Personalized Remote Monitoring and Prediction System for COVID-19 Patients

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Summary. *The aim of this study was to assess whether an algorithm of a newly developing programme configures a precise state of health predictions for hospitalised patients with COVID-19 infection.*

Methods. A retrospective observational study design was applied. The study consisted of 100 patients who had been tested positive for COVID-19 infection and their vital signs were monitored. According to the collected data on patients' physiological parameters and provided responses to the questions related to the infection, prognoses for the state of health were generated by the system. The accuracy of estimated predictions for the health condition was evaluated and compared with the real-time health status of patients.

Results. The results revealed that predictions provided by an algorithm for vital signs, including respiratory rate, systolic blood pressure, temperature and pulse, were quite accurate (> 90%). Oxygen saturation was the only physiological parameter with the lowest precision (72.82%). While comparing the real-time and predicted health condition of patients for today, 90.07% of all generated prognoses coincided with the actual state of health. Nevertheless, the accuracy of the prognosis decreased slightly (84.89%) for the patients' status of health predictions for tomorrow.

Conclusions. This study indicates that the system for predicting the prospective vital signs and the state of health of a patient is precise and effective. Utilisation of this program could help to enhance the delivery of health care, improve the outcomes for patients in the hospital and ensure the well-being of patients at home.

Introduction

The Coronavirus disease (COVID-19) induced by a newly discovered virus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has forced the world industries to alter essentially (1). Speedy human-to-human contagion possibilities that involve contact transmission through touching the infected patient's mucosal secretions, as well as direct transmission by droplet inhalation when the patient coughs or sneezes, have developed a greater potential to contaminate and spread among humans (2). As the disease escalates across the globe, it has intensely affected the medical sector and put enormous pressure on medical personnel and facilities (3).

Healthcare professionals face a seven times higher risk of obtaining severe COVID-19 than other occupational groups (4). According to the World Health Organization (WHO) estimate, around 115 500 medical staff members (ranging from 80 000 to 160 000) out of a worldwide healthcare workforce of 135 million people may have died from January 2020 to May 2021 (5). The shortage and reuse of prerequisite high quality personal protective equipment several times, incremented workload and ineffective management in the context of the pandemic outbreak have led frontline COVID-19 workers to occupational stress (6, 7). Moreover, work-related pressure rises by resolving moral dilemmas as patients are ought to be triaged by chance of survival, age, or health problems due to a lack of medical equipment and beds in a hospital setting (5, 8).

Owing to the exposed gaping weaknesses of the healthcare system by the pandemic, telemedicine can help significantly improve the provision of health services (9). The main three elements of telehealth are an online and offline interplay between the health provider and the patient, mutual sharing of information and remote patient monitoring (10). By integrating virtual remote consultations, the risk of transmission of the virus is diminishing (9). In addition to that, the convenience of telemedicine is

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based on saving time, which reassures satisfaction for both patients and physicians (11).

However, medically correct decisions to ensure proper follow-ups and quality of consultation require accurate remote patient monitoring (12). Owing to the several forms of health status severity caused by the infection, ranging from asymptomatic to life-threatening cases of COVID-19, patients require meticulous monitoring for potentially abrupt changes in health conditions that are anticipated by the deterioration of physiological parameters (13). Telemedical systems allow real-time monitoring of vital signs, offering help to a patient 24 hours a day, seven days a week, as well as identifying and notifying health experts of changes in the health status at the precise moment, and thus managing the frequency of patient consultations, depending on the severity of the condition (14).

During the global COVID-19 pandemic, amongst the most prevalent symptoms (loss of taste or smell, dyspnoea, cough, fatigue, headache), high fever, arrhythmia, and low oxygen saturation level are the most worrisome signs (15–17). In the presence of fever, it can signal a response to inflammatory receptors (18). COVID-19-related high body temperature often exceeds 38.0°C and lasts for more than five days. Nevertheless, approximately half of all patients with COVID-19 do not have a fever since their first appointment (19, 20). Fever may lead to an increase in the respiratory rate (RR) (21). It is an additional substantial measurement for patients with COVID-19, as the deviations from the norm may determine unsatisfactory consequences (22). Respiratory rate is measured manually by counting chest raises in a particular amount of time (23). Although COVID-19 was first assumed to be a respiratory disease, it is now recognised that the virus affects the human heart, circulatory and other vital systems (24). Due to a fever or inflammation, the virus may cause an increase in the heart rate as the heart works harder to circulate more blood throughout the body to fight the disease (25). It is considered that COVID-19 has an impact on the autonomic nervous system, wherefore observing pulse fluctuations might indicate a strong approaching inflammatory reaction defined by the production of a great amount of pro-inflammatory cytokines, called a 'cytokine storm' (26, 27).

A diverse spectrum of potential sequelae endangers non-hospitalised individuals with COVID-19 infection – hence it is fundamental to monitor and analyse a patient's symptoms in real-time since a sudden deterioration is possible (28). The aim of the current study was to evaluate the accuracy of a newly developing programme that generates prognoses for patients' vital signs and the state of health.

Methods

Study Design. A retrospective observational study was conducted. The study enrolled 100 patients who had been confirmed to have COVID-19 infection and their vital signs were monitored. Using the collected data, the parameters were calculated. The patients were classified into three groups following the severity of the disease: mild, moderate and severe health condition. The accuracy of the programme was tested.

Participants. A study sample consists of 100 patients (18 years old and older) with COVID-19 infection. There are no exclusion criteria in the retrospective part. Medical histories of all patients with COVID-19 infection were analysed until the biomedical study sample size of 100 medical histories was reached. The study sample (15 in the prospective part + 100 in the retrospective part = 115) was calculated according to the 95% confidence interval.

Organisation of the Study. The study was performed from June to July of 2021 and involved hospitalised patients with COVID-19 infection from December of 2020 till June of 2021 at the Kaunas Hospital of the Lithuanian University of Health Sciences (LSMU). The study assessed patients' measured main vital signs (pulse, temperature, respiratory rate, systolic blood pressure) and answers to the questions (Do you feel breathlessness? Do you feel shortness of breath while doing light physical activity? Do you feel shortness of breath at rest? Do you cough up yellowish/greenish/reddish phlegm? Do you feel pain in the chest? Do you feel chest pain during moderate exercise? Do you feel chest pain at rest or during light exercise?). While evaluating the indicators, the percentages of data from the questions (Do you feel shortness of breath while doing light physical activity? Do you feel shortness of breath at rest? Do you feel chest pain during moderate exercise? Do you feel chest pain at rest/during light exercise?) were too low; therefore, these questions were not suitable for testing the system. The remaining questions and vital signs had near 100% data quality, hence they were utilised to evaluate the precision of the accuracy.

As some patients received supplemental oxygen therapy, an additional criterion of oxygen therapy was included in the retrospective analysis. After monitoring the most important vital indicators and assessing the responses given by the patients to the questions, the prognosis of vital signs and the health condition of each patient was calculated and provided by the algorithm. The accuracy of prognoses was reckoned up by analysing and comparing the predicted and a precise moment measured physiological indicators, evaluating the system's real-time and tomorrow's estimated prognoses for the state of health among the patients.

Ethical Consideration. Ethical approval for this study was granted by the Kaunas Regional Biomedical Research Ethics Committee (14 May, 2021, No. BE–2–75). To maintain patient privacy and data safety, the patient coding was utilised.

Results

A total of 100 patients participated in the study to test the reliability of the newly developed monitoring system. The research enrolled 50 men (50%) and 50 women (50%) who tested positive for COVID-19 infection. The age of the patients ranged from 18 to 81 years with the average of 46.1. The distribution of age groups of men and women who participated in the study is displayed in Fig. 1.

Amid the research, specific physiological parameters and their norms were determined. Based on these factors, deviation ranges of vital signs that could indicate a change in the health condition were chosen. The patients were divided into three groups according to their status of health: mild, moderate, and severe. The standards and deviations of the parameters which are distinctive to the exact health status are shown in Table 1.

Depending on the condition of the patients, the participants were hospitalised for different numbers of days, and therefore the case-history of vital signs obtained differs between the patients. The average number of days followed for each patient's vital sign history was 11.9. Most vital signs case-histories were collected from the patients who were being followed in the hospital for 10–15 days.

During the study, only 91 cases were included in a follow-up research based on the data from a retrospective analysis of 100 patients. Due to a paucity of data, results from the other 9 cases were not considered relevant for testing the accuracy.

The results showed that based on the retrospective data obtained from 91 patients, the 24-hour prognosis most accurately indicated mean respiratory rate (96.57%) and systolic blood pressure (94.92%), but the lowest prediction accuracy was foreseen for mean saturation (72.82%) (Table 2).

Assessing the current state of patients' health, based on predictions of individual indicators configured by the algorithm, it was found that the prognosis of the condition of patients was quite accurate (90.07%). The incorrect condition generated by the system, including both higher

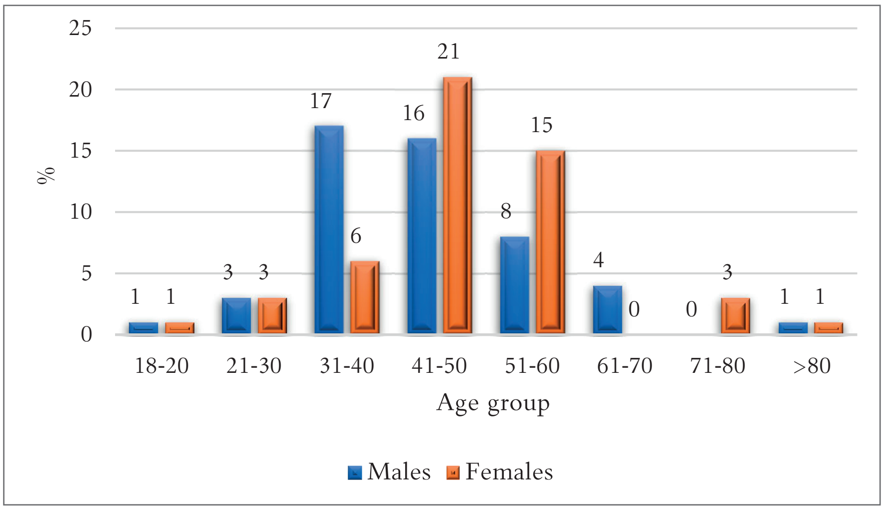

Fig. 1. Distribution of age groups of men and women who participated in the study

Table 1. Norms and aberrations of vital signs

	Magnitudes		
Parameters	Standard	Moderate health condition	Severe health condition
Oxygen saturation (SpO2) (percentage)	⩾ 96	95–92	⩽ 91
Respiratory rate (breaths per minute)	12–20	9–11; 21–24	⩽ 8; ⩾ 25
Arterial blood pressure (mmHg)	101–219	91–100	⩽ 90; ⩾ 220
Heart rate (beats per minute)	51–90	41–50; 91–130	⩽ 40; ⩾ 131
Temperature (°C)	36.1–38.0	35.1–36.0; 38.1–39.0	⩽ 35; ⩾ 39.1

Table 2. Average accuracy of 24-hour predicted indicators

Indicator	Average accuracy (%)
Respiratory rate	96.57
Systolic blood pressure	94.92
Temperature	94.39
Pulse	92.35
Oxygen saturation	72.82

(6.67%) and lower prognosis (3.26%), fell short of one-tenth of inaccurate results (Fig. 2). Table 3 depicts the distribution of the patients' predicted and former state of health by the time. When comparing the results obtained, most of the results of an accurate prediction consist of a predicted mild state of health, which corresponded to the real state (77.29%). A small proportion of the inaccurate prognosis consisted of a predicted over-high health status, where the system-predicted average health status in the real time was mild (6.30%). However, the results also showed that the system did not accurately predict a more serious condition when the prognosis signalled a mild medical condition that was average (2.96%) or the predicted average health status at that time was severe (0.16%).

When evaluating the algorithm's health predictions for tomorrow, most of the predictions coincided with the actual state of health of the patient. However, in this case, the percentage accuracy of the prognosis decreased slightly (84.89%). The results showed that the system was more likely to warn of tomorrow's more severe condition than it occurred (10.77%) (Fig. 3). An analysis of the conformity between the resultant patients' next day condition prognosis and the real state of tomorrow is presented in Table 4. The biggest discrepancy in the prognosis committed by the system was the prediction of the moderate patients' tomorrow health status, which was mild the next day (10.30%). Likewise, the system several times out of all the presented predictions inaccurately provided a prognosis of tomorrow's mild health status, which was indeed average (3.92%). The amiss prophecy of the severe

Table 3. Allocation of today's predicted and realistically manifested state of patient's health

	Predicted state of health for today	The real state of health for today	Results (%)
CoHigher prognosis	Moderate	Mild	6.30
	Severe	Mild	0.07
	Severe	Moderate	0.31
Accurate prognosis	Mild	Mild	77.29
	Moderate	Moderate	10.75
	Severe	Severe	2.02
Lower prognosis	Mild	Moderate	2.96
	Mild	Severe	0.14
	Moderate	Severe	0.16

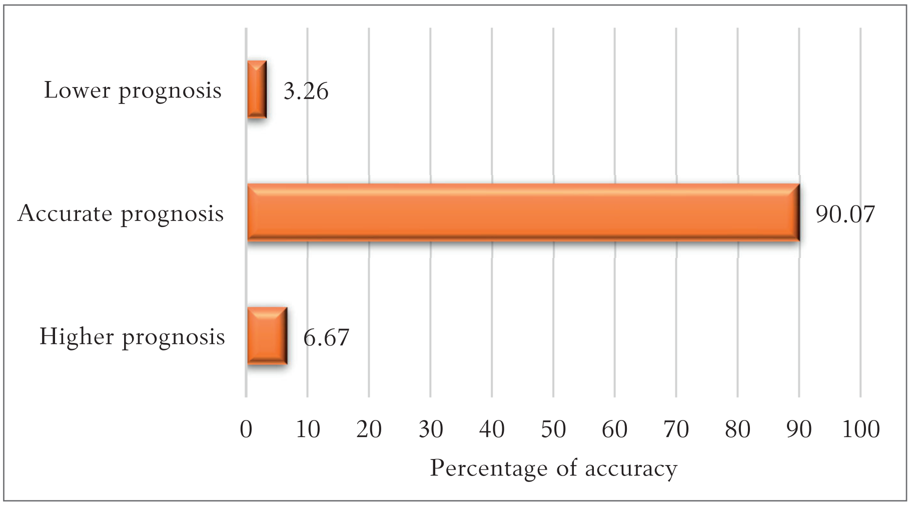

Fig. 2. Accuracy of the prognosis of the state of health state for today

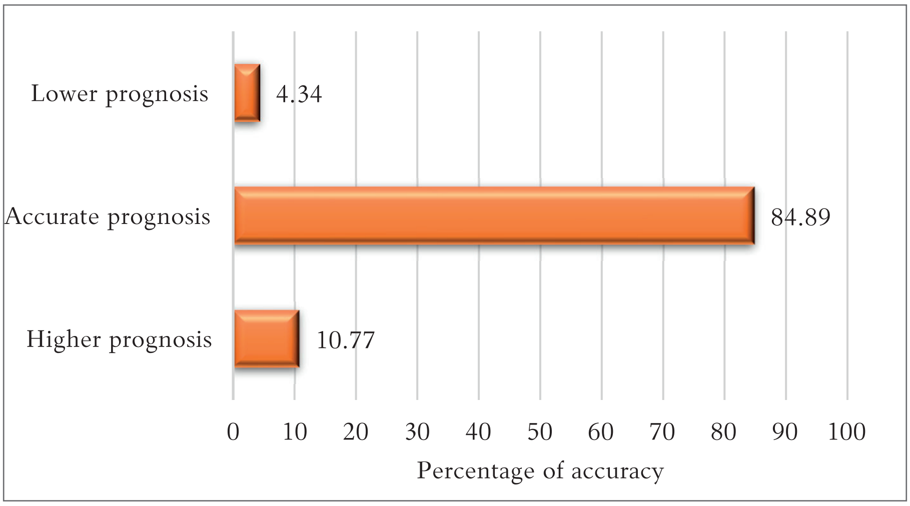

Fig. 3. Accuracy of the prognosis of the state of patient's health state for tomorrow

Table 4. Allocation of tomorrow's predicted and realistically manifested state of patient's health

	Predicted state of health for tomorrow	The real state of health for tomorrow	Results (%)
Higher prognosis	Moderate	Mild	10.30
	Severe	Mild	0.07
	Mild	Moderate	0.40
Accurate prognosis	Mild	Mild	71.80
	Moderate	Moderate	10.99
	Severe	Severe	2.09
Lower prognosis	Mild	Moderate	3.92
	Mild	Severe	0.15
	Moderate	Severe	0.28

real-time condition for patients, when a mild or a moderate condition was predicted, in both cases together, does not account for any half percent of all the recorded cases.

Discussion

In the face of a global pandemic, the upsurge of digital technologies' daily usage, including in the health care system, has determined an increased consideration of telemedicine's avail. Due to the improved access in terms of long-care management and its comprehensiveness, the level of telehealth implementation has risen (29). However, the fundamental part of rigorous telehealth provision is accurate remote patient monitoring and observation. This study aimed to ascertain how accurately a newly developed system predicts prospective vital signs and the state of health, thus helping to inform about possible changes in the course of the disease. Retrospective data from 91 participants of 100 patients in the study were used to assess the results, as the monitoring period for the health parameters of the remaining 9 patients was too short to make predictions and evaluate them. The results show that a researched programme could be beneficial for tracking and predicting vital signs and the health condition for statistically accurate predictions.

Our study determined that the accuracy of the algorithm's provided prognosis is reliably high, considering patients' physiological parameters and later analysing them with the predicted ones. Comparing the forecasts provided by the algorithm for today and tomorrow, a noticeably more accurate prognosis calculation was evaluated for the upcoming 24-hour period than after it. Faulty calculation prognosis might have been influenced by inaccurate patients' answers to the questionnaire when the patient perceives the symptoms in a perfunctory manner or vice versa, overestimates the symptoms. The formulation of patients' health status prognosis may have been distorted owing to the sudden change in the health status between periodical monitoring that was not recorded during the last measurement of vital signs. Furthermore, incorrect measurements for unforeseen reasons may have resulted in misprediction. Additionally, Merilahti et al. in their research on long-term health monitoring with wearable technologies encountered unexpected technical problems. Issues were related to the equipment damage because of the natural phenomena, which may have affected the results of the study.

Although in this study the received number of inaccurate health status prognoses is minor, incorrect system predictions can have a negative impact on patients' emotional and physical health. A false-higher prognosis necessitates additional testing of the patient or specific treatment to improve the patient's condition when in fact this is not necessary. Moreover, it may indirectly and adversely affect other patients who are in a severe and life-threatening condition at the time, because of the physician's concentration on the mispredicted patient's medical condition. Analogically, concern rises because of the provided inaccurate false, i.e., lower prognosis. This wrong health status supposition may result in a delay in illness identification, resulting in a poor patient condition due to exacerbated symptoms. Delayed disease diagnosis results in late accurate treatment designation which could have a detrimental effect on the patients' health and cause irrevocable consequences.

This research established that based on retrospective data obtained, pulse, respiratory rate, systolic blood pressure, and temperature were the most accurately predicted parameters by the system. However, oxygen saturation was the least correct predicted indicator among the patients. Fallacious results of the oxygen level might be caused due to the reasons mentioned before or a sudden deterioration in the patients' health condition owing to the COVID-19 induced silent hypoxia, which is inherent by a drastically abrupt saturation drop within a few hours (30).

Accurate measurement of vital indicators is essential to ensure that the newly developed system for predicting the health status does not mislead both the patient and the physician. Correct monitoring of physiological parameters and remote observing could encourage patients to monitor their health more closely without the necessity to visit the health centre on numerous occasions and to attain overall wellness. Nevertheless, Pecina et al. after their randomised controlled trial of daily home monitoring stated that home telemonitoring does not relatively enhance the perception of self-care; conversely, it can have a negative influence on it.

The realisation of the telemedicine programme would prevent the risk of misinterpretation of the patient's vital signs. It would forestall the disease from exacerbation due to timely noticed changes in the health status by the system. The patient and the healthcare professional would be notified of the unusual changes. Therefore, a doctor or a nurse practitioner could provide an immediate consultation remotely using telecommunication, determine the severity of the illness, discuss the principles of treatment and care, and advise when to seek help. The system could help to prevent queues in a hospital setting, as well as alleviate close contact with people to guarantee utmost protection against the infection, which is a crucial point during a pandemic.

Conclusions

The study revealed that the observed system for forecasting the prospective vital signs and the state of health of a patient is accurate. The utilisation of this programme could help to enhance the delivery of health care, ensure the well-being of patients at home, and improve the outcomes for patients in the hospital. Due to the lack of research on this topic presently, future efforts are required for effective implementation of the system, as it demands a faultless algorithm, accurate measurements of physiological parameters and efficient communication between health providers and patients.

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Statement of Conflict of Interest

The authors state no conflict of interest.

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