REVIEW ARTICLE

TELEMONITORING OF BIOMEDICAL PARAMETERS - TECHNOLOGICAL ASPECTS AND APPLICATIONS

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Abstract: The article presents the main technological aspects of systems of telemonitoring of biomedical parameters, based on the example of research carried out in the Łukasiewicz Research Network — Institute of Medical Technology and Equipment, Zabrze. Medical telemonitoring covers technologies for the acquisition, processing and analysis of biomedical information. Data sources and technologies for obtaining biomedical information are an important element of medical telemonitoring. Medical telemonitoring systems are one of the main elements of telemedicine or telehealth. Telemonitoring of vital biomedical parameters is mainly used to perform remote diagnostics and medical rehabilitation. This applies primarily to patients from the so-called "high risk" groups, who are treated or rehabilitated outside hospitals. An important area for the application of medical telemonitoring is the safety of people working under extreme or stressful conditions. Telemonitoring of vital parameters can also be used to increase the safety of those who engage in physical activity for health promotion, sports and performance.

Keywords: telemedicine, telehealth, medical telemonitoring, biomedical parameter acquisition, vital signs monitoring, long-term surveillance

INTRODUCTION

Medical telemonitoring can be defined as a use of ICT to transmit biomedical information in order to perform a remote diagnosis and medical surveillance. Medical telemonitoring systems are an important element of telemedicine. Telemedicine or telehealth is an interdisciplinary branch of medicine integrating medical and technical sciences. Within the framework of telemedicine, five main groups of telemedicine technologies can be distinguished: telemonitoring, telediagnostics, telerehabilitation, telesurgery and teleconsultation. The primary function of medical telemonitoring systems is to transmit information, generated and preprocessed in the patient's environment, to a local or remote monitoring and surveillance center, where this information is further processed and analyzed to support diagnosis or medical surveillance [11,24,25,26,27,28,31]. In this case, information generated in the patient's environment means biomedical signals and parameters recorded inside or on the surface of the patient's body, visual or thermal imaging of patient's body parts, parameters of the patient's environment. Medical telemonitoring systems transmit information including biomedical signals, parameters and images. Bioelectric signals, such as: ECG, EEG or EMG are recorded directly by means of appropriate sensors — electrodes. Biomedical parameters, such as: body temperature, pulse, respiratory rate or blood pressure are measured by means of appropriate transducers, which transform the physical quantity, corresponding to the measured parameter, into the value of this parameter. The measurement of environmental parameters is carried out in a similar manner, such parameters include: air temperature and pressure, atmospheric particulate level or noise level. The generation of biomedical images, such as visual imaging, thermal imaging, ultrasounds or X-rays, requires the use of appropriate devices, generally operated by qualified medical personnel. The final recipient of information generated in medical telemonitoring systems is always a medical specialist, who conducts medical supervision and, based on the processed information, decides on appropriate treatment. Medical telemonitoring systems will be used with increasing frequency in everyday medical practice [7,8,22,23,31]. The use of teletransmission technologies to transfer biomedical information overcomes geographical barriers and provides remote medical care to patients wherever they may be located [18,23,24,28,30]. In particular, telemonitoring of biomedical parameters provides the basis for building telemedical systems for various applications.

There are biomedical parameter telemonitoring systems solutions available on the market, mainly for the purpose of performing remote cardiac surveillance [7,11], in particular of patients with the latest generation of cardioverter-defibrillators offered by the manufacturers of these devices [6,15]. By contrast, biomedical parameter telemonitoring systems for other applications are still not very widespread. In this respect, intensive research and development work is being carried out in a number of scientific centers aimed at the development of effective, non-intrusive technologies for the acquisition and processing of biomedical information under conditions of normal patient life activity [5,12,21]. Such works have also been carried out for a number of years at the Łukasiewicz Research Network — Institute of Medical Technology and Equipment (abbreviated to Łukasiewicz-ITAM). The results of these works have been used in Łukasiewicz-ITAM in the development of usable versions of various medical telemonitoring systems. The technological solutions of the systems developed enable surveillance of patients, including pregnant women, at their place of residence, monitoring of people in various environmental conditions and long-term monitoring (periods longer than 7 days). These systems are presented in the second part of this article.

GENERAL STRUCTURE OF MEDICAL TELEMONITORING SYSTEMS

Medical telemonitoring systems are an essential part (subsystem) of telemedical systems, which constitute the technical implementation of functions enabling the remote provision of medical services [7,18,19]. The basic function of telemedicine systems is the transmission of information between the patient and the doctor under conditions that exclude the possibility of direct contact. To carry out this teletransmission, the available telecommunication technologies are used. These mainly include online wireless communication technologies [1,23,28]. Telemedicine systems must ensure the mutual, undisturbed flow of information between the patient and the doctor, which means that the required medical action is taken remotely on the basis of an analysis of the information obtained by the doctor, but with the addition of informing the patient of the results of that analysis and the necessary follow-up action to be taken by the patient. The general structure of the medical telemonitoring system is presented in fig. 1.

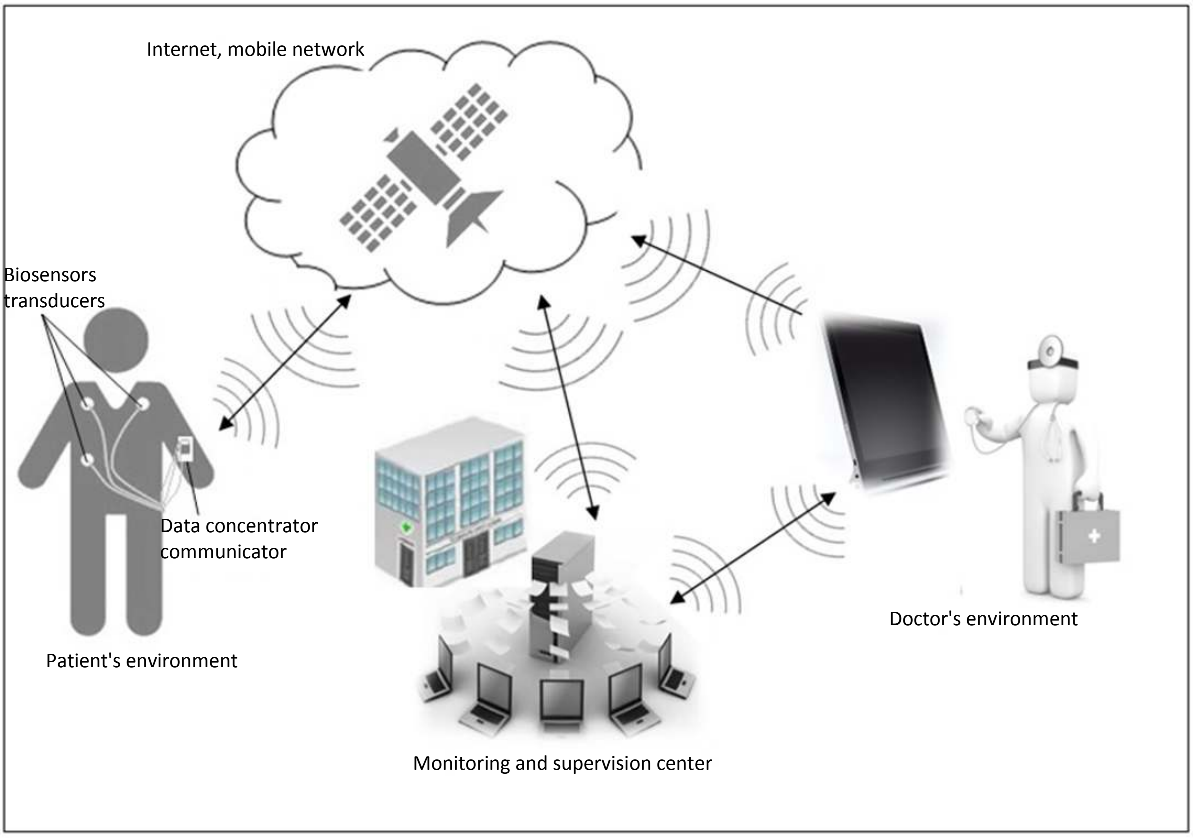


Fig. 1. General structure of a medical telemonitoring system.

Modern medical telemonitoring systems consist of four essential elements:

1) Devices in the patient environment — forming a data acquisition network.
2) A telecommunications network enabling local (within the data acquisition network) and remote (to a monitoring and surveillance center) transmission of biomedical information.
3) Devices storing, processing and analyzing medical information in the monitoring and surveillance center (servers in the monitoring center, distributed servers forming a computing cloud).
4) Devices in the doctor's environment.

The patient's environment features devices enabling the acquisition of biomedical information, its initial processing and sending it through a telecommunications network to the information collection and processing center. There are communication devices on the doctor's end, such as desktop or laptop computers, PDAs or smartphones, allowing the doctor to access individual patients' medical information, stored and properly processed in the monitoring and surveillance center [21,26,28].

The most important part of medical telemonitoring systems is a biomedical signal and parameter acquisition network called the Body Area Network (BAN), which consists of sensors and biomedical signal transducers placed on the patient's body and connected to a concentrator data communicator module (usually a smartphone), worn by the patient [1,25,28]. The system can use a wired connection — Cable Body Area Network (CBAN) as presented in fig. 2a or a wireless connection — Wireless Body Area Network (WBAN) as in fig. 2b. The design of the BAN depends on the purpose of the medical telemonitoring system. The technical and operational parameters of this network determine mainly the quality and usefulness of the entire medical telemonitoring system.

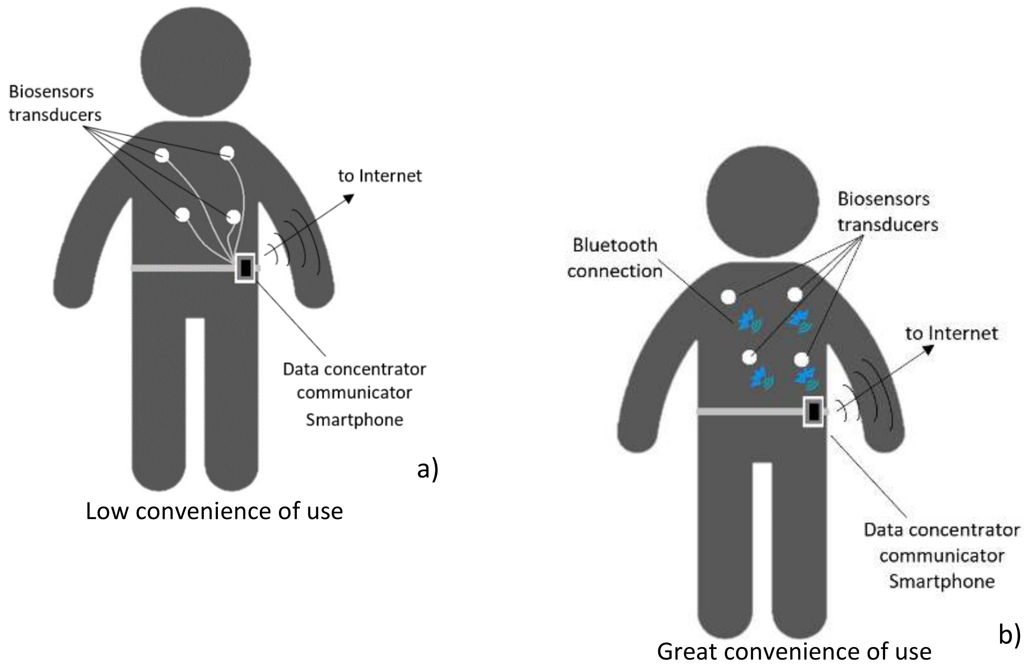


Fig. 2. a) Sensors of Cable Body Area Network — CBAN. b) Sensors of Wireless Body Area Network — WBAN.

The acquisition of information in the patient's environment involves the recording and processing of signals received directly from the patient's body as well as other biomedical and environmental data generated by devices worn by the patient or located in the patient's environment. Depending on the purpose of the medical telemonitoring system, the data acquisition network includes various sensors and transmitters of biomedical signals (including bioelectrical signals) as well as transmitters and instruments measuring environmental parameters [9,10,12,21]. The sensors are used to directly record bioelectrical signals from the body surface. Surface bioelectrical signals, i.e. electrocardiogram (ECG), electroencephalogram (EEG), electromyogram (EMG), are generated by tissues of individual organs, in this case the heart, the brain and muscles. On the surface of the body, variable electrical potentials are recorded over time.

In turn, transducers convert various physical biomedical signals, e.g.: breathing movement of the chest, exhaled air flow, heart sounds, blood flow, ECG signal, bioimpedance signals — into another physical value, which corresponds to the measured medical (vital) parameter. Based on studies carried out at Łukaszewicz-ITAM and available literature data [1,8,19,26] a set of signals, biomedical and environmental parameters monitored in various medical telemonitoring systems can be defined. This set includes:

1) Biomedical signals: ECG, EEG, EMG, REO and ICG (bioimpedance signals).
2) Biomedical parameters: heart rate (HR), heart rate variability (HRV), oxygen saturation (SpO2), heart stroke volume (SV), chest and abdominal impedance changes, chest hydration (TFC), abdominal hydration (AFC), pulse rate, blood pressure, peak expiratory flow (PEF), respiratory rate, tidal volume, minute ventilation, frequency of coughing, cough intensity. body temperature, blood sugar level, fat layer thickness, physical activity.
3) Environmental parameters: particulate matter level (PM2.5), sulfur dioxide content (SO2), nitrogen dioxide content (NO2), temperature, humidity, atmospheric pressure, insolation (light intensity in the patient's environment).

The value of these parameters is determined by special modules for the measurement of physiological and environmental parameters, to which appropriate sensors and signal transducers are wired or connected wirelessly. Data from these modules are transmitted via Bluetooth to a smartphone, with a special application installed, and from where they are transmitted via GSM network to the monitoring center.

In medical telemonitoring systems, the quality of monitoring and remote supervision of patients depends mainly on the quality of acquired biomedical information and the quality of transmission channels transferring data to the medical supervision center. The quality of information obtained in the patient's environment is determined by the design technologies of sensors and biomedical signal transducers used for this purpose, while the quality of data transmission channels in the telemedical system depends on the technology and technical parameters of the communication network.

In medical telemonitoring systems, the acquisition of biomedical signals and parameters under natural life activity conditions is particularly important. This area includes the development of technologies for the acquisition of biomedical information by non-invasive and non-intrusive methods. Research work in this area is aimed at developing bioelectric signal acquisition systems, in the form of textronic structures integrated with clothing — the so-called “wearable health monitoring systems”. The basis of these systems are maintenance-free sensors (biosensors) and biomedical signal transducers, integrated with clothing, providing effective, reliable measurements of bioelectrical signals under natural life activity conditions of adults and children. Including developing physical activity for rehabilitation, recreation and sports purposes.

Another observed area of intensive development of medical telemonitoring systems is the broad application of computational intelligence for processing and analysis of biomedical information in these systems. Computational intelligence or CI is a field of science that deals with solving problems that cannot be described by means of effective models, effectively algorithmicized. To solve these problems, the methods of computational intelligence are used, which allow to build “intelligent” (self-improving, heuristic) computational algorithms based on “data-based learning methods”. Computational intelligence methods are widely used in medicine to process and analyze biomedical information. These find application in particular in: processing and analysis of biomedical signals and images, processing and analysis of medical data of patients, design of medical procedures, design of the so-called “patient flow” in a hospital, creating expert systems supporting prophylaxis, diagnostics and medical therapy, management of health care units.

Four groups of medical technologies can be distinguished within the framework of telemedicine: telemonitoring and medical supervision, telediagnostics, telerehabilitation and teleconsultation.

There are solutions available on the market, dedicated mainly for telecardiology in hospital applications. The technological and conceptual challenge is to develop systems to monitor and supervise various biomedical parameters collected in the patient's natural living environment as well as the hospital environment and beyond it. Teleminitoring and medical surveillance systems have been developed in Łukaszewicz-ITAM to meet these challenges, enabling: supervision at the patient’s home, including of pregnant women, monitoring people in various environmental conditions and long-term monitoring.

Selected telemonitoring and medical surveillance systems for various areas of application, developed in Łukaszewicz - ITAM are presented further in the article.

HEALTH SURVEILLANCE AT THE PATIENT'S HOME

Integrated systems of medical telemonitoring developed in Łukasiewicz-ITAM enable comprehensive care of the patient [26]. The designed solutions enable health surveillance of the elderly, chronically ill patients and pregnant women at their place of residence [14,16]. It is well known that telemedicine care systems become particularly effective if they promote health-oriented behavior and healthy lifestyles, allowing patients to continue to function in their existing environment [14,24,27]. Such systems include:

A. The Revitus Home Rehabilitation System

The system uses Adaptive Network Topology (WPAN — Wireless Personal Area Network) for communication of modules located on the patient, the WPAN Bluetooth network for communication inside the house, the GSM network (WWAN — Wireless Wide Area Network) and the Internet (WAN — Wide Area Network) for communication with the monitoring and surveillance center. The Revitus system is equipped with an effort controller and a communicator and monitoring module (**Błąd! Nie można odnaleźć źródła odwołania.**). The monitor module is used to monitor electrical heart activity, respiratory function, body water accumulation, blood pressure, body weight and motor activity. The results of the measurements are available only to authorized medical personnel in the monitoring center. The system configuration is presented in Fig. 4.

Communicator module Monitoring module

Fig. 3. Revitus system components.

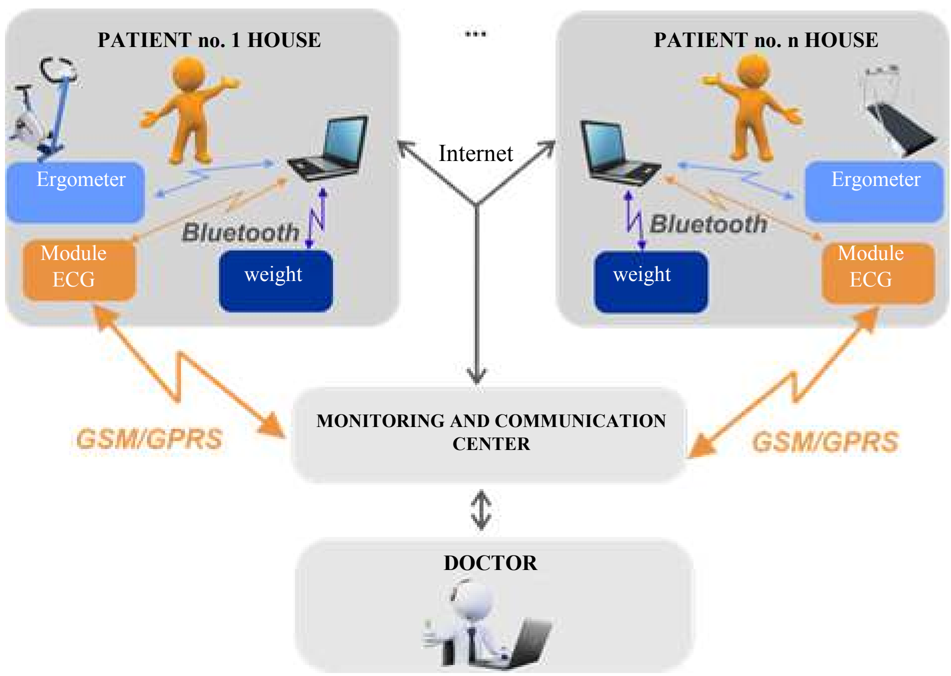
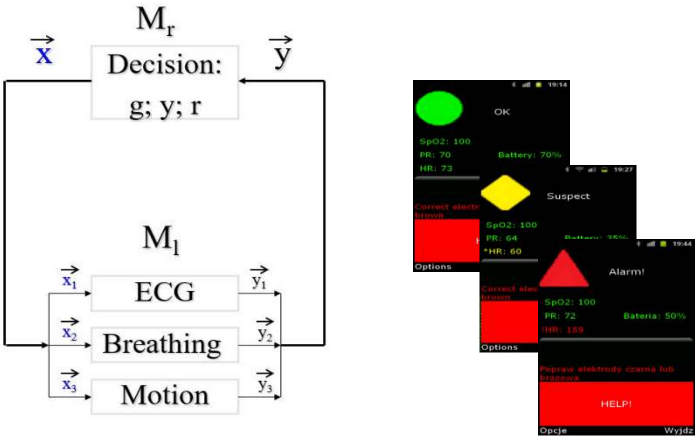


Fig. 4. Configuration of the REVITUS home telemedicine system.

B. EDFAS — Telemedical surveillance of the elderly and disabled

EDFAS was developed as part of the EUREKA initiative. It enables remote surveillance of elderly and disabled people at their homes (**Błąd! Nie można odnaleźć źródła odwołania.**). The monitoring module included in the system enables non-invasive acquisition of two differential ECG leads including a chest impedance signal, a photopletismogram and acceleration signals to which the patient is subjected in three orthogonal axes. The system allows to indicate the position of the monitored patient's body — standing, lying or sitting. The system software allows to determine the patient's condition on the basis of decision parameters determined with the Moore and Mealy automata algorithm (F).



F

Fig. 5. Convolution of Moore and Mealy automata in a monitoring system.

Based on the obtained analysis results, the software operating in an online mode generates special notifications (green, yellow, or red) on the screen. If a situation potentially dangerous to the patient is detected, the software generates an audible signal (a beep) to warn the patient and sends the analysis results to a physician consultant. While operating in an offline mode, the physician has an overview of the recorded processes allowing for a detailed analysis of the recorded events.

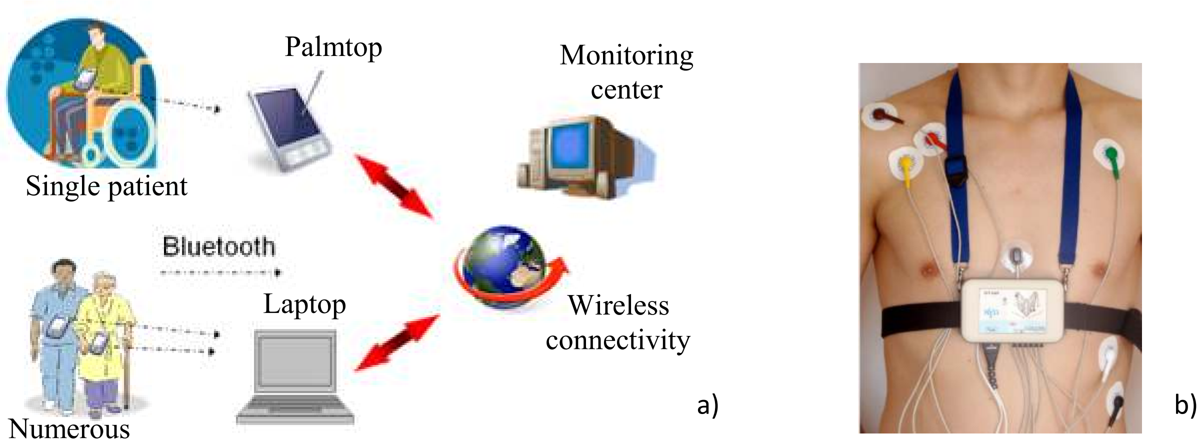


Fig. 6. a) EDFAS system, b) Monitoring module.

C. Telemedical surveillance system for pregnant women

The telemedical monitoring system for pregnant women allows for performing cardiotocographic monitoring of the patients' at their homes, with real-time monitoring carried out by a central station located in the hospital (Fig. *7*). The conventional monitoring of the fetus is carried out by means of monitoring devices called cardiotocographs [14,16]. In the system, the basic method of assessing the condition of the fetus during pregnancy is recording and analysis of the mother's and the fetus's biophysical signals, such as:

1) Fetal heart rate (FHR)
2) Uterine contractions (UC):
   - automatically detected fetal movements, i.e. fetal movement profile (FMP),
   - the movements of the fetus as reported by the mother.

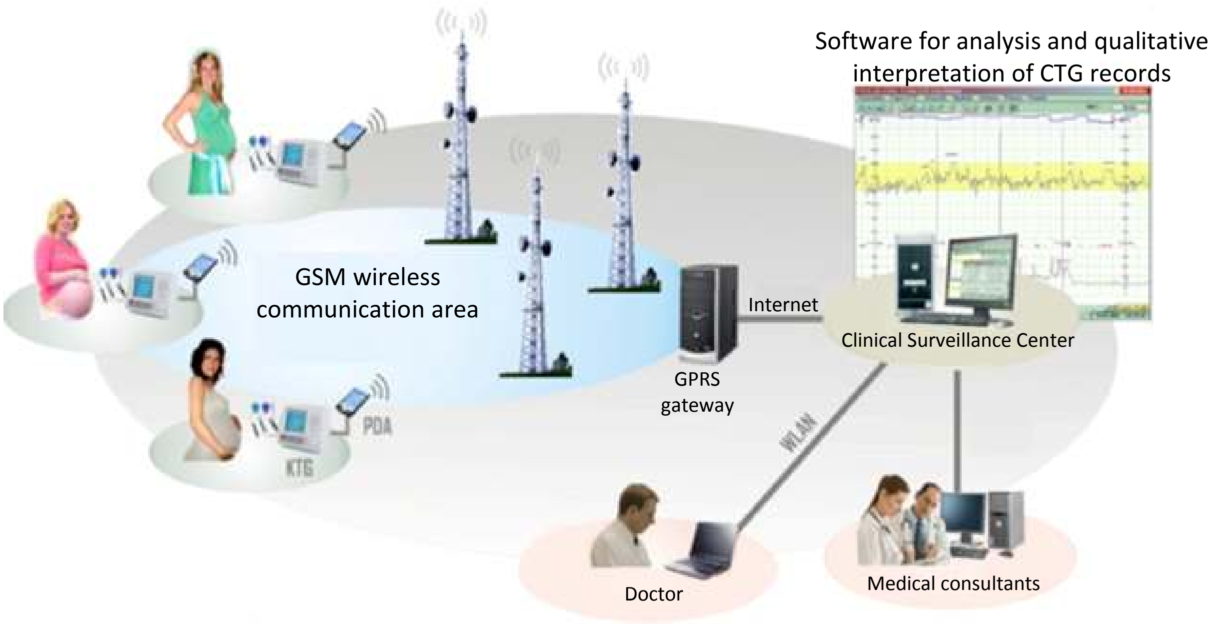


Fig. 7. Telemedical surveillance system for pregnant women.

MONITORING PEOPLE IN VARIOUS ENVIRONMENTAL CONDITIONS

ICT systems for interactive assessment and shaping of a person's physical activity in their environment will make it possible to take into account individual psychophysiological characteristics and environmental conditions during rehabilitation, training or professional activities. An example of such a solution can be the system for monitoring psychophysiological parameters of people during the performance of their professional activities SMP-300.

A. SMP-300S — System for monitoring psychophysiological parameters of persons during their professional activities

The SMP-300 system is designed to register psychophysiological and environmental signals under flight conditions and is primarily used to examine pilots (**Błąd! Nie można odnaleźć źródła odwołania.**). However, its scope can be extended to other professional groups, such as: drivers, machinery operators, miners or athletes.

The system allows to monitor ECG signals, pulse and electromyographic signals, measure heart rate, respiratory rate, blood saturation, arterial blood pressure as well as skin acceleration and impedance. It also monitors environmental parameters, such as ambient temperature and humidity, atmospheric pressure, as well as flight parameters, such as speed, altitude, slope and course. The system allows to document the course of the examination in the form of reports and records in the database.

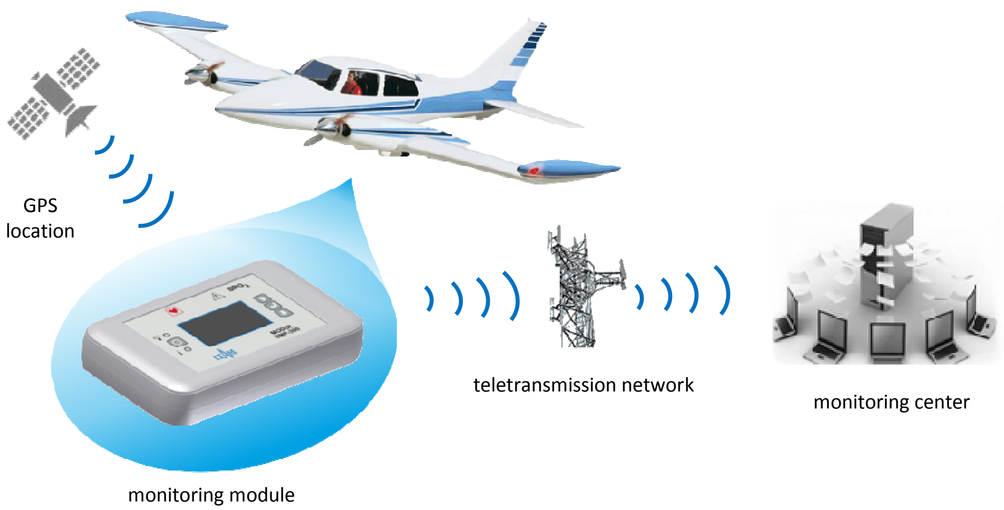


Fig. 8. SMP-300S — System for monitoring psychophysiological parameters of persons during their professional activities.

LONG-TERM MONITORING

The possibility of 24-hour monitoring and consultation allows for comprehensive patient care while reducing the cost of patient treatment. In order to be able to monitor the patient around the clock in a non-invasive manner and with the least possible inconvenience for the patient, it is necessary to develop the smallest possible portable, battery-powered measuring modules. The MONITEL-HF system offers such possibilities.

A. MONITEL-HF — Heart failure monitoring system

The Monitel-HF system was developed as part of a project financed by the STRATEGMED programme. Monitel-HF is a multi-module system consisting of an ECG and pulse wave signal recording unit (Monitel 1), a unit for recording body position, galvanic skin response and temperature (Monitel 2), a unit for recording chest and abdominal bioimpedance signals (Monitel 3), **Błąd! Nie można odnaleźć źródła odwołania.**. The system is used to acquire, visualize, process and save data obtained from measurement modules [21]. The monitored parameters are collected by a network of personal sensors located on the patient's body and transmitted wirelessly to the operator's station. The operator's station in the MONITEL-HF system is a desktop or laptop computer with an operating system running the Monitel-HF application.

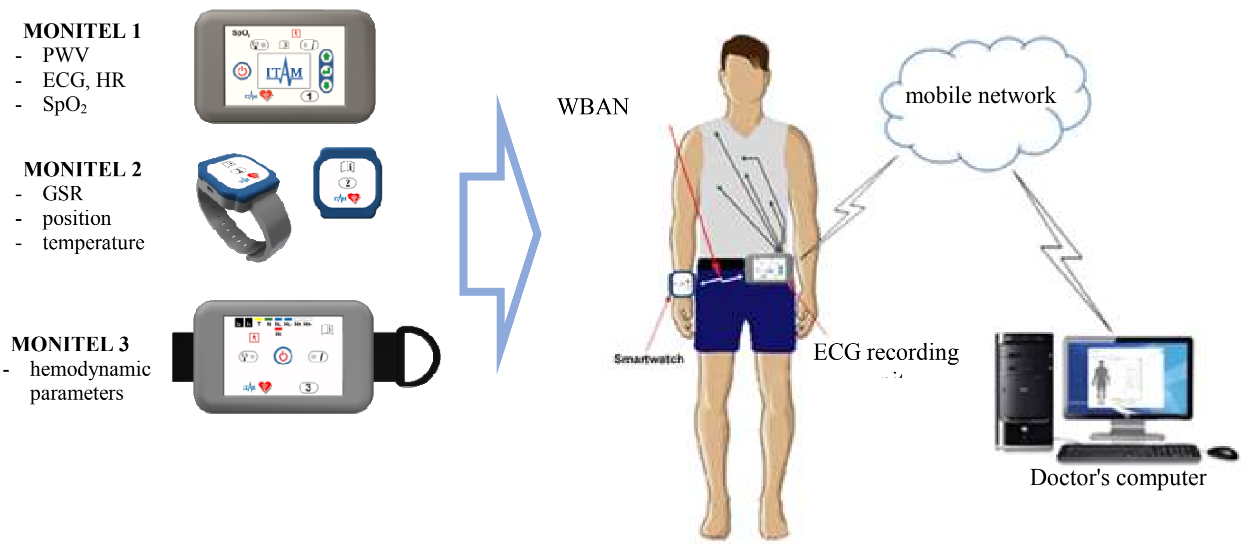


Fig. 9. MONITEL-HF — Heart failure monitoring system.

SUMMARY

The recent years have seen an extensive development of medical telemonitoring systems, which are used in practically all fields of medicine. As a result of the technological advancements, it is possible to implement innovative solutions which until recently seemed to be nothing more than a vision of a distant future. Progressive miniaturization of electronic circuits, development of telecommunication and Internet technologies, advanced mobile devices (smartphones, such as the iPhone), have contributed to the creation of a number of original designs, such as Revitus, EDFAS, SMP-300 or Monitel-HF, dedicated to specific applications.

For several years now, medical telemonitoring systems have become increasingly widespread to carry out monitoring and health surveillance of people of various age groups and suffering from a variety of medical conditions. Although this mainly concerns the elderly, there is also a growing interest in telemedicine surveillance among younger people, e.g. pregnant women, people working in extreme conditions, people engaged in extensive physical activity for recreational or sports purposes. An example of an offer for these groups are the systems developed in Łukasiewicz-ITAM, which have been additionally commercialized (SMP-300, Monitel-HF and a telemedicine system for the health surveillance of pregnant women).

However, it should be borne in mind that, despite the benefits of telemedicine, its widespread use still requires intensive patient education and a steady increase in the availability of information technologies allowing for remote health monitoring.

Medical telemonitoring systems require effective technologies for extracting biomedical information from the human body, in its natural living conditions, in particular those related to its motor activity. The motor activity of both a healthy person and a patient is the main source of bioelectrical signal interference, recorded by means of electrodes (biosensors) on the body surface. As we know, these signals are the basis for determining numerous biomedical parameters. Also, the biomedical parameters recorded or determined indirectly by transducers are very susceptible to disturbances resulting from the motor activity. Therefore, work is underway in a number of research centers to develop effective, non-intrusive technologies for the acquisition of signals and biomedical parameters [4,16,17,32] that are much less susceptible to disturbances caused by motor activity. A focused research direction is emerging to develop a biomedical information acquisition network fully integrated with clothing which can be worn with ease. These clothes take various forms, of e.g.: T-shirts, H-shirts, vests, belts, necklaces, bracelets, ear plugs.

A prospective solution for this purpose seems to be the development of a textual network of bioelectrical signals acquisition, adapted to the conditions of human motor activity, realized as a network of bioelectrical signal sensors (biosensors, dry electrodes) and biomedical parameters transducers, placed directly within the structure of the fabric, or built into the fabric of which the clothing is made. The network could be made in the form of a flexible T-shirt or H-shirt or vest. Biomedical parameter sensors and transducers (piezoelectric, resistive, inductive, capacitive, bioimpedance) would be connected by flexible signal paths or wirelessly with a miniature signal and biomedical parameter recording unit (concentrator-transmitter), also built into clothing.

The opportunity of providing continuous medical care without the need for physical presence of a doctor, makes telemedicine systems particularly useful in obstetrics. The IoT-type system of telemonitoring high-risk pregnancy provides the possibility of controlling the recording equipment located on the patient's side remotely and enables interactive communication with medical personnel. In this case, the development of an effective algorithm to control the monitoring session is an important research problem. Biomedical information acquisition technologies used in modern medical systems are still quite burdensome for the patient (e.g. ECG electrodes are difficult to put on, the electrodes cause skin irritation on contact points, skin-to-electrode contact is unstable), sometimes even invasive (e.g. blood sugar measurement by puncturing) and often require the help of another person in order to properly attach sensors and transducers to the patient's body.

The need to reduce the inconvenience of modern biomedical information acquisition technologies is a condition and at the same time a motivator for further development of medical telemonitoring systems. These technologies are based on the achievements of biomedical engineering, which have seen a particularly intensive development in recent years. This is an encouraging premise for the further development of medical telemonitoring and telemedicine in general.

AUTHORS' DECLARATION

Study Design: Ewelina Sobotnicka, Daniel Feige, Aleksander Sobotnicki, Adam Gacek, **Data Collection:** Ewelina Sobotnicka, Daniel Feige, Aleksander Sobotnicki, Adam Gacek, **Manuscript Preparation:** Ewelina Sobotnicka, Adam Gacek. The Authors declare that there is no conflict of interest.

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