HealthSupervisor: Mobile Application for Round-the-Clock Remote Monitoring of the Human Functional State

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Abstract

In this article, an application for smartphones that allows supervisors to observe constantly the functional state of their clients is proposed. The application is based on wireless devices and is designed to monitor the human functional state round-the-clock regardless of their location. The human functional state is estimated on the analysis of the following parameters: the oxygen level in the blood, pulse frequency and respiratory rate, continuously and remotely. These data from the pulse oximeter wirelessly connected to the client's smartphone will be sent to the server, where the supervisor will receive information about the client functional state and can decide on further activity. Importantly, in this way it will be possible to track the functional state in clients that need constant observation, at first with Covid-19 and with other diseases such as asthma, vascular diseases, and cancer. An article provides detail description of the proposed round-the-clock remote monitoring method, depicts the elements of the monitoring system and organization of the data transmission network, presents the structure of the round-the-clock remote monitoring system and the organization of remote monitoring by supervisors of client's functional state using the HealthSupervisor mobile application. The algorithms of data processing in HealthSupervisor mobile application are described and the main features and benefits of using the HealthSupervisor mobile application are presented.

Keywords

Mobile application, remote monitoring, human functional state, blood oxygen saturation, heart rate, respiratory rate.

1. Introduction

The mobile application is installed on the client smartphone and on the smartphone of its supervisor and allows round-the-clock remote monitoring of the client functional state by the supervisor. It is also possible to monitor your functional state on your own.

The mobile application allows supervisor to constantly observe the oxygen level in the blood of its client, its pulse frequency and respiratory rate, and to recognize of acute deterioration of its functional state. Supervisor will be informed about clients who need immediate inspection by message and see the prioritized clients list with people who need inspection at the top of this list.

For example, given a large number of clients and significant occupancy of hospitals, lack of medical staff, high infection probability in direct contact with clients (the share of physicians among all clients with COVID-19 is very high), the difficulty for medical staff to be constantly wearing protective clothing, etc., there is no doubt that there exists an urgency of creating tools for round-the-clock remote monitoring of the functional state of clients with COVID-19. Thus, the proposed

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HealthSupervisor system can be used in clinical practice and epidemiological studies of clients with COVID-19.

It can also help to track the progression of lung diseases (pneumonia, tuberculosis, asthma, lung cancer, etc.) and the effects of treatment.

It can also be used to monitor the functional state of the elderly people, athletes, children, etc.

This paper is organized as follows: Section 2 presents most recent reviews on remote monitoring of the human functional state methods and different technologies. Section 3 provides detail description of the proposed round-the-clock remote monitoring method. Section 4 depicts the elements of the monitoring system and organization of the data transmission network. The structure of the round-the-clock remote monitoring system is presented here. Section 5 presents the results of the pulse oximeters selection. Section 6 presents the organization of remote monitoring by supervisors of client's functional state using the HealthSupervisor mobile application. Section 7 shows the data processing organization in HealthSupervisor mobile application. Section 8 gives main features and benefits of using the HealthSupervisor mobile application. Section 9 considers the compliance of the data received from the wireless devices and the data displayed to the user of the HealthSupervisor application. Section 10 describes the future works. Section 11 concludes the paper.

2. State-of-the-art

Remote monitoring of the human functional state by the means of digital technologies is an emerging research field. Digital technologies allow to monitor and capture medical and other health data from humans and electronically transmit these data to healthcare providers for assessment and, when necessary, recommendations and instructions. Using these technologies also encourages humans to take more control of their health [1], [2], [3].

Today, the most pressing problem is the fight against coronavirus. Therefore, in the material of the article, considering the organization of remote monitoring of the human functional state, we will focus mainly on this and related diseases. Assessment of the lung condition of a client with respiratory disease usually involves measuring blood oxygen saturation (SpO2), because hypoxia in certain clinical scenarios indicates the presence of pneumonia. Blood oxygen control allows assessing the severity of the disease in clients with COVID-19 and the dynamics of its development. It is known that the SpO2 level is much lower in clients, who are in a severe stage of the disease. At SpO2 $<90\%$ clients with COVID-19 have higher values of pneumonia markers and, accordingly, a higher risk of dying from coronavirus infection [4], [5]. Calibrated oximeters are used in clinics to measure blood oxygen saturation.

However, due to the peculiarities of respiratory coronavirus infection (SARS-CoV-2), these stationary oximeters alone are not sufficient for the treatment of clients with COVID-19. Firstly, there is a high risk for supervisors to be infected by clients with this disease in the hospital. This statement is confirmed by a significant proportion of medical staff among clients with COVID-19 [6]. Secondly, the large occupancy and often overcrowding of hospitals with clients with COVID-19, leads to the impossibility of continuous monitoring of clients by supervisors, the number of which is often insufficient. Moreover, in the case of treatment of clients, who are in a serious or critical condition, it is important to monitor them continuously so as not to miss the possible rapid deterioration of clients, which for the above reasons is often not possible to achieve. After all, there are known facts when due to the impossibility of providing simultaneous care to many clients with a limited number of staff, some clients died [7].

The peculiarity of respiratory infection of coronavirus 2 (SARS-CoV-2) is also that in many clients the disease is asymptomatic or mild, which allows monitoring of clients and, if necessary, their treatment at home [8]. But, as practice shows, there remains a risk of the rapid deterioration of clients' state, which requires its continuous monitoring. The same applies to clients with COVID-19, discharged from the hospital.

It should be noted, that today clients have the opportunity to buy pulse oximeters based on a smartphone in the form of bracelets, finger ring devices, earbuds, etc. in a store [9]. These devices can be especially useful for clients with COVID-19, as they allow them to monitor their condition themselves. And many of the clients actually use them. What is more, this applies not only to the sick but also to healthy people, who are at risk of infection, especially the elderly or clients with severe chronic diseases, which are known to badly tolerate the disease. To date, there is no data on the effectiveness of the use of these devices in the fight against coronavirus. It is clear that not all clients are able to constantly monitor themselves using these devices, analyze the results of current and previous measurements, and decide on the need for treatment. This situation is largely similar to self-medication and can be detrimental to the client, as clients may be late to recognize the need to see a supervisor, which can greatly complicate the recovery process.

In [8], the organization of remote monitoring of blood oxygen saturation of a group of 193 clients with COVID-19 was described. After the discharge, these clients were given the NoninConnectTM 3230 Bluetooth® (Nonin Medical Inc. MN, USA). Pulse oximeters were linked with a smartphone application, specifically designed to monitor oxygen saturation and asphyxia, observed in people with COVID-19 (clientMpower Ltd, Dublin, Ireland). All data was encrypted and sent to a secure cloud database, which was accessible only to members of the COVID monitoring team. The smartphone application sent an automatic request to check oxygen saturation at rest and after stress four times a day for 14 days after discharge from the hospital, and clients could enter additional data / measurements as desired. Pop-up tips also asked if the client felt short of breath. If the client chose "yes", they were asked to use a visual analog scale to measure it. If the oxygen saturation measurements were 94% or less, a warning was issued, as a result of which an SMS message was sent to a monitoring team consisting of respiratory physicians and nurses. After the notification, the team contacted the person, and if there was persistent hypoxia, worsening of symptoms, or any other cause for concern, they were instructed to go to the hospital to assess the need for hospitalization. The developers of these devices have clearly confirmed that their use has increased the availability of hospital beds without harm to clients, provided early detection of acute deterioration of recently discharged clients, and provided the opportunity for reassessment and readmission if necessary.

As can be seen, in the example above the mobile application conducts surveys of clients who are involved in the monitoring process and have to send the required data to the cloud database, where this data is processed by members of the COVID monitoring team.

3. Round-the-clock remote monitoring method

We have developed tools [10] that allow supervisors to simultaneously remotely monitor the functional state of many clients in hospital wards (those under observation and those in critical condition) without direct contact with them, and to integrate intelligent functionality to warn supervisors of dangerously low oxygenation levels, as well as those being treated at home (Fig.1). The supervisor can establish indicator limits for each client personally and will be informed when those limits would be crossed. This allows the supervisor to set limits accordingly to the client's state, features etc.

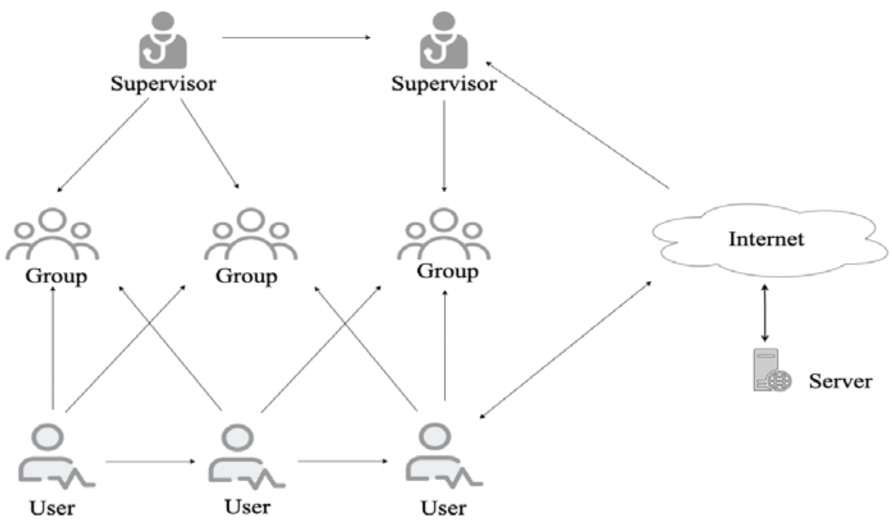

Figure 1: Round-the-clock monitoring of clients' condition by a supervisor

Clients are equipped with personal pulse oximeters connected to their smartphones. The data received from clients' smartphones are automatically transferred via the Internet to the server, on which the Server software is installed. On the server side data is processed and stored. Supervisors have access to client data on the Server from mobile applications on their smartphones which is represented as different graphs and tables. Each supervisor has the possibility to create their own groups of clients, which allows them to differentiate clients with group name.

The same tools provide clients the ability to independently monitor the oxygen level in the blood, pulse frequency and respiratory rate, allow them to obtain test results and recommendations for their improvement. For example, Figure 2 shows a personal application Huawei Health, associated with the bracelet Honor Band 5, which in addition to the rest displays oxygenation data (bottom left).

Figure 2: Example of a client's mobile application and display of oxygenation level

In addition to the numerical value, the color displays the client's condition: green - healthy, orange - dangerous, red - urgent hospitalization. On the right, the measurement data for the selected time period can be found.

Client supplements are not available to the supervisor. They are observed only by a client whose functional state is monitored.

4. Elements of the monitoring system and organization of the data transmission network

The monitoring system includes: a sensor network of wireless pulse oximeters and linked smartphones with the HealthSupervisor mobile application installed, which are used to interact with wireless pulse oximeters and to process the results of monitoring the condition of clients; Server software to collect real-time blood oxygen levels, pulse frequency and respiratory rate 24 hours a day from monitored and critically ill clients, ensuring the protection of personal data; HealthSupervisor mobile applications of supervisor to monitor functional state of clients and to warn supervisor of dangerously low oxygenation level.

The structure of the round-the-clock remote monitoring system is given in Fig.3.

Pulse oximeters of clients who are in clinics, hospitals, enterprises, as well as at home, form sensor field 1, which is connected to the Internet through a network of appropriate access points 2. Pulse oximeter data is asynchronously transmitted to the data processing center on the Server.

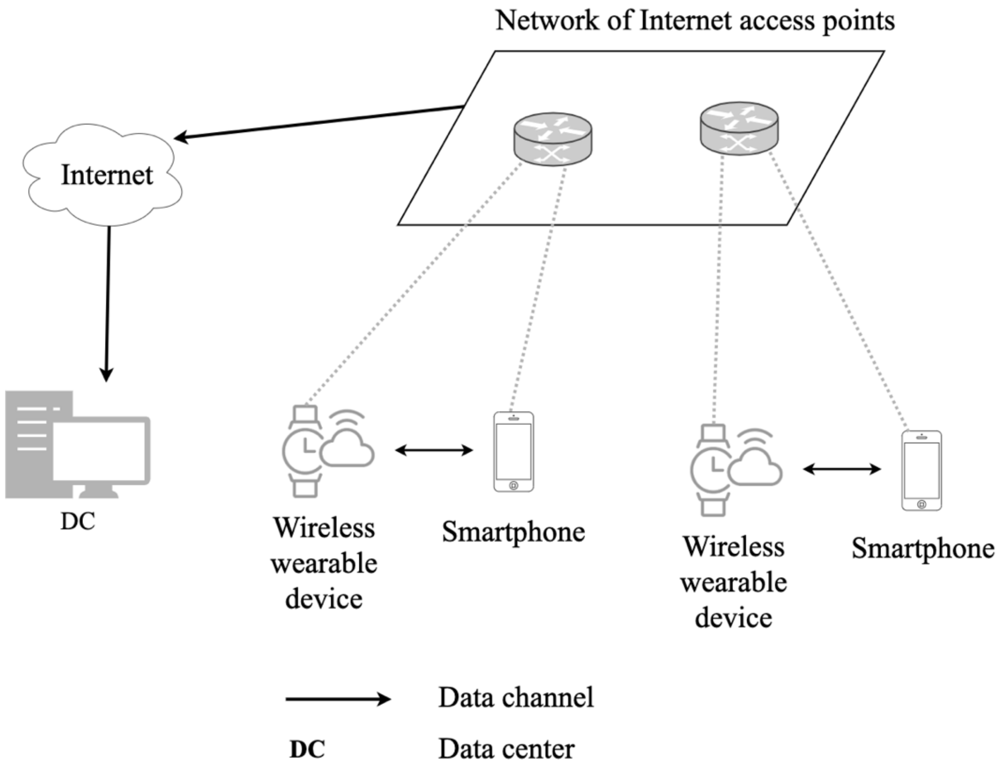

Figure 3: Structure of the round-the-clock remote monitoring system

5. Selection of pulse oximeters

Pulse oximeters, which are used in the systems for 24/7 monitoring of lung function, must be connected to a smartphone via the Bluetooth interface to transmit measurement data.

Mobile applications connected to heart rate monitors must integrate with GoogleFit on Android and Apple Health on iOS to combine data from different sensors.

Pulse oximeters must be portable and have a long battery life.

The accuracy of their blood oxygen saturation measurement should not be lower than in calibrated medical devices.

Pulse oximeters should measure blood oxygen saturation with SpO2 over certain time intervals without the human intervention.

Based on the above, we can form

Based on the conducted analysis of pulse oximeters available on the market, were selected devices that can be used in cyber-physical systems for 24/7 monitoring of lung functions, what means they are portable, have wireless communication function with a smartphone (via Bluetooth) and provide the ability to export saturation data blood oxygen SpO2 to GoogleFit on Android and Apple Health on iOS.

Data on their compliance with the above criteria are summarized in table 1.

Table 1
Characteristics of pulse oximeters

Name and description	Appearance	Price	Measurement accuracy	Periodic measurement	Battery life	Data export, Google or Apple	Dimensions, cm / Weight, g
Pulse oximeter BM1000A [10]. Pocket, for measurements on a finger.		4800	98%	Manual	Depends on batteries	+	70 g
Pulse oximeter "BIOMED" BP-10VB [11]. For measurements on the finger.		1185	98%	Manual	Depends on batteries	+	50 g
Beurer PO 60 Bluetooth® pulse oximeter [12]. For measurements on the finger.		~3000	98%	Manual	Depends on batteries	+	58.5 x 30 x 33, 49 g
Pulse oximeter Xiaomi iHealth Air Wireless Pulse Oximeter PO3 [13]. For measurements on the finger.		1 049	98%	Manual	Depends on batteries	+	62 x 33 x 28, 50 g
Huawei Band 4 Pro – fitness bracelet with pulse oximeter [14].		1 849	97%	Manual	1-10 days	+	45 x 19 x 1, 25 g
Honor Band 5 – fitness bracelet with pulse oximeter [15].		745 – 1 018	97%	Manual	1-14 days	+	43 × 17.2 × 11.5, 22,7 g

Table 2 (continue)
Characteristics of pulse oximeters

Name and description	Appearance	Price	Measure-ment accuracy	Periodic measure-ment	Battery life	Data export, Google or Apple	Dimen-sions, cm / Weight, g
Garmin Vivosmart 4 – fitness bracelet with pulse oximeter [16].		4 700	97%	Manual and sleep tracking	2-14 days	+	15 x 10.5 x 19.7, 17.1 g
Garmin Vivoactive 4 – smart watch with round-the-clock pulse oximeter [17].		9 276 – 11 030	97%	24/7 tracking	2-9 days	+	45.1 x 45.1 x 12.8, 50.5 g
Apple Watch Series 6 – smart-watch with manual SpO2 measurement and sleep tracking [18].		12600 – 16000	97%	Manual and sleep tracking	1 day	+	44 x 38 x 10.4, 36.5 g

From the point of view of ease of use, fitness bracelets are the best, because they do not interfere with daily human activities. In terms of frequency of measurements, the best are smart watches and pulse oximeter on finger – Beurer PO 60. In terms of autonomy, bracelets and watches are the best. In terms of measurement accuracy, all tested oximeters are approximately equal. Smartphones are the leaders in terms of compatibility with services.

Therefore, according to the set of criteria for 24/7 monitoring of lung functions cyber-physical systems, smartwatches are the best. They exceed other tested pulse oximeters in all criteria except for ease of use, where they are second only to fitness bracelets.

6. Organization of remote monitoring by supervisors of client functional state using the HealthSupervisor mobile application

The client receives or buys a mobile device with a pulse oximeter, which has a wireless connection, and installs on his smartphone an application for this mobile device that is compatible with GoogleFit on Android or Apple Health on iOS. The client then connects the bracelet and the mobile application using Bluetooth technology. After that, he installs the HealthSupervisor mobile application on his smartphone. In the mobile application on a device with a pulse oximeter, the client enables data exporting to the HealthSupervisor application. Afterward, the HealthSupervisor application must be registered on the Server through the settings of the application itself.

After registration, the HealthSupervisor mobile application starts transmitting client parameters to the server for storage and processing.

The HealthSupervisor application (Figure 4) registers with the Server and accesses client data. The supervisor remotely sees the running data and the history of the parameters of their clients, as well as messages about the critical condition of the client. The same information client can see on his application as well - which means he may supervise himself.

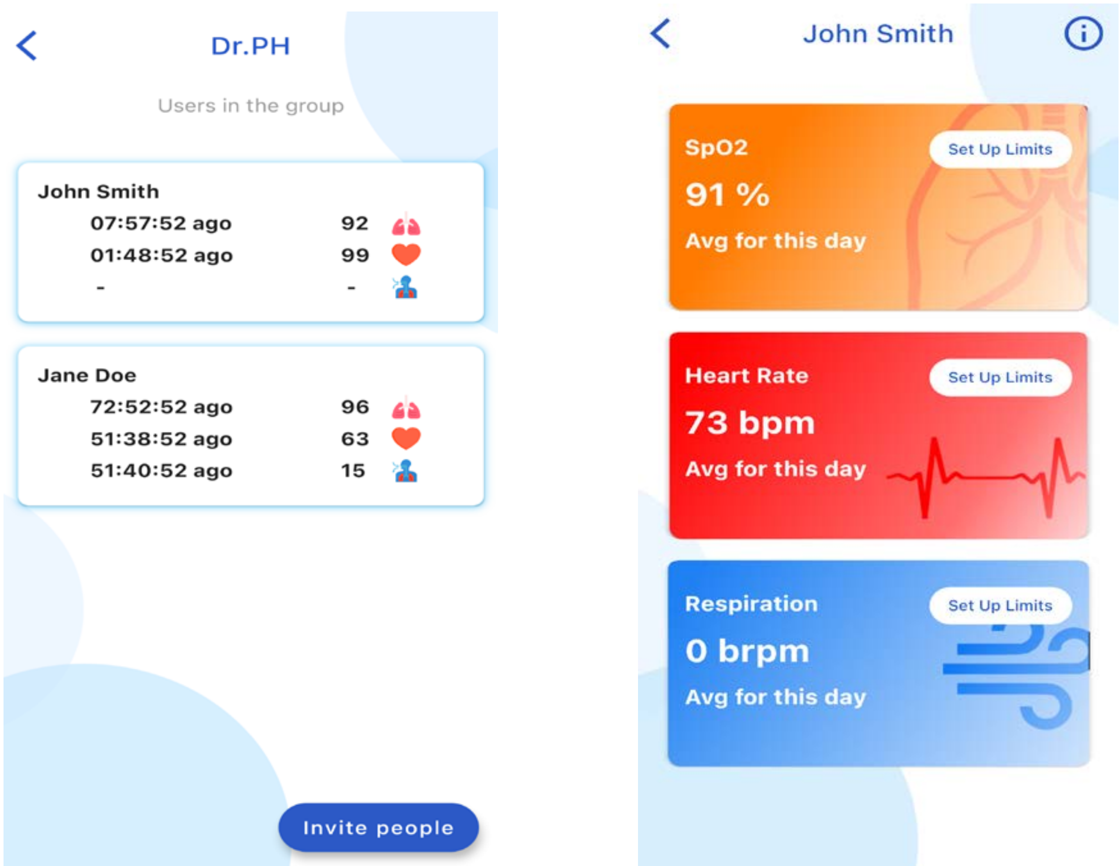

Figure 4: Presentation of client data in the HealthSupervisor application

On the supervisors page the client has the possibility to check the list of his supervisors and the time of their last indicators inspection by them as well as the supervisor's contact information (Fig.4). On the same page, at any time the client can refuse access to his data so the supervisor could not see any data till clients give that permission again. From the supervisor side it is possible to delete the group, accept or decline the client's apply.

Measurements by mobile devices with a pulse oximeter can be performed manually or automatically. In the first case, the participation of the client is required for measurements. In the second case, the mobile device automatically performs measurements without the client's participation.

The data measured by the pulse oximeter are transmitted using Bluetooth technology to the client's smartphone (Fig. 6). Then the data are automatically sent to the server without the client's participation through the network of the mobile operator or WiFi network.

The processing of client personal data in the HealthSupervisor system complies with the recommendations of the GDPR. In addition, cryptographic protection of information is provided. For this purpose, standard mechanisms and protocols are used.

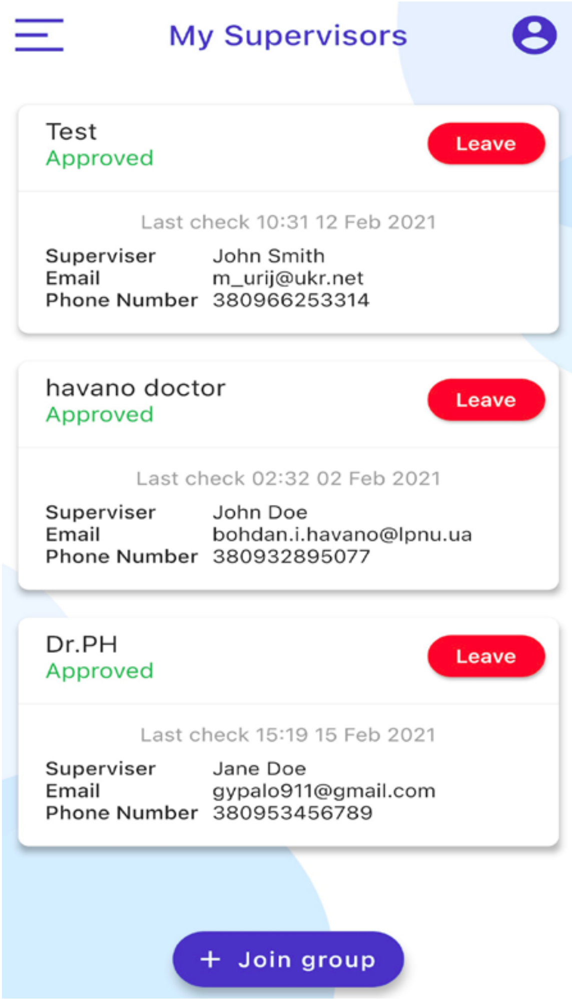

Figure 5: Client's supervisors list

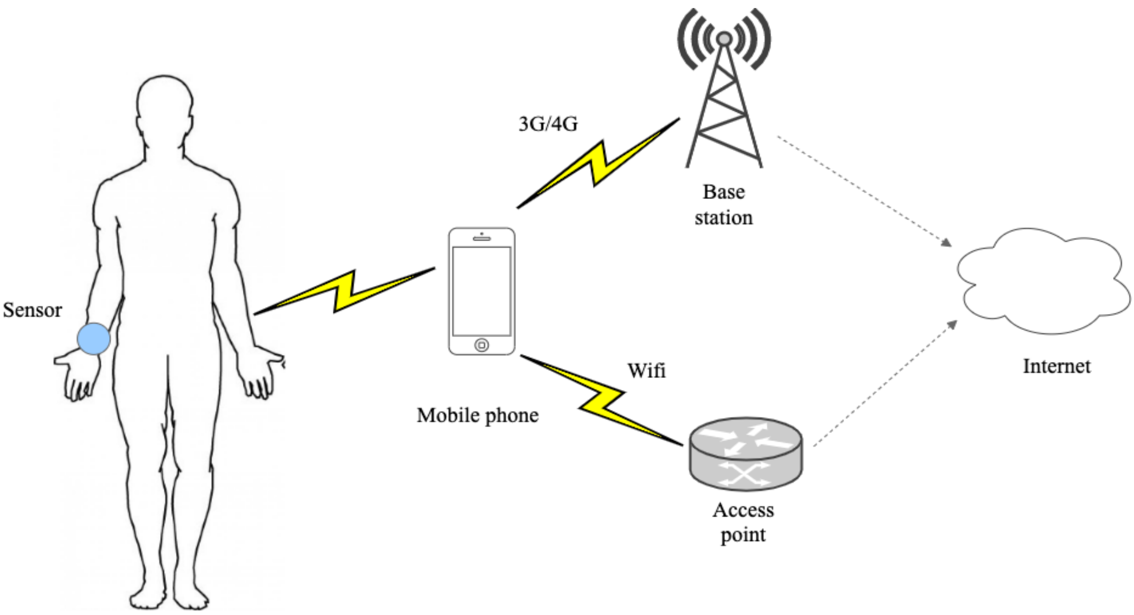

Figure 6: Transmission of data measured with a pulse oximeter using Bluetooth technology to the client's smartphone

7. Data processing in HealthSupervisor mobile application

Supervisors often do not have enough time to be distracted to self-execute the analysis of indicators of various measuring devices. It is very important that the information is presented in a processed form. In this case, from the point of view of clarity, the best for perception is a graphical representation of information.

Data which is sent from devices to the server is raw so it has to be processed. Our algorithms process these data, sort them by measurement time including client's time zone, avoiding duplicates and store it for future easy usage by HealthSupervisor application. It allows making better representation of client's indicators and having possibility to overview client's indicators history which is highly important for supervisors.

Another important thing is to show the sorted clients list to the supervisor with critical clients at the top of it. Along with message notifications it allows the supervisor to urgently check the client's indicators and functional state. Critical state is defined by limits created by the supervisor per each indicator and individually per each client (Fig. 7).

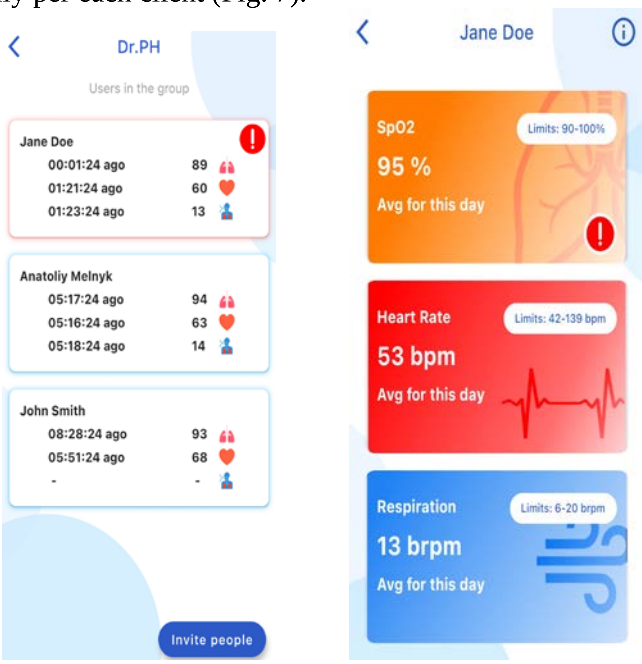

Figure 7: Critical indicators warning

The HealthSupervisor mobile application presents graphs of average values of indicators for the day, week and month, as well as graphs of minimum and maximum values. There is also a list with recent five indicators for fast check. For example, in Fig. 8 the graphs of average (top), minimum and maximum (bottom) values of blood oxygen saturation of two clients are shown, obtained during the week. As can be seen, the average values are within acceptable limits. However, the minimum values of the first client are a cause for concern. Therefore, the supervisor should pay attention to them and conduct additional research, in particular to analyze all the indicators obtained from the first client. To do this, in the application HealthSupervisor it is possible to view all the measured indicators on the basis of which the graphs are based. The indicators of the second client are satisfactory.

In the process of measurement, the question of reliability of the measured indicators is important. In particular, the accuracy of the measurement may be affected by external factors, such as the position of the human body or the movement during the measurements. For example, measuring blood oxygen saturation while a client is moving may be inaccurate. Therefore it is necessary to process the received indicators. We consider it inappropriate to use tracking filters, in particular the Kalman filter, because they distort the obtained indicators. At the same time, creating a histogram of indicators for the period of time and the ratio of the periods of maximum or minimum values of the indicators to the total measurement time will be useful.

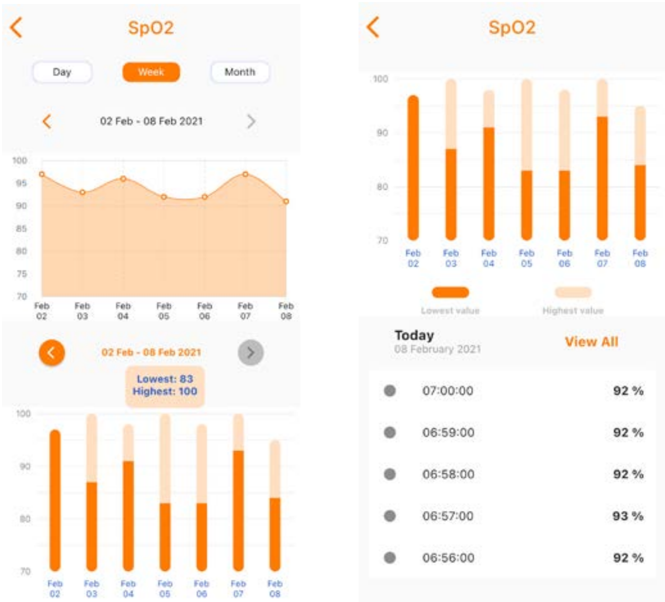

Figure 8: Detailed SpO2 indicator information in the HealthSupervisor application

Figure 8 (right) shows a histogram of indicators for a certain (selected) period of time and the mechanism of value of indicators selection. Figure 9 (left) shows the mechanism for indicators selecting by date. This mechanism makes it easy for the supervisor to view the important information.

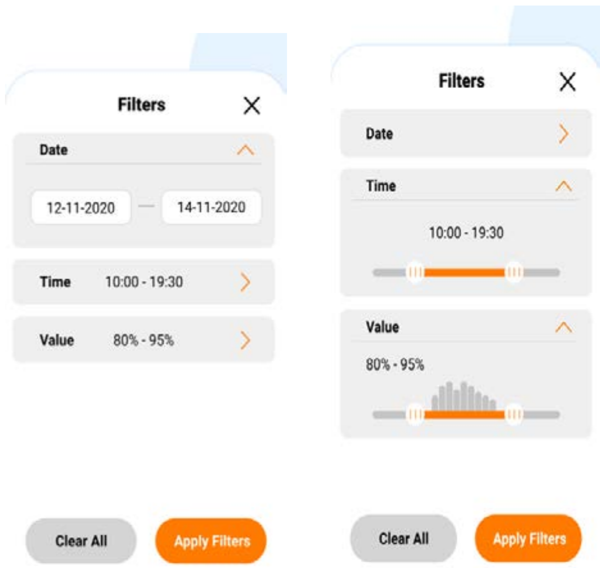

Figure 9: Histogram of indicators for a selected period of time and the mechanism of value of indicators selection (right), and the mechanism for indicators selecting by date (left)

8. Main features and benefits of using the HealthSupervisor mobile application

The HealthSupervisor mobile applications have the following main features:

- Assignment of clients to supervisors,
- Automatic collection of data on the condition of clients without their participation and transmission of these data via the Internet to the server,
- Remote monitoring of the oxygen level in the blood, pulse frequency and respiratory rate,
- Ability to add control functions for other health parameters,

- Accumulation of control results and archiving of data history for each client,
- Monitoring 24 hours a day and without contact between the client and the supervisor,
- The presence of a function of warning the supervisor about the dangerously low oxygen level in the client's blood, high or low pulse frequency, and high or low respiratory rate,
- The possibility to set individual limits per each client by supervisor,
- Ensuring the possibility of self-monitoring by clients of their functional state.

Among the benefits of using the developed mobile application at first is the possibility of constant clinical observation of clients that increases the chances that their condition will not be brought to a critical level.

It is also important that remote monitoring of clients with COVID-19 reduces the need for physical contact, which significantly reduces the likelihood of infection for both physicians and clients, and allows physicians to do so round-the-clock, 7 days a week, without a demand to visit a client. As a result, the number of clients in hospitals and staff overload can be decreased. Mobile applications allow family physicians to care for clients who have mild or moderate symptoms.

And, very importantly, HealthSupervisor application provides organized storage of the received data on the client's condition. This gives an additional advantage in the organization of client monitoring.

9. Compliance of the data received from the wireless devices and the data displayed to the user of the HealthSupervisor application

We have checked the compliance of the data received from the wireless devices and the data displayed to the user of the HealthSupervisor application. For the testing the following wireless devices were chosen: Garmin Vivoactive 4, Garmin Vivosmart 4, Beurer P60, Huawei Band 4. The choice of these devices was based on the fact that they provide continuous export of data to the smartphone. The following parameters were considered to check the compliance of the data received from the wireless devices and the data displayed to the user of the HealthSupervisor application: oxygen saturation, heart rate and respiration rate.

For each parameter there is a table in the HealthSupervisor application with all the measured data received from the devices and in addition the graphs for easy viewing of the data. After synchronisation with the Apple Health application, the same values were recorded and displayed in the Health Supervisor application. There were not detected any changes in the measured data values.

As a result, it was found that each data item in the HealthSupervisor mobile application is not distorted and fully corresponds to the corresponding data item received from wireless devices. The HealthSupervisor mobile application does not make any changes to the data that are transferred to the user from the wireless devices.

10. Future works

The main goal in close future is to analyze collected data to create a smart system of recommendations for the supervisor about each user individually and for all users of the group generally. There will be developed graphs that show trends in measured data. Summarized statistics on all indicators, it would be possible to view several indicators for a certain period of time on one graph. Using artificial intelligence technology, it would be possible to forecast future indicators of the functional state and cluster patients depending on the group, anthropometric data, and other parameters. Also, it is possible that would be implemented generalized analytics for a certain period of time and its export.

There are also plans to change certain processes of the system to improve the user experience, such as background synchronization and data analysis, group search, and more.

One of the areas of further work on the development of the HealthSupervisor system is the development of a method for automatic remote adjustment of operation of the biomedical data acquisition and primary processing means, performed by a Garmin bracelet or another one that transmits data from patient to his smartphone or tablet. The need for such an adjustment may arise in the process of observing the patient's health in order to improve the accuracy and reliability of data acquisition, profiling of individual indicators or updating functional characteristics. The method can be based on the technology of self-configuration of computer devices with reconfigurable logic [20] and on the method of remote synthesis of computer devices for FPGA-based IoT nodes, proposed in [21].

11. Conclusion

On our opinion, continuous health monitoring will soon be one of the leading areas of health care. The proposed solution belongs to this area and could have immediate technological and social impact to help health systems and the public cope with the difficulties posed by the COVID-19 pandemic.

We have developed application that allows supervisors to simultaneously remotely monitor the functional state of many clients in hospital wards (those under observation and those in critical condition) without direct contact with them, and to integrate intelligent functionality to warn supervisors of dangerously low oxygenation levels, as well as those being treated at home. The supervisor can establish indicator limits for each client personally and will be informed when those limits would be crossed. This allows the supervisor to set limits accordingly to the client’s state, features etc. Observation may be performed by a doctor, someone from the family if an older or disabled person is monitored, a coach who monitors the state of team members, etc. The application is based on wireless devices and is designed to monitor the human functional state around the clock, regardless of their location. The human functional state is estimated on the analysis of the following parameters: the oxygen level in the blood, pulse frequency, and respiratory rate, continuously and remotely. These data from the pulse oximeter wirelessly connected to the client's smartphone will be sent to the server, where the supervisor will receive information about the client's functional state and can decide on further activity.

The monitoring system includes three components: a sensor network of wireless pulse oximeters and linked smartphones with the HealthSupervisor mobile application installed, which are used to interact with wireless pulse oximeters and to process the results of monitoring the condition of clients; Server software to collect real-time blood oxygen levels, pulse frequency and respiratory rate 24 hours a day from monitored and critically ill clients, ensuring the protection of personal data; HealthSupervisor mobile applications of supervisor to monitor functional state of clients and to warn supervisor of dangerously low oxygenation level.

The pulse oximeters that can be used for 24/7 monitoring have to be portable, have wireless communication function with a smartphone (via Bluetooth) and provide the ability to export the measured parameters to GoogleFit on Android and Apple Health on iOS.

Implemented in the mobile application algorithms process results of monitoring, sort them by measurement time including client’s time zone, avoiding duplicates and store it for future easy usage by HealthSupervisor application. It allows making better representation of client’s indicators and having possibility to overview client’s indicators history which is highly important for supervisors.

Importantly, in this way, it will be possible to track the functional state in clients that need constant observation, at first with Covid-19. It also can be used to monitor clients with other medical diseases such as asthma, vascular diseases, and cancer.

Mobile applications can be used in both clinical practice and epidemiological studies, and can help monitor disease progression and treatment outcomes.

Developers of mobile applications conducted a series of seminars, which were dedicated to demonstration of the applications work to several relevant institutions and officials in health care structures, in particular:

- members of the anti-crisis headquarters for combating the spread of acute respiratory disease COVID-19 in Ukraine caused by the coronavirus SARS-CoV-2,
- the council of doctors and the management of the Lviv Pulmonary Health Center,
- the leadership of Lviv regional hospital of veterans of wars and repressed after Yurii Lypa.

At all seminars, doctors positively assessed the possibilities of the created tools and confirmed the need for their practical application.

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