HealthyLungs: Mobile Applications for Round-the-Clock Remote Monitoring of Lung Function in Patients with COVID-19

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***Abstract*—The paper proposes smartphone applications, that allow doctors to continuously observe the main organ of patients, affected by the coronavirus, – the lungs. The applications are based on wireless devices and designed in a way to monitor the state of patients' lungs round-the-clock and regardless of their location. Therefore, created applications allow the doctor continuously and remotely (e.g. from their office) see the level of oxygen in the patient's blood. These data from the pulse oximeter with a wireless connection will be send via the patient's smartphone to the server, where the doctor will receive information about the patient's condition and can decide on further treatment. With these applications, doctors will be able to monitor the condition of their patients, who are in hospital wards as well as at home, on observation or outpatient treatment. What is important, this way it will be possible to track the condition of the sick not only with Covid-19 but also with other diseases, for example, asthma, vascular diseases or cancer.**

Keywords—COVID-19, Pulse Oximetry, Lung Function, Smartphone, Mobile Applications, Round-the-Clock Remote Patient Monitoring.

I. INTRODUCTION

COVID-19, a disease caused by a severe acute respiratory infection of coronavirus 2 (SARS-CoV-2), which spreads rapidly around the world and claimed many lives [1], [2]. The lungs are the main and first organ of a person affected by COVID-19 and a severe condition (pneumonia) often leads to death [3]. Therefore, continuous monitoring of lungs condition and blood oxygen levels in patients with COVID-19 can save many lives. The use of our mobile applications for round-the-clock remote monitoring of lung function in patients with COVID-19, which are installed on patients' and doctors' smartphones, will allow doctors to remotely control the condition of patients' lungs and will help to choose treatment options. Moreover, remote monitoring will allow doctors to have less contact with infected patients and will reduce the risk of contracting the disease from them. Remote monitoring will allow hospitals to be unloaded and patients to be monitored and treated at home. Remote monitoring will ensure the recognition of acute deterioration of discharged patients and the need for their readmission. Given a large number of patients and significant occupancy of hospitals, lack of medical staff, high infection probability in direct contact with patients (the share of physicians among all patients 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 lung function of patients with COVID-19. Thus, the proposed HealthyLungs system can be used in clinical practice and epidemiological studies of patients 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.

II. THE STATE OF THE ISSUE

Assessment of the lung condition of a patient with the 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 patients with COVID-19 and the dynamics of its development. It's known that the SpO2 level is much lower in patients, who are in a severe stage of the disease. At SpO2 <90% patients 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 [6], [7].

However, due to the peculiarities of respiratory coronavirus infection (SARS-CoV-2), these stationary oximeters alone are not sufficient for the treatment of patients with COVID-19. Firstly, there is a high risk for doctors to be infected by patients with this disease in the hospital. This statement is confirmed by a significant proportion of medical staff among patients with COVID-19 [8]. Secondly, the large occupancy and often overcrowding of hospitals with patients with COVID-19, leads to the impossibility of continuous monitoring of patients by doctors, the number of which is often insufficient.

Moreover, in the case of treatment of patients, 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 patients, 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 patients with a limited number of staff, some patients died [9].

The peculiarity of respiratory infection of coronavirus 2 (SARS-CoV-2) is also that in many patients the disease is asymptomatic or mild, which allows monitoring of patients and, if necessary, their treatment at home [10]. However, as practice shows, there remains a risk of the rapid deterioration of patients' state, which requires its continuous monitoring. The same applies to patients with COVID-19, discharged from the hospital.

The design and development of portable pulse oximetry kit products that are equipped with GPS and their integration with IoT technology is the main focus of research in [11]. Similarly, in [12] is described an intelligent wearable device and the corresponding algorithm for COVID-19 positive patients that is capable of predicting and notifying the increase in severity of the virus. This device will monitor the patient's body condition such as heart pulse rate, oxygen saturation level, body temperature, hand movements due to restlessness and process this information simultaneously. Consequently, when the virus is predicted to advance to its next stage, an alert will be sent to the person taking care of the patient.

However, It should be noted that today patients have the opportunity to buy pulse oximeters based on a smartphone in the form of bracelets, finger ring devices, earbuds, etc. in a store [5] that solve the problem of measuring blood oxygen saturation. These devices can be especially useful for patients with COVID-19, as they allow them to monitor their condition themselves. This is why many patients 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 patients with severe chronic diseases, which are known to badly tolerate the disease. To date, there are no data on the effectiveness of the use of these devices in the fight against coronavirus. It is clear that not all patients 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 patient, as patients may be late to recognize the need to see a doctor, which can greatly complicate the recovery process.

The efficiency of using pulse oximetry as a home monitoring tool for patients with initially nonsevere COVID-19 to identify need for hospitalization was estimated in [13]. This study found that home pulse oximetry monitoring identies need for hospitalization in initially nonsevere COVID-19 patients when level of oxygen in the patient's blood is less than 92%. Home SpO_2 monitoring also reduces unnecessary emergency department revisits.

In [8], the organization of remote monitoring of blood oxygen saturation of a group of 193 patients with COVID-19 was described. After the discharge, these patients 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 (patientMpower 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 patients could enter additional data / measurements as desired. Pop-up tips also asked if the patient felt short of breath. If the patient 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 patients, provided early detection of acute deterioration of recently discharged patients, and provided the opportunity for reassessment and readmission if necessary.

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

The IoT-based health monitoring system with wireless body sensor networks, application server and a gateway that can be used for data acquisition and transmission is developed in [14]. The prototype of the monitoring system uses home pulse oximeter for measuring SpO 2 and heart rate and an Android application working as IoT gateway to collect data from sensor and adding location information before sending the data to server, from which medical staff can explore and visualize measurement results of patients and their location in a dashboard. This IoT-based health monitoring system allows doctors' to monitor patient's condition trying to recover themselves in self-isolation at any time, but both patients and doctors are tied to certain places, that is, the system is not mobile.

III. PROBLEM STATEMENT

We have posed the following problems that must be solved when creating a HealthyLungs system: 1) assignment of patients to doctors; 2) automatic collection of data on the condition of patients' lungs without their participation and transmission of this data via the Internet to the server; 3) remote monitoring of blood oxygen levels in patients with COVID-19; 4) remote monitoring of heart rate in patients with COVID-19; 5) accumulation of control results and archiving of data history for each patient; 6) monitoring 24 hours a day and without contact between the patient and the doctor; 7) the presence of a function of warning the doctor about the dangerously low oxygen level in the patient's blood; 8) ensuring the possibility of self-monitoring by patients of their lung function.

IV. PROPOSED ROUND-THE-CLOCK REMOTE MONITORING METHOD

We have developed tools [15] that allow physicians to simultaneously remotely monitor the lungs of many patients in hospital wards (those under observation and those in critical condition) without direct contact with them, and to integrate intelligent functionality to warn physicians of dangerously low oxygenation levels, as well as those being treated at home (Fig. 1).

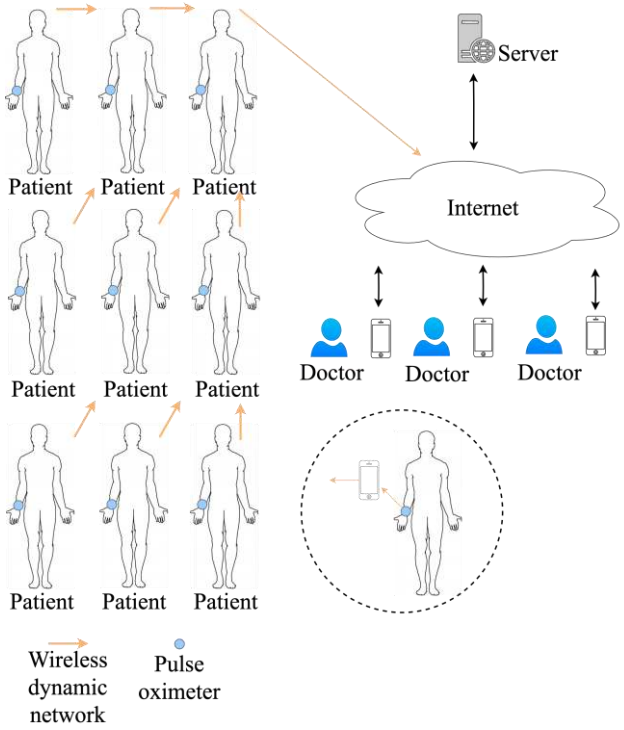

Fig. 1. Round-the-clock monitoring of patients' condition by a doctor.

Patients are equipped with personal pulse oximeters connected to their smartphones. The data received from patients' smartphones are automatically transferred via the Internet to the server, on which the HealthyLungs Server software is installed. Doctors have access to patient data on the HealthyLungs Server from mobile applications on their smartphones. Each doctor has his own group of patients.

The same tools provide patients with COVID-19 the ability to independently monitor pulmonary function, allow them to obtain test results and recommendations for their improvement.

In addition to the numerical value, the color displays the patient's condition: green - healthy, orange - dangerous, red - urgent hospitalization. On the right, the measurement data for the selected period can be found. Patient supplements are not available to the physician. They are observed only by a patient whose lung condition is monitored.

V. ELEMENTS OF THE HEALTHYLUNGS MONITORING SYSTEM AND ORGANIZATION OF THE DATA TRANSMISSION NETWORK

The HealthyLungs monitoring system includes:

- sensor network of wireless pulse oximeters and linked smartphones with the HealthyLungs P mobile application installed, which are used to interact with wireless pulse oximeters and to process the results of monitoring the condition of patients;
- HealthyLungs Server software to collect real-time blood oxygen levels 24 hours a day from monitored and critically ill patients, ensuring the protection of personal data;
- HealthyLungs D doctors' mobile applications to monitor lung function of patients with COVID-19 and to warn doctors of dangerously low oxygenation level.

The structure of the round-the-clock remote monitoring system for lung function in patients with COVID-19 by doctors is given in Fig. 2.

Pulse oximeters of patients 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 are asynchronously transmitted to the data processing center on the HealthyLungs Server.

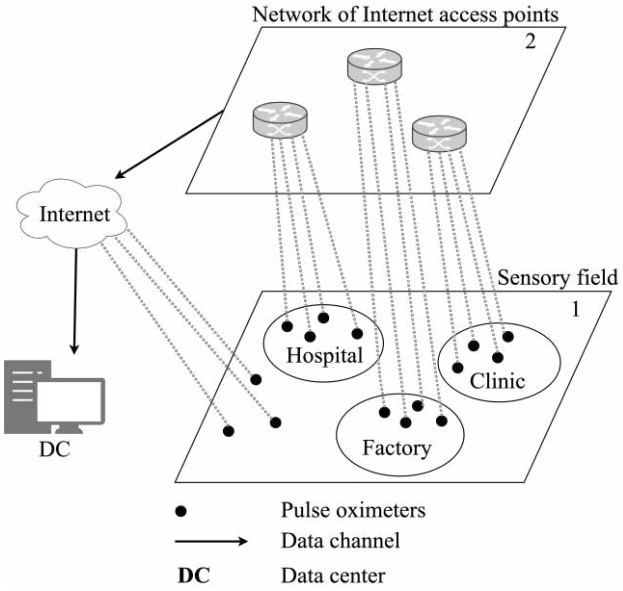

Fig. 2. Structure of the round-the-clock remote monitoring system for lung function in patients with COVID-19.

VI. ORGANIZATION OF REMOTE MONITORING USING THE HEALTHYLUNGS MOBILE APPLICATIONS

The patient 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 HealthKit on iOS.

The patient then connects the bracelet and the mobile application using Bluetooth technology. After that, they install the HealthyLungs P mobile application on their smartphone. In the mobile application on a device with a pulse oximeter, the patient enables data exporting to the HealthyLungs P application.

The information measured by the pulse oximeter is transmitted using Bluetooth technology to the patient's smartphone. Then the data are automatically sent to the

server without the patient's participation through the network of the mobile operator or WiFi network (Fig. 3).

Afterward, the HealthyLungs P application must be registered on the HealthyLungs Server through the settings of the application itself. After registration, the HealthyLungs P mobile application starts transmitting patient readings to the server for storage and processing. The HealthyLungs P application is intended exclusively for data transfer to the server.

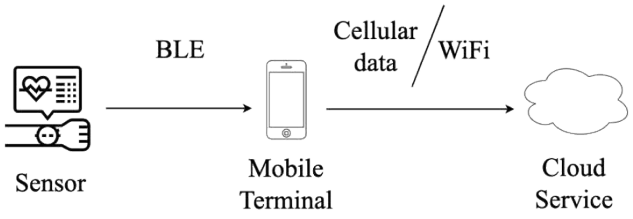

Fig. 3. Transmission of data measured with a pulse oximeter using Bluetooth technology.

The patient can see his data in the smartphone application on a mobile device with a pulse oximeter.

The HealthyLungs D doctor application (Fig. 4) registers with the HealthyLungs Server and accesses patient data. The doctor remotely sees the running data and the history of the readings of their patients, as well as messages about the critical condition of the patient.

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

The processing of patient personal data in the HealthyLungs 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.

VII. Data Processing in HealthyLungs Mobile Applications

During the COVID-19 pandemic, due to the large number of patients in hospitals, doctors do not have enough time to be distracted to self-execute the analysis of indicators of various medical 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.

The HealthyLungs D mobile application presents graphs of average values of indicators for the day, week and month, as well as graphs of minimum and maximum values. For example, in Fig. 5 the graphs of average (top), minimum and maximum (bottom) values the patient's blood oxygen saturation are shown, obtained during the week.

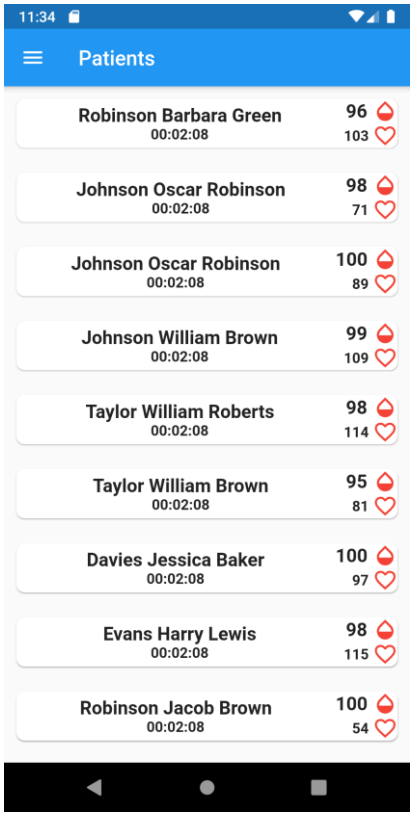

Fig. 4. Presentation of patient data in the HealthyLungs D application.

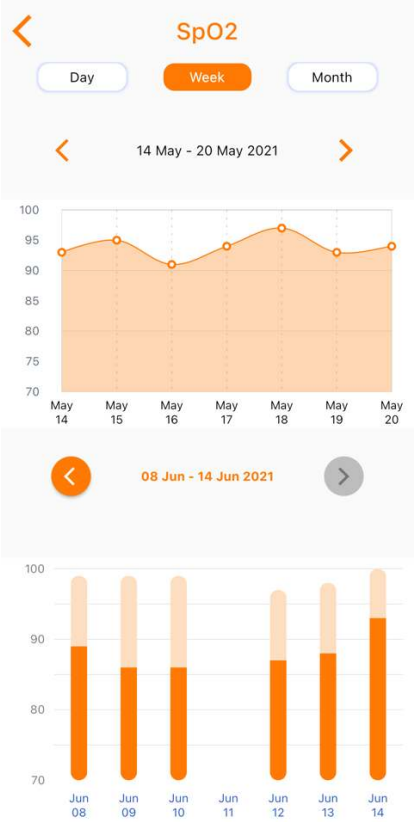

Fig. 5. Presentation of patient data in the HealthyLungs D application.

As can be seen, the average values are within acceptable limits. However, the minimum values are a cause for concern. Therefore, the doctor should pay attention to them and conduct additional research, in particular to analyze all

the indicators obtained from the patient. To do this, in the application HealthyLungs D it is possible to view all the measured indicators based on which the graphs are build.

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 patient 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 and the ratio of the periods of maximum or minimum values of the indicators to the total measurement time will be useful.

Fig. 6 shows a histogram of indicators for a certain (selected) period and the mechanism of value of indicators selection.

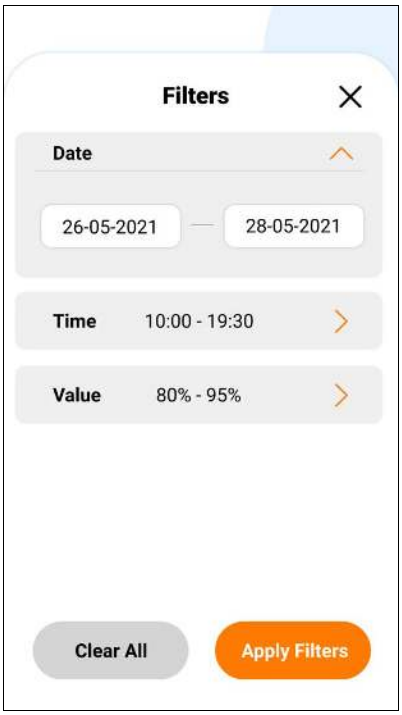

Fig. 6. The mechanism for indicators selecting by date.

Fig. 7 shows the mechanism for indicators selecting by date. This mechanism makes it easy for the doctor to view the important information.

VIII. Main Results and Benefits of Using the HealthyLungs Mobile Applications

The article presents a new method of round-the-clock remote monitoring of the functional state of the patient, according to which the values of the indicators are measured by a portable device attached to the client and wirelessly transmitted to his smartphone, which differs in that the values of the indicators from his smartphone are transmitted through a wireless Internet connection to the server on which they are stored and analyzed, and from this server, upon request from the smartphone of the doctor, they are transmitted to its smartphone and reflect on its screen..

The HealthyLungs system, which implements the proposed method, in addition to a portable measuring device, a device for wireless transmission of information, and a patient's smartphone, includes a server and a doctor's smartphone.

Among the benefits of using the developed mobile applications at first is the possibility of the round-the-clock clinical observation of patients that increases the chances that their condition will not be brought to a critical level.

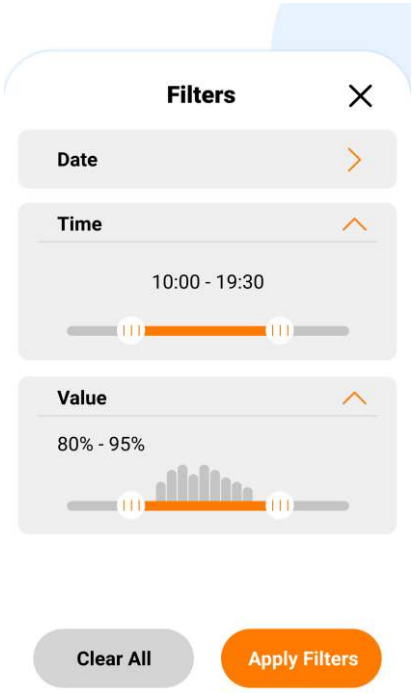

Fig. 7. Histogram of indicators for a selected period and the mechanism of value of indicators selection.

It is also important that remote monitoring of patients with COVID-19 reduces the need for physical contact, which significantly reduces the likelihood of infection for both physicians and patients, and allows physicians to do so round-the-clock, 7 days a week, without a demand to visit a patient. As a result, the number of patients in hospitals and staff overload can be decreased.

Mobile applications allow family physicians to care for patients who have mild or moderate symptoms.

In addition, very importantly, HealthyLungs applications provide organized storage of the received data on the patient's condition. This gives an additional advantage in the organization of patient treatment.

IX. Conclusion and Future Works

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.

The proposed mobile applications provide doctors with round-the-clock remote monitoring of lung function of patients with COVID-19.

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 Google Fit on Android and Apple Health on iOS.

As it is shown in [16], where selection of pulse oximeters was performed, 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 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.

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 HealthyLungs applications.

Mobile applications for round-the-clock remote monitoring by physicians of lung function in patients with COVID-19 can be used in both clinical practice and epidemiological studies, and can help monitor disease progression and treatment outcomes.

The main goal in close future is to analyze collected data to create a smart system of recommendations for the observer about each client individually and for all clients. There will be developed graphs that show trends in measured data.

Using artificial intelligence technology, it would be possible to forecast future indicators of the functional state and cluster clients depending on the group, anthropometric data, and other parameters. In addition, 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.

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