Remote Monitoring of Vital Functions - Proof-of-concept System

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Abstract - Modern information communication technologies (ICT) acting as a support to the medical activities is one of the possibilities to increase the efficacy of the health care system and to decrease its costs. We developed a proof-of-concept system, which uses modern, moderately-priced and user-friendly technology solutions, e.g. wireless body sensors for data acquisition, advanced algorithms for local analysis of data, widely available personal terminals for visualization of measurements, and the existing communication infrastructure for data transfer, either to medical experts or to a personal database. We pay a special attention to the fusion of different body sensors in order to keep their number at minimum. On the other hand, we want to improve reliability of the system with the introduction of a simple video sensor in order to prevent the rising of false alarms. We show that such a system can achieve a reliability needed for commercial implementation in applications offering services that can contribute significantly to an improved quality and efficiency of the medical care.

I. Introduction

The introduction of modern information communication technologies (ICT), as support to medical activities, is one of the possibilities to increase the efficacy of the health care system and to decrease its costs. This basic premise is included in all strategic plans of the EU and the rest of the world. Numerous studies have confirmed the benefit of the development of Telemedicine/Telecare systems [1, 2]. We are proposing a proof-of-concept system, which uses modern, moderately-priced and user-friendly technology solutions.

The health of hospitalized patients is regularly assessed by periodic measurements of indicators of vital functions, like respiratory rate (RR), heart rate (HR), blood pressure (BP) and body temperature (TT). With close monitoring of these patient parameters and according to dynamic changes, necessary medical assistance can be provided. The indicators of vital functions in the non-intensive wards are normally measured by nurses several times a day and then manually entered in the patient's charts. In case of clinical deterioration, additional treatment measures are needed, the effects of which are also assessed with the monitoring of indicators of vital functions. If the patient's condition deteriorates and continuous monitoring is needed, the patient is transferred to the intensive care unit. However, the intensive care unit has a limited number of beds. If the patient's condition deteriorates between the periodical measurements performed by nurses, the consequences for the patient could be fatal.

In addition to the issue of intermittent monitoring of vital functions in non-intensive wards, there are other weaknesses in the current health care system. The interpretation of the patient's condition and the consequent measures taken depend on the personnel, who could be, in certain conditions, overwhelmed with work or busy with other patients. The measured indicators can also be inaccurate, sometimes being biased by the presence or inexperience of the medical personnel and therefore unreliable. The subsequent interpretation of the documented measurements can be difficult because they are based on insufficient or unreliable data.

The proposed system for remote monitoring of vital functions establishes a virtual state of semi-intensive care unit, which significantly improves the quality of hospital care. Patients are fitted with body sensors for vital functions. The sensors communicate with the personal terminals (size of a mobile phone) via wired or wireless connections. The measurements are stored in the personal terminal for monitoring and later processing with automated procedures based on the comparison with threshold values, predetermined rules and automatic learning. The data are sent to a computer server, which maintains a database and is responsible for the presentation, alerts and necessary actions.

II. System Architecture

The scheme of the proposed system for remote monitoring of vital functions is shown in Fig. 1.

The design of the system takes into account the existing technical standards, allowing easy connection of various body sensors and their immediate replacement if an improved version becomes available. The system allows the connection of new sensors, which could help improve the monitoring of the patient's condition, for example, sensors for remote monitoring of respiratory acoustic phenomena (cough, obstruction), or video sensors for the analysis of live video (with the consent of the patient). Some of the measurements are feasible with our custom sensors [3]; for others, like blood pressure measurements, new unobtrusive and non-invasive body sensors are to be developed; remaining measurements are realized by inexpensive commercially available sensors.

For the transmission of measurements we use standard technologies (Ethernet, Bluetooth, Wi-Fi, etc.) and the Internet, which offers an inexpensive implementation, as well as wide availability. The information is available on

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site and controlled/monitored by the staff on call, which enables immediate detection of deterioration in the patient's state and prompt actions.

Based on the graphic presentation of a critical vital parameter and its recent changes, it is possible to evaluate the effectiveness of a treatment and to foresee a possible deterioration. An alarm will alert the possibility of deterioration before the vital parameter reaches the critical value. Based on the simultaneous evaluation of multiple variables, the program will provide the threat level and its trend (MEWS) [4]. The analysis of vital functions in a longer time period allows for the implementation of the cognitive methods, for example, analysis of a cardiogram over longer time period contributes to the personalized patient's threat level [5, 6].

III. Implementation Concepts

The implementation of the proposed system significantly increases the research potential of medical institutions. The system provides documented measurements and events obtained in an objective manner during different stages of the well-being of patients or other users (elderly, athletes, etc.). The system could be upgraded with new medical research methods. Following are related research activities and findings that contribute in the system implementation.

A. Development and implementation of a system for sound diagnosis of pneumonia

In clinical medicine, the gold standard for diagnosis of pneumonia is the X-ray imaging; nevertheless, in a clinical examination, pneumonia is diagnosed only in a small proportion of ill children. Computer analysis of the sounds in adult patients with pneumonia has been proved to confirm the diagnosis [7]; however, the method uses sixteen microphones, which is not suitable for clinical use. The proposed system enables development of convenient and computerized systems, designed by a smaller number of microphones, which spare the patients from the X-ray radiation.

B. Development of multifunctional body sensors

Body sensors should be non-disruptive to users; therefore, we consider small and multifunctional wireless sensors. We have already prototyped a differential wireless bio-electrode (WBE) for measuring ECG [8]. Other features can be also added to this electrode: EEG, vascular pressure, skin resistance and respiratory rate measurements. Such an electrode will represent an important worldwide technological breakthrough. An example of the prototype multisensory electrode is shown

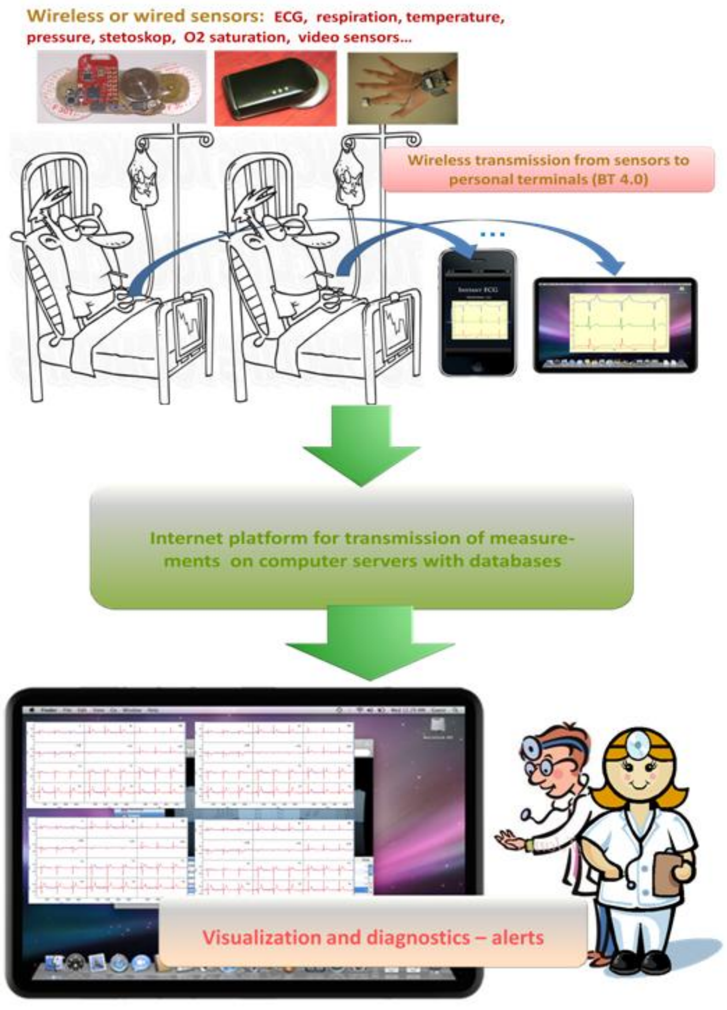


Figure 1. Conceptual scheme of the system for remote monitoring of vital functions

in Fig. 2a. On the measured raw ECG signal (Fig. 2b), a respiration signal as an envelope of the R-peaks is clearly visible.

Furthermore, a new prototyped muscle contraction (MC) sensor [9] is considered for integration into the system. The sensor is relatively small and light. It is based on a novel principle for measuring muscle tension during muscle contractions and provides important data about patient's muscular activities. Additionally, we consider the option to use the MC sensor for detection of the tactile pulse. The sensor could be also adopted for measurement of changes in the blood pressure. An example of the prototype MC sensor and a preliminary measurement of the tactile pulse are shown in Fig. 3a and Fig. 3b, respectively.

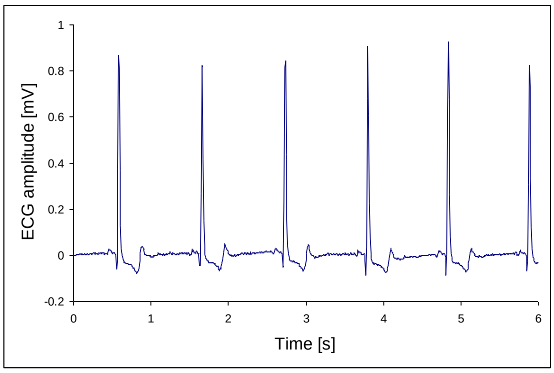
C. Long-term monitoring of ECG records

One of the advantages of the proposed system is the ability for continuous monitoring of ECG. In a recently published study on children with RSV bronchitis, the presence of abnormal heart rhythm was also found [6]. Long-term monitoring of ECG is an important source of data for confirming the correlation of the two diseases, which is not known so far.

D. Synthesised 12-channel ECG

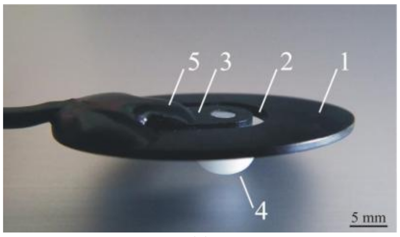
The 12-lead electrocardiogram (ECG) is the gold standard in cardiology and lies at the center of the decision pathway for the evaluation and management of patients. However, the conventional 12-lead ECG is obtained from ten electrodes connected with wires to a data collecting device. Its application therefore imposes obtrusion and has negative effects on patient comfort. Moreover, due to the fact that the standard positions of the precordial electrodes are often difficult to locate

(a)

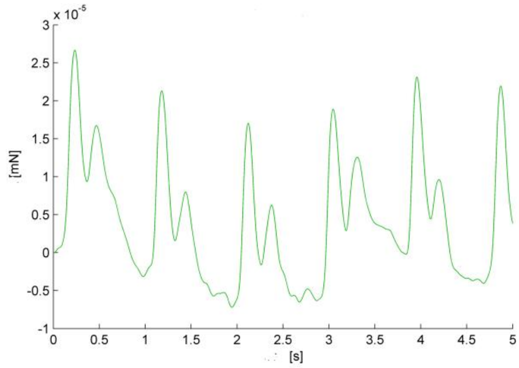


(b)

Figure 2. (a) A prototype of the WBE with two self-adhesive disposable electrodes, a lithium coin battery and a ceramic chip antenna. (b) An example of an ECG recorded wirelessly – raw signal.



(a)



(b)

Figure 3. (a) A prototype of the muscle contraction (MC) sensor. (b) An example of measured tactile pulse.

accurately, particularly in women and children, the application of the conventional 12-lead ECG device can be impractical.

The WBE provides an alternative that resolves the standard 12-lead ECG devices imperfections. It enables minimal use of wires on the body and consequently maximal wearing comfort. The WBE enables the measurement and transmission of only local potential differences, i.e. bipolar measurements, from two closely placed skin electrodes. The measurements from few WBEs thus form a lead system that can potentially be used for reconstruction of the 12-lead ECG.

The fact that almost all electrocardiographic knowledge is accumulated in the 12-lead ECG imposes a need for the synthesis of the 12-lead ECG from the lead system of WBEs. In previous work [3] we have shown how to perform personalized synthesis for each patient. The positions of three wireless electrodes may be chosen by respecting signal/noise ratio [10] or by efficient personalized algorithm [3] developed for that purpose.

The algorithm for determining personalized positions of the WBEs, together with the algorithm for the synthesis, produces the 12-lead ECG that contains the same diagnostic information as the one obtained by a conventional device. The synthesized 12-lead ECG, compared to the 12-lead ECG obtained by a conventional device, is presented on Fig. 4. The synthesized 12-lead ECG is shown in red and the measured 12-lead ECG is shown in blue. The figure represents a case with no significant difference between the two ECGs.

The synthesis of the 12-lead ECG can be done on personal terminals, immediately after receiving the measurements from the WBEs, or later on the computer server.

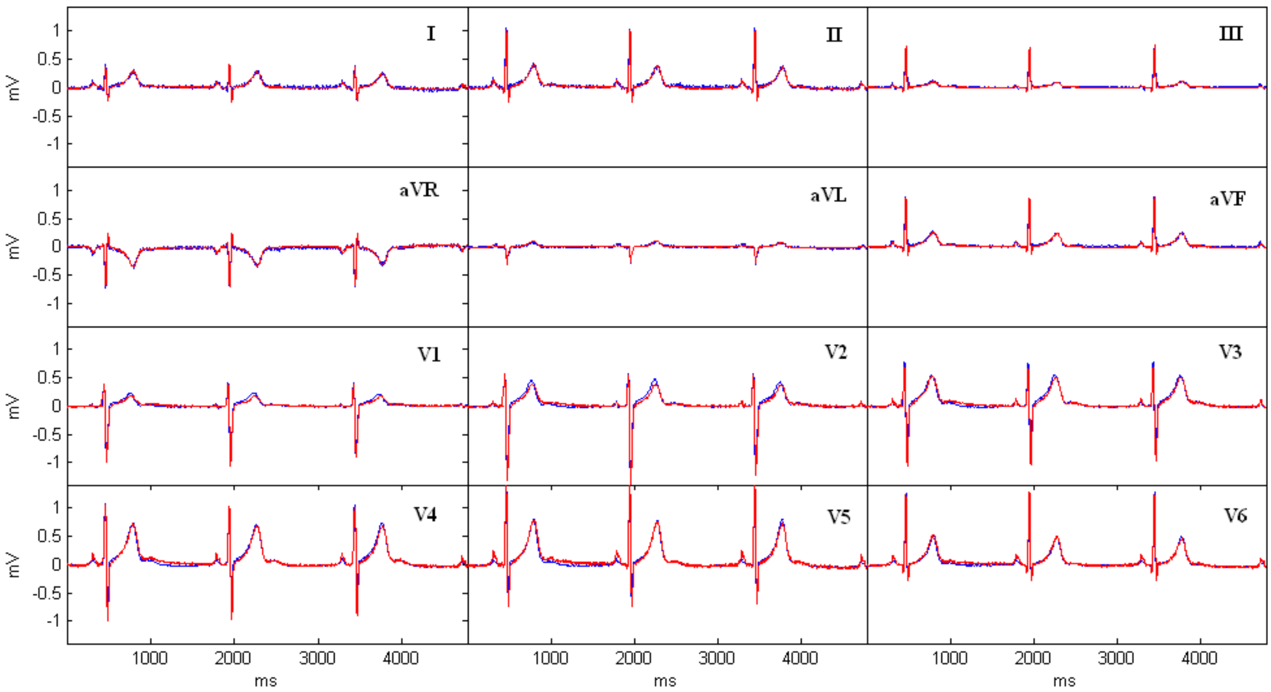


Figure 4. 12-lead ECG obtained by a conventional device (blue) compared to synthesized 12-lead ECG (red)

E. Visual sensors

One of the most critical problems that influence a sustainable use of monitoring systems is issuing false alarms. The personnel that assists and manages a monitoring system cannot tolerate false alarms above some minimal limit. We pay special attention to overcome this problem with multilevel alarms based on data from more than a single sensor. To improve the quality of patients' status interpretation, we introduce visual sensors consisting of simple and low cost video detectors [11]. Visual sensors will not allow interference with personal intimacy. The video detectors cover just a near area of the patient's bed and, after a simple local video processing, detect and store patients' motion, movement and position. Based on these additional data, an improved reliability of raised alarms can be obtained.

F. Development of platforms for transmission, representation and collection of data

The transmission of data from the sensors, and later its representation, are planned on two levels: to the patient itself and to the medical personal.

First, we have wireless transmission of the measured data from the sensors to personal terminals, like Smartphones or other portable smart devices. Custom made applications provide the opportunity for suitable representation of the transmitted data and the possibility for the patient to monitor its vital functions. We have already developed an application that provides a comfortable option for telemonitoring of the heart activity. We use the prototyped wireless bipolar body electrode [8] to record ECG wirelessly, coupled with the advantages of existing portable smart devices to display the real-time data from the electrode [12]. Local processing of the measured data and alarm triggering can be done already on the portable device. For example, the reconstruction of the standard 12-lead ECG from three wireless bipolar body electrodes can be additionally preformed already on the Smartphone and the reconstructed signal appropriately displayed.

Second, a SOAP (Simple Object Access Protocol) client on the portable platform transfers relevant data (for example, ECG data when an alarm has been triggered) to a computer server. The transferred data on the server is appropriately visualized to the medical personal for diagnostic purposes, and also is collected in a database for further analysis.

The wireless technology considered for transmission of measured data from the sensors to personal terminals is the newest version of Bluetooth technology – low energy Bluetooth 4.0. It enables direct communication between WBEs, and newest Smart phones and devices with incorporated Bluetooth Smart technology.

Bluetooth low energy protocol is low-cost wireless solution designed to meet special requirements for long-term operation in devices with limited energy capacity (e.g. coin-cell battery). Its ultra-low peak, average and idle mode power consumption and enhanced working range enables the WBEs to operate on a single coin-cell battery for several days while transmitting live stream of raw ECG data. Based on our preliminary measurements, we conclude that the low power Bluetooth 4.0 enables 4 days of external power supply independency for a WBE with a small coin battery. The maximal bit-rate of the data payload is 1 Mb/s, which is sufficient also for high resolution short-term measurements.

IV. CONLUSION

We have designed a pilot system for continuous monitoring of patients at risk and thus contribute to the significantly elevated quality of health care and patient safety. Widespread, accessible, and tested ICT solutions from the field of measuring sensor systems, mobile communications and network services, are incorporated into the system. Medical expertise are also included through the software for analysis of measurements, as well as the triggering of alerts and alarms for urgent action. The responses of medical personnel to clinical deterioration in patients will be faster; therefore the patients will experience fewer complications in case of sudden deterioration of their health. The work of medical personnel will be less stressful and more efficient.

The applicability of the proposed system is not limited only to hospitals and health care centers, where the added benefit of the system will enable "doctor-to-doctor" and "patient-to-doctor" communication. The system can be also installed in nursing and patients' homes, e.g. for early postoperative care. The patient-friendly approach will contribute to easier diagnostics and reduction of healthcare costs.

The proposed system for remote monitoring of vital functions acts as a test ground for medical staff and a basis for the future Telemedicine/Telecare services. Improved and clinically evaluated system will be an interesting product for the international markets, and opportunity for R&D companies.

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