Integration of Wireless Health Technology within the UK Healthcare System: past, present and future

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ABSTRACT

Chronic diseases (also known as long-term conditions) are defined by the World Health Organization as “health problems that require on-going management for years or decades”. In 2008, there were 15.4 million people in England with a chronic disease [2]: diabetes on its own takes up approximately 10% of the National Health Service’s annual budget [18]. Patients with chronic diseases account for 52% of all family practice appointments, 65% of all hospital outpatient appointments and 72% of inpatient bed days [2].

For the expenditure on chronic disease to be reduced, there has to be a decrease in the number of unplanned hospital admissions and emergency visits to primary care physicians. This can only be achieved if patients are enabled to manage their condition better. In this paper, we firstly examine the impact of wireless health technology on supporting diabetes self-management, based on lessons learnt from clinical trials. We show that targeted interventions can achieve an improvement in patient outcomes and a projected decrease in healthcare costs. We consider the requirements for long-term monitoring, and finally we discuss an emerging application of wireless health, early-supported discharge of hospital patients following surgery.

Keywords

wireless health, chronic disease, self-management, diabetes, stroke, COPD, patient monitoring, non-contact sensing

1. SELF-MANAGEMENT

Improved self-management, coupled with regular education, is seen as the best means of slowing the inexorable rise of healthcare spending on chronic diseases but the challenge is to create sustainable, large-scale programs capable of delivering both. As Wilson et al. [22] wrote in the British Medical Journal in 2005: “The evidence backing the use of disease-specific self-management programmes like diabetes is strong. The challenge is how to move to a programme that can support the many millions of patients who might benefit.”

The introduction of GPRS (and subsequently 3G) in Europe in 2002 and 2003 presented an opportunity to develop wireless technology to support the self-management of chronic disease. Over the last decade, the number of people owning a cell phone in the UK has nearly trebled (from 36% of the population in 2000 to 91% in 2011), and one in seven households are now cell-only. Today’s cell phone is a portable device for real-time entry and review of data, which can be used to support self-management strategies. However, the introduction of new technology for healthcare needs to be supported by evidence if it is to be adopted by healthcare professionals. The highest grade of evidence is the randomized controlled trial, and so we carried out a randomized trial of the effect of introducing cell phone technology to support the self-management of type 1 diabetes in young adults aged from 18 to 30 [4].

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 thirty years ago [17]. The main aim of self-management is to inject sufficient insulin to keep blood glucose levels down, taking into account food intake and physical activity, whilst aiming to avoid hypoglycemia (low blood sugar). 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 [9]. For our clinical trial, we developed a wireless health solution with an electronic glucometer (OneTouch Ultra, Lifescan, High Wycombe, UK) linked to the patient’s cell phone via Bluetooth [4] and a patient diary on the phone to record insulin dosage, physical activity, and food intake. The physical separation between the glucometer and the cell phone is important as a fully integrated cell phone incorporating a glucometer would become a medical device which would have to be approved by the FDA.

The control group and the intervention group were both given the Bluetooth-enabled glucometer, the cell phone and the electronic patient diary on the phone. In addition, the intervention group was given feedback in the form of color-coded screens on the phone summarizing their blood glucose control, both in the short term (last 48 hours) and in the long term (up to one month).
A specialist diabetes nurse with web access to the self-monitoring data also phoned the intervention group patients regularly to discuss their diabetes management, spending on average 11 minutes per month with each patient.

Figure 1 demonstrates that the intervention had the desired effect on the blood glucose values recorded during the clinical trial. The histogram for the intervention group is clearly shifted towards the left, with a mean blood glucose for that group of 8.9 mmol/L (160.2 mg/dL) compared to a mean value of 10.3 mmol/l (185.4 mg/dL) for the control group ($p < 0.00001$). The long-term glycemic control for both groups improved, but there was a bigger improvement for the intervention group, with a statistically significant reduction in HbA1c after 9 months from 9.2% to 8.6% ($\text{difference } 0.62\%, \ p = 0.001$). HbA1c is a long-term measure of glycemia over the lifespan of red blood cells (approximately 120 days). A 1% decrease in HbA1c leads to a 33% to 37% reduction in the risk of microvascular complications (blindness, kidney disease and lower-limb amputation), with the associated decrease in healthcare costs in the long term.

The main lesson from the trial may be seen in Figure 2. The regular support from the specialist diabetes nurse ensured high compliance by the patients in the intervention group (as measured by the number of blood glucose readings transmitted by the patients each week) throughout the nine months of the trial. Good self-management, which leads to improved outcomes, requires patient compliance with the recommended self-monitoring schedule, and this was achieved in the intervention group by having a healthcare professional interact at least once a month with those patients, on the basis of shared data.

## 2. TARGETED MONITORING

### 2.1 Insulin Titration in Type 2 Diabetes

Another way to ensure high compliance is to design intervention strategies of finite duration, for example for titrating medication dosage to an optimal level. When first diagnosed, type 2 diabetes is usually controlled through diet and exercise. As insulin resistance builds up over time, oral anti-hyperglycemic agents (such as metformin) are prescribed to keep blood glucose levels within range. Eventually, the addition of insulin injections becomes necessary for many individuals with type 2 diabetes.

We investigated the feasibility of a cell-phone based system for patients with type 2 diabetes who had commenced insulin therapy but remained poorly controlled [7]. All patients except one successfully completed the six-month study. They were provided with the Bluetooth-enabled glucometer and a cell phone with a pre-loaded software application. They were instructed to measure their fasting blood glucose each day before breakfast and use these values to adjust their insulin dose according to a self-titration algorithm. A specialist diabetes nurse reviewed the
patients’ data every two or three days using a secure website, and provided general support and advice.

As shown in Figure 3, blood glucose control improved, with a mean decrease in HbA1c of 0.66% (\(p = 0.05\)), and a mean insulin dose increase of 17 units (\(p = 0.006\)). Compliance with self-monitoring was high, with readings available for 6.2 days per week, although use of the cell phone decreased during the study, emphasizing again the difficulty of maintaining compliance beyond a period of three to four months.

2.2 Anti-hypertensive Medication for Stroke Patients

As with the self-monitoring of blood glucose in type 1 diabetes or insulin-treated type 2 diabetes, clinical studies have previously shown (see, for example, [1]) that blood pressure control is better in patients with treated hypertension who self-monitor at home using a blood pressure (BP) monitor and inflatable cuff. Hypertension is a major modifiable risk factor for recurrent stroke, but in practice rates of control are low. We therefore investigated the feasibility of using wireless health for the home monitoring of blood pressure to improve control after a transient ischemic attack (TIA) or minor stroke [5].

We studied consecutive patients with acute TIA and minor stroke in the Oxford Vascular Study (OxVASC) [15]. After prescription of standard BP lowering therapy on discharge from the hospital, patients measured their BP three times daily at home with a Bluetooth-enabled BP monitor (Stabil-O-Graph mobil, IEM GmbH, Stolberg, Germany) for one to three months, depending on control. Measurements transmitted automatically in real time by the cell phone were checked daily on a secure web page in the Oxford Stroke Unit. If BP was consistently above the guideline value (> 130/80 mmHg), anti-hypertensive therapy was intensified.

203 (92%) of 220 consecutive patients (mean age 70; 29% ≥ 80 years) agreed to undertake home monitoring, of whom 7 (3.5%) withdrew within one month. Monitoring resulted in 192 changes in BP-lowering medication in 128 patients (63%). Figure 4 shows the data for one such patient, with BP measurements transmitted three times a day. The BP measured in the outpatient clinic on discharge from the hospital was 130/80 mmHg. Self-monitoring at home showed that the systolic BP was consistently higher, and, after daily review in the Stroke Unit, anti-hypertensive therapy was intensified on Day 16. This led to a rapid decrease in the systolic blood pressure in the last ten days, as shown in Figure 4. Averaged across all 203 patients in the study, the BP was 148/82 at entry and 127/73 mmHg at the 6-month follow-up clinic. Patient satisfaction (0 poor to 100 excellent) with home monitoring was high (mean score 88.3), with 90% approving of intensive monitoring and 88% being reassured by the automated surveillance [5].

Wireless health technology for home BP monitoring worked well for most patients discharged from hospital after a TIA or minor stroke, irrespective of age, and patient satisfaction was high. Monitoring had a clear impact on the titration of medication for the majority of patients, and was associated with good blood pressure control six months after discharge from hospital. This reduces the risk of the patients having a subsequent stroke, which leads to a higher quality of life for these individuals and a reduction in costs for the health service provider.

3. LONG-TERM MONITORING

3.1 Android COPD Application

The number of hospital bed days taken up by patients with one or more chronic diseases is putting a severe strain on the UK healthcare system. Often these are patients with Chronic Obstructive Pulmonary Disease (COPD) or Congestive Heart Failure (CHF), who go back and forth between the hospital and their home or residential care. For example, 30% of the COPD patients admitted to hospital in any given year for treatment of acute exacerbations are re-admitted at least once within the year [2].

![Figure 4. Self-monitoring of BP (systolic pressure in red, diastolic pressure in yellow) by a 79-year old patient using wireless health technology after discharge from hospital following a minor stroke. Anti-hypertensive therapy was increased on Day 16 (shown by the dashed vertical line), leading to a decrease in systolic blood pressure over the next ten days.](image-url)
If the number of unplanned hospital admissions could be decreased, the economic burden of chronic disease management would be greatly eased. Self-monitoring of peripheral arterial oxygen saturation (SpO2) using a pulse oximeter is often used in the management of COPD patients at home [8]. This requires patients to use a finger probe connected to a pulse oximeter for a few minutes each day. These measurements, in combination with the daily recording of symptoms such as breathlessness and sputum color in an electronic patient diary, help with adjusting the management of the condition using inhaler and breathing techniques, together with home exercise.

We are designing a wireless health system for the long-term management of COPD, based on Android smart phones and tablets, and a Bluetooth-enabled pulse oximeter (Onyx II, Model 9560, Nonin Medical Inc, Plymouth, MN). The software application includes both a self-management module with prompts to use the inhaler or adapt the exercise regime, and a psychological well-being module, to track the patient’s mood. The mix of questions in the symptom diary and the frequency of recording SpO2 values can vary according to the patient’s health status. Symptom information will be integrated with the physiological data (heart rate and SpO2), the answers to the mood questionnaire, and environmental factors such as pollution levels and temperature. Alerts will be generated and transmitted to the respiratory nurses in the Oxfordshire COPD team, whenever there is a departure from expected patterns.

3.2 Non-contact Vital Sign Monitoring

A major obstacle to the widespread adoption of wireless health solutions for the long-term monitoring of chronic disease is the “human cost” of data collection. Many frail, elderly people find it difficult to continue with regular self-monitoring on a daily basis. Non-contact sensing of vital signs offers a new approach to the monitoring of such patients in their homes. The possibility of measuring reflectance-mode photoplethysmographic (PPG) signals remotely using a camera was first reported by Wieringa et al. [19]. Verkruiysse et al. [21] subsequently showed that PPG signals could be remotely acquired from the human face with ambient light as the source and a simple digital camera as the detector placed more than 1m away from the subject. Recently, Poh et al. [13] have used a webcam to record videos of facial regions in healthy human volunteers, using independent component analysis to extract the PPG waveform from regions of interest in the image. This allowed them to calculate the heart (or pulse) rate and derive an estimate of respiratory rate from the heart rate variability. Interference from artificial light, for example fluorescent lights, presents problems however, as aliased components of the artificial light appear at random frequencies close to the cardiac frequency component of the light reflected from the subject’s face.

We have recently proposed [16] a differential technique in which the light reflected from regions of interest in the digital camera image is modeled by a set of auto-regressive (AR) models [11]. The poles which correspond to the aliased ambient light interference in the image of the subject’s face are then cancelled from knowledge of their location in the image of the background. We have tested this technique in elderly patients undergoing hemodialysis in the Oxford Kidney Unit, in a clinical study during which the patients were also monitored with a chest band (to measure respiratory rate) and a pulse oximeter (to record heart rate and SpO2). Between 30 and 40% of these elderly patients experience intra-dialytic hypotension, an episode which is often preceded by physiological instability characterized by variations in heart rate, respiratory rate and SpO2.

Figures 5 and 6 show the results of the AR-model based analysis of the PPG signals recorded with a digital camera 1 m away from a dialysis patient who also suffers from obstructive sleep apnoea. The camera-derived estimates of respiratory rate and SpO2 are in good agreement with the values obtained from the chest band and the fingertip pulse oximeter. At present the SpO2 estimates are calibrated from the fingertip pulse oximeter readings during the first two minutes of the 4-hour dialysis session. It is clear, however, that changes in SpO2 can be accurately followed by tracking the amplitude of the dominant pole in the AR spectra of the red and green camera signals.

4. CONCLUSION AND DISCUSSION

We have designed wireless health modules to support self-management in type 1 diabetes, and to titrate medication (both insulin and oral medication) in type 2 diabetes and in patients at high risk of a recurrent stroke. In each case, both the technology and the software applications were evaluated in clinical trials so as to increase the evidence base for wireless health. We are now developing open-source software modules for the long-term monitoring of COPD patients using Android smart phones and tablets. These modules will be informed by the evidence base for symptom diaries in COPD and will allow the frequency of self-monitoring to be adjusted according to the patient’s health status. The development of the open-source software applications is being carried out with a view to creating a set of modules for chronic disease management for validation by the National Institute for Health and Clinical Excellence (NICE – www.nice.org.uk).

We have so far considered the use of wireless health technology to support self-management and avoid unscheduled visits to the Emergency Room or unplanned admissions to hospital. Healthcare costs can also be controlled by ensuring the timely discharge of patients from hospital, for example following surgery. At the moment, in the UK, patients with a hip fracture may receive early supported discharge [14] to intermediate care (continued rehabilitation in a community hospital or residential care unit), thereby releasing a more expensive bed in the acute hospital.

We have recently completed the first phase of a clinical trial in the Oxford Cancer Centre designed to assess whether continuous monitoring of vital signs following Upper Gastro-Intestinal (GI) surgery, with computer-generated alerts to detect patient deterioration, could reduce patient length-of-stay in hospital. Heart rate, respiratory rate, SpO2, blood pressure, and temperature are the five vital signs which are measured non-invasively in hospital patients outside the Intensive Care Unit. With a combination of wearable sensors and Bluetooth connectivity, it is now possible to acquire a subset of these measurements (heart rate, respiratory rate and SpO2) continuously in ambulatory patients [6] [10].

200 patients were recruited during Phase 1 of this clinical trial. The median length of stay on the ward was 9 days. Our initial analysis focused on the 128 patients with normal physiology throughout their stay on the ward and who stayed on
the ward for a minimum of 4 days (which corresponds to the 10\textsuperscript{th} percentile) and a maximum of 29 days (90\textsuperscript{th} percentile). After Day 4, most of the patients in this group had recovered from the cancer surgery. We established that there were no significant changes in the vital-sign distributions from halfway through these patients’ stay to the time of their discharge from the ward [12]. This suggests that these “normal” patients could have been considered for discharge, or provided with a lower level of care, halfway through their stay, as they were already stabilized by then.

This opens up the possibility that such surgical patients could also be discharged to intermediate care, supplemented with wireless health monitoring technology. “Digital plasters” [3] [22] can now provide continuous monitoring and wireless transmission of vital-sign data for several days. As the reliability of wireless health technology improves, its deployment for monitoring patients outside acute hospitals will become more widespread, with early-supported discharge a candidate for early adoption.

ACKNOWLEDGEMENTS

The work described in this paper was funded by the NIHR Biomedical Research Centre Programme. Dr David Clifton and Mauricio Villarroel are supported by the Wellcome Trust and EPSRC under grant number WT 088877/Z/09/Z.

REFERENCES

Figure 5. The top trace shows the amplitude of the red, green and blue signals reflected from the face of a dialysis patient during a 4-hour dialysis session. The three plots below it show the estimates of heart rate, respiratory rate and SpO$_2$ derived from autoregressive models of the reflectance signals recorded with a digital camera 1 m away (in red) in comparison with the reference values for these physiological variables, which are measured with a chest band and a fingertip pulse oximeter (in black).

Figure 6. The top trace shows the amplitude of the red, green and blue signals reflected from the face of a dialysis patient during a 10-minute period of obstructive sleep apnea. The three plots below it show the camera-derived estimates of heart rate, respiratory rate and SpO$_2$ in comparison with reference values for these physiological variables.