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From computers to ubiquitous computing by 2010: health care

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Over the past decade, miniaturization and cost reduction in semiconductors have led to computers smaller in size than a pinhead with powerful processing abilities that are affordable enough to be disposable. Similar advances in wireless communication, sensor design and energy storage have meant that the concept of a truly pervasive 'wireless sensor network', used to monitor environments and objects within them, has become a reality. The need for a wireless sensor network designed specifically for human body monitoring has led to the development of wireless 'body sensor network' (BSN) platforms composed of tiny integrated microsensors with on-board processing and wireless data transfer capability. The ubiquitous computing abilities of BSNs offer the prospect of continuous monitoring of human health in any environment, be it home, hospital, outdoors or the workplace. This pervasive technology comes at a time when Western world health care costs have sharply risen, reflected by increasing expenditure on health care as a proportion of gross domestic product over the last 20 years. Drivers of this rise include an ageing post 'baby boom' population, higher incidence of chronic disease and the need for earlier diagnosis. This paper outlines the role of pervasive health care technologies in providing more efficient health care.

Keywords: pervasive health care; wireless; body sensor networks

1. Introduction to ubiquitous wireless body sensor networks

Wireless sensor network (WSN) technology has evolved for a broad range of indications and settings in our everyday lives, but does not specifically address the needs of human body health monitoring, where both external (wearable sensing) and internal (implantable sensing) environments exist. The human body is a smaller scale environment than most WSNs are designed for, and requires appreciation of a slightly different set of challenges. The realization that

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proprietary designed WSNs are not ideally suited to monitoring the human body and its internal environment has led to the development of wireless *body sensor network* (BSN) platforms with on-body computational ability, offering truly ubiquitous patient monitoring. Specifically designed for the wireless networking of implantable and wearable body sensors, the BSN architectures aim to set a standard for the development of a common approach towards pervasive monitoring.

The key component of a BSN is the 'node complex', which comprises a number of sensors connected to a small processor, wireless transmitter and battery. When combined, this offers the ability to seamlessly integrate patient data in the home, office and hospital environments. The BSN node ensures the accurate capture of data from the sensor to which it is connected, carries out low-level processing of these data and then wirelessly transmits this information to a local processing unit (LPU). The data from all the sensors are in this way collected by the LPU, processed further and fused before being wirelessly transmitted to a central monitoring server via a wireless LAN, Bluetooth or mobile phone (GPRS or 3G) network (Lo & Yang 2005). Miniaturization of the BSN node is a key to making these devices small enough to be considered truly pervasive as anticipated by Moore's Law, which states that the number of transistors that can be placed on an integrated circuit is increasing exponentially, doubling approximately every 2 years (Vosburgh & Newbower 2002).

2. The role of pervasive sensing in health care

The limitations in current health care monitoring technologies and diagnostic tools are that, in order to make a diagnosis, they require the patient to frequent a hospital or clinic environment. This not only represents just a snapshot in time of the disease process (which is continuous and therefore requires more dynamic monitoring), but also has an impact on the patient's physiology in a way that can make diagnosis more difficult. The best example of this is the 'white coat syndrome' that results in patients' recorded blood pressures being much higher when visiting their physicians than it normally is, as an acute stress response to being in a new setting that is perceived as threatening (Den Hond *et al.* 2003). This has meant that the diagnosis of hypertension (high blood pressure affecting approximately 50 million individuals in the United States alone; Chobanian *et al.* 2003) can take months, with repeated measurements needing to be taken by both patient and doctor to determine the true blood pressure. Other examples of chronic diseases that would benefit include abnormalities of heart rhythm or arrhythmias (occurring in as many as 4% of the population over the age of 60, increasing with age to approx. 9% in octogenarians; Go *et al.* 2001), heart failure (affecting approx. 5 million people every year in the United States and a contributing factor to approximately 300 000 deaths each year; Hunt *et al.* 2001) and diabetes mellitus, a well-known chronic progressive disease resulting in several end-organ complications.

As a result, for chronic diseases, conditions such as these where deterioration in health is more gradual, being able to monitor a patient continuously in their own environment, be it home, work or outdoors, is a key. In the case of hypertension, ambulatory blood pressure monitoring would result not only in more accurate diagnosis but also more effective monitoring of response to therapy, thereby aiding a more tailored approach to patient monitoring. Pervasive sensing of blood pressure may indeed allow more accurate monitoring of the trend in blood pressure reduction when a patient is started on anti-hypertensives. Wireless BSNs offering ubiquitous computing are one solution to this problem and may ultimately be half of a 'feedback loop', where the other half would involve administering a variable rate of medication such as through a drug delivery pump. This would provide truly pervasive health care. In the case of diabetes, the BSN technology would allow the networking of wireless implantable and attachable glucose sensors to be used not only in monitoring patient glucose levels but also in 'closed feedback loop' systems for drug (insulin) delivery, thereby externalizing the role of the human pancreas.

Aside from chronic disease, there are several other scenarios that would benefit from pervasive wireless monitoring technologies. Acute diseases that require hospital admission result in patients going from being admitted, treated and monitored intensively while they are in the hospital ward. Ultimately, however, they are discharged to a completely unmonitored home environment where it is impossible to determine their clinical progress. As a result, a patient is kept in hospital long enough to be absolutely sure that they will not need further monitoring, even though they may be relatively well. Having the ability to monitor patients at home would not only enable patients to return to their preferred environment quicker, but also give the clinician confidence in being able to send them home earlier.

Finally, pervasive BSNs may prove invaluable in regular and non-intrusive monitoring of 'at-risk' population groups such as the elderly. With people in industrialized nations living longer than ever before and an increase in average life expectancy of more than 25 years over the last century, the size of this group is set to increase, along with their demand on health care resources (Butler 1997). Identifying ways of monitoring this ageing population in their home environment is therefore very important, with one key example of the usefulness of this approach being the vulnerable periods during months of non-temperate weather. There is evidence to suggest that at times of the year when weather conditions are at their extremes (either very cold or very hot), elderly patients are at increased risk of requiring hospital admission (Koken *et al.* 2003; Aronow & Ahn 2004). They are at risk because they are not able to seek medical help early enough for simple and treatable conditions, which eventually may lead to significant morbidity. An example of this is an elderly individual who lives alone and suffers a chest infection that he fails to identify and seek help for until the infection requires hospital admission or even ventilatory support. This could all be potentially avoided if the infection, or change in patient habit as a result of this infection, was picked up early and antibiotic therapy initiated.

The concept of an unobtrusive environmental 'home sensor network' to monitor an elderly person's social health (giving feedback to not only the carers and family of that elder but also the elder individual themselves) is one that is being developed by companies such as Intel (Dishongh *et al.* 2005). While such an environmental sensor network attempts to monitor social well-being by identifying the individual and the level of activity he or she is undertaking, it is easy to see how this network could communicate with a BSN relaying physiological data about the individual. Combining both wearable and environmental networks would allow for a much better appreciation of the context in which the sensing is taking place.

3. Personalized health care

In a population consisting of several vulnerable groups mentioned above, the need for effective individualized health monitoring and delivery has resulted in the concept of 'personalized health care'. Monitoring systems that fulfil this are expected to be 'dynamic' and customized to specifically address the health needs of individuals. In essence, personalized health care systems aim to take into account an individual's chronic (long-term) and episodic (short-term) health care needs, and have clear health care objectives. They also aim to account for the cognitive level of the patients, their ease with the technology and both social and community factors. BSNs offer perhaps the greatest chance of developing a personalized health care system where treatment may be tailored to the patient at several levels. First, at the monitoring level, such a system would have to reliably observe the patient's physiology, activity and context, detecting adverse changes in their well-being early. Second, at the delivery of care level, data processing and decision-making algorithms must prompt the appropriate action to deliver correct therapy. Drug delivery, which as previously mentioned is at present dosed according to population averages, could be tailored exactly to an individual's needs, perhaps by infusion rather than by tablet. Ensuring the safety and reliability of such a closed-loop system is going to be a real challenge. The cost-effectiveness of such a personalized health care system over existing lower technology solutions is also important and is likely to drive their development. New bionic technologies such as neuromodulation and neurostimulation devices are likely to enable the BSN to interact with and control a patient's physiological systems themselves. Ultimately, these devices could use information from the BSN sensors to control the human body's musculoskeletal system itself. Perhaps one of the most successful examples of a bionic device in clinical use is the cochlear implant, which has had tremendous impact on patient's lives (Giorgiou & Toumazou 2005). Third, at the research level, pervasive health care systems will allow doctors to learn much more about the disease processes they commonly come across in clinical practice. Finally, at the information delivery level, giving patients their personalized information (according to their health care needs) is likely to help them understand and self-manage their conditions more appropriately (Abidi & Goh 2000). The ultimate aim of all this is the early detection of disease leading to an early intervention, both of which are attributes that may make personalized health care-based treatment the next best thing after prevention itself.

In order to deliver truly personalized health care, the BSN sensors have to become invisible to the patient, thereby avoiding activity restriction or behaviour modification. While sensor miniaturization and implantability are potential solutions to this, another option being explored is the integration of the sensor into non-clothing items that patients already wear. A ring sensor developed at MIT, for example, can act as an ambulatory telemetric continuous health monitoring device (Asada *et al.* 2003). This wearable biosensor uses advanced photoplethysmographic techniques to acquire data on the patient's heart rate, heart rate variability and oxygen saturation. This ring sensor contains an optical sensor unit, an RF transmitter and a battery, connected to a microcomputer in the ring itself. This ensures onsite low-level signal processing, data acquisition, filtering and bidirectional RF communication with a cellular phone that can access a website for data acquisition and clinical diagnosis.

4. Implantable sensing

The development of implantable sensors offers the BSN one of its most exciting components. The European Commission project 'Healthy Aims' (http://www.healthyaims.org/) has been focusing on specific sensor applications, namely for hearing aids (cochlear implant), vision aids (retinal implant), detecting raised intraocular pressure (glaucoma sensor) and intracranial pressure sensing (implantable pressure sensor). Other implantable devices include Medtronic's 'Reveal Insertable Loop Recorder' (http://www.medtronic.com/reveal), which is a fully implantable cardiac monitor used to record the heart's rate and rhythm at the time of unexplained fainting, dizziness or palpitations. The device provides the clinician with an ECG that can be used to identify or rule out an abnormal heart rhythm as the cause of these symptoms. CardioMEMS is a company that produces an implantable pressure sensor developed at the Georgia Institute of Technology, which can record pressure readings following implantation into an aneurism sac at the time of endovascular repair (Allen 2005). This implanted sensor then provides a means of monitoring the repair over the following years. Finally, Given Technologies has developed an endoscopy capsule that transmits images of the small bowel as it travels through the gastrointestinal tract (Spada *et al.* 2005). Implantable sensors continue to evolve, and their integration with wearable sensors is an important part of the development of pervasive health care monitoring technologies.

5. Future challenges

Although the BSN platforms aim to provide the ideal wireless setting for the networking of human body sensors and the setting up of pervasive health monitoring systems, there are several other technical challenges that lie ahead. These include the need for better sensor design, MEMS integration, biocompatibility, power source miniaturization, low-power wireless transmission, context awareness, secure data transfer and integration with therapeutic systems. A framework for integrating ambient and wearable sensors is likely to be a key part of developing truly pervasive health monitoring systems. Ambient environment sensors used to monitor patients unobtrusively in their home environment can for example be combined with wearable sensors to overcome some of the inaccuracies of wearable sensing alone.

The acceptability to patients and ethical aspects of BSNs are also an important consideration if this technology is to become the mainstream. For example, while there is little evidence that people would be willing to 'wear' sensors for a prolonged period of time outside a hospital setting, examples of other technologies that people have embraced in their lives include the Bluetooth headset and mobile telephone. This suggests that people may also respond well to technologies that will prevent them from going to hospital unnecessarily. Implantable sensors require closer ethical considerations, although the examples of pacemakers and implantable cardiac defibrillators (ICD) show that provided the clinical need is great enough this intervention becomes acceptable.

Personalized health care systems will generate a wealth of information for the health care provider above and beyond what is currently available. How this information will be accumulated, stored and interpreted, and how health care systems will respond to adverse events, must all be considered. It is important to appreciate that at present while much patient information is collected by continuous monitoring, for example during hospital admission, most of this information is lost. Although personalized pervasive health care systems will collect a vast amount of information, separating this into 'important' and 'non-important' is going to require very accurate context sensing. Mining these data and representing them to a user are yet another challenge, as is dealing with false alerts caused, for example, by movement artefact or electrode/sensor dropout. Finally, as previously mentioned, reacting to this information is going to require major process automation and structural change to existing health care systems.

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