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In the spotlight: BioInstrumentation

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1. Introduction

Over recent decades a very large number of studies have been vigorously carried out to develop invasive and non-invasive physiological measurement bioinstrumentation, for use in areas such as basic and clinical medicine, healthcare and welfare science, sports science, and others. Non-invasive measurement is generally considered to be the most desirable approach for practical use, but in addition there is a significant increasing need to monitor physiological variables in a manner that allows the subject to be unconstrained, which can be achieved by the so-called ambulatory or wearable monitoring techniques. This means that biological sensors and/or miniaturized measuring units are to be carried by the subject or are to be embedded in his/her clothes. The development of such monitoring approaches through modern technological advances has progressed remarkably, and this review briefly introduces several areas where such recent advances have been made.

2. Ambulatory/Wearable Physiological Monitoring

As is well recognised, the first attempts to develop a portable ECG device with radio telemetry, called "*Radioelectrocardiography*" [1], and then with tape recording [2] were reported by N. J. Holter. Refinements of such systems are now commercially available and widely used in clinics as the Holter ECG recorder [see Ref. 3]. Following Holter's epoch-making initiative, numerous research studies have been carried out aiming to monitor a wide range of physiological variables during ambulatory use. In particular, a portable sphygmomanometer, the "ambulatory blood pressure monitor (ABPM)" [4, 5], which is based on the auscultation and/or cuff-oscillometric method [6], has been one successful example akin to the Holter ECG recorder, and these two are now widely used in clinical medicine as key devices. Also, modern micro-electronics and mechanical technologies have enabled us to produce more compact and convenient devices for home use.

Fig. 1 shows the basic construction of a typical ambulatory/wearable monitoring system, consisting of a biological sensing unit (BSU), a portable measuring unit (PMU) for signal processing and data storage, and a data reproducing and display unit (DRU), which is usually a conventional personal computer (PC). The BSU and the PMU are carried by the subject, and in the BSU are either conventional biological sensors/electrodes or sensing devices embedded into the subject's clothes. For signal processing and data storage in the PMU, a microcomputer-based system is usually adopted at present to make it more compact and convenient to operate. Over the last decade advances in information and communication technologies have led to the use of wireless communications between BSU and PMU and between PMU and DRU.

A selection of recent attempts at physiological monitoring relating in particular to cardio-pulmonary, human activity and biochemical information are now briefly described.

(a) Cardio-pulmonary monitoring

Due to the importance of evaluating cardiovascular and pulmonary function there have been many attempts over the past several decades to develop appropriate ambulatory/wearable physiological measurement systems. These have been based on key physiological variables, including the ECG, blood pressure (BP) and respiration.

Considerable improvements as compared with the initial Holter ECG recorder have been made in terms of miniaturization and data storage in the PMU and regarding data communications. In addition, much effort has been given to improving the design and fabrication of ECG electrodes. Wet-gelled spot electrodes remain the most common approach, but efforts continue to be made to improve dry electrode designs as such an electrode is thought by some workers to offer good prospects of achieving long-term electrical stability for ambulatory use. As previously reviewed in this Spotlight column [7, 8], several approaches to measure ECG using dry electrodes have been introduced, although further improvements of the electrical characteristics were still required. Recently Gargiulo et al. [9] have reported an approach based on the use of conductive rubber electrodes together with an ultra-high input impedance ECG amplifier and, with Bluetooth wireless communication, have demonstrated 24 hours successful ECG monitoring. It is interesting to note that their system was actually applied to the measurement of the ECG during body-building and swimming exercises and they also claimed its usefulness to prevent an athlete's sudden death due to a syndrome called "athlete's heart" [10, 11].

An interesting approach to monitoring such vital signs as ECG and respiration was implemented within the WEALTHY project [12, 13], supported by the 5th Framework IST (Information Science and Technology) Programme of the European Union. In this research woven sensors that could be worn without any discomfort for the user were developed. The fabric sensors were woven from smart fibres and yarn having conducting and piezoresistive properties. These were formed and integrated into well-fitting garments and then used to obtain recordings of vital signs. It is reported that the system can provide reliable and satisfactory data as compared with conventional standard methods. It was also reported that the proposed system could assist patients during rehabilitation training or subjects working in extremely stressful environmental conditions, ensuring continuous surveillance.

There have been several recent attempts to use textile electrodes as wearable sensors. Mitchell et al. [14] devised a t-shirt embedding a textile-based piezoresisistive sensor together with a Zigbee wireless transmitter for the monitoring of breathing. Wireless communication was made between the sensor and a PC installed in a Zigbee receiver, where the respiration signal was displayed in real-time to present to a subject for breathing exercises. It is stated that this wireless biofeedback system could be useful for breathing training that is a part of the treatment for respiratory illnesses such as cystic fibrosis.

Just recently, Rantala et al. [15] designed an interesting wearable optical sensor sewn into clothing for the ambulatory monitoring of respiration and tidal volume. The sensor has 16 specially aligned optical fibres. The intensity of light passing through the fibres changes in response to fibre bending due to respiration and a signal representing changes in tidal volume is thereby obtained.

Photoelectric plethysmography is also promising as a convenient means for ambulatory use. As an interesting healthcare application, Fletcher et al. [16] developed a wearable photo-plethysmographic sensor with wireless networking to monitor photo-pulsations. This is combined with a sensor for measuring electrodermal activity (EDA) from the wrist designed by

Poh et al. [17], to evaluate autonomic nervous activity. They proposed two types of network systems; one was with IEEE 802.15.4 so as to apply multiple sensors and the other with Bluetooth to communicate directly with a mobile phone.

In contrast to these vital signs that can be monitored with relative ease, arterial blood pressure (BP) and cardiac output (CO) are the essential parameters for the detailed evaluation of cardiovascular haemodynamic functions. Through a considerable amount of research and development activity and effort, the ABPM has become one of the most successful examples of the commercialization of research outcome. This device is quite convenient for practical use, measuring BP at a set interval of 30 min or more. However, this means that it can acquire less than 48 data points per day [18, 19]. Because there are approximately 80,000-100,000 BP data points per day produced by individual cardiac beats, only about 0.05% of the complete BP data set can be obtained by ABPM. It is therefore desirable to acquire BP on a beat-by-beat basis. It is furthermore apparent that the acquisition of BP and CO data together on a beat-by-beat basis combined with other cardiovascular data would be much more powerful. For example, this could enable the detailed analysis of haemodynamic responses and autonomic regulation of the cardiovascular system to be carried out in response to various stressful daily activities.

With this as a background, the author’s group has recently developed a new beat-by-beat cardiovascular haemodynamic monitoring system both for ambulatory and/or stationary use [20] on the basis of a technological combination of the volume-compensation [18, 19, 21] and transthoracic electrical admittance methods [18, 19, 22-24]. Recently, Ogawa et al. [25] have applied this system to the assessment of cardiovascular stress reaction on a beat-by-beat basis in response to daily activities using the recently proposed Gregg's method [26]. They clearly demonstrated the separation of active, passive and mixed stress coping during daily living.

(b) Activity monitoring

The importance of ambulatory activity monitoring is well recognized in the fields of gerontology, rehabilitation, exercise training and general healthcare. In the field of rehabilitation, for example, a therapist must evaluate motion characteristics, for example during standing up walking, and other activities. However, it is very much a situation in which the therapist must usually make assessments subjectively by direct observation and quantitative assessment of activities is highly desirable. One method employed is to make recordings using a 3-dimensional motion capture system, but the range over which such recording is possible is usually limited and data analysis is complicated, rendering this system unsuitable for use in practical rehabilitation.

Some wearable instruments capable of monitoring activity [27-32] and gait and posture [33, 34] using sensors such as an accelerometers, a gyro-sensors and so on, have been developed. One such development has been reported by Motoi et al [35], and this enables the monitoring of static and dynamic posture changes in the sagittal plane together with gait and walking speed. The system uses three miniaturized units fixed to the trunk, thigh and calf and it measures their angles with respect to the gravitational direction using accelerometers and gyro-sensors. Each unit has these sensors as well as a Zigbee transmitter for wireless communication for real-time observation and a micro-SD card for long-term recording. The authors successfully demonstrated the viability of this system for the quantitative evaluation of the efficacy of rehabilitation programs as well as normal daily activities.

Another noteworthy attempt aimed at exercise training is reported by Lee et al. [36] This system is capable of monitoring activity along with the ECG using a tri-axial accelerometer and conductive fabric electrodes embedded in a shirt. This sensing unit is networked with IEEE 802.15.4 Zigbee W-PAN (wireless personal area network). It is noted that this type of sensing network could be promising for many kinds of data acquisition by retrofitting a large number of miniaturized sensors.

(c) Biochemical monitoring

To date, numerous developments have been focused on physiological monitoring relating to cardio-pulmonary and activity information as mentioned above. However, there have been few attempts to monitor biochemical quantities for ambulatory use, despite its usefulness and importance to evaluate biochemical status for healthcare management. In this context, Yang et al.

[37] recently attempted to fabricate a biosensor directly printed on underwear, similar to a screen-printing process onto the textile substrate. The authors described the detection of 0–3 mM ferrocyanide, 0–25 mM hydrogen peroxide and 0–100 M NADH. It is also noteworthy that the European Union project called “BIOTEX” developed biochemical-sensing techniques using a textile-based wearable biosensor to monitor pH and sodium (Na+) in sweat [38-40]. Here, the sensing part consists of (1) a passive fabric pump made of a super absorbent material for the continuous suction of sweat from the skin, (2) a pH sensitive dye, and (3) an LED/photo-detector pair to measure colour changes of the dye due to the changes of the solute concentration in sweat. They also used a pair of gold electrodes and ion-sensitive membrane as the wearable sodium sensor.

3. Future Aspects

Recent developments and the present status of non-invasive and ambulatory/wearable monitoring were briefly introduced in this review. In the light of the growth of the aging society worldwide, such monitoring techniques will be increasingly required as a possible scheme for preventive medicine, early diagnosis, rehabilitation and sports medicine, as well as timely treatment of lifestyle-related diseases.

Several research approaches described herein appear innovative and groundbreaking, particularly in the developments of instrumented garment systems and wireless communication techniques with miniaturized sensors. Optimistically it might be anticipated that such convenient instruments could be made available at reasonable costs in the future, although there are still numerous challenging obstacles to be addressed, such as the rather conflicting needs for small size, wear comfort, simplicity of operating procedures, accuracy, power management, stability and so on for truly practical use.

Taking the availability and potential of these techniques to contribute in many biomedical fields into consideration, further comprehensive studies will still be required to realize this potential and thereby achieve an advanced and truly practical approach. Nevertheless, the considerable recent dramatic advances in microelectronic, micromechanical, information and communication technologies will doubtless resolve the problematic issues that still remain.

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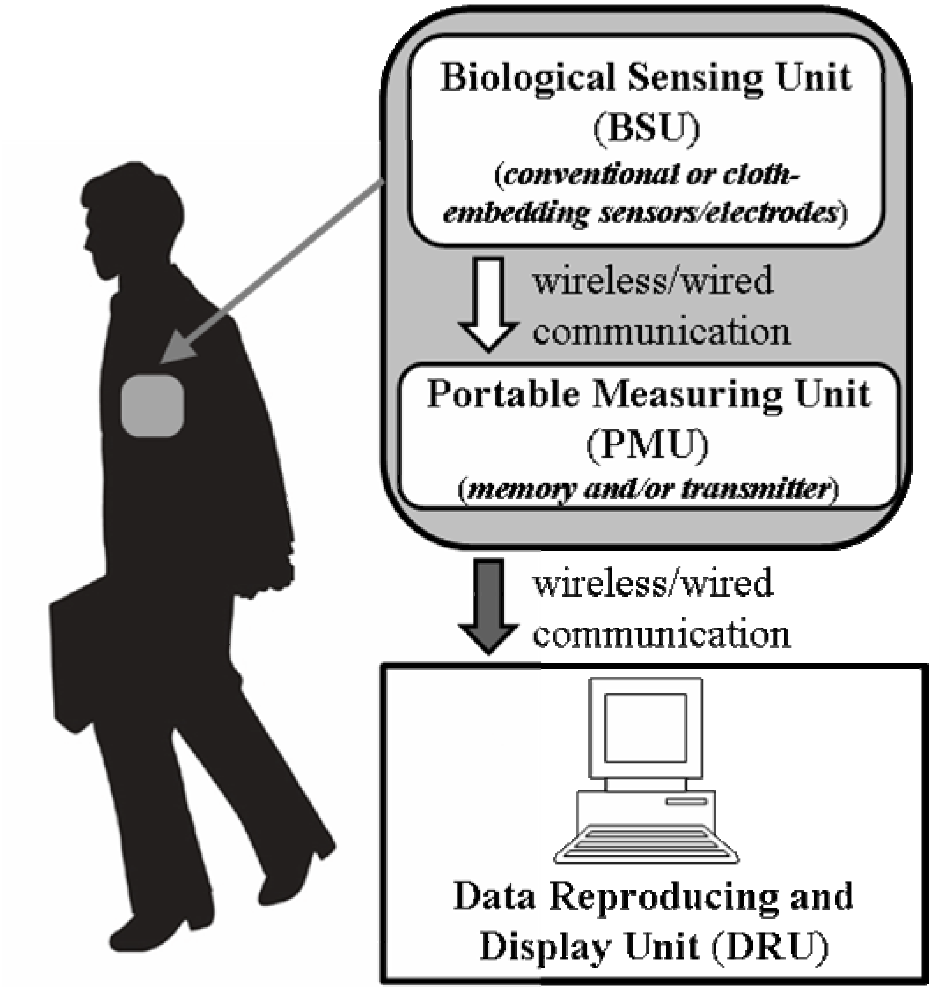

(Fig. 1: K. Yamakoshi)

Figure Legend

Fig. 1: Outline of basic construction of ambulatory/wearable monitoring system. The system mainly consists of a biological sensing unit (BSU), a portable measuring unit (PMU) and a data reproducing and display unit (DRU). See text for further explanation.