Semiconductor wireless technology for chronic disease management

L. Tarassenko and D.A. Clifton

With most chronic diseases, monitoring of one or more physiological variables (vital signs) can inform the management of the patient. In active monitoring, the patient adjusts medication dosage according to the value of the measured variable. Passive monitoring is associated with the more advanced stages of chronic diseases and requires the use of wearable sensors. Digital plasters which exploit recent advances in semiconductor technology can now provide continuous monitoring and wireless transmission of patients’ vital signs for several days. The ideal digital plaster, or adhesive patch, for long-term passive monitoring would incorporate both electrical and optical measurements. Other promising technologies for the future include implantable sensors and non-contact vital sign imaging.

Introduction: Over the last 50 years, healthcare expenditure has outpaced GDP growth by about 2% a year in most OECD countries. Chronic disease management accounts for 80% of this growth [1]. Chronic diseases (also known as long-term conditions) are responsible for the World Health Organisation as ‘health problems that require ongoing management for years or decades’. According to the figures for 2008, there are 15.4 million people in England with a chronic disease [2]; diabetes on its own takes up approximately a tenth of the NHS budget each year, a total exceeding £9 billion [3]. Patients with chronic diseases account for 52% of all GP appointments, 65% of all outpatient appointments and 72% of all inpatient bed days [2].

In this review Letter, we focus on those chronic diseases for which monitoring of one or more physiological variables can inform the management of the patient: asthma, diabetes, hypertension, chronic heart failure (CHF), and chronic obstructive pulmonary disease (COPD). Each chronic disease has its own requirements, but we will attempt to make generic points which are broadly applicable to all such diseases.

First, we distinguish between active and passive monitoring. The former is well established as a component of self-management in chronic diseases such as type 1 diabetes or asthma, whereby the patient adjusts medication dosage according to the value of the measured variable. Passive monitoring is associated with more advanced chronic diseases, such as moderate-to-severe COPD or CHF. Such monitoring usually requires the use of wearable sensors for periods of time which may vary from minutes to days. The evaluation of passive monitoring for chronic disease management has so far been limited to pilot studies, however, and systematic reviews highlight the need for further research [4].

Active self-monitoring: Self-monitoring of peak expiratory flow (PEF) has been part of self-management for asthma patients since the invention of the Wright peak flowmeter, a simple mechanical device, more than 50 years ago [5]. Similarly, regular blood glucose monitoring throughout the day has been a feature of self-management in type 1 diabetes, since the introduction of the first electronic glucometers 30 years ago [6]. For patients who require insulin injections (people with type 1 diabetes or insulin-treated type 2 diabetes), the main aim of self-management is to take sufficient insulin to keep blood glucose levels down, whilst avoiding hypoglycaemia (low blood sugar). For asthma patients, the main aim of self-management is the appropriate use of inhalers to deal with worsening symptoms, especially the use of steroids to cope with exacerbations as they begin to develop.

Self-monitoring may achieve improvements in outcome not only by judicious control of medication (‘the expert patient’) but also by providing advanced warning of adverse events (exacerbations for asthma patients and hypoglycaemia for diabetes patients) and also giving insights into factors that influence the course or progression of a disease and can support lifestyle changes. There is strong evidence showing the benefits of blood glucose testing to adjust insulin dose for people with type 1 diabetes in the context of a well-defined management plan [7]. The use of peak flow monitoring to improve outcomes for asthma has also been shown to be effective when embedded in an educational framework with patient-defined action plans [8]. Several studies (e.g. Cappe et al. [9]) have shown that blood pressure control is better in patients with treated hypertension who self-monitor at home using a blood pressure monitor and inflatable cuff.

The frequency of self-monitoring will depend on the patient’s chronic disease [10]. For example, patients with type 1 diabetes should measure their blood glucose (BG) levels three or four times a day, whereas hypertensive patients need only check their blood pressure once or twice a week. Patients with asthma should ideally monitor their peak flows in the morning and evening.

Self-monitoring in asthma or type 1 diabetes is the first step in a measure-evaluate-act feedback loop. The action consists in adjusting the dose of bronchodilator (using a reliever inhaler) or corticosteroids (using a preventer inhaler) based on the measurement of PEF, or in adjusting the dose of insulin, based on the measurement of BG, linked in both cases to an evaluation of the measurement in the context of other, relevant information. For asthma patients, evaluation involves an assessment of symptoms such as breathlessness, and for diabetes patients, food intake and physical activity need to be reviewed. This information is usually recorded on paper in a patient diary. The introduction of mobile phones with data storage and transmission capabilities, when the General Packet Radio Service (GPRS) network was switched on in 2002, enabled the implementation of an electronic patient diary on the phone. We developed at that time an integrated solution with an electronic BG (or PEF) meter linked to the patient’s mobile phone via Bluetooth [11–13]. The physical separation between the electronic measuring device and the mobile phone is important as a fully integrated phone becomes a medical device and hence requires the relevant regulatory approvals.

Passive monitoring: The percentage of hospital bed days taken up by patients with one or more chronic disease is putting a severe strain on healthcare systems. Often these patients oscillate back and forth between hospital and home or residential care. For example, 30% of COPD patients admitted to hospital in any given year for treatment of acute exacerbations are readmitted at least once within the year. The problem will only become worse with time unless the management of these patients in the community improves: by 2022, the proportion of people aged 65 and over in England will have risen to 10.8 million [2]. If we could decrease the number of unplanned hospital admissions, the economic burden of chronic disease management would be greatly reduced. The main objective of remote monitoring solutions (‘tele-health’) is to identify patient deterioration before it becomes sufficiently serious that the patient has to be admitted to hospital. A major obstacle to the widespread adoption of these solutions is the ‘human cost’ of data collection. Many frail, elderly people find it difficult to continue with regular self-monitoring on a daily basis. Passive monitoring of vital signs with unobtrusive sensors is therefore an attractive option for them.

Heart rate, respiratory rate, arterial oxygen saturation (SpO2), blood pressure, and temperature are the five vital signs which are measured non-invasively in hospital patients outside the Intensive Care Unit. They are recorded periodically by nursing staff on the general ward, but patients in more acute areas, such as the High-Dependency Unit or the Coronary Care Unit, are continuously monitored using bedside monitors. With a combination of wearable sensors and Bluetooth connectivity, it is now possible to acquire a subset of non-invasive measurements (heart rate, respiratory rate and arterial oxygen saturation) continuously in ambulatory patients [14, 15]. ‘Digital plasters’ which exploit recent advances in semiconductor technology [16, 17] can now provide continuous monitoring and wireless transmission of vital-sign data for several days. As the reliability and robustness of this technology improve, its deployment into the home for remote monitoring of patients with chronic diseases will become more widespread.

The lower-power, silicon technology in digital plasters is designed to measure electrical currents or voltages, usually differentially. The electrocardiogram, recorded between two electrodes on the skin, provides a means of monitoring the patient’s heart rate. The injection of a small, high-frequency current (typically 100 kHz) through the same pair of electrodes allows the respiratory rate to be derived from the changes in electrical impedance of the thorax during breathing. Skin temperature can also be sensed, although its relationship with core temperature depends on ambient temperature and perfusion at the site of measurement. Accelerometers can be micro-machined into the silicon substrate, to provide information on body position which can be integrated with vital-sign data.

Non-invasive measurements, which require different types of silicon sensors (light-emitting diodes and photodetectors), provide other non-invasive vital-sign data. The coloured substance in blood, haemoglobin,
Semiconductor technology is at the core of two new solutions which will increase the robustness of passive monitoring in the near future: implantable sensors and non-contact PPG imaging. Implantable silicon sensors will soon be a viable option for managing patients with the most severe forms of chronic disease. Patients in the advanced stages of heart failure and/or pulmonary hypertension have a very restricted lifestyle unless the disease is controlled through medication. The most important measurement for adjusting medication dosage is pulmonary artery pressure (PAP). A number of implantable sensors for continuously measuring PAP are under development [26, 27], but one of the most promising approaches is a pressure-sensing surface acoustic wave device which is implanted during a simple catheterisation procedure when the patient is in hospital [28]. After the patient has returned home, PAP measurements can be made at any time (e.g. once every five minutes), by interrogating the sensor by radio from a pocket-sized reader situated near the patient. This reader is similar to a mobile phone and it can be wirelessly linked to a remote care.

Non-contact sensing of heart rate and SpO2 using webcams and ambient light, which has recently been demonstrated under controlled conditions, offers a radically new approach to the passive monitoring of patients in their homes. The possibility of measuring PPG signals remotely using a camera (rather than a probe attached to the finger, ear, or toe) was first reported in the scientific literature about five years ago [29, 30]. Verkruysse et al. [31] subsequently showed that PPG signals could be remotely acquired from the human face with ambient light as the source and a simple, digital, consumer-level camera as the detector placed more than 1 m away from the subject. More recently, Poh et al. [32, 33] have used a webcam to record videos of facial regions in human volunteers, using independent component analysis to extract the PPG waveform from regions of interest in the image. This then allowed them to calculate both the heart rate and an estimate of respiratory rate from the RSA component of heart rate variability. Ambient light interference from artificial light, e.g. fluorescent lights, presents problems, but non-contact sensing of vital signs could have a major impact on chronic disease management.

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L. Tarassenko and D.A. Clifton (Institute of Biomedical Engineering, Department of Engineering Science, Old Road Campus Research Building, University of Oxford, Oxford OX3 7DQ)
E-mail: lionel.tarassenko@eng.ox.ac.uk

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