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CRITICAL CARE

REVIEW

Health technology assessment review: Remote monitoring of vital signs - current status and future challenges

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Abstract

Recent developments in communications technologies and associated computing and digital electronics now permit patient data, including routine vital signs, to be surveyed at a distance. Remote monitoring, or telemonitoring, can be regarded as a subdivision of telemedicine - the use of electronic and telecommunications technologies to provide and support health care when distance separates the participants. Depending on environment and purpose, the patient and the carer/system surveying, analysing or interpreting the data could be separated by as little as a few feet or be on different continents. Most telemonitoring systems will incorporate five components: data acquisition using an appropriate sensor; transmission of data from patient to clinician; integration of data with other data describing the state of the patient; synthesis of an appropriate action, or response or escalation in the care of the patient, and associated decision support; and storage of data. Telemonitoring is currently being used in community-based healthcare, at the scene of medical emergencies, by ambulance services and in hospitals. Current challenges in telemonitoring include: the lack of a full range of appropriate sensors, the bulk weight and size of the whole system or its components, battery life, available bandwidth, network coverage, and the costs of data transmission via public networks. Telemonitoring also has the ability to produce a mass of data - but this requires interpretation to be of clinical use and much necessary research work remains to be done.

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Introduction

Remote monitoring, or telemonitoring, can be regarded as a subdivision of telemedicine - the use of electronic and telecommunications technologies to provide and support health care when distance separates the participants [1]. Telemonitoring involves the use of audio, video, and other telecommunications and electronic information processing technologies to monitor patient status at a distance. The patient and the carer/system surveying, analysing or interpreting the data could be a few feet apart, but more often they will be in different areas of the same building, different buildings or different towns. In theory, they could even be in different countries or continents. The first case of direct transmission of a patient variable was that of an electrocardiograph (ECG) in 1905 by the inventor of the ECG, Einthoven [2]. However, the routine use of telemonitoring began in 1961 when the ECG, respiratory rate, electro-oculogram and galvanic skin response of the first human in space, Yuri Gagarin, were continuously monitored by doctors on earth. Figure 1 shows typical ECG tracings from Neil Armstrong, Buzz Aldrin and Michael Collins, received at the Mission Control Center approximately 384,467 kilometres away, during various periods of the Apollo 11 mission to the moon in 1969.

This review will provide a broad overview of this resurgent field of medical remote monitoring and will describe the components of telemedicine, the current clinical utilisation and the field's obvious challenges. Where possible, the article provides the appropriate references to allow the interested reader to obtain additional information.

Components of telemonitoring

At its simplest, the monitoring of a person's vital signs involves an observer (usually a clinician) using their own senses directly (that is, without any intervening technology) to determine pulse rate, breathing rate, and so on. Added sophistication is produced by introducing simple technology such as a sphygmomanometer, stethoscope or thermometer, but still the act of monitoring is

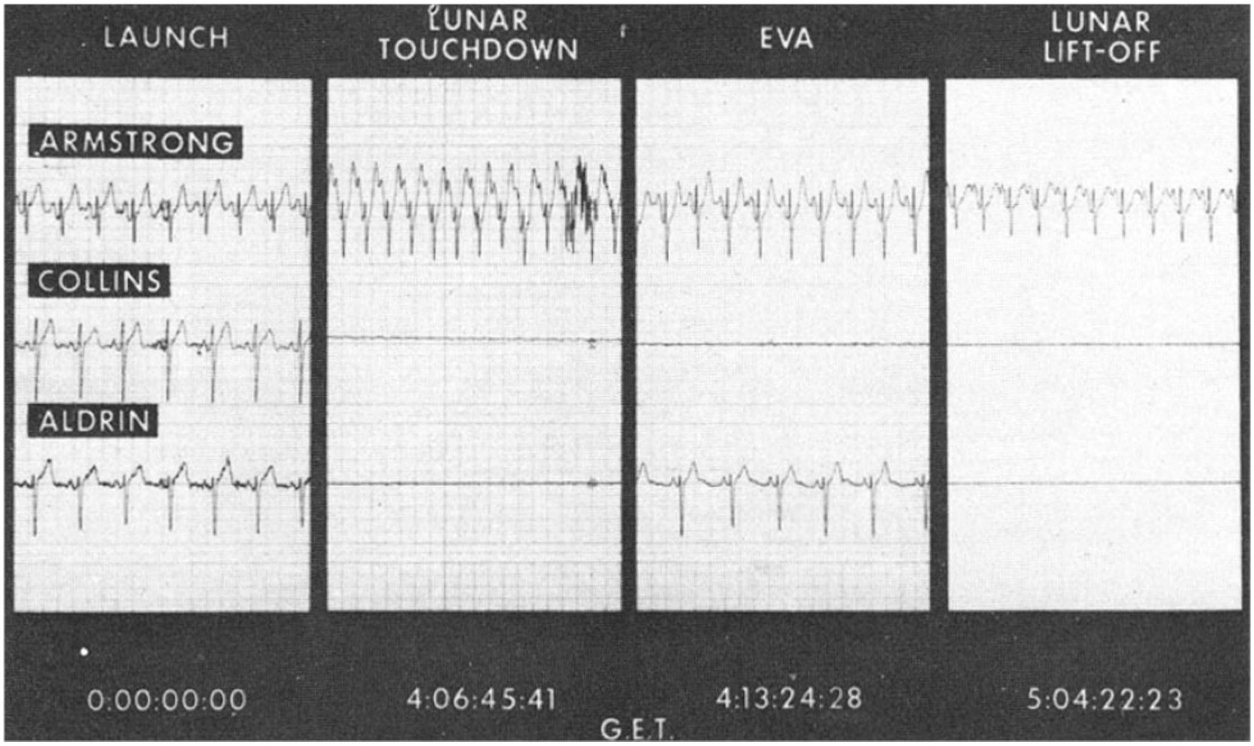

Figure 1. Electrocardiograph signal received at Mission Control during various periods of the Apollo 11 mission (NASA). (http://history.nasa.gov/SP-368/p492b.htm)

performed directly by the clinician. All remaining processes, up to and including synthesising the appropriate response, occur in the clinician's brain. The advance of technology, with the final stage of remote monitoring, has separated the various links in the chain between measuring and acting, and made explicit the chain of events, actions, processing and decisions linking the patient and the clinician.

The various links in this chain may include the following: data acquisition using an appropriate sensor; transmission of these data from patient to clinician; integration of the data with other data describing the state of the patient; synthesis of an appropriate action, or response or escalation in the care of the patient, and associated decision support; and data storage. The second, third and fourth items can occur in any order and may be repeated at different stages. These stages will now be considered in detail.

Data acquisition using an appropriate sensor

Sensors, their modes of action, and the signals (vital signs) they measure are well known and are beyond the scope of this article. However, it is worth noting that newer modalities of measurement are emerging [3]. Any physiological parameter that can be measured can theoretically be telemonitored. Table 1 lists those variables for which this has been successfully achieved [4]. Measurements from sensors may be continuous or intermittent. The time to the next measurement may be determined by the last value. The sensor may be remote from the patient (for example, using Doppler radar to count breathing rate) [3] or intermittently used by the patient [5] or even continuously worn by the patient (for example, the remote patient monitoring system is integrated within a 'smart garment') [6]. The measurement and collection of the data may be entirely automatic, or may involve a human (usually a clinician or the patient) in invoking the measurement or in performing it (for example, nurses entering vital signs data into a handheld computer) [7].

The transmission of data from patient to clinician

Depending on the setting, transmission of data can be by wired or wireless connections. Modalities include both wired and wireless computer networks, telephone networks and mobile phone networks. Systems that identify the available modalities and use them accordingly for the transmission of data are being developed. The transmission technology is the essential glue in the various possible chain topologies. Its capabilities (bandwidth, coverage, cost of use, and so on) predicate the functions and capabilities of the other components. Transmission

Table 1. Physiological parameters that have been successfully telemonitored [5]

Heart rate
Blood pressure
Respiratory rate
Temperature
Pulse oximetry
Heart sounds
Electrocardiograph (ECG)
Pacemaker parameters
Electroencephalogram (EEG)
Electromyograph (EMG)
Spirometry
Body weight physical activity
Fetal heart rate
Basal metabolic rate
O_2 consumption
CO_2 production
Blood glucose
Blood lactate
Blood ethanol
Intracranial pressure
Intravesical pressure
Intrauterine pressure

technologies will need to be chosen according to the particular use envisaged. Transmission of data from patient to clinician may be continuous or may only occur when a pre-defined exception state has occurred (for example, when a potentially dangerous heart rhythm is detected) [8] or when connectivity is available.

Currently, different systems tend to use proprietary standards for transmission of data. As such systems become more common place, standards such as HL7 will become more widely used to allow integration and total systems building. Governments have set aside portions of the electromagnetic spectrum for the specific use of wireless telemetry, though these are not always standardised across international regions and there are severe bandwidth limitations and interference issues. Therefore, most medical device companies develop for the internationally agreed 2.4 to 2.5 GHz industrial, scientific and medical band (ISM) [9], though, since this is not medicine-specific, it is open to possible interference and overcrowding.

Wireless transmission protocols in use include wi-fi (802.11 a/b/g/n) at 2.45 GHz and 5.8 GHz, and Bluetooth at approximately 2.45 GHz. Newer low-power, though lower-bandwidth, protocols that are also gaining favour include ANT [10] and Zigbee [11]. The Continua Health Alliance [12] has been formed to standardise both the protocols for transmission of medical data and the devices themselves, so devices can securely and reliably communicate with each other but this is at an early stage.

Integration of the data with other data describing the state of the patient

This may be done by a computer or a clinician, or both. Computer integration and/or analysis of data and their synthesis into information on which to act can happen anywhere in the chain and may be distributed across it. Amongst other things, this depends upon what data are being transmitted along the chain, which itself depends on the available bandwidth and its cost. Raw data could be transmitted (for example, three-lead ECG) or simply the heart rate; a full set of vital signs could be transmitted or simply a derived value such as an early warning score [13] or other index of patient severity of illness [14].

The detection of a particular patient state as a result of computer integration and/or analysis of data and their synthesis may be used to trigger transmission of the data themselves [8]. These are all inter-related engineering decisions specific to a particular application.

Synthesis of an appropriate action, or response or escalation in the care of the patient, and associated decision support

This depends on context. In hospital, it might be a decision to admit to an ICU or to call a rapid response team; in the community, the action could be to arrange a visit by a community nurse. Such a decision could be made by an 'intelligent' system but at present would certainly involve human input. Importantly, though, such 'systems' could push the data to the responsible clinician for a decision to be made when pre-determined criteria had been satisfied, removing the need for continuous human monitoring. What such escalation (or de-escalation) criteria should be is both context-dependent and probably unknown. The extent of synthesis and decision support ranges from applying the above criteria for escalating clinical input to simply making background contextual information available to the responsible clinician to reduce diagnostic and decision errors, and improve patient safety and quality of care [15].

Data storage

At one extreme this may be local storage of data in the sensing device to allow, for example, a breathing rate to be determined prior to transmission or the short-term storage of data to allow the data prior to a critical event to be transmitted as supporting information along with notification of the critical event [8]. At the other extreme, it could be the formation of a large database of vital signs to determine and validate calling criteria for rapid response team activation [7]. Such data are almost certain to become an essential part of the electronic patient record. Medico-legal as well as contractual and billing issues will demand the storage of the majority of these data.

Clinical use of telemonitoring

Telemonitoring is being used in the home, at the scene of a medical emergency, in transit via the ambulance service and in the hospital.

Home

In the home, telemonitoring is characterised by a patient being monitored by a number of devices and the subsequent, real time or delayed transmission of derived data via the domestic or mobile telephone service to a remote monitoring service or healthcare provider. These devices may monitor physiological data (for example, pulse, blood pressure, SpO_2, blood glucose) or the performance of equipment such as implantable defibrillators or pacemakers [16,17]. Most commonly, telemonitoring is used for the distant surveillance of patients with chronic disease, such as chronic heart failure, chronic obstructive pulmonary disease and diabetes mellitus. However, fetal heart rates and the level of activity of elderly people have also been monitored [4,18]. The same type of technology may also be used to record a patient's subjective response to specific pre-set questions about their health [5]. Table 2 lists a selection of studies with positive outcomes attributed to telemonitoring. It has been estimated that the use of remote monitoring of chronic disease to prevent deterioration by early detection and intervention in the community could save approximately $197 billion in the USA over the next 25 years [19].

However, other studies have not shown any change in measured parameters with home-based monitoring and intervention for asthma [20] or hypertension [21]. Systematic reviews on chronic disease management and telemonitoring, although acknowledging the potential benefit of telemonitoring, highlight the need for further research [22-24]. Interpretation of the significance of the reported results of most pre-hospital telemonitoring studies is difficult because not only has the frequency of vital sign measurement been arbitrarily chosen - ranging from continuous to symptom-based [21,25-36] - but medical review and intervention based on the collected data also varied from immediately based on alarms to monthly [21,27-30,34,36-38].

Disaster medicine

Systems are being developed that would enable emergency medical services to tag and physiologically monitor large numbers of patients at a remote site, that is, the site of the disaster or a triage centre [39]. Such systems would provide first responders, disaster command centres and supporting hospitals with medical data to track and monitor the condition of up to thousands of victims on a moment-to-moment basis using vital signs monitoring and location tagging (similar to global positioning system tagging).

Ambulance services

Use of telemedicine in ambulances has so far focussed primarily on patients suspected of suffering a myocardial infarction. ECG data from these patients has been transmitted to a designated hospital and a decision is then for either pre-hospital thrombolysis [40] or redirecting the ambulance to a centre for primary angioplasty [41], both of which have been shown to reduce the time to treatment compared to traditional in-hospital assessment. Other parameters transmitted from ambulances include non-invasive blood pressure, arterial oxygen saturation, blood glucose concentration and body temperature [42].

In hospital

In hospital, the interest in telemonitoring has been driven by the need to balance the conflicting requirements posed by increased population age, increased patient severity of illness, increased incidence of concurrent illness, reduced staffing levels and raised patient expectation regarding patient safety. Telemonitoring could be used in any area of a hospital, but is perhaps most pertinent in critical care areas and the general wards.

Critical care areas

In the USA, VISICU, a Philips healthcare company, has implemented over 30 remote ICU programmes, in which intensivists and physicians provide supplemental monitoring and management of ICU patients at workstations in an off-site, centralized facility (the eICU). Bedside monitor data, lab results, patient treatment charts, ventilator and other equipment settings and outputs from audiovisual equipment in the ICU patient rooms are available to the eICU staff, who also have access to physician note- and order-writing applications. When the eICU team is allowed full and direct management of the patient, these systems have been reported to reduce mortality by up to 33% [43], number of ventilator days by up to 25% [43] and length of stay in the ICU by up to 17% [44]. A criticism of the eICU is that these benefits may only be apparent in an environment where there is a shortage in the number of intensivists to adequately provide an onsite 24/7 specialist-led service. Other descriptions of the use of telemonitoring in critical care include the provision of support for patients requiring mechanical ventilation at home [45], which has proved to be successful in the weaning of a patient from home mechanical ventilation without onsite specialist help [46].

Table 2. Telemonitoring studies with a positive outcome

Paper	Setting	Disease	Parameters measured (frequency)	Transmission frequency	Review frequency	Outcome
Breslow 2007 [43,44]	In hospital - ICU	Multiple - all critically ill patients	Multiple continuously; all measured parameters + video monitoring	Continuously	Continuously	Reduced mortality by up to 33%, number of ventilator days by up to 25%, length of stay by up to 17%
Antonicelli *et al*. 2008 [30]	Community	Chronic heart failure (CHF)	BP (daily), ECG (weekly), body weight (weekly), 24-h urine output (weekly)	Daily	Weekly	Telecare versus usual care: decreased hospital readmission 9 versus 26 ($P < 0.01$); trend towards decreased mortality 3 versus 5; total patients 28 versus 29 (N = 57)
Fursse *et al*. 2008 [29]	Community	Diabetes, hypertension, CHF	Blood glucose (daily), BP (daily), SpO_2 (daily)	Daily	On alerts, regularly - not specified	Mean reductions of 11 mmHg systolic and 2 mmHg diastolic in patients with CHF, 0.4% HbA1c in those with diabetes, and 12 mmHg systolic and 2 mmHg diastolic in those with hypertension (no control group; N = 29)
Green *et al*. 2008 [31]	Community	Hypertension	BP (twice weekly)	Twice weekly	Fortnightly	Higher proportion of patients (after 12 months) whose BP was controlled (<140/90); telemonitored group 56% versus usual care 31% (80% increase; N = 778)
Kisner *et al*. 2008 [61]	In hospital - ward	Atrial fibrillation post CABG	SpO_2 (continuously)	Continuously	On alerts	Incidence of atrial fibrillation in telemonitored group was 14% versus 26% (prior to telemonitoring; $P = 0.016$; N = 119; control cohort = 238)
Morguet *et al*. 2008 [33]	Community	CHF	Weight (daily), BP (daily), pulse rate (daily), ECG (on request)	Daily	Twice weekly, on alerts	50% reduction in hospital admissions (38 versus 77/100 patient years, $P = 0.034$), 54% reduction in hospital length of stay (317 versus 693 days/100 patient years; $P < 0.0001$) (N = 128)
Nakamoto *et al*. 2008 [63]	Community	Hypertension: drug trial of temlisartan versus amlodipine	BP (twice daily)	Twice daily	End of study	Evening systolic BP reductions higher in telmisartan versus amlodipine group (13 ± 3 versus 6 ± 3 mmHg); non-significant differences in morning BP reduction between both groups; better daytime normalisation with telmisartan (N = 40)
Nielsen *et al*. 2008 [27]	Community	ICD, pacemaker	ECG (continuously)	Daily, on alerts	On alerts	26% of unplanned clinic visits initiated by telemonitored data (N = 260)
Ricci *et al*. 2008 [28]	Community	ICD, pacemaker	ECG (continuously)	Daily, on alerts	Fortnightly, on alerts	37% of patients had changes to their medication, device reprogramming, or were called in for further investigations (N = 117)
Woodend *et al*. 2008 [34]	Community	Angina, heart failure	BP (daily), weight (daily), ECG (not specified)	Daily	Weekly	32% reduction in hospital admission (0.4 versus 0.59 hospital readmission rate per patient, $P = 0.048$); 46% reduction in length of stay in hospital if readmitted (2.11 versus 3.93 days, $P = 0.038$) (N = 249)
Parati *et al*. 2009 [35]	Community	Hypertension	BP (not specified)	Not specified	On alerts	Increased daytime BP normalization (<130/90), 62% versus 50% ($P < 0.05$); less frequent treatment changes, 9% versus 14% ($P < 0.05$) (N = 228)

BP, blood pressure; CABG, coronary artery bypass graft; CHF, chronic heart failure; ECG, electrocardiograph; ICD, implantable cardioverter-defibrillator.

Systems that monitor patients' physiological parameters during home hemodialysis also exist [47].

Remote monitoring of vital signs of ward patients provides the possibility of obtaining pre-ICU data - even to the point of using these data to decide if ICU admission is required. It may also allow earlier, safe discharge of patients from the ICU as they can be reliably remotely monitored by ICU staff. Perhaps, most interestingly, it potentially allows ICU staff to survey the whole population of monitored in-patients and to intervene as necessary - a technology-enabled pro-active outreach service [7].

Ward patients

Many hospitalised patients suffering adverse events (for example, in-hospital cardiac arrest, unanticipated ICU admission or death) exhibit physiological deterioration in the period before the event [48-50]. Sometimes this is detected, but often there is insufficient monitoring [51-55]. For example, the 2007 National Confidential Enquiry into Patient Outcome and Death report [54] noted that 'not only are appropriate observations performed less often than is desirable, when they are performed, their frequency is inappropriately low in a significant proportion of patients'. Other failures in the system of recognising and responding to patient deterioration include a failure to call for experienced help and a failure of responders to respond [48-51].

Outreach/medical emergency team data appear to indicate that early identification and intervention of deteriorating patients reduces the incidence of adverse events. In one multicentre study Chen and colleagues [56] analyzed 11,242 serious adverse events and 3,700 emergency team calls and found for every 10% of increase in the proportion of early emergency team calls there was a 2.0 reduction per 10,000 admissions in unexpected cardiac arrests (95% confidence interval (CI) 2.6 to 1.4), a 2.2 reduction in overall cardiac arrests (95% CI 2.9 to 1.6), and a 0.94 reduction in unexpected deaths (95% CI 1.4 to 0.5).

It is now advised that a clear physiological monitoring plan, which details the parameters to be monitored and the frequency of observations, should be made for each patient, and that there should be a graded response to patient severity of illness [7,53]. Other recent reports also recommend an increase in the range and frequency of physiological parameters monitored in general ward patients [51-55]. This could be achieved by increasing levels of nurse staffing, as this has been shown to reduce adverse outcomes [57], but there are limits to the extent to which nursing numbers can be increased. However, technology can enable the continuous capture and transmission of physiological parameters and the advent of early warning systems allows for a mechanism of automatic analysis of these signals, theoretically enabling the clinical expertise of medical professionals to be focussed on those patients who are at greatest risk of deterioration. Telemonitoring technology therefore has the potential to increase patient care and is thus regarded as an integral part of the UK National Health Service Connecting for Health Programme [58].

There are many publications from ICUs, high dependency units or cardiac care units that describe data telemetry from a bed-bound patient to the nurses' station. However, descriptions of the use of such technology in the general wards of hospitals are rare. Cale [59] has described the hospital-wide implementation of a wireless telemonitoring system in a Californian hospital that transmits patient parameters to a 'war room', where these are monitored by biomedical technicians 24 hours a day. The use of a wireless pulse oximeter in a Zurich hospital [60,61] is claimed to reduce the incidence of atrial fibrillation (14% versus 26% prior to telemonitoring, P = 0.016) in coronary artery bypass graft patients by early detection of desaturation and implementation of oxygen therapy. A unique characteristic of this system is that it either pages the doctor directly or sends an SMS text message to their mobile phone alerting them of the desaturation and providing a history of the event. In the UK, nurses in some hospitals use the VitalPAC system for collecting routine vital signs data at the bedside using standard personal digital assistants (PDAs) wirelessly linked to the hospital's intranet system. Here raw and derived data are integrated with patient demographic and laboratory information, allowing raw physiology data, early warning scores, vital signs charts and oxygen therapy records to be made instantaneously available to any member of the hospital healthcare team [7].

Some obvious challenges

Currently, the technology for telemonitoring is far from mature and there are still technological issues to be addressed. These include: the lack of a full range of appropriate sensors; the bulk weight and size of the whole system or its components (particularly in relation to patient-worn systems); the identification of invalid data (for example, from sensors that become detached/displaced); battery life; available bandwidth; network coverage; and the costs of data transmission via public networks.

There will also be challenges for adoption of such systems because individuals may see constant physiological surveillance as intrusive. As with genetics testing, there may even be insurance-related issues [62]. There are also potential cultural problems to be tackled in relation to the deployment of such technology in healthcare organisations, as they produce requirements for new ways of working. Another major problem is that telemonitoring has the ability to produce a mass of data that require interpretation to be of use. New data analysis methods therefore need to be devised and validated. Mistakes in this analysis could have medico-legal consequences.

However, despite all the potential hurdles, it is likely to be only a matter of time before smart systems continuously monitor every patient from the moment they are admitted to the point of discharge from hospital (and possibly beyond).

Abbreviations

CI = confidence interval; ECG = electrocardiograph.

Competing interests

VitalPAC™ is a collaborative development of The Learning Clinic Ltd and Portsmouth Hospitals NHS Trust. Professor Gary Smith's wife and Dr David Prytherch's wife are shareholders in The Learning Clinic Ltd. Professor Smith and Dr Prytherch are engaged in research with McLaren Applied Technologies and Laerdal Medical who both manufacture patient monitoring devices.

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