) bathtub (reproduced with permission), (b) shower, (c) toilet (reproduced with permission), and (d) dressing mirror (reproduced with permission).

Fig. 10 Fixed and moving invisible monitors. (a) Dining table and a ceiling lamp with a built-in video camera, (b) car seat, (c) car steering wheel (photographs provided by Denso, reproduced with permission).

Mirror” has an appearance of a cosmetic mirror but has a thermal sensor embedded to measure the temperature of facial skin without physical contact [96].

Many other fixed and movable objects can serve as invisible monitors for daily monitoring. A “magic carpet” embedded with a mesh of optical fibers detects deflected light patterns and is able to estimate walking ability of the elderly for early detection of erratic movements and mobility problems [97].

Figure 10 shows (a) a dining table and a ceiling lamp with a built-in video camera, (b) a car seat, and (c) a car steering wheel as invisible monitors. The dining table can be used to monitor daily nutrition intake by the video camera integrated within the ceiling lamp above the table [98]. Capacitive electrodes are embedded in a chair [21] or car seat [99] to monitor ECG while sitting. Two pieces of metal electrodes are affixed to the left and right sides of the steering wheel to detect ECG, and a reflective photoelectric sensor is embedded on the right side for photoplethysmography when driving [100].

Many modalities of invisible monitors based on various engineering principles, which can be deployed in furniture indoors or moving vehicles outdoors, are being developed.

3. Tasks and Topics for Future Study

Daily healthcare is a more pressing challenge than ever before in the aging society due to the dominance of chronic diseases in the elderly. To facilitate effective healthcare, studies have aimed to achieve increased data collection rates, more accurate interpretation of physiological significance, less disturbance of daily activity, ease of use, and usability by untrained and unskilled users [101]. Remarkable technical innovations have facilitated seamless monitoring of physiological information, and a wide variety of solutions and products have covered various scenarios in daily life. More options are now available regardless of indoors or outdoors, awake or asleep, sedentary or ambulatory.

Nevertheless, many political, administrative, medical, and technical problems remain to be resolved. A WHO report pointed out that current societal systems do not sufficiently distinguish between acute and chronic care, and patients are seldom provided with a long-term management plan for chronic conditions to ensure the best outcomes. This report suggested that an innovative strategy and action plan at the national level is required. Healthcare should be considered as a long-term investment that will yield national dividends. Countries must change their policies to establish a stepwise framework to offer a flexible and practical approach; for example, by making health insurance applicable to not only diagnosis and treatment but also prevention and health promotion. Such a framework will lead to significant improvements in prevention of chronic disease [102].

Collaboration between the medical field and engineering societies is of paramount importance. Medical doctors and healthcare workers should recognize the current shift in the medical paradigm from irregular clinical visits to home-based daily monitoring, play an active role in promoting health and not merely treating disease, make full use of newly developed devices, attract more attention from other related sectors, and act as a bridge among end-users, developers and policy makers. Engineering societies should supply accurate, convincing, and reliable evidence that seamless monitoring in daily life can reduce medical and health insurance costs. Provided that the importance of seamless monitoring in daily life is acknowledged by all relevant stakeholders from policy makers and end-users to healthcare workers and medical doctors, awareness will be shared and cooperative actions will be taken promptly from the administrative and enterprise levels to the community and individual levels.

To overcome the obstacles to further popularization, several technical aspects must be emphasized, such as how to detect physiological information without interfering with activities of daily living, how to perform in-depth data analysis for comprehensive and accurate interpretation of physiological significance, and how to provide a secure platform for individuals and physicians.

Persistent data collection is indispensable in daily health management because health condition tracking requires data accumulation over a long period. The requirement for minimal disturbance of activities of daily living often limits technical options and leads to issues such as low signal-to-noise ratio (SNR) and poor signal quality. Utilization in the daily environment and by nonprofessional users is frequently a cause of inaccurate measurements, uncontrollable data loss, and interrupted monitoring. Even those aware of the importance of daily monitoring to main-

tain a healthy life and sufficiently motivated to monitor their physiological conditions may still hesitate to manipulate a complicated medical device on a daily basis [103]. These problems usually reduce the reliability of deep mining of physiological information.

For persistent data collection in daily scenarios, user-centered affinity with various sensors and measurement sites should be taken into account; innovative modalities should include some common features such as scalable systematic architecture to allow personalized customization, autonomous troubleshooting and automatic recovery from failure, network-based administration for remote assistance, zero maintenance, and fully automated operation to reduce the need for user intervention. An ambitious clinical trial to facilitate health management even in healthy individuals is currently underway, in which a tiny cardiac monitor, approximately one-third the size of a AAA battery, is implanted in the chest over the heart for continuous monitoring up to 3 years [104].

However, issues remain regarding poor signal quality, fragmented information, and data discontinuity due to unavoidable data loss in measurement and transmission over the network. To obtain reliable results from such multifaceted data, appropriate models to estimate the signal quality index (SQI) of the measured data are necessary to establish an optimal threshold for exclusion of lower SQI data. More robust algorithms are required to complete and surrogate inconsistent data due to outliers and artifacts. These will improve the reliability of the analytical outcomes. A series of attempts have been undertaken to deal with the missing RR intervals during daily monitoring, using several statistical models [105–107]. Physiological significance can therefore be interpreted more accurately in terms of identifying the statistical links between dynamic health condition and physiological information, and to provide explicit evidence for health management practice.

Fortunately, Big Data platforms and cloud computing infrastructure are open, scalable, and can be used to store and share huge volumes of information over the network. This facilitates realization of efficient mining of not only physiological information but also psychological and social well-being data that can be collected from the social networking service (SNS) infrastructure, and provides an effective approach to evidence-based health management using a holistic view of health. Insufficient privacy protection due to systematic security vulnerabilities is another major problem when large amounts of personal data are transferred, exchanged, and stored over network infrastructure. Traditional measures such as one time password (OTP), secure sockets layer (SSL), and secure electronic transactions (SET) protocols, as well as redundant and replicate system implementation can guarantee data security and protect privacy. Moreover, identity authentication by automatic identification of personal physiological information is another available security option in biomedical systems.

Charging the battery of monitoring devices during the day is inconvenient for the user. Power solutions are thus critical for maintaining consistent monitoring. Energy harvesting through optical and thermal conversion as well as wireless radio-electromagnetic transmission may provide solutions to these issues [108, 109]. Indoor illumination can provide not only lighting but can also carry information over distances [110]. A conventional home

can be turned into an intelligent hub for implementation of healthy aging management by embedding a variety of such monitors into the furniture and appliances.

As gathering of data for a short period does not provide significant evidence for quantitative evaluation of health, informed consent should be obtained from the users for their daily involvement over a long period. In contrast to occasional clinic visits, daily monitoring requires constant input from the users either by their involvement in self-management or by provision of essential information to ensure optimal outcomes. Seamless monitoring using the approaches described here has many advantages such as rapid response to emergent situations, less inconvenience to the user, minimal intrusion by concealment, no requirement for sensors to be attached to the body, gender neutrality and one-size-match-all. Therefore, such approaches are beneficial for elderly persons who are generally unfamiliar with manipulation of technical equipment. This will result in greater acceptance of "aging in place" in elderly healthcare.

4. Conclusions

It is an arduous task to select symbolic instances from the huge numbers of publications worldwide. We therefore did not intend to cover all aspects of seamless monitoring in this article. Instead, we have presented an overview of this emerging field through retrospective examination of the achievements over the past several decades, to encourage further collaborations among different professional disciplines and at various administrative levels.

The borders among portable, wearable, and invisible monitors are becoming rather indistinct. One device can be transformed into another when the application scenario changes. A wearable outdoor monitor can turn into an invisible monitor when used indoors. Although many challenges remain, with the maturation of technical and societal atmospheres and the dream of achieving a healthier and longer life through innovation, the prospect of seamless monitoring is a promising emerging field of interdisciplinary research. This is referred to as "Metrology of Health" or "Healthology," which aims to quantify the overall health status in an integrative manner and to untangle the causal connections among longevity and relevant determinants such as pathogenesis and immunity, meteorological and environmental factors, and social behavioral-psychoneurotic interactions, through further exploration.

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Conflict of Interest

The authors declare no conflict of interest.

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