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Wearable Sensor Systems: The Challenges

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***Abstract*— Given the soaring costs associated with the treatment of ever more prevalent chronic disease, it is widely agreed that a revolution is required in health care provision. It is often thought that the necessary technology already exists for the home-based monitoring of such patients and that it is other factors which are holding back the more widespread clinical uptake of these new tools. The authors suggest that the necessary sensor-related technologies are often not as advanced as may first appear; certainly they are generally not adequate for the robust, long-term monitoring of patients under real-life conditions. An additional problem is the evident efforts to apply a given sensor and related technology platform to any and all monitoring scenarios without sufficient consideration of patient needs and the clinical requirements. The authors review the key sensing platforms and suggest the applications for which they are best suited.**

I. Introduction

IT is now widely recognised that there is a need to radically change the present Healthcare system by introducing systems which encourage citizens to develop self-care habits, monitoring their health status in order to prevent/manage disease [1]. Ideally, these novel systems should be capable of conveniently, discreetly and robustly monitoring patients in their homes and while performing their daily activities without interfering significantly with their comfort or lifestyles. Wearable monitoring technologies could play a pivotal role in such a healthcare revolution.

The technology platform is based on wearable sensors which are combined with ubiquitous computing and data processing for user guidance and intelligent assistance. Currently, this combination attracts great interest in the Healthcare domain in the light of the ever increasing health costs associated with the management of chronic diseases (mainly cardiovascular disease, cancer, diabetes and obesity). The greater deployment of such technologies, especially among the elderly or those at higher risk, would provide everyday patient-centred care and reduce the number of costly hospital-based critical interventions.

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II. Wearable Monitoring Platforms: Possibilities and Limitations

There are several key aspects of wearable technology for vital signs monitoring which need to be taken into account by system designers and developers. The first is the diverse environment where the device is planned to be used: at home, while exercising, in the swimming pool, etc. The size and nature of the targeted patient population involved is also an important consideration: for example a large population monitored to maintain "wellness" and/or fitness or a smaller more specialist group of people, for instance subjects having a high risk of cardiac or respiratory events and patients during rehabilitation programs.

User competence and motivation are other important factors. People using the device can on the one hand be skilled professionals, some even associated with healthcare provision – first responders, ambulance workers, nurses. Alternatively, they can be members of the general public who, although under the surveillance of professionals, may be applying/using the device on their own.

An automatic diagnosis or situation evaluation component may or may not be integrated into the device which could at least partly replace the professional in routine cases when he/she is not accessible/required, or which could be used to help more optimally manage emergency situations.

There therefore exists a wide variety of possible monitoring scenarios, from global to person-adapted. It is important to recognize the (present) limitations and advantages of currently available monitoring platforms and their suitability to a given monitoring scenario. This is a very important point as there is a widespread tendency to try to apply the same technology platform to all monitoring scenarios, regardless of the needs of the patient and the clinical application involved. Abraham Maslow has been quoted as saying that "to the man who only has a hammer in the toolkit, every problem looks like a nail."

Existing monitoring platforms can be grouped as follows (i) "Holter-type" systems with standard sensor designs and locations, (ii) Body-worn sensor patches, (iii) Body-worn bands and harnesses, (vi) Portable/wearable devices and fashion accessories, (v) "Smart garments" and (vi) Implanted systems.

A. *"Holter-type" Systems*

Many wearable sensor systems, which we shall term "Holter-type" systems, are characterised by their use of standard sensors that are placed in standard locations by a professional, usually for only a limited period of time for research/diagnostic purposes (e.g. detection of arrhythmias, sleep disorders) and involving concerned and therefore motivated patients. The sensors are physically connected to a portable recording/transmitting device, the latter often attached to the subject's belt, worn as a necklace or housed in a waistcoat designed specially for such applications.

This type of wearable system often significantly curtails/affects the patient's activities, for example the person cannot take a shower, and the multiple wires involved restrict motion and the subject's level of comfort. In addition, the long connecting wires and the traditional sensor designs and locations used can give rise to large amounts of motion-induced biosignal artefacts.

These systems also tend to require significant professional surveillance. Initially to place the sensors in the proper locations, setup the device, instruct the user and then to occasionally interact with the subject to ensure all is in order.

Although a sizeable number of published wearable systems resemble "Holter-type" systems, especially those that have focused on the device at the expense of the sensors, they are unsuitable for many of the applications targeted. These essentially prototype systems are generally too obtrusive and cumbersome for widespread use, especially for elderly patients and for those with physical disabilities. Patient compliance/motivation is also a significant problem. These system are however acceptable for the short-term monitoring of concerned patients under the close supervision of clinical staff.

B. *Adhesive Sensor Patches*

Adhesive patches with integrated wiring and sensors can be worn by patients for short- to mid-term monitoring applications (up to one week or intermittently over an extended period).

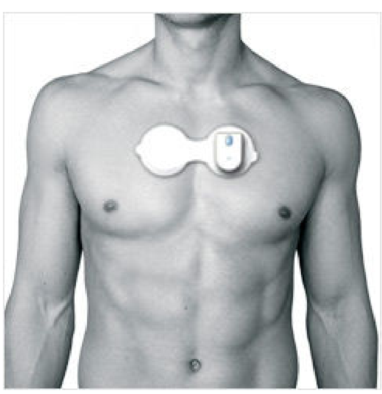

Fig. 1. Intelesens' vital signs monitoring patch VitalSens VS100

A miniaturised telemetry device capable of recording/ transferring/ storing data can be mounted on the patch itself and is usually equipped with wireless technologies (see Fig. 1.) [2]. This type of wearable system maximises patient comfort and is generally sufficiently discreet for use in most real-life situations. The patch-based systems can in some cases even be used in the shower. These attractive advantages however come with the requirement of modifying sensor designs and locations. The work of Gemperle et al. [3] on wearable computing clearly demonstrated that there are only a limited number of body sites that lend themselves to the comfortable wearing of a system such as a monitoring sensor patch.

Not only must the chosen body site enable the comfortable, convenient and unobtrusive wearing of a patch, it must also be possible to locate and use sensors within the patch's small foot print which are capable of measuring with sufficient accuracy and robustness the desired biosignals. Clinically suitable sites will most likely be on or near the torso and located on sites which will not experience significant twisting or stretching of the skin, otherwise the patch will cause shearing of the skin layers and biosignal artefacts.

The required move from the standard recording locations for the various sensors used to the single, small patch foot print involves the development of novel transduction mechanisms, sensor designs and signal processing. Data analysis and interpretation are important issues as new techniques are needed in order to present data to health professionals in the format they are used to interpreting. Alternatively, automatic interpretation must be developed - this is a significant challenge as expert system automation is still an ongoing area of research.

Patch systems have proved suitable for the short to mid-term monitoring of subjects in a range of clinical settings and work is underway to further extend the range of biosignals that can be thus monitored through the development of novel sensors

C. *Body-worn bands and harnesses*

Sensors can be integrated into many tight-fitting clothes and accessories such as gloves, wrist/forearm bands, arm bands, torso belts or harnesses. This approach has the potential to greatly reduce skin irritation problems associated with adhesive patches. Gemperle et al. [3] studied the "wearability" of such bands and produced an interesting list of potentially suitable body sites.

Sensor systems built into wrist/forearm bands for the monitoring of vital parameters (such as skin temperature, electrodermal activity, pulse wave velocity, activity...) should enable discrete and comfortable monitoring. Moreover, wrist-worn devices in particular tend to benefit from patient acceptability, making the wrist a preferential location for monitoring.

Sporting applications already successfully exploit chest bands, usually involving cardiac frequency assessment based on a single ECG lead recorded from non-standard locations, e.g. the Premium Heart Rate Monitor by Garmin Ltd. [4]. Such systems can now be found, for example, in professional cycling races where cardiac frequency is widely monitored in real-time.

Arrays involving a number of sensors/electrodes integrated into bands enable the assessment of a range of parameters including blood flow and respiration; body composition using such techniques as Electrical Impedance Tomography (EIT) and impedance/inductive plethysmography. Combining several such arrays can enable more advanced studies of the torso or limb under study.

VivoMetrics has developed a light-weight chest harness which is capable of monitoring respiration rate, heart rate, activity, posture and skin temperature. This is a harness version of their traditional "LifeShirt" [5], where sensors were integrated into a full garment. The chest harness ensures the quality of contact between key sensors and a large area of potentially suitable skin sites for bio-signal recording on the torso. If the sensors and their skin contact are suitably designed, such a convenient system could provide good short and medium term monitoring.

Similarly, the appropriate design of sensors could enable headbands and even hats to record a range of potentially useful signals, including EEG, EMG, EIT and brain core temperature. An example is the Brain Core Thermometer developed by the Biomedical Sensors group in Lyon, France [6].

In several of the above examples, the sensors must optimally (i) be accurately and reproducibly placed in the correct anatomical positions, (ii) be held in firm contact with the skin (iii) not require skin or sensor "prepping", (iv) not give rise to motion artifacts, (v) not cause skin irritation, etc..

Such bands/harnesses are optimal for the monitoring of, for example, athletes, firefighters and military personnel etc on an intermittent basis or for relatively short term applications

D. Portable/wearable devices and fashion accessories

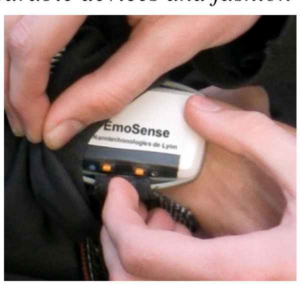

Fig. 2. EmoSense, a wrist-worn device to monitor cardiac frequency, electrodermal activity and skin temperature

Many patients on the move have a need of "on demand clinical support rather than continuous monitoring of their condition. In such cases a small, portable monitoring system, integrated into a standard fashion accessory (e.g. wallet, watch (Fig. 2. [7]), or mobile phone, would be more suitable and patient compliant than a "smart garment". Platforms developed for long term and continuous monitoring are not appropriate as the patient cannot be expected to wear such a system everyday if their need for medical help/reassurance is only very occasional. Such "on demand" systems could be designed to give direct feedback to the patient in order to let the patients to improve their awareness and to better manage their condition. If appropriate, the information can be transmitted to a remote monitoring station for some form of clinical interaction.

The main challenge for these applications, as with the portable devices which already exist, is the avoidance of mis-diagnoses resulting from misplaced or malfunctioning sensors. The accurate location of the sensors for the recording of many "vital sign" parameters is not trivial and the design of an easy-to-apply system capable of recording clinically viable information is a major challenge.

E. Smart Garments

Adhesive patches, although very promising, will generally produce skin irritation problems when the patch is worn for more than a few days. Holter-type systems can also be worn for a few days by highly motivated patients. For longer term monitoring, suitable "smart garments" are probably required.

The use of "smart garments" appears very promising for several reasons: firstly, devices and leads could be well integrated in seams and pockets, and secondly the skin surface is relatively large (about 1.5 m^2) with approximately 90% of it covered by clothes. Thus sensors could, in theory, be placed close to the skin over the key organs one may wish to monitor. The sensors could theoretically cover virtually the whole of the body's surface, including sites traditionally used for standard monitoring, e.g. sites for the twelve leads of ECG monitoring.

However, problems associated with quality of contact, motion artifact and patient comfort arise from the relative movements of the skin and loose fitting clothing. Only a relatively small part of the skin surface can in fact be used for sensor applications, and generally only through the use of tight-fitting clothing or elasticated sections in otherwise "normal" clothing. These constraints generally prevent us from locating traditional sensors on traditional sites.

One possible solution is to reposition modified sensors in non-standard locations to ensure a good, comfortable contact with the skin, thus avoiding artifacts due to, for example, excessive body hair, muscle noise (i.e. EMG), and body flab (i.e. motion artifacts in ECGs). In order to exploit the full potential of such wearable garments, the monitoring of vital signs from non-standard locations will require the development of novel sensing technologies which lend themselves to the constraints involved. Clinicians will have to come to terms with the new locations, sensors and information recorded from the patients and this may be a significant hurdle to overcome.

F. Implantable Systems

While awaiting the development of suitable sensors for smart clothing to enable robust long term monitoring of typical patients, the use of implantable systems similar in concept to Medtronic's implantable event recorder (Reveal) appears potentially promising for many applications. At present, sensors and a small monitoring device are implanted under the skin during a minor surgical procedure and the system used to monitor heart rhythms for a year or two [8].

These implantable devices are gradually incorporating additional sensors, for example to measure blood pressure, to better monitor heart failure and they are being developed for use in many other applications.

III. WEARABLE MONITORING PLATFORMS: THE SENSOR BOTTLENECK

The present evolution in healthcare is due more to governmental-pull than to (solely) technological-push. National governments and international organisations such as the World Health Organisation are behind the push to revolutionise health care delivery and decrease cost. One is often given the impression that the wearable monitoring technologies required for this revolution are already in place and that it is other aspects such as device interoperability and financial reimbursement which are holding back the clinical uptake of the new systems. The present authors, however, suggest that the key sensor-related technologies required for this revolution have generally not been sufficiently advanced. When the other issues have been successfully addressed, it is the authors' belief that in many cases the sensor-related technologies will be found ill suited for robust use under real-life conditions.

It is suggested that this misconception is largely due to the positive descriptions of systems which are essentially clinically untested prototypes. For a publication, we as academics can wear a relatively crude, cumbersome, user-unfriendly system for a few minutes, long enough to record a short segment of artefact-free recordings under rather idealised conditions. However, the design of a robust system which will be accepted and worn by a patient and which will work reliably for extended periods of time under real-life conditions is a much more challenging problem.

In order for a promising prototype monitoring system to develop into a robust, user-friendly, clinically-viable device, a product champion must continue to labour on what are generally academically-unappealing aspects of the device's design such as patient comfort and compliance, sensor artifacts etc. It is at this stage that academics tend to move onto more appealing and academically rewarding projects. One is therefore left with a wealth of apparently attractive systems in the literature which are essentially clinically-unproven prototypes.

The problem is not helped by the difficulties and expense involved in organising meaningful clinical testing of a new device. Instead, researchers tend to assess their systems using models, phantoms, patient simulators etc... Sadly these research tools tend to ignore the key problem areas to be addressed in wearable monitoring – those associated with the patient-sensor interface. Patient compliance, artefact problems and similar thorny issues are completely ignored in such standard bench tests. Sadly, this approach is so widespread that it has become something of a cliché in the wearable sensing area.

Government bodies could help improve the situation by simplifying and decreasing the costs associated with the organisation and management of the vitally-needed clinical testing of promising healthcare products. Additionally, the creation of "living labs", encouraging the involvement of clinicians and patients at the earliest stages of a product's design and development, would be a laudable and productive initiative.

IV. CONCLUSION

Given the wide range of possible monitoring scenarios, it is impossible to address them all satisfactorily with the same sensor and wearable monitoring platform. It is therefore important to appreciate the advantages and limitations of the various approaches, to choose the most promising for a given application and to tailor it further.

The basic "Holter-type" system, which tends to include most published prototype systems involving an electronic device and standard sensors attached via connecting cables, is best used for the short term (a few days) monitoring of motivated patients under close clinical supervision. Adhesive patch sensor systems appear optimal for monitoring victims at a disaster site and for many short-medium term (up to a week) monitoring applications. Some sensor belts and harnesses appear very promising for many applications, including some longer term monitoring situations. Truly long term monitoring requires the development of novel sensors integrated into "smart garments" or implantable systems. There is a significant market for "on demand" monitoring and some promising portable systems already exist.

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