Video-based Patient Monitoring System
Application of the System in Intensive Care Unit

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Abstract: The paper presents the video-based monitoring system to assess the physiological parameters and patient state in intensive care unit. It allows to measure thoracic and abdominal breathing movements, remote plethysmography signals, tissue perfusion, patient activity and changes in psycho-emotional state. Thus, the system provides a comprehensive assessment of patient state without contact. The system works in usual illumination conditions of intensive care unit and consists of a personal computer with specialized software and two low-cost Logitech C920 webcams with RGB sensors (8 bit per channel), 30 Hz sampling frequency and 640x480 pixel resolution. The webcams were placed at a distance of 80 cm above the patient's body. The software provides automatic assessment of psychophysiological parameters and determination the following patterns: heart rate, heart rate variability, asystole and arrhythmias, breathing rate, spontaneous breathing recovery, breathing muscle tone and patient consciousness recovery, motor activity and control of ventilation parameters. The proposed system can be used as an additional diagnostic tool of anesthesia equipment for non-invasive patient monitoring in intensive care unit.

1 INTRODUCTION

Modern clinical monitoring devices presuppose the presence of a large number specialized contact sensors placed on patient body for continuous evaluation of vital physiological parameters. The minimal set of intensive care unit equipment consist of pulse oximeter, multichannel electrocardiograph, impedance pneumograph, temperature sensor, and tonometer. An additional equipment depends on specific diseases of the patient.

Contact-based equipment connection requires approximately 5 minutes by a pre-trained medical staff. It is more difficult to maintain constant contact with equipment in stressful situations, for example, when the patient wakes up and trying to move hands or change position of the body. In that case, the quality of patient monitoring procedure largely depends on intensity care unit staff discipline, because it is necessary to provide constant visual control of patient condition by a nurse or in specific situations by a doctor.

At present time, video-based remote measurement technologies are continuously investigating. The recent technologies remote and imaging photoplethysmography (Wang et al., 2017), optoelectronic plethysmography (Aliverti et al., 2000) allow to measure skin blood volume changes and chest wall respiratory movements, respectively.

In this work the non-invasive video-based patient monitoring system for intensive care unit was proposed. It does not require any contacts with patient body and potentially allows to reduce presence time of qualified medical personnel near to patient bed. The proposed system contains modules which measure the physiological parameters and changes in patient psycho-emotional state. Thus, it allows to monitor functional state for patients with limitation of use conventional contact devices.

In general, the proposed video monitoring system can be used as an additional device of non-invasive patient monitoring systems to obtain complex psychophysiological information in conjunction with anesthesia equipment.

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2 MATERIALS AND METHODS

The proposed system, consists of only inexpensive and accessible components which are selected as a most suitable for common conditions of intensive care unit. In particular, the most important criteria for webcams were possibility of a reliable determination remote plethysmography signals with minimal intrinsic noise and ability to turn off automatic image correction settings. The system software was developed on the basis of real-time algorithms to provide working abilities on an ordinary personal computer.

2.1 System Architecture

Since all components of the system are affordable and widespread, the greatest difficulty in creating such system are analysis and development of video processing technologies, designing system architecture for physician needs with taking into account performance requirements.

The software architecture of the proposed video monitoring system is shown in Figure 1. Architecture structure can be conditionally represented as a set of consecutive stages and processing modules. The stages are conventionally determine logical separation of video processing and data analysis procedures to consecutive set of operations. Each psychophysiological measurement technology was separated as a software module.

Stages of the proposed system:

1) Video capture. This is the first stage, where the set of frames from two or more video cameras is recorded and transmitted for further calculations;
2) Video processing. This is the most computationally intensive stage where received videos are processed as a sequence of frames to measure the significant physiological signals, psycho-emotional features and attributes. All these data are transmitted for further analysis in the next stages;
3) Buffering. The buffering stage allows to analyze the received data in the frequency and time domains in the subsequent stages, and estimate intensity of occurring changes, depending on individual buffer sizes for each module;
4) Signals processing and features extraction. At this stage, analysis of received data buffers is performed to determine the quality of measured signals and calculate significant physiological parameters and patterns, such as respiratory rate and heart rate.
5) Patient state prediction. A comprehensive analysis of measured physiological parameters is an important part of modern patient monitoring systems. These part is responsible for detecting and informing medical staff about existing problems and emergency situations.
6) The display of patient state and physiological parameters assessment. This is the final stage where the physiological parameters and signals of patient state were presented on display with audio notification in emergency situations. At this stage the software should allow to customize interfaces and predefined conditions to provide the features and signals which are necessary for a doctor.

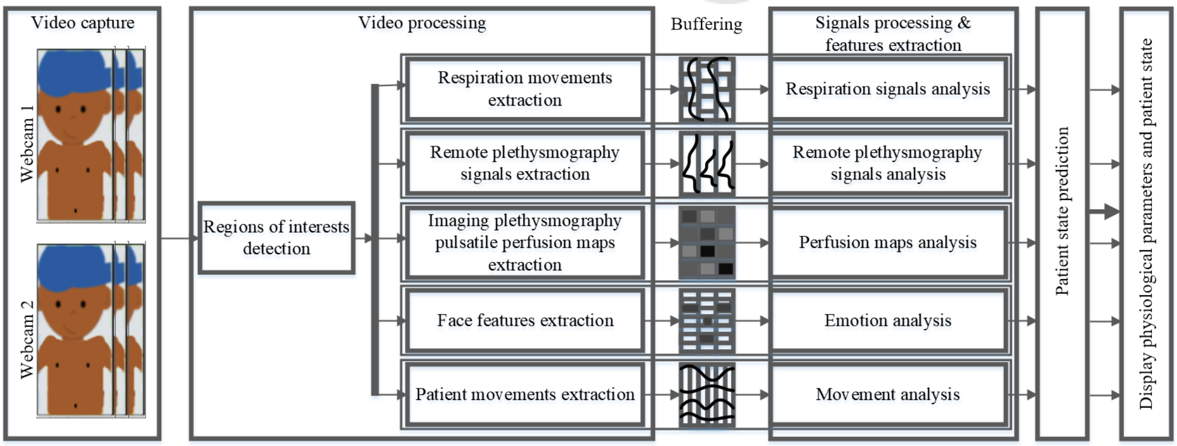


Figure 1: Block diagram of system architecture.

Determination of physiological parameters according to above mentioned stages was carried out by following modules:

- Regions of interest detection. This module is designed to automatically determine locations of various parts of the patient's body on the image. The choice of parts (regions of interest) can be determined or adjusted by a doctor depending on individual patient characteristics or diseases and the structure of the patient's body. In general, the module allows to detect:
  - the face region, landmarks, structure features and direction of sight (King, 2015);
  - right and left lung regions, with projections of each lung lobe onto the chest wall;
  - abdominal regions: epigastric, umbilical, hypogastric, bilateral-subcranial, flank and iliac regions;
  - regions marked by a doctor as a cross;
- Respiratory movements extraction and analysis. Using of respiratory movements evaluation technics can be considered as an optimal way to diagnose respiratory parameters (Aliverti et al., 2000). This module assesses respiratory movements and their characteristics in various regions of interest in different directions. The dynamic changes of respiratory movements are measured (Brochard et al., 2012; Hess et al., 2015);
- Imaging plethysmography analysis. Imaging plethysmography technology was firstly proposed by Vladimir Blazek group (Blazek et al., 1996) .That allows to measure and create a maps of skin perfusion. At the moment, significant achievements in this direction are made at the works (Kamshilin et al., 2015; Moco et al., 2016). The recent work (Rubins et al., 2017) proposed that perfusion maps can be used to analyze the depth of anesthesia;
- Remote plethysmography signals extraction and analysis. Remote photoplethysmography (rPPG) technology is different than imaging photoplethysmography. The goal of that technology is to obtain the best pulsation signal, assuming that in selected region the skin perfusion changes occur almost simultaneously. The main achievements in this technology are presented in following works: (de Haan and Jeanne, 2013a; Lewandowska et al., 2011; Poh et al., 2010; Sun et al., 2013; Verkruysse et al., 2008; Wang et al., 2017).

Thus, above mentioned modules provide control over main physiological parameters and patterns recorded by using the anesthesia equipment and bedside monitoring systems.

It is well known that, medical personnel should carry out continuous visual observation of changes in psycho-emotional state, check movement's activity and position of the body to ensure the safety of patients in the intensive care unit and conduct timely adequate medical and diagnostic procedures. Modern video processing technologies allow to register and analyze these parameters which are inaccessible to contact methods. In the proposed system for solving similar problems, the following modules are used:

- Patient face feature extraction and psycho-emotional state analysis. Modern video processing technics allows to assess person psycho-emotional state by measurements of facial expression changes according to existing emotion models (Sun et al., 2004). For example, the sudden pain state can be observed as a fast dynamic expression changes with high rate of motor activity. Grimaces and facial distortions can be a consequence of an insufficient level of sedation. A fast and periodic jaw movements can indicate an unintended hypothermia, which requires additional medical staff activity;
- Patient movements extraction and analysis. This module produces a qualitative and quantitative assessment of patient movement's activity by real-time tracking body and head position. The unnatural position of the body may indicate the presence of internal or external irritating factors. Excessive motor activity during the recovery of consciousness is also an important factor, which required constant monitoring, especially with artificial ventilation. Thus, patient position on the bed, motor activity and stress level on previous module may help to predict the awake moment.

The combination of these modules and steps allows to create a new system that provides registration of many conventional physiological parameters. At the same time, it offers additional possibilities due to evaluation of skin perfusion, analysis of psycho-emotional state and movements of the patient. In the future, such structure provides easy integration of new technologies for estimating physiological parameters. They can be added in form of additional separated modules.

2.2 Experiment

The system was tested on the video data which were recorded at the Department of Anesthesiology and Resuscitation of Regional Anti-Tuberculosis Dispensary (Yekaterinburg, Russia). The study involved 17 patients (male and female) aged from 24 to 76 years with surgical lung diseases. Each patient provided written informed voluntary consent prior to study procedures. Immediately before the study each patient underwent surgery operation on the thoracic cavity. The example of scheme and study conditions were presented in Figure 2.

After the operation in nearest postoperative period, patients enter the intensive care unit where they have regained consciousness from 30 minutes up to 2 hours on artificial ventilation until full recovery of muscle tone, consciousness and adequate spontaneous breathing is made.

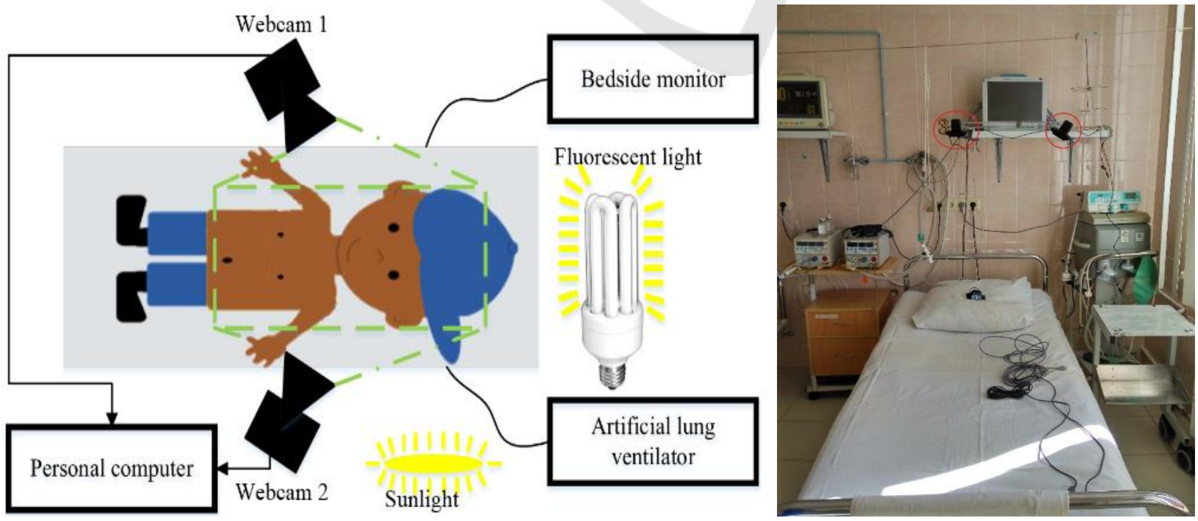
The artificial ventilation was provided by using two different types of ventilation devices. The choice of the device was made by the doctor, depending on patient diseases. 16 patients were ventilated by using the high frequency jet-ventilator (HFJV) ZisLine JV100A (Triton Electronics Systems Ltd., Russia, registration №2010/08739). 1 patient was ventilated by using mechanical ventilator ZisLine MB200 (Triton Electronics Systems Ltd., Russia, EC registration №D1237200008).

To measure reference physiological signals, the contact bedside monitor MP 6-03 (Triton Electronics Systems Ltd., Russia, registration №2007/00597) was used. It allows to independently and simultaneously measure the electrocardiography (ECG), photoplethysmography (PPG), impedance pneumography, blood pressure signals and obtain more complex and informative parameters, such as blood oxygen saturation, magnitude of cardiac output, peripheral vascular resistance, respiratory rate, heart rate and some other values.

The illumination in intensive care unit was made by fluorescent lamp sources which selected and placed in accordance with requirements of Russian standard for medical equipment SanPiN 2.1.3.2630-10 dated May 18, 2010. The part of illumination was provided by sunlight entering through the window as shown in Figure 2b).

The experiments were recorded in lossless LAGS format with 1-minute-long sequences of AVI containers by using two low-cost Logitech C920 webcams located above the patient's body at a distance of 80 cm. Each camera was installed to capture frames which contain patient face and body (down to the waist), as shown in Figure 2a). Each frame was captured with 640x480 pixels resolution in RGB format (8 bit per channel) and 30 Hz sampling frequency. The full database size is 1.5 TB of video and 100 MB of source signals.

Video processing and analysis were carried out by using a personal computer and specialized software, created in accordance with the previously mentioned architecture. The software was written in C++ with the use of open-source libraries and frameworks OpenCV, FFmpeg and others. It is allow to measure all above mentioned parameters and signals in real-time with using less than 500 Mb RAM memory per camera.



a) b)

Figure 2: Experiment: a) experiment scheme, b) photo of experimental conditions (webcams are marked as red circles, HFJV was placed on the left side, mechanical ventilator was placed on the right side, bedside monitor stayed on the rack).

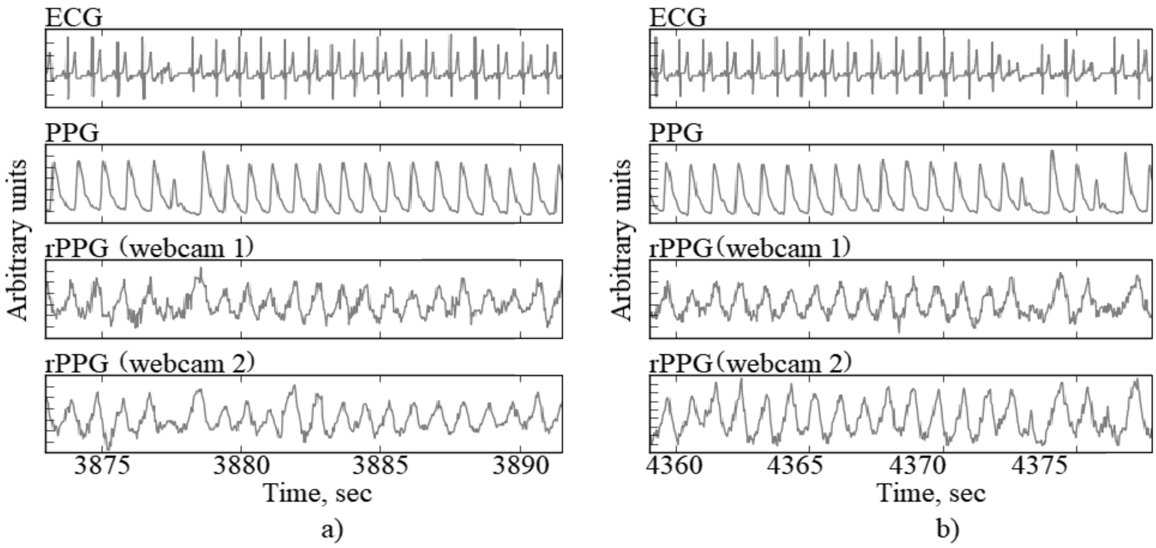


Figure 3: The synchronized ECG, PPG and rPPG signals with examples of a) asystole and b) arrhythmia diseases.

3 RESULTS

The immediate postoperative period is having one of the most stressful conditions for many patients. For example, the heart rate and heart rate variability, respiration rate are significantly greater than in normal patient state. Moreover, during stress more heart and other diseases are occurring. Therefore, the measuring techniques must be sensitive and operate in difficult conditions.

In our previous works (Kublanov and Purtov, 2015), as well as the work of other researchers (de Haan and Jeanne, 2013b; Wang et al., 2017), the possibility of recording the heart rate from rPPG data was shown with an accuracy of about 2 beats per minute compared to data recorded by the ECG and PPG signals. It should be noted that there are a delay and differences between heart beats measured by those signals, because of the fact that they are formed by various technics in different areas of the patient's body.

Figure 3 present the examples of heart failures such as asystole and arrhythmia on the simultaneously recorded ECG, PPG signals and rPPG signals obtained independently by two web-cameras from patient 5. There are the first examples of cardiac disorders by using the rPPG technology. It can be noted that rPPG and PPG signals have a different wave shape, but at the moments of asystole or arrhythmia both of them have a cardiac pulse with a much smaller amplitude than in normal condition.

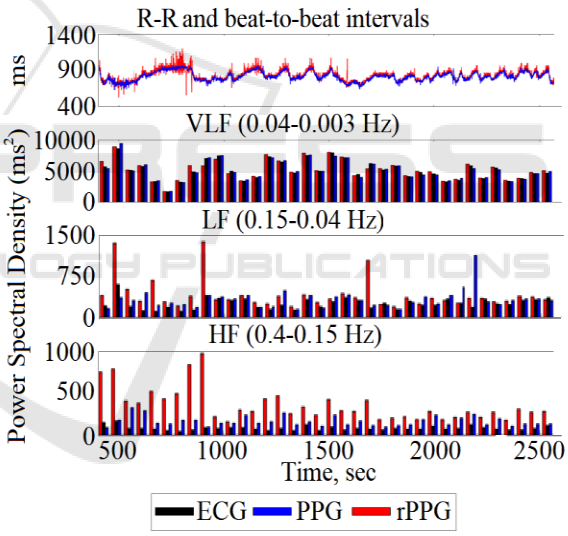


Figure 4: The example of power spectral density values of ECG, PPG and rPPG signals during the HFJV.

Earlier, at work (Kublanov et al., 2017) we showed the possibility of determining the parameters of heart rate variability under normal patient conditions. Figure 4 shows examples of power spectral density for high frequency (HF), low frequency(LF), and very low frequency (VLF) bands of heart rate variability signals measured by rPPG, ECG, and PPG techniques for patient 1 who underwent the surgical operation less than 10 minutes ago. It can be noted that, as in our earlier work, the power spectral density values obtained in the VLF and LF bands are similar between ECG, PPG and rPPG. At the same time, in the HF band, the assessments of all of them has a different quantitative and qualitative values.

rPPG signal in period started from 0 second up to 1000 second contained the noise caused by medical procedures, which have an influence on the intensity of patient's face illumination. That is the reason of significant variations of power spectral density in HF and LF frequency bands. However, they slightly affected on the values of power spectral density in the VLF frequency band.

Our recent abstracts (Kontorovich et al., 2017a, 2017b) firstly presented the results of estimating the artificial ventilation frequency with an accuracy less than 1 breath cycle per minute. It is shown that video monitoring of patient chest wall and abdomen movements allows to determine spontaneous breathing during artificial ventilation, as well as evaluating of muscle tone recovery and adequacy of spontaneous breathing.

The Figure 5 presents the signals of chest wall and abdomen movements at the moment of spontaneous breathing restoration. To determine the best area for breathing recovery evaluation the left and right lung regions, left and right lumbar regions and navel region were selected. Presented movements were measured in a line from the head (positive direction) to the navel (negative direction).

It can be noted that in the first period of breathing recovery the thoracic respiratory movements are much weaker than diaphragmatic movements, especially in comparison with the navel region. The navel region is optimal for determining first breathing recovery attempts, even in comparison with other abdominal regions. In our study this is true for all subjects, regardless of height, weight and lung diseases.

It can be seen from the presented graphs, that during spontaneous breathing the abdomen regions are moving down while the chest wall is moving up. These movements directions correspond to muscle physiological activity and can be used as an additional information to separate the spontaneous breathing from other movements.

The example of patient wakening assessment is shown in Figure 6. The figure contains the time interval with expert and predicted values of patient state. The black line shows the values obtained by the expert. The red line shows the automatically predicted values by our pre-trained model which use the face changes and patient movements as a features.

The markup consists of three possible states: the upper state - in which the patient is awake, the medium state - at which the patient lies quietly with closed eyes and it looks like patient is sleeping, the lower state - when the patient's face is hidden or the system cannot find it.

The vertical bold black line on the Figure 6 shows the extubation moment, when in general the patient feels discomfort caused by tracheostomy tube. That discomfort does not allow him to sleep, and it can be clearly seen on the graphs. The process starts from about 2400 seconds, when the patient wakes up several times and falls asleep. Closer to 2700 seconds the patient attracts the attention of medical nurse, who determined the adequacy of spontaneous breathing recovery, and produced the extubation.

The resulting implementation is based on use of following features: distances between the eyelids and lips, the position of the head, head movements and some other characteristics and their derivatives with using 1-second-long buffers of features.

To ensure high-speed performance and high accuracy, we used an algorithm based on decision trees with a preliminary feature selection and dimension reduction. In this case, the prediction time of patient awakening state takes less than 1 ms.

A more detailed description of the results, algorithms and modules implementation of the proposed system will be presented in our further works.

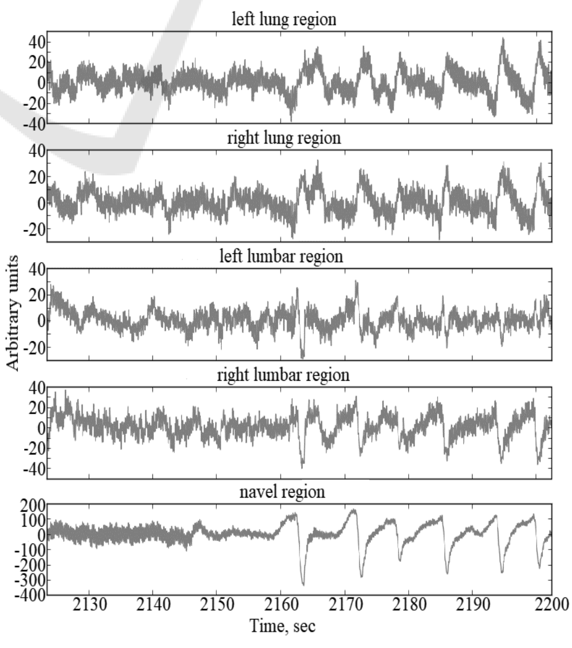


Figure 5: The beginning moment of patient spontaneous breathing recovery during the HFJV.

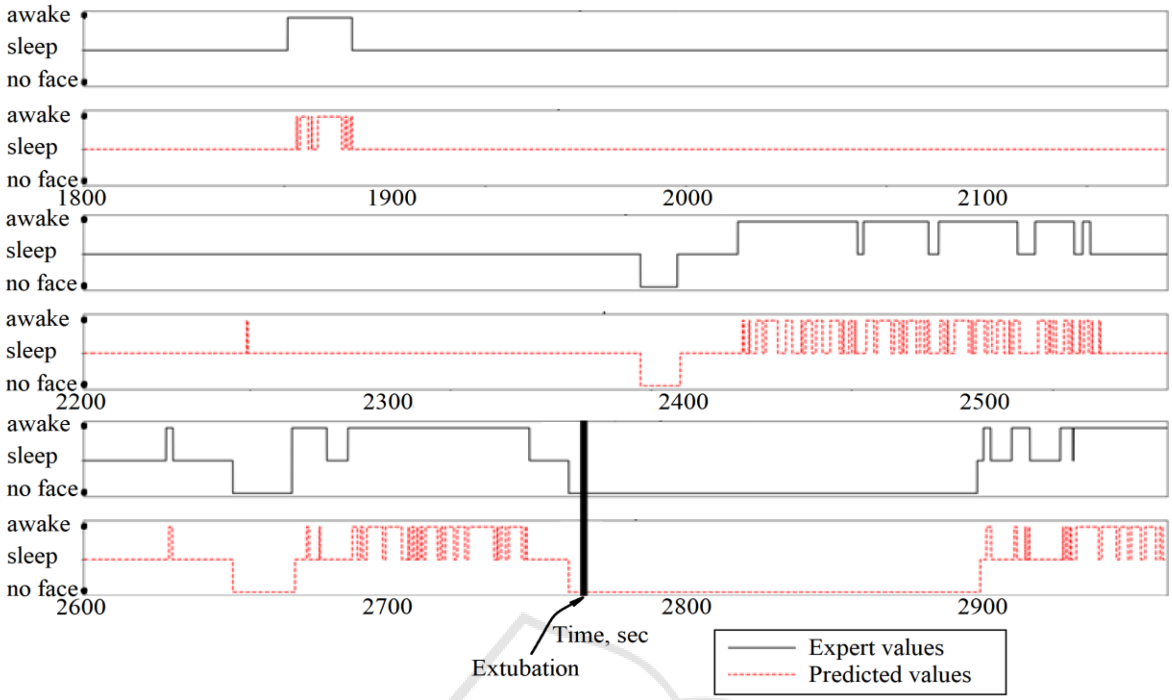


Figure 6: The examples of prediction patient activity by using the expert (black line) and automatic (red line) systems.

4 DISCUSSION AND CONCLUSIONS

The proposed system is inexpensive, compact, multifunctional, energy efficient and mobile. It allows to determine the common physiological parameters of the patient, and extend it by using modern video-processing technics. The psycho-emotional state and physical activity of the patient can be evaluated by the system. Due to this, it is possible to introduce it in intensive care unit equipment not only in large medical centers, but also in regional offices.

The article firstly showed the possibility of determining asystole and arrhythmia diseases by using rPPG technology. It is shown that the most significant area for determining the spontaneous breathing recovery moment is the area near to the navel. The first prediction results of the patients awakening from the state of anesthesia are shown.

The most promising direction for the system is integration it into existing medical equipment, such as a bedside monitor or artificial ventilator.

Data storage integration will allow to perform further expert analysis and integrate it in the digital healthcare and telemedicine systems, regardless of the patient's location.

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