# The Hospital of the Future

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Abstract
Despite efforts to address the problem, the detection of deteriorating patients in hospital is often later than it should be. A number of technologies could be used to provide the basis of a solution. The process of recording vital signs may be improved both through the automated transmission of the measured parameters to an electronic patient record and through the use of unobtrusive wearable monitors which track the patients' physiology continuously. Electronic charting systems could make the recorded vital signs readily available for further processing. This would enable software algorithms to be used to identify deteriorating patients with greater sensitivity and specificity than the existing, paper-based track-and-trigger systems. Electronic storage of vital signs also makes intelligent alerting and remote patient surveillance possible. The benefits which may be derived from these technologies are strongly dependent on implementation, with poor-quality deployment likely to worsen patient care.

Keywords
early warning score, emergency treatment, monitoring, patient safety, vital signs

Key Points
- Current systems for identifying and responding to patient deterioration in hospital can be improved through the use of new technologies.
- Tools for the electronic recording and storage of vital signs enable improvements to patient safety by making the vital signs available for further processing by computerised systems.
- Software algorithms for computing Early Warning Scores have the potential to be more sensitive and specific than existing paper-based counterparts.
- The realisation of benefit from technology is highly dependent on the quality of its implementation.
Figures & Tables

1.

Figure 1: Generic components of a system to identify and respond to deteriorating inpatients
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<tr>
<th>Device</th>
<th>Form factor</th>
<th>Parameters Recorded</th>
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<tbody>
<tr>
<td>Intelens Aingeal(^{12})</td>
<td>Attaches via magnets to an adhesive pad placed on the chest wall</td>
<td>ECG</td>
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<td>Respiration via impedance pneumography</td>
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<td>Motion and activity via tri-axial accelerometer</td>
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<td>Equivilal EQ-02(^{13})</td>
<td>Worn in a small pocket in a thoracic belt</td>
<td>ECG</td>
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<td>Respiration via resistive strain gauge</td>
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<td>Motion and activity via tri-axial accelerometer</td>
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<td>Core temperature can be measured if patients are asked to swallow a core temperature pill</td>
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<td>- Pulse oximetry</td>
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<td>- Galvanic skin resistance (sweating)</td>
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<td>Sotera Wireless</td>
<td>Wrist-worn module with ECG leads connected to standard chest electrodes</td>
<td>ECG</td>
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<td>VisiMobile(^{14})</td>
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<td>Respiration rate via impedance pneumography and accelerometry</td>
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<td>Skin surface temperature</td>
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<td>Pulse oximetry</td>
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<td>Motion and activity via tri-axial accelerometer</td>
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<tr>
<td>Zephyr Bio-Harness(^{15})</td>
<td>Belt worn around the chest</td>
<td>ECG</td>
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<td>Respiration rate</td>
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<td>Skin surface temperature</td>
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<td>Motion and activity via tri-axial accelerometer</td>
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<tr>
<td>Nonin WristOx2 3150(^{16})</td>
<td>Wrist-worn module with a conventional pulse oximetry probe</td>
<td>Pulse oximetry (giving both SpO(_2) and heart rate)</td>
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<td>Isanys LifeTouch(^{17})</td>
<td>A small adhesive patch worn on the chest</td>
<td>ECG</td>
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<td>Respiration rate derived from the ECG signal</td>
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<td>Proteus Raisin Patch(^{18})</td>
<td>A small adhesive patch worn on the torso</td>
<td>Heart rate (via ECG)</td>
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|                        |                                                                           | Medication ingestion (requires patients to take an additional identifier pill, or for their pharmacist to put their tablets inside a special}
identifier capsule, or for patients to use special versions of their pills which are manufactured to incorporate an ingestible chip

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<th>Device</th>
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<th>Function</th>
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<td>HealthStats BPro (^{19})</td>
<td>A watch-like device</td>
<td>Ambulatory blood pressure using applanation tonometry</td>
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Table 1: Examples of commercially-available novel wearable sensors
Over the last decade much work has been undertaken to determine how best to reliably identify and treat patients who suffer unexpected clinical deterioration whilst in hospital. Much of this has been prompted by studies which have demonstrated that many deteriorations are not detected in a timely fashion leading to unplanned admission to Intensive Care or cardiac arrests which could have been avoided had appropriate care been instituted at an earlier stage. Factors contributing to avoidable cardiac arrests have been examined in a number of studies, most notably the National Confidential Enquiry into Patient Outcome and Death (NCEPOD) report in 2005. These have identified a wide variety of systemic problems, ranging from failure to record patient vital signs with sufficient frequency to failure to respond appropriately to a patient identified as having deteriorated. Following NICE guidance hospitals in the UK have implemented Early Warning Scores (also called track and trigger scores) to aid detection of the deteriorating patient on the general ward. Yet, despite these, late detection of such patients remains a problem.

As part of its on-going work to address this issue, the Royal College of Physicians has recently published proposals for a National Early Warning Score (NEWS), advocating that it should be widely adopted across NHS hospitals with the aspiration that improvements in patient care will occur through standardisation of alerting thresholds and escalation procedures. Implementation of NEWS will require a hospital to change observations charts, adjust escalation pathways and re-train staff. This therefore represents an opportunity to consider how recent technological developments could improve the identification of deteriorating patients.

A system for identification and treatment of patients who are deteriorating may be conceived as being divided into the following components: devices to measure markers of abnormality (patient monitors recording vital signs), a system to record the collected data (often a paper chart), a system to analyse the recorded data (such as an Early Warning Scoring System) and a system to respond to the results of the analysis (a hospital’s alerting and escalation pathways). This article aims to give an overview of the technological options for each of the components and how they might develop in the future. Whilst there is overlap with technologies used in intensive care environments the article will primarily focus on systems applicable to Level 1 wards.

**Measurement of Vital Signs**

The existing standard of care in British hospitals is continuous monitoring in high dependency and intensive care areas and intermittent monitoring using “spot-check” monitors on Level 1 wards. The latter may be augmented by continuous monitoring using either portable bedside monitors or wireless telemetry devices on wards where the necessary wireless access points have been installed but this is generally the exception rather than the rule.

The typical hardware used for recording vital signs on the Level 1 ward can be improved in a number of ways. Introduction of spot-check monitors capable of wirelessly transmitting the recorded observations to an electronic charting system should lead to process improvements by eliminating
transcription errors and speeding the process of recording observations. Wireless spot check monitors can either be purchased as systems with integrated wireless networking cards or created by retrofitting existing monitors with an additional device to allow wireless transmission. An alternative strategy for improving the observation recording process is to move to more widespread use of continuous (or near-continuous) recording of vital signs using multi-parameter monitors, with any intermittent measurements, such as measurement of blood pressure, being triggered by the monitor. Theoretically this should lead to detection of abnormal physiology at the earliest possible moment as well as reducing the incidence of observations being missed or being taken too infrequently. When this approach was trialled using existing bedside monitors in both medical and surgical populations, no benefit was found on intention-to-treat analysis. A key observation from the study was that only 16% of patients assigned to be automatically monitored remained connected to their monitors for the entirety of the intended 72 hours. The most common reasons cited for removal of monitoring were patient request and to allow patients to mobilise, clearly demonstrating the ergonomic inadequacy of conventional bedside monitors for long term recordings in ambulatory patients. In order for continuous monitoring to provide benefit in a general ward population, monitoring equipment needs to be more comfortable and less restrictive.

In response to this challenge a number of manufacturers have developed novel monitors. Wearable monitors in the form of cardiac telemetry devices are already established in the hospital environment. However, the majority of devices designed for in-hospital use rely on installation of a radio-frequency network specific to the device to transmit the acquired data. Installing the requisite network access points is costly and ties the hospital to a single provider of telemetry. The devices themselves are bulky in comparison to some of the newer monitors under development (see below) and most are restricted to monitoring ECG, though a few can additionally record oxygen saturations. Such solutions do not remove the need for intermittent monitoring as the other vital signs also need to be recorded. The newer monitors on the market, examples of which are listed in Table 1, are generally closer to being wearable for prolonged periods and many record a more diverse set of physiological parameters, including motion (which can be used both to detect patient falls and to measure patient activity levels). Only one device available to date, the Sotera Wireless VisiMobile, is explicitly targeted at the hospital environment and claims to measure all five commonly recorded vital signs. The remainder are either designed to cater for outpatient monitoring or for short-term use in high-risk environments.

Unfortunately these newer wearable monitors are not yet suitable for widespread deployment as clinical monitoring devices in a hospital environment, partly as a result of the lack of suitable supporting software optimised for use by clinical staff in a hospital environment and partly because of the design choices made when targeting them at out-of-hospital use. In a recent assessment of three novel monitors, none of them managed to record data consistently for 24 hours. However, given the considerable amount of interest in home monitoring using wearable monitors (the Department of
Health spent over £30m funding the recent Whole System Demonstrator trial to assess the benefits of telehealth) it is likely that these systems will mature rapidly. Wearable sensors are not the only monitoring technologies being explored. Sensors woven into clothing, printed on transfer tattoos, and embedded into furniture are being developed. Monitors need not be physically attached to patients in any way: non-contact sensing technologies include video cameras, doppler radar and ultra-wideband radar. Such sensors are not currently sufficiently developed to allow mainstream use in the hospital environment but they offer the promise of ubiquitous monitoring without impairment of patient mobility. However, an ergonomic monitor that simply transmits data to a remote screen or stores the information locally is far less useful than a wearable monitor connected to a system that stores the recorded data and makes it available for further analysis. The nature and potential benefits of analysis are discussed below. Such processing of the data is greatly facilitated by the adoption of open standards for the storage and transmission of data. This has been widely recognised and consortia such as the Continua Healthcare Alliance and Integrating the Healthcare Enterprise have been formed by key industry players to promote the use of open standards. Their efforts are complemented by work done in the open-source community, a notable example being the OpenEHR project, whose standards for the storage, retrieval and exchange of patient data have been adopted by the NHS through the Connecting for Health programme.

Charting of Vital Signs
Existing practice in most UK hospitals is to record the vital signs on a paper chart and for the nurse recording the observations to add the scores for each vital sign parameter, and enter the overall early warning score on the chart. This approach has a risk of error both in assigning the correct score to each vital sign parameter and in calculating the total score. Other well-described problems with the paper chart are poor legibility, inaccurate plotting and the possibility of misplacing or losing the chart. These flaws are frequently cited as reasons for introduction of electronic charting systems. Such systems may be broadly divided into three categories: charting modules which are part of an electronic patient record application, standalone charting systems and charting systems which are designed to work solely with the wireless spot-check monitors described above. Studies investigating the benefits of electronic systems report highly variable results, in part because their success or failure is defined in narrow terms such as the speed of data entry or user acceptance rather than from a broader clinical perspective (which in itself is only one of many pertinent perspectives) and in part because benefits measured in a non-clinical setting may not correspond to benefits on the ward. Furthermore, the introduction of electronic charting systems may lead to unintended consequences by paradoxically making data less easily accessible to nursing staff. Despite over two decades of development in this field, there are still many lessons to be learnt regarding the optimal design and functionality of such systems. Nevertheless, such systems do enable
a transformative change in the way that vital sign data are used: storing the data electronically makes them available for more complex and varied processing that is afforded by calculation of an integer Early Warning Score.

**Processing of Vital Signs**

Existing early warning scores are designed to be simplistic in order to facilitate calculation using pen and paper, a design choice which limits the sensitivity and specificity they can hope to achieve. A completely electronic system enables integration of non-vital sign parameters (such as laboratory results) and patient-related factors (such as age and comorbidities) into a scoring system as well as facilitating complex analysis of vital signs. Rather than making the assumption that vital signs are independent variables, the subtle interactions between them can be assessed in a probabilistic manner to determine earlier whether a patient is clinically deteriorating. An example of such a system has been trialled on a surgical step-down unit in the US and was found to be effective in predicting physiological instability before it became overt.

The trends of the vital signs over time or statistical derivatives may also be used to improve alerting algorithms. Alerting thresholds may be personalised on a patient-by-patient basis using short-term trends or historical-steady-state values. With continuous data, as might be provided by wearable monitors, it is possible to use the recorded waveforms to derive parameters that have prognostic significance, such as heart rate variability, ECG dispersion or the entropy of the signal. In the future it is likely that computerised algorithms will be used to augment or replace today’s Early Warning Scores. It may be that rather than having one algorithm reporting a patient’s status, multiple complementary algorithms will be used simultaneously, each reporting on the patient’s condition from a different perspective. This would allow resolution of the tension between providing a probability of imminent death (NEWS and its precursor ViEWS) and providing early warning of abnormal physiology to enable timely intervention.

**Alerting**

Electronic acquisition and storage of observations provides further potential for benefit through the generation of "smart alerts". The most commonly employed alerting technology employed on the general ward today is the local single parameter alert, whereby any one of the vital signs breaching a pre-set threshold will cause the bedside monitor to sound an audible alarm. Unfortunately this approach usually leads to a large number of false alarms, partly because the thresholds are often left at default settings, irrespective of the condition of the patient who is being monitored, and partly because signal artefact is often misinterpreted by the monitor. One study carried out in an operating theatre environment showed that 75% of alarms were spurious and only 3% indicated serious patient risk. In an environment where patients are able to move freely the false alarm rate may be even higher. The problem is exacerbated by the fact that the audible alarms generated by patient monitors are just one
group of a whole host of audible alarms emitted from ward devices ranging from inflatable mattresses to patient call bells. This quickly leads to the onset of so-called “alarm fatigue” which causes staff to cease responding to the alarms in a timely fashion. In the most extreme of cases this can lead to missing the fact that a monitored patient is dying. Using intelligent alerting systems may help address this problem. These may either generate alarms based on multiple parameters, in a similar fashion to an early warning score, or suppress alarms until a single parameter has consistently exceeded a pre-set threshold, thereby avoiding the problem of alarming due to transient episodes of artefact.

Computer-generated alarms need not sound at the bedside; they may be delivered remotely to a nursing station, as happens in many Level 2 and Level 3 areas, or they can be linked directly to the clinicians’ pagers. One study on an orthopaedic ward found that sending alerts from pulse oximeters directly to medical emergency teams led to a significant reduction in number of ICU admissions despite the fact that the thresholds for alerting were set to arterial oxygen saturations less than 80% and heart rate under 50bpm or over 140bpm. Alerting can be based on the hospital Early Warning Score and the same abnormal score may be used to generate multiple alerts which are sent in a sequential fashion to different clinical team members depending on the severity of the abnormality and the response times. A study of one such system has indicated that this may lead to clinical benefit, though the results were not definitive. Such systems may help avoid the problem of ward staff recognising that a patient is deteriorating but not calling for help due to socio-cultural factors.

Other approaches to remote alerting involve setting up a centralised monitoring room where patients attached to telemetry devices are surveyed by monitor technicians who call the ward staff via a dedicated hotline if they identify important changes in a patient’s condition. Remote surveillance of patients could conceivably also be used to identify patients before they are escalated or as part of a handover process, such as occurs to a Hospital at Night team.

**Potential for Benefit**

The concepts outlined in this article have been discussed in the literature for over two decades. In that time significant progress has been made in the implementation of these ideas. Further refinement is especially needed in algorithms for detecting the deteriorating patient along with better methods for assessing their merits. Endpoints that have been previously employed such as length of stay, ICU transfer and mortality are influenced by wide range of factors which may lead to erroneous characterisation of the effectiveness of the systems under study and make it difficult to make rational choices about the best algorithms to employ.

Realisation of benefit is strongly dependent on the quality of the implementation, user acceptance and the cultural and organisational factors surrounding the introduction of these systems. Poor implementation not only fails to result in benefit but may in fact make care worse.
Considerations surrounding the implementation of a technological solution should not be restricted to the technology and the infrastructure that directly supports it. Each technology is supported by a plethora of other systems and the impact on each of these must be assessed. For instance, according to the report which describes it, NEWS will result in an increased alert rate in many hospitals if the suggested triggers for escalation are used. One estimate, based on a database of vital signs from a mixed medical and surgical population, is that in a 1000 bed hospital 500 “amber” alerts and 200 “red” alerts will be generated per day. This may necessitate reorganisation of existing response teams or deployment of extra resources to ensure that the alerts are addressed in an effective and timely manner. Organisations which introduce NEWS without providing capable response mechanisms risk the alerts being ignored on occasion, with all the problems this entails.

Care must be also exercised in identifying the assumptions made when justifying the introduction of new technology. There is yet to be any conclusive evidence that Early Warning Scores improve patient outcomes, or that minimising errors in recording observations or calculating Early Warning Scores has any significant clinical impact. That these process changes will be beneficial might seem to be self-evident until one considers that nurses frequently rely on cues other than the observations chart to determine whether a patient is deteriorating and use the observations to support their clinical intuition. Introduction of poorly-designed systems can discourage nurses from utilising their clinical impressions because there is nowhere to record them or clinical judgement is removed from the escalation process.

**Conclusion**

There are a vast array of technologies, either currently available or in development, that promise to significantly improve patient care. Of these, the ones with the greatest potential to bring benefit are the systems that electronically store patients’ observations and make them available for further processing. Such systems offer benefits both directly, by addressing flaws in the recording process, and also by acting as a foundation upon which other safety systems, such as computerised algorithms and remote alerting systems, may be deployed. For full realisation of the clinical benefits great care must be taken in the implementation of these technologies as poor quality deployment may lead to worse patient care.

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