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Design and implementation system of mobile oxygen concentrator and telemedicine for comprehensive treatment of SpO_2

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Abstract

Respiratory diseases such as hypoxemia or infections caused by viruses such as coronavirus disease 2019 (COVID-19) cause the patient's oxygen saturation (SpO_2) to drop dramatically. SpO_2 below average values (< 90%) can cause organ dysfunction and even death. To prevent this, the patient must be given supplementary oxygen for a specific duration and observe the patient's SpO_2 changes during the oxygen therapy. Based on these problems, a solution can be offered by utilizing digital technology to integrate medical products such as oxygen concentrators (Oxycon), oximeters, etc., which a doctor can monitor remotely (telemedicine); therefore, the doctor can decide the treatment time accurately by autopilot integrated system. This study aimed to design a system for SpO_2 therapy to monitor the patient who uses a mobile oxygen concentrator integrated with a smartphone application and facilitates lung specialists to control the patient's progress. In this study, a prototype of Oxycon was made, which produced a concentration of oxygen up to 95% stably during the treatment, which can be remotely controlled and integrated with telemetry communication and telemedicine applications that can operate according to the needs of lung specialists. Determination of the therapy time parameter determines the success of the SpO_2 therapy process to avoid the adverse effects of excess oxygen entering the body.

Keywords

Medical oxygen concentrator, Telemedicine Apps, SpO_2, IoT, IoMT.

1.Introduction

The challenges of living in crowded mega-city areas such as Bandung and Jakarta have several threats of respiratory diseases. Respiratory disease problems are caused by air pollution and airborne viruses due to human respiratory tract droplets such as coronavirus disease 2019 (COVID-19). Air pollution poses a significant threat to human health, the environment, and the quality of life of millions of people [1]. Air pollution due to particulates such as carbon black and Sulphur, with an increasing tendency from 2010 to 2022, may harm respiratory health [1, 2]. If air quality problems are not addressed immediately, they can have a devastating impact, and humans may require masks or something that can provide more oxygen. Looking at future air quality challenges, a study is also required to examine the proper methods to answer future challenges and needs in terms of comfort of life and health care.

There are several options to meet the need for a higher oxygen supply, one of which is to use oxygen concentrators (Oxycon). Oxycon products are already widely circulated in the market, but increased production efficiency and effectiveness need to be improved through further research schemes. Based on research conducted by [3], Oxycon with the pressure swing adsorption (PSA) method is the best method to be applied to mobile Oxycon. In addition, to meet future needs that are all integrated with the internet network, it is necessary to study the integration between health products and the application of the internet of things (IoT) or what can be called the internet of medical things (IoMT) to create telemedicine products so that doctors can treat patients remotely.

Then, to apply Oxycon products to patients undergoing oxygen therapy, a system of monitoring the level of oxygen saturation (SpO_2) in the patient's body is needed. Because excessive administration of supplementary oxygen can harm patients [4], to

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implement a SpO_2 monitoring system, you can use mobile medical devices such as Oximeters [5]. However, the mobile Oximeter must be considered ergonomic and practical in its application. Oximeter products on the market can wirelessly connect to smartphones using Bluetooth low energy (BLE). This communication method needs to be improved regarding the effectiveness of real-time monitoring of telemedicine applications. BLE can only be connected device-to-device without the need for an internet connection. In contrast, the market for real-time telemedicine requires real-time data where the Oximeter device must be able to connect directly to the database. Therefore, it is necessary to assess the implementation and what kind of wireless communication system is best applied to the Oximeter to send data in real-time properly.

Meanwhile, to integrate Oxycon and Oximeter into telemedicine products, a study on the IoMT is needed that specifically studies wireless body area network (WBAN), middleware management, and application design that suits the needs of patients and doctors. Each patient incorporated in the IoMT system is equipped with a WBAN sensor node that collects and monitors vital signs such as temperature, heart rate, blood pressure, etc., regardless of the patient's condition and location. The collected information is then received by the intelligent mobile device using one of the wireless communications such as Bluetooth, Wi-Fi, etc. [6]. The expected wireless communication of a WBAN system is real-time. In real-time systems, the calculation value depends on the timely answer [7].

To address the mentioned problems, this study aims to provide a comprehensive analysis regarding the oxygen concentrator as a telemedicine tool for the treatment of respiratory diseases based on the perspective of system and software development. Our contribution to this study can be described as follows:

- To leverage and optimize SpO_2 treatment with pure oxygen stably and at a specific time by analyzing patient condition by doctor and telemedicine application.
- We present an oxygen concentrator (Oxycon) and oximeter wearable real-time integrated telemedicine apps that are applied to treat respiratory diseases remotely.

In this study, the design and implementation of the PSA technique that has been optimized was carried out to create a mobile oxygen concentrator that is integrated with a smartphone application for monitoring patients and lung specialists.

This paper consists of several sections. Section 2 presents various works related to this research. Section 3 covers the design and implementation of the study, encompassing the pneumatic system, oxygen concentrator controller, telemetry system, cloud service, and the use case of the mobile application. Sections 4 and 5 present the results and discussion. Finally, in section 6, this paper concludes with a discussion of future directions.

2.Related works

Telemedicine comprises five types: telemonitoring, teleconsultation, telerehabilitation, telespirometery, and tele-education. Telemedicine-based interventions such as telemonitoring, teleconsultation, telerehabilitation, telespiromentery, and teleeducation can enhance patient-centered care and improve self-care in lung transplantation [8]. Based on a literature study by Gholamzadeh et al. [8], telemedicine-based care solutions can provide a practical approach for patients and clinicians by applying remote patient monitoring in lung transplantation. In the application of telemedicine technology there are many digital technology developments that support the success of these activities such as the development of smart sensors that produce high-accuracy data acquisition, IoT that prevent cyber-attacks, big-data and data analytics to provide quality data analysis, virtual-, augmented-, mixed-reality to visualize data, models, and analysis results, web and cloud enable computing to perform data storage management, high performance computing system to improve data processing performance, and communication network to improve real-time data acquisition and communication with the minimum possible delay time. *Table 1* summarizes the key supporting technologies in telemedicine implementation.

The development of telemedicine studies, mainly focusing on its accuracy, still needs attention compared with traditional methods. The survey conducted by Gangwani et al. [9] reviewed the records of all patients who received telemedicine consultation during the COVID-19 pandemic time frame of March 1, 2020, to March 1, 2021, in the Department of Oral and Maxillofacial, giving the result of the paper showed that telemedicine can be effectively utilized in performing consultations for routine oral and maxillofacial surgery (OMS) procedures, especially dentoalveolar surgeries. However, given the lack of a control group and the observation nature of this study, the result must be interpreted with caution [8]. Several study that focuses on telemedicine for COVID-19 treatment they are contributed on the role and positive effects of telemedicine on the volume of outpatient clinics during the COVID-19 pandemic and its future developments studied [10], remote monitoring of SPO_2 in individuals with COVID-19 pneumonia [11], determine the accuracy of planned OMS procedures for patients initially seen through telemedicine during the COVID-19 pandemic [9], and the role of telerehabilitation in the rehabilitation medicine training program of a COVID-19 referral center in a developing country [12]. Other study claim that the usage of telemedicine among health care professionals in China is relatively insufficient, indicating the need for further development and implementation of telemedicine services [13], besides that telemedicine techniques can be used to establish a diagnostic and therapeutic strategy for obstructive sleep apnea syndrome, with the creation of a Wide Core Sleep Laboratory as a process controller [14]. Furthermore, home SPO_2 telemonitoring can help predict disease trajectory and identify patients who may require further medical intervention. Regular monitoring and adherence to telemedicine programs are important for better outcomes [15]. Therefor our study focuses on monitoring patients' home SPO_2 levels using telemedicine equipment, such as pulse oximeters connected and treat them use Oxycon to supply the oxygen in real-time. The position of our study is shown in *Table 2*.

Table 1 Key enabling technologies identify from the literature

Technology	**Reference**	**Focused activity**
Smart sensor	[16-19]	Data acquisition
Industrial IoT	[20–25]	All five activities
IoMT	[26–28]	Cyber Security
Big-data and data analytics	[20, 16, 23, 18, 25]	Data analysis
Machine-learning, deep-learning and artificial intelligence	[20, 21, 16, 17, 29]	Data analysis
Virtual-, augmented-, mixed-reality	[22, 23, 30]	Visualization (data, models, and results)
Other virtual (simulated) environment and computer aided design models	[31–33]	Data analysis and visualization
Web and cloud enable computing	[17, 34, 33, 15]	Data analysis, storage and visualization
High performance computing systems	[18, 30]	Data analysis, storage and visualization
Communication network, and location-based sensors	[35–38, 6]	Data acquisition and communication

Table 2 Telemedicine study position for respiratory therapy

Study	**Patient data**		**Medical device data**			**Traditional methods**	**Telemedicine methods**
	SpO_2 (%)	**Temp (C)**	**O_2 (%)**	**Flow liter per minute(Lpm)**	**Time(s)**		
Tartaglia et al. [10]	-	-	-	-	-	-	*
Ma et al. [13]	-	-	-	-	-	*	*
O'Carroll et al. [11]	*	*					*
Coma-Del-Corral et al. [14]	-	-	-	-	*	-	*
Bartczak et al. [15]	*	-	-	-	*		*
Russo et al. [39]	-	-	-	-	*	*	*
Lo et al. [40]	-	-	-	-	*	*	*
Gangwani et al. [9]	-	-	-	-	*	-	*
Sklar and Munshi [41]	-	-	*	*	*	*	-
Leochico et al. [12]	-	-	-	-	-	-	*
Ku et al. [42]	-	-	-	-	*	*	*
Our study	*	-	*	*	*	*	*

3.Methods

Design and implementation

In this study, the first step is to know the research clarification about the need and the main problem of remote medicine. The second step is to design a pneumatic system for the PSA process to produce optimal concentrated oxygen integrated with telemetry communication. Then, the following design is to make an Oxycon controller system and a telemetry system. The third step is to design the Oximeter to monitor the patient's condition during SpO_2 therapy remotely. After the system works as expected, a cloud service and database system is designed to accommodate patient data using the Oxycon and Oximeter tools. After Oxycon is integrated with the database, a smartphone application is created that patients and treating doctors use to facilitate monitoring. At the same time, the administrator logs in using the web-based application. To validate that this system works well, we collect the data from the database and analyse it to get an insight into the performance system. The study can be seen comprehensively in *Figure 1*.

In oxygen therapy patients, several rules must be applied by paying attention to the patient's condition and the target to be achieved in healing. By the practices described in some scientific article sources [8, 9], an algorithm can be made to treat respiratory diseases in patients. This algorithm is shown in *Figure 2*. This respiratory therapy processing algorithm is handy as a fundamental design of telemedicine applications.

Telemedicine was developed to provide healthcare to underprivileged and inaccessible areas and aims to provide equal access to medical care irrespective of geographical location [43]. Telemedicine facilities vary in the form of telephones, video calls, websites, or applications on smartphones and desktops. The main advantage of telemedicine services is the use of technology to eliminate distance, geographical restrictions, and associated costs, especially for medical services in remote areas that lack medical personnel [13]. On the other hand, telemedicine services invite various topics that have the potential to become ethical issues relevant to its implementation, including matters of patient privacy and confidentiality, as well as changes in doctor-patient face-to-face interaction. One of the primary risks associated with telemedicine systems is the potential breach of patient data confidentiality and security, which includes text, audio, and visual/video data [44].

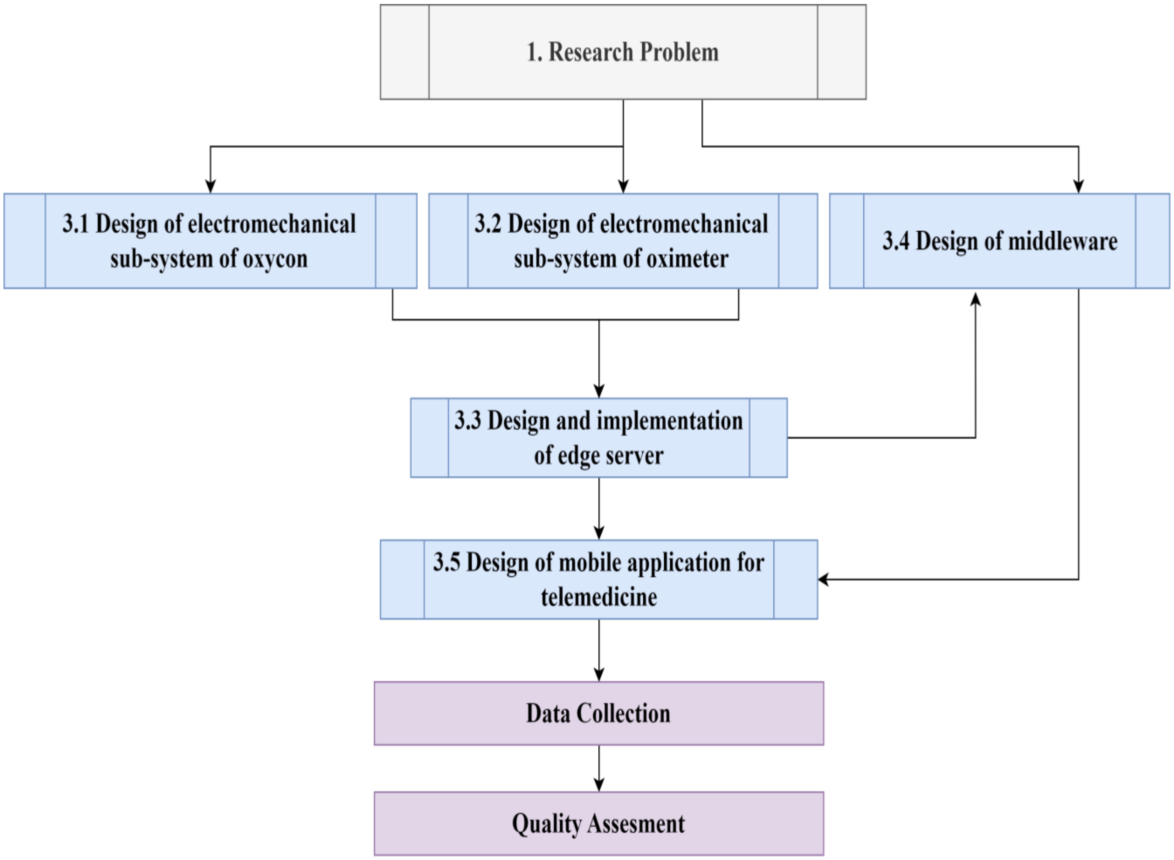
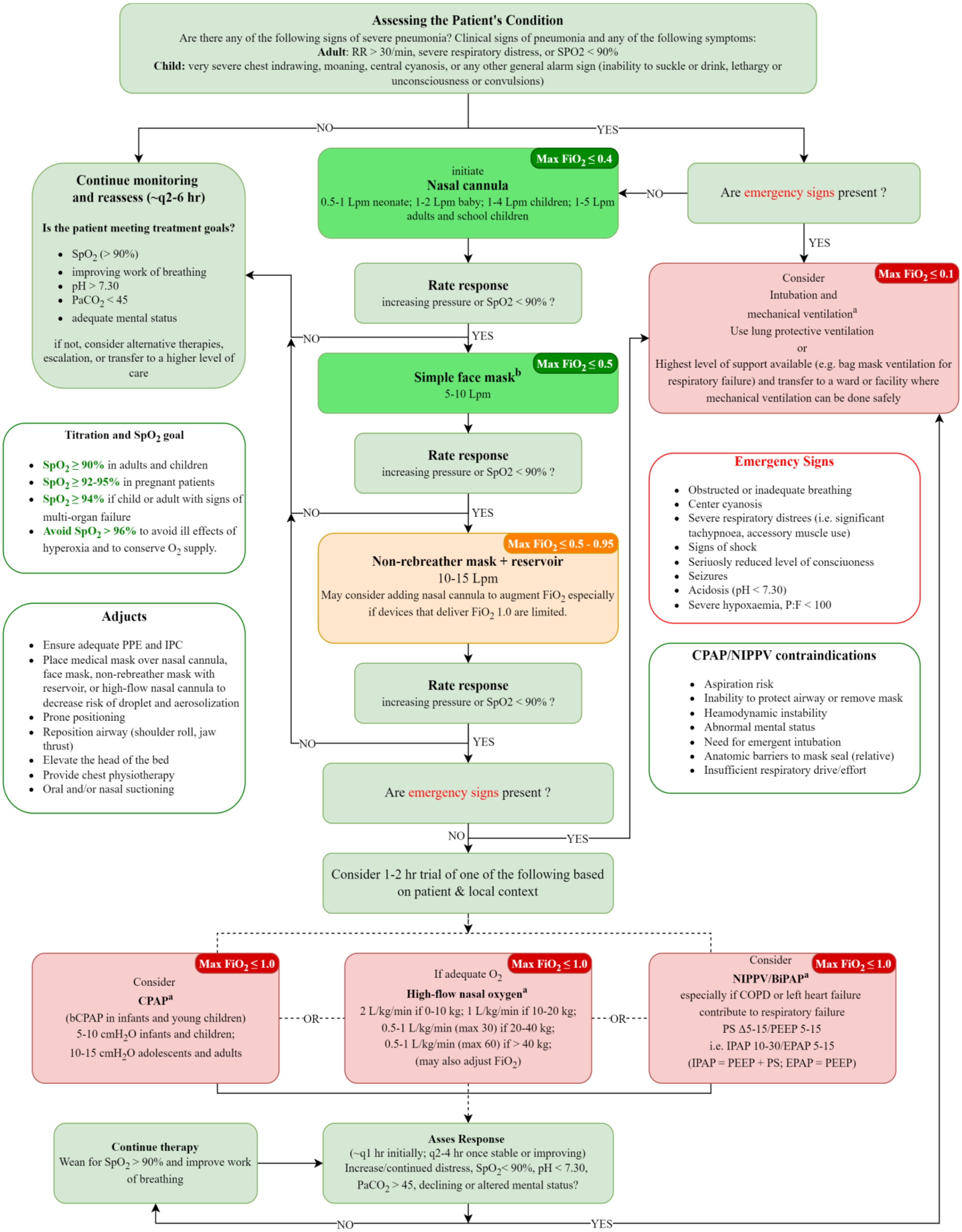


Figure 1 System design of oxygen concentration mobile



Assessing the Patient's Condition

Are there any of the following signs of severe pneumonia? Clinical signs of pneumonia and any of the following symptoms:

Adult: RR > 30/min, severe respiratory distress, or SPO2 < 90%

Child: very severe chest indrawing, moaning, central cyanosis, or any other general alarm sign (inability to suckle or drink, lethargy or unconsciousness or convulsions)

Continue monitoring and reassess (~q2-6 hr)

Is the patient meeting treatment goals?

- SpO_2 (> 90%)
- improving work of breathing
- pH > 7.30
- $PaCO_2 < 45$
- adequate mental status

if not, consider alternative therapies, escalation, or transfer to a higher level of care

initiate **Nasal cannula** 0.5-1 Lpm neonate; 1-2 Lpm baby; 1-4 Lpm children; 1-5 Lpm adults and school children

Are emergency signs present ?

Rate response increasing pressure or SpO2 < 90% ?

Consider Intubation and mechanical ventilation[a]

Use lung protective ventilation

or

Highest level of support available (e.g. bag mask ventilation for respiratory failure) and transfer to a ward or facility where mechanical ventilation can be done safely

Simple face mask[b] 5-10 Lpm

Rate response increasing pressure or SpO2 < 90% ?

Titration and SpO_2 goal

- **$SpO_2 \geq 90\%$** in adults and children
- **$SpO_2 \geq 92\text{-}95\%$** in pregnant patients
- **$SpO_2 \geq 94\%$** if child or adult with signs of multi-organ failure
- **Avoid $SpO_2 > 96\%$** to avoid ill effects of hyperoxia and to conserve O_2 supply.

Emergency Signs

- Obstructed or inadequate breathing
- Center cyanosis
- Severe respiratory distrees (i.e. significant tachypnoea, accessory muscle use)
- Signs of shock
- Seriuosly reduced level of consciuoness
- Seizures
- Acidosis (pH < 7.30)
- Severe hypoxaemia, P:F < 100

Non-rebreather mask + reservoir 10-15 Lpm

May consider adding nasal cannula to augment FiO_2 especially if devices that deliver FiO_2 1.0 are limited.

Adjucts

- Ensure adequate PPE and IPC
- Place medical mask over nasal cannula, face mask, non-rebreather mask with reservoir, or high-flow nasal cannula to decrease risk of droplet and aerosolization
- Prone positioning
- Reposition airway (shoulder roll, jaw thrust)
- Elevate the head of the bed
- Provide chest physiotherapy
- Oral and/or nasal suctioning

Rate response increasing pressure or SpO2 < 90% ?

CPAP/NIPPV contraindications

- Aspiration risk
- Inability to protect airway or remove mask
- Heamodynamic instability
- Abnormal mental status
- Need for emergent intubation
- Anatomic barriers to mask seal (relative)
- Insufficient respiratory drive/effort

Are emergency signs present ?

Consider 1-2 hr trial of one of the following based on patient & local context

Consider **CPAP**[a] (bCPAP in infants and young children) 5-10 cmH_2O infants and children; 10-15 cmH_2O adolescents and adults

If adequate O_2 **High-flow nasal oxygen**[a] 2 L/kg/min if 0-10 kg; 1 L/kg/min if 10-20 kg; 0.5-1 L/kg/min (max 30) if 20-40 kg; 0.5-1 L/kg/min (max 60) if > 40 kg; (may also adjust FiO_2)

Consider **NIPPV/BiPAP**[a] especially if COPD or left heart failure contribute to respiratory failure PS Δ5-15/PEEP 5-15 i.e. IPAP 10-30/EPAP 5-15 (IPAP = PEEP + PS; EPAP = PEEP)

Continue therapy Wean for $SpO_2 > 90\%$ and improve work of breathing

Asses Response (~q1 hr initially; q2-4 hr once stable or improving) Increase/continued distress, $SpO_2 < 90\%$, pH < 7.30, $PaCO_2 > 45$, declining or altered mental status?

Figure 2 Respiratory therapy rule

3.1Design of electromechanical sub-system of Oxycon

In general, the process of analyzing the design of Oxycon has system requirements that are divided into two categories, namely functional and non-functional requirements [45]. Applicable requirements are activities that the system must perform. For example, the pressure, temperature, and humidity of the air applied to the absorbent zeolite sieve tube. The functional requirements in prototyping this product are based on the procedures and rules used by the system to run the proposed algorithm. At the same time, non-functional requirements are system characteristics other than activities that must be carried out or support the system. To distinguish between functional and non-functional requirements, you can use a framework to identify and classify these requirements. The functionality usability reliability performance and security (FURPS) framework is frequently utilized to assess a system's functionality, usability, reliability, performance, and security. *Figure 3* shows the non-functional requirements of the Oxycon system consisting of mechanical sub-systems, such as the design of the cooling sub-system, the creation of the dehumidifier sub-system, the design of the compression pump engine sub-system, and the design of the Oxycon product prototype enclosure. Then, in other aspects, the functional requirements of the Oxycon control system are electro-mechanical sub-systems and hardware such as control boards composed of microcontrollers, resistors, diodes, voltage regulators, capacitors, etc. The functional requirements of the Oxycon system are software sub-systems, such as the PSA control algorithm and physical sub-systems, such as the physical parameters of compressed air in a zeolite sieve absorbent tube.

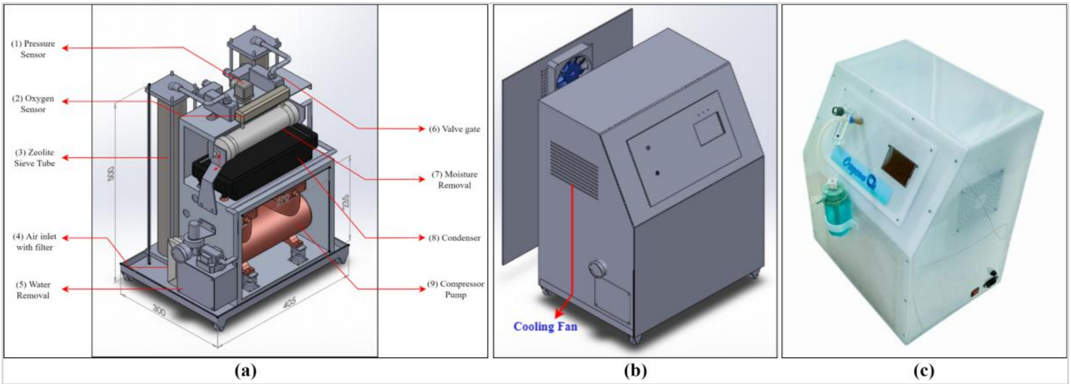


Figure 3 Design of Oxycon integrated telemetry communication (a) modeling of optimize Oxycon; (b) modeling of Oxycon optimizing the cooling system; (c) implemented Oxycon

The hardware of this system consists of several sensors integrated by a microcontroller. To facilitate installation between sensors and other supporting components, a printed circuit board (PCB) is made. The PCB contains each pin of each sensor, including the oxygen sensor, pressure sensor, and valve, which function as a control unit and data acquisition. The microcontroller processes the data from the sensor readings before sending it to the ESP32 module as a Wi-Fi module. (see *Figure 4*).

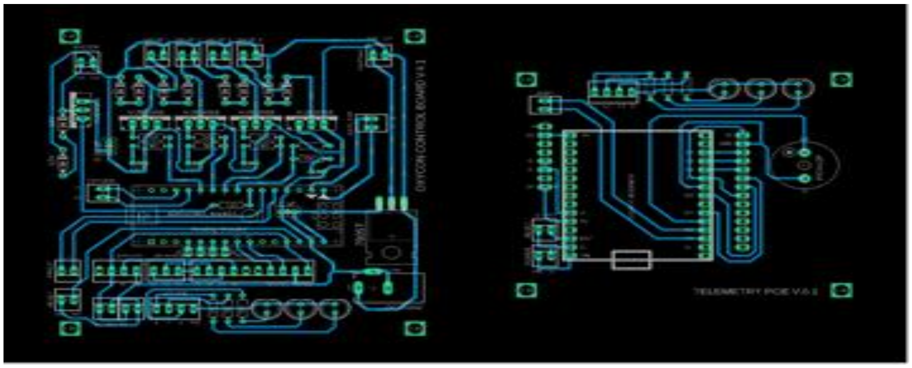


Figure 4 Schematic of control system and sensor reading

The design of the monitoring system and telemetry system implemented at Oxycon is based on device communication through universal asynchronous receiver transmitter (UART), BLE and wireless local area network (WLAN) methods. Communication between microcontroller devices using UART serial communication. Microcontroller as a transmitter with 8-bit processor specifications, 16 MHz clock frequency, 32 kB bootloader, 2 kb internal static random access memory (SRAM), 1 kb EEPROM, and serial communications such as UART, SPI, and I2C. At the same time, the system on a chip (SoC) is a receiver with 32-bit processor specifications, 448 kB ROM, 520 kB SRAM, 40 MHz Wi-Fi/Bluetooth, 802.11n Wi-Fi (2.4GHz), 8 MHz internal oscillator, 8-bit digital for analogue converter, and serial communications such as SPI, I2S, I2C, and UART.

The oxygen concentrator sensor (OCS) communicates with the microcontroller via a serial UART. OCS reading data in the form of oxygen concentration (O_2%), oxygen flow as liter per minute (Lpm) and oxygen temperature (Celsius). There are three indicators in the O2% reading: if O_2% <50%, then the red indicator light is on; if O_2% is > 50% and O_2% <82%, then the yellow indicator light is on; and if O_2% > 82% then the green indicator lights up. Furthermore, a pressure sensor reads the oxygen pressure that accumulates in the collection tube and is subsequently distributed to the patient. After the microcontroller receives the sensor reading data, the microcontroller then sends the data to the SoC via UART serial communication. After the SoC gets the data, the data is then processed to be displayed via the liquid-crystal display (LCD) and sent to the database server via WLAN communication (see *Figure 5*).

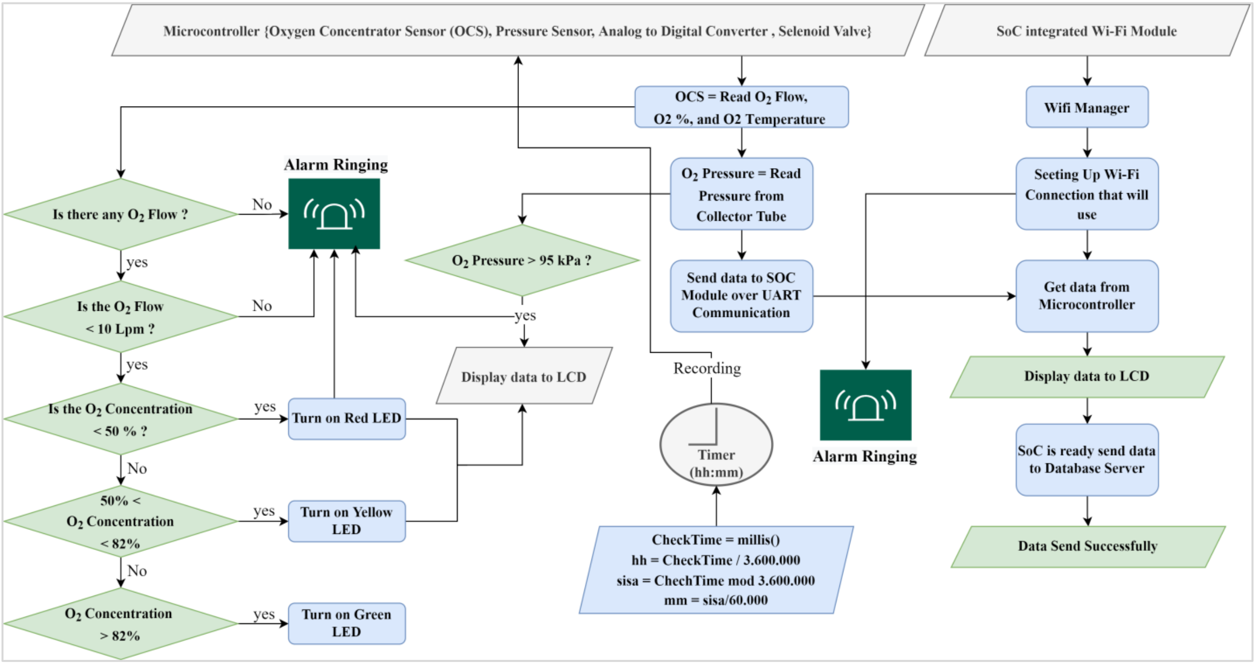


Figure 5 Flowchart of pneumatic control system and sensor reading

3.2Design of electromechanical sub-system of oximeter

The development of non-invasive medical devices such as oximeters has been widely circulated in society with standardized quality. However, regarding integration with the WBAN architecture, these commercial products use BLE wireless communication (see *Figure 6 (c)*), which technically cannot directly connect to the database server. To realize IoMT, commercial oximeters must be integrated with WLANs such as Wi-Fi (see *Figure 6(a)* and *(b)*) [46]. Integrating commercial Oximeter products into the IoMT system is a challenge in itself. For the Oximeter to connect to a WLAN, it requires a device that functions as a receiver that can communicate via BLE and Wi-Fi. When the Oximeter measures SpO_2, heart rate, pulse/perfusion rate (PR), and perfusion index (PI), the device immediately sends data to the receiver via BLE communication. The data received by the recipient is then obtained according to the needs of IoMT. After the recipient gets the data, the data is then sent to the database server for use by the telemedicine application.

To find out the best communication system that can be implemented on a WBAN, specifically on an Oximeter device, it is necessary to make an Oximeter device that uses a Wi-Fi communication system. Architecturally, the oximeter device that uses a WLAN or Wi-Fi communication system can be seen in *Figure 7 (a)*. The architecture of the Oximeter device that uses the BLE communication system is shown in *Figure 7 (b).*

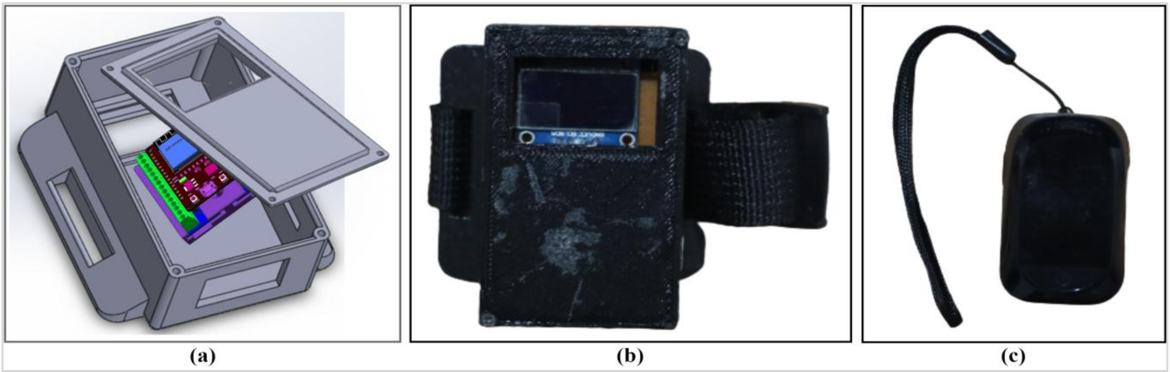
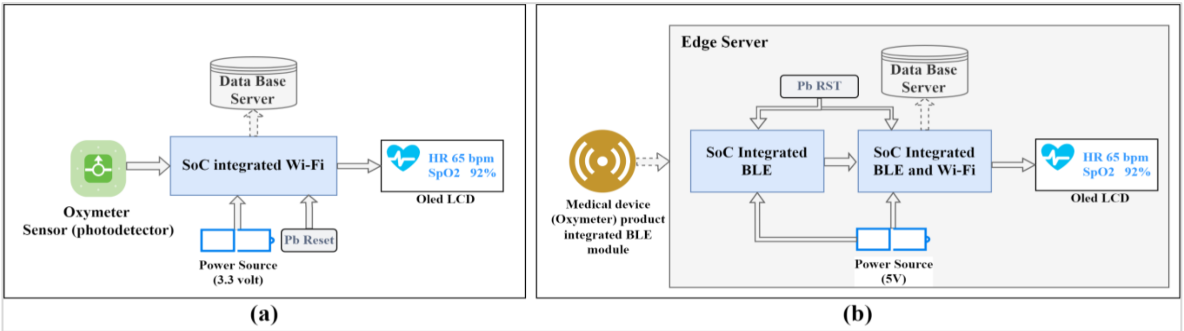

(a) (b) (c)

Figure 6 Oximeter integrated telemetry (a) Design Oximeter with Wi-Fi communication; (b) Implemented Oximeter with Wi-Fi communication; (c) Oximeter with BLE communication



(a) (b)

Figure 7 Architecture of oximeter integrated telemetry (a) Oximeter with Wi-Fi communication; (b) Oximeter with BLE communication to edge server

3.3Design and implementation of Edge server

Technically, the process of integrating commercial Oximeter products into the IoMT system by creating devices that function as receivers and transmitters (edge servers) [46]. In this case, we use two espressif system 32-bit (ESP32) SoC modules as receivers and transmitters with 2.4 GHz Wi-Fi and Bluetooth specifications. The first ESP32 module (M-1) is an Oximeter scanning device and acquires data via BLE communication. M-1 verifies the Oximeter device using a universally unique identifier (UUID) code. Two UUID codes must be known to be able to obtain data from the Oximeter, namely the BLE remote service UUID and the BLE characteristic UUID. The second module, namely ESP32 (M-2), functions as a device that sends data obtained by the first module to the database server. M-1 and M-2 work in sync, meaning M-2 can receive data from M-1 if M-2 is connected to a WLAN. So that the M-2 can be easily attached to a WLAN, a Wi-Fi manager system is implemented so that the scanning process can be done quickly by a smartphone. After M-2 has successfully connected to the WLAN, M-2 can receive M-1's acquisition data from the Oximeter. If M-2 has received the data, then M-2 sends data to the database server every 3 seconds (see *Figure 8*).

The results of the implementation of the edge server design used to receive data from WBAN devices with BLE communication are shown in *Figure 9*.

The edge server device features an interface in the form of an OLED LCD measuring 29.30 mm × 27.57 mm, along with a pairing button for establishing a connection between the edge server and a WBAN device using BLE communication, and it connects to

Wi-Fi. Additionally, it has a reset button and two indicator lights: a green light indicating data reception from the WBAN device and subsequent transmission to the database server, and a red light indicating a lack of device connection.

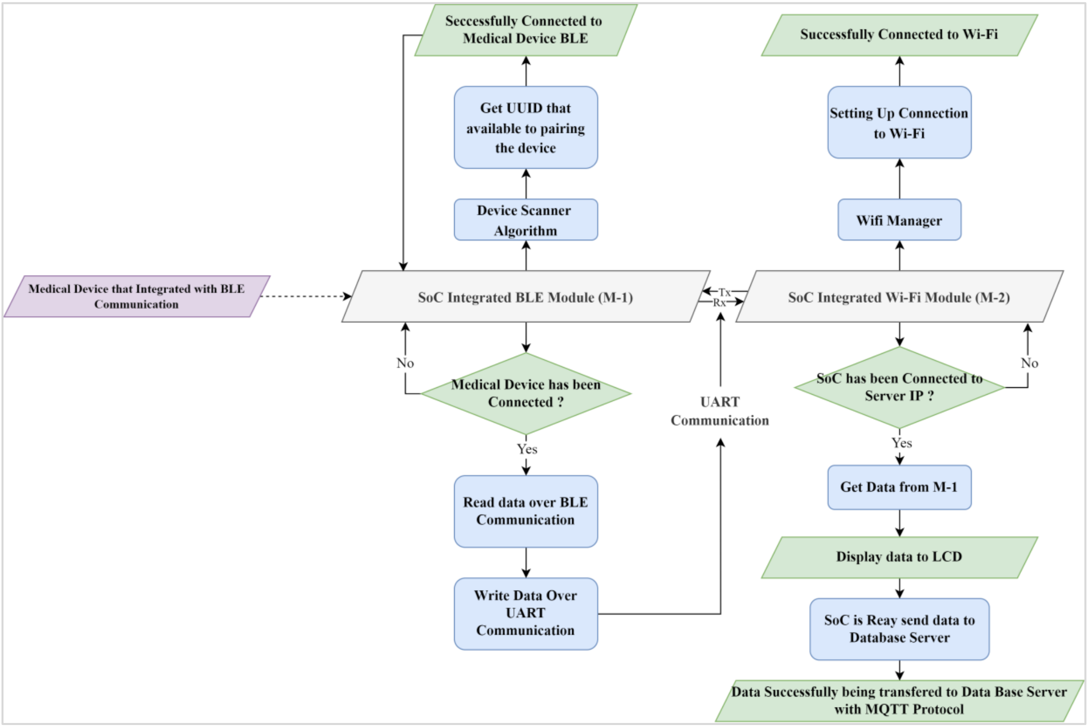


Figure 8 Algorithm state machine data acquisition of oximeter products and telemetry systems (edge server)

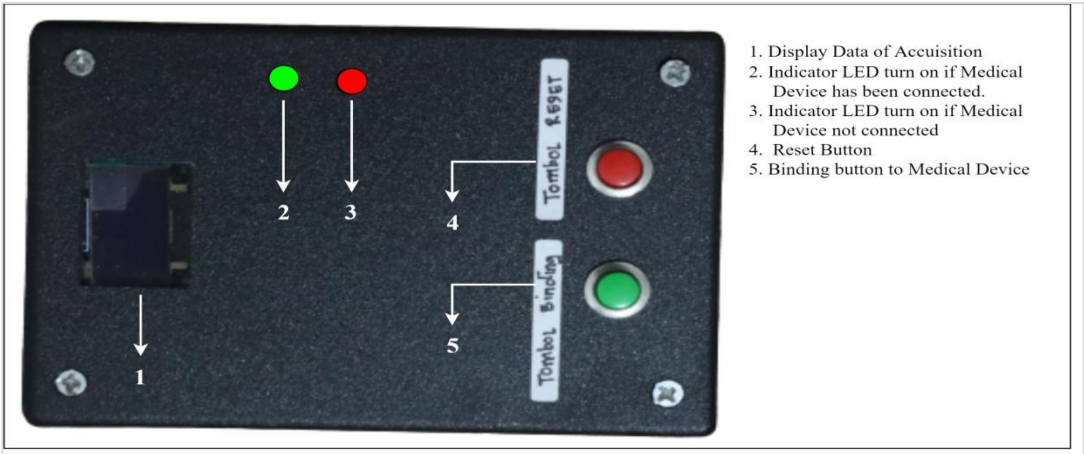


Figure 9 Oximeter integrated telemetry (a) Design Oximeter with Wi-Fi communication; (b) Implemented Oximeter with Wi-Fi communication; (c) Oximeter with BLE communication

3.4 Design of middleware

The data transmission system depicted in *Figure 10* is divided into four parts. The first part is the telemetry process, which reads data by the microcontroller from the data acquisition device in measured parameters (oxygen flow rate, temperature, bpm, SpO_2, pressure). The data is stored in a database via the internet, using the ESP Wi-Fi module as the internet gateway in the second part. The third part involves sending data from the data acquisition unit to the cloud storage area. Data received by the ESP module is transmitted as a hypertext transfer protocol (HTTP) request, and the server housing the database (cloud storage) responds to the client through the internet network. The fourth part encompasses the data analysis process. To facilitate users and medical personnel in monitoring, a user interface is built in the form of a website and mobile application that can be monitored in real-time.

Specifically, the third part is implementing cloud services by implementing a three-tier architecture consisting of the presentation, application, and data tiers. The authors build web applications in the presentation tier because they can be accessed from any device via a browser, choosing the Angular web application framework version 12 with the typescript programming language. This framework has good documentation and code management, so it helps the development process. Application tier implemented using representational state transfer application programming interface (RESTful API) applications that implement HTTP methods. The author chooses the H.API framework, which runs on the node.js runtime using JavaScript. The author chose this framework because it is robust, scalable, and reliable when serving data with JSON models and single-page applications such as Angular. The data tier uses a separate database with a particular purpose, namely for measurement results. Data that requires sorting at times utilizes a time series database, whereas a relational database is employed for managing informational requirements. There is a need for technology that uses an open licensed database to support research so that it can use all the features provided [47].

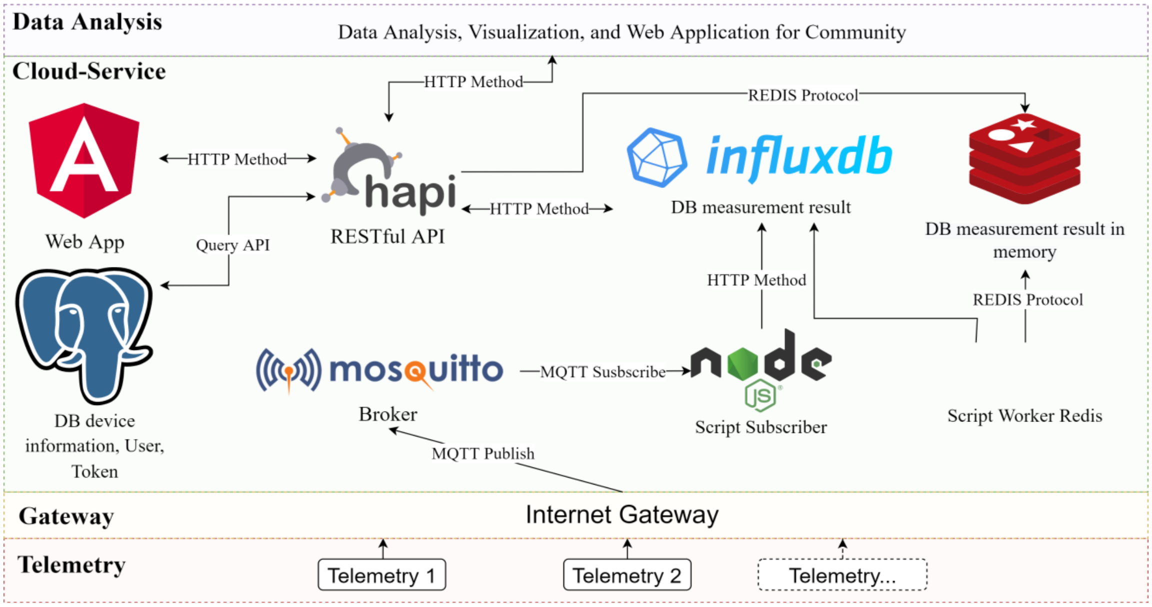


Figure 10 IoT system for data transfer

3.5 Design of mobile application for telemedicine

To develop mobile applications, we used Flutter as a framework. Flutter is a framework Google supports as an open source for building natively compiled and multi-platform applications. With Flutter, we can compile code in fast performance on any device, such as iOS, Android, web, and desktop. Besides that, Flutter promises the developer to create a beautiful cross-platform application from a single codebase.

Flutter employs the Dart programming language to ensure that programmers practice null safety programming. Null safety programming helps prevent runtime errors caused by unintentional access of null variables, which can be challenging to debug. With null safety, the compiler can optimize the code to create smaller binaries and faster execution. Dart is also open-source, so we can create and modify the code with open-source community support. In this project, we used Dart 2.18, which is available with Objective-C and Swift interoperability and has improved networking, type inference, and asynchronous code performance.

In this project, we created two kinds of mobile applications available for Android. The first application is for the patient or patient in charge, and the second is for the doctor. The application is used to input patient data, such as name and phone number, at the registration step and monitor the device's output in real-time. The patient application also provides information on the doctor's name and phone number assigned by the admin to monitor the patient. The most important task of the patient's application is connecting the oxygen concentrator device with its patient, so the device sends and stores biometry patient data with the associated patient in the database.

The primary purpose of the doctor's application is to help doctors monitor the device's current output for each patient assigned to them. Once the oxygen concentrator is powered on and connected to the internet, the doctor can access essential biometric parameters of the patient, including SPO_2 levels and the oxygen outflow rate from the concentrator. The doctor can also contact the patient or patient in charge directly from the apps via the phone number provided by the patient during the registration process.

We created an admin web page to assign doctors in charge to patients. This web is provided for the admin person. The admin's main job is to set a doctor to its patient.

Following the patient registration process, the administrator promptly assigns doctors to the respective patients. The admin can also activate and deactivate the doctor's account and input the doctor for registration. Each doctor needs admin verification before being assigned to monitor a patient's biometry data.

An overview of the use case for all actors is shown in *Figure 11*. This use case diagram shows that all actors must log in before carrying out an activity in the system. Registration only applies to doctors and patients, while admin accounts cannot be registered outside the system. The use case shows that the patient can do several things, such as login, register, and connect the oxygen concentrator device with the patient himself so that later, the data sent to the device correlates with the appropriate patient information. Furthermore, doctors can log in, register and view patient medical data information. Doctors can also view historical data from patients. For admin actors, they can verify the information of doctors who register and assign doctors to supervise patients based on sensor data obtained from the tool in real time.

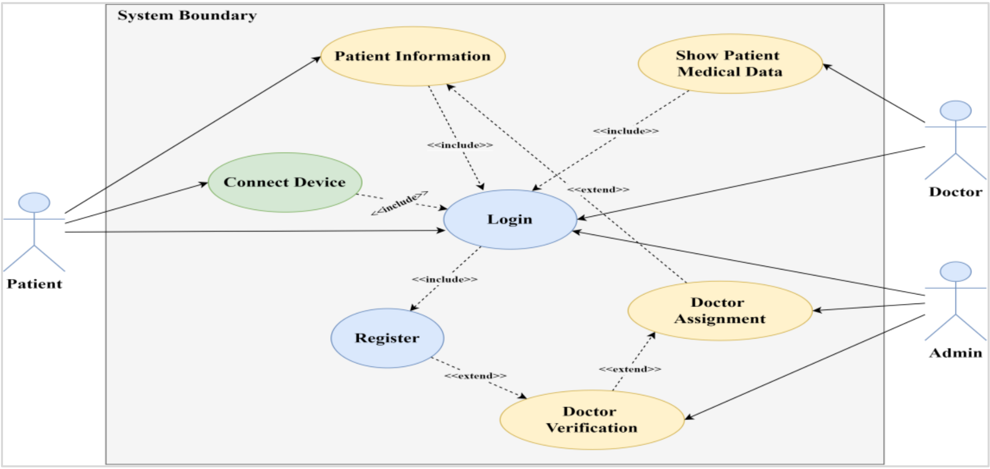


Figure 11 Use case diagram for users

Sequence Diagram 1 can be seen in *Figure 12:* Patient logs in and registers identify the object and the actors involved:

a. Patient
b. Oxycon information system (OIS)
c. User credential database (UCD)
d. Email system

Steps in the use case patient login and register:

a. Before logging in, the user must already have an account.
b. Accounts can be obtained by registering in the information system through the mobile application. Registering is done by filling in patient information data.
c. After entering personal data, the information system requests the email system to send an account confirmation link for account activation via email. Patient activates the account by opening the link provided.
d. Patient accounts that have been activated can then log in by entering the email and password used when registering.

e. If the email and password are appropriately verified and available in the UCD, the patient's account can be logged into the system.

Sequence Diagram 2: Patient connects Oxygen Concentrator

Sequence Diagram 3: Admin verify doctor data.

Sequence Diagram 4: Admin assigns doctors to supervise patients.

Sequence Diagram 5: Doctor logs in and registers

Sequence Diagram 6: Doctor looking at patient's medical data.

Figure 13 is a website intended for doctors. *Figure 13 (a)* is an authentication page to verify doctor data via email and password. In *Figure 13 (b)* is a list of patients undergoing treatment with the doctor concerned. In contrast, *Figure 13 (c)* is a patient detail page that contains the name of the patient being monitored, patient contact (which has been integrated by the patient'sWhatsAppp application), and parameters that the patient's condition in the form of oxygen rate, SpO_2, temperature, and pressure in real-time.

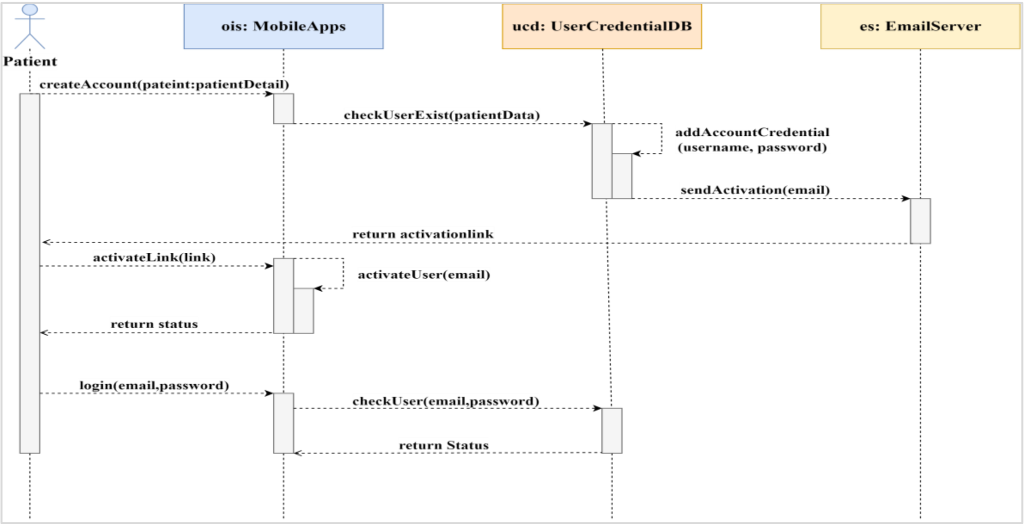
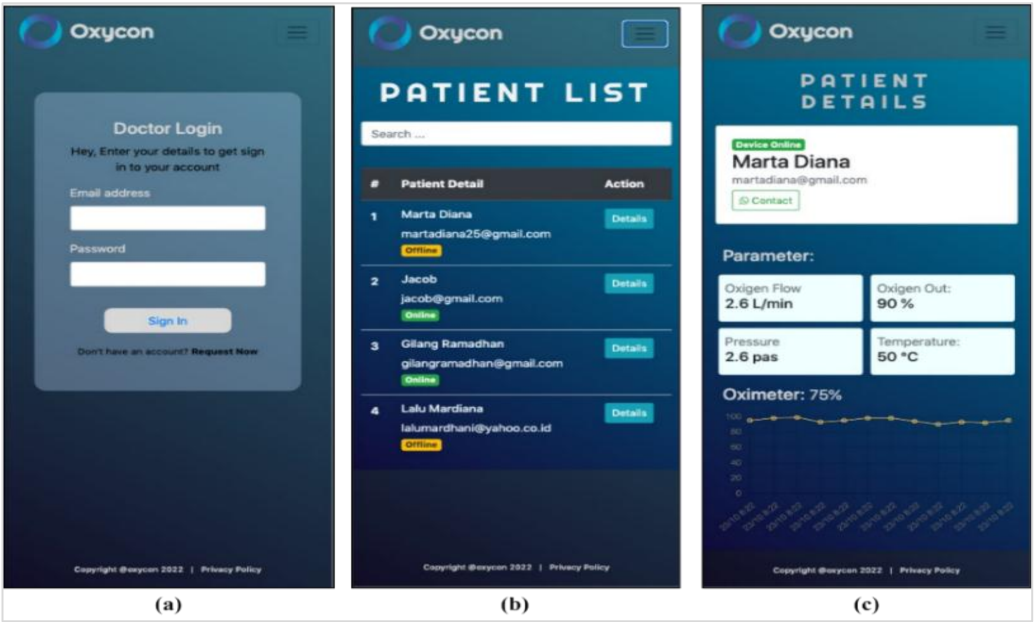


Figure 12 Sequence diagram for users



Hey, Enter your details to get sign in to your account

Don't have an account? **Request Now**

(a)

#	Patient Detail	Action
1	Marta Diana martadiana25@gmail.com Offline	Details
2	Jacob jacob@gmail.com Online	Details
3	Gilang Ramadhan gilangramadhan@gmail.com Online	Details
4	Lalu Mardiana lalumardhani@yahoo.co.id Offline	Details

(b)

Device Online

Marta Diana

martadiana@gmail.com

Parameter:

Oxigen Flow
2.6 L/min

Oxigen Out:
90 %

Pressure
2.6 pas

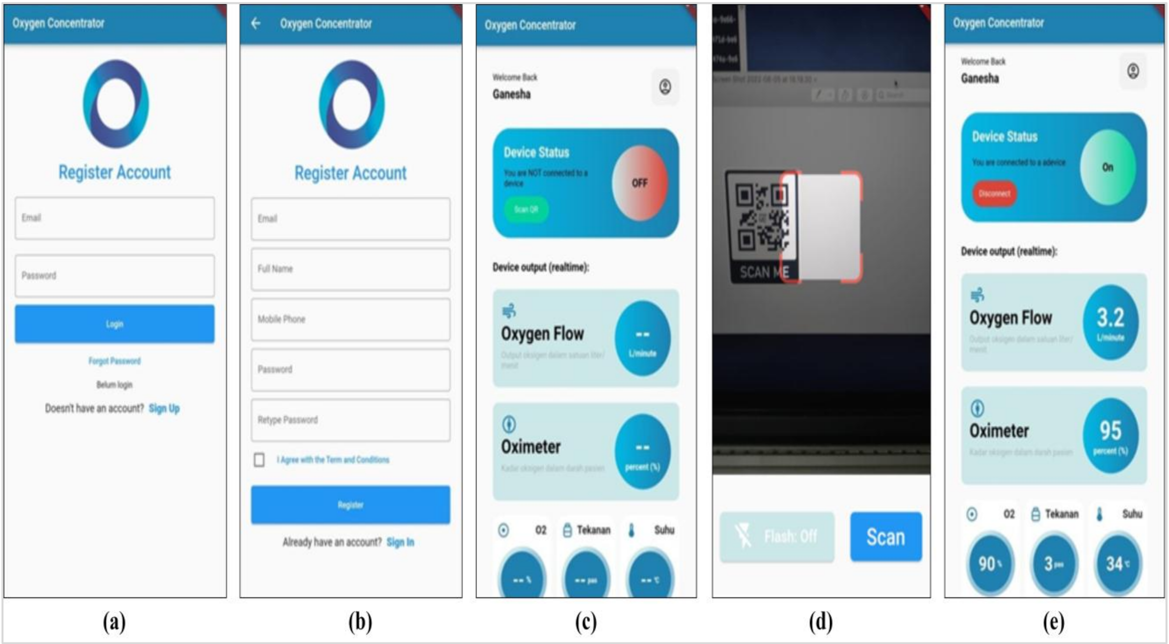
Temperature:
50 °C

Oximeter: 75%

(c)

Figure 13 Homepage of smartphone application for doctor, (a) Authentication, (b) Patient list, (c) Patient detail information

The application successfully designed for patients (see *Figure 14*) has a register page, homepage 1-page, quick response code (QR) scan page, and homepage 2-page. The register page is the start page that customers can see when downloading the application. If you already have an account, you must enter your registered email and password; if not, you can register if you still need to press the Sign-Up button. Homepage 1 is the page customer where successfully logged in or registered. In this menu, you can find details about the customer, the device's connection status, and real-time oxygen concentrator output. To access this information, the customer must press the "Scan QR" button and scan the QR code affixed to the device. The QR scan page contains a display when the customer presses the Scan QR button to scan the QR Code on the oxygen concentrator device. Homepage 2 contains information if the device is connected and in the ON status. Likewise, indicators of each sensor parameter are displayed in real time. Customers can also disconnect real-time equipment used if it is deemed necessary by pressing the button.


You are NOT connected to a device

You are connected to a adevice

Figure 14 Telemedicine application UI/UX (a) Login page; (b) Registration page (%); (c) Main menu page; (d) Device QR identification; (e) The main page that has been connected to the database server

4.Result

Based on our previous research on Oxycon for telemedicine [3], Oxycon system testing has been carried out for one month with a throwaway prototyping development system. The development method is carried out to get the best performance from the oxygen concentrator, utilizing design, implementation, and evaluation in parallel. By continuing to evaluate, a truly tested product design is obtained so that the goal of creating an oxygen concentrator device can be appropriately achieved; oxygen production with a purity of 95% was achieved stably during the test. Test duration was carried out for 6 hours daily, as shown in *Figure 15.*

In the process of telemedice therapy, many medical devices are used by patients to monitor health conditions with invasive measurements. One of the important devices in SPO_2 therapy is using an oximeter. However, oximeters are available for telemetry needs with BLE communication systems so that an edge server is needed to transmit data via internet communication to the main server. In addition, we also compare oximeters with Wi-Fi communication and BLE oximeters, which is the best among them. Testing the developed Oximeter (DIY) device with a Wi-Fi communication system was conducted by comparing the readability results of SpO_2 readings in patients with standardized Oximeter readings. The measurement results show that the measurement value of the DIY Oximeter can measure the patient's SpO_2 with good accuracy if compared to standardized Oximeter device. The mean absolute percentage error (MAPE) value is 0.874 % and the

SpO_2 value of the DIY Oximeter with a MAPE rounding value of 0.811%. *Figure 16* is the result of the testing DIY Oximeter against standardized Oximeter during one hour of use. In terms of measurement between two Oximeters show the same trend with the same measurement object, so it can be said that DIY Oximeters are reliable to be used as SpO_2 measurements but need to be standardized the Health Facility Security Canter.

Then, the next test is the electric energy consumption of DIY Oximeter devices and standardized Oximeters. DIY Oximeter devices use 3.3 VDC Lithium polymer batteries with a capacity of 700 mAh and standardized Oximeter devices with 3.3 VDC Ni-MH batteries with a capacity of 700 mAh. Standardized Oximeter devices with BLE communication can turn on for up to 12 hours, while DIY Oximeter devices can last for 2 hours.

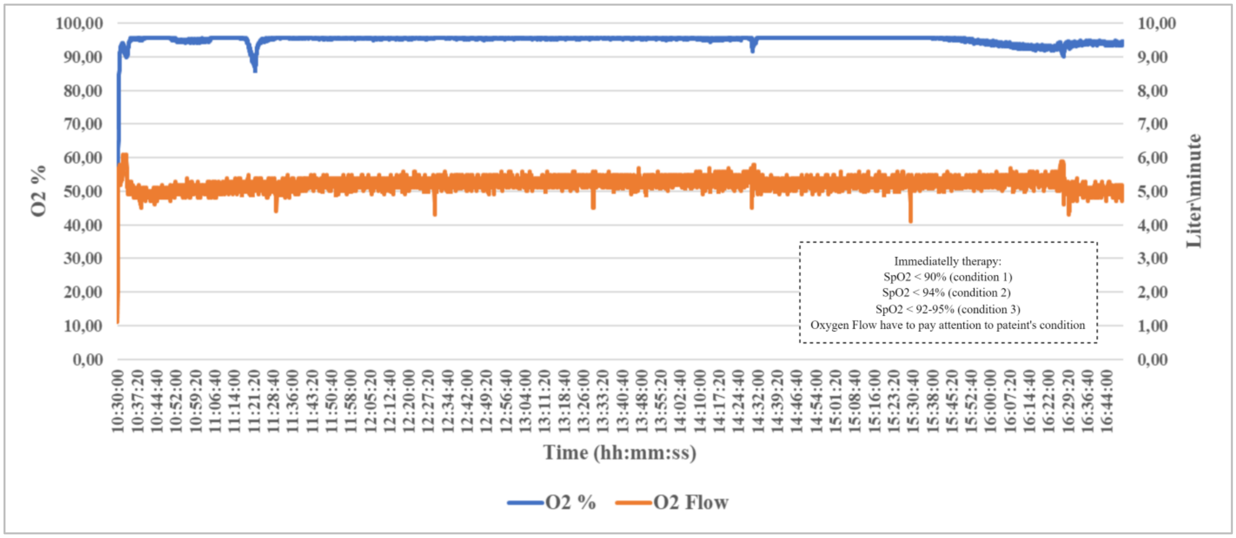


Figure 15 Pure oxygen concentration production with PSA technique

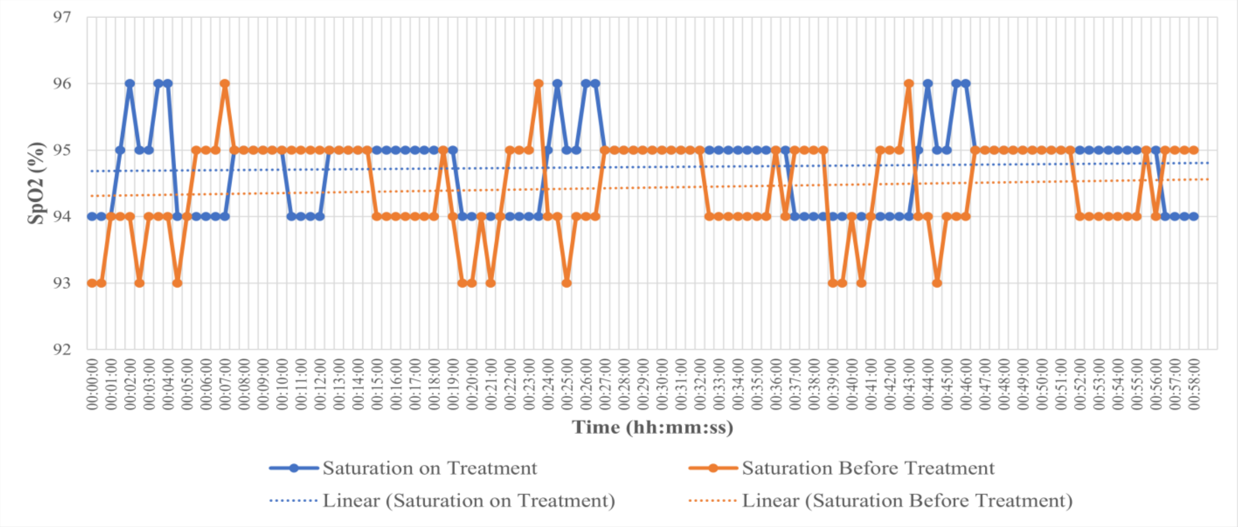


Figure 16 Testing for changes in saturation during the therapy process and before therapy

Next, testing of sending data from the microcontroller to the gateway is carried out for 40 minutes with a delay of 2 seconds. The results show good real-time system performance, as shown in *Figure 17 (a).* During the testing process, the data that must be sent to the server is 2400 seconds divided by 2 seconds for each data, which is 120a. The total percentage of successful data transmission to the gateway is 100% from the test result statistically, the average time for sending data to the gateway is 9 milliseconds and the maximum delay is 50 milliseconds. Meanwhile, the test results for transmitting data from the gateway to the server provide good real-time system performance results, accompanied by request time-outs caused by several things, including temperature noise, obstructions made of metal materials, and rainy weather, impact on signal attenuation (see *Figure 17 (b)*). Statistically, the results of measuring real-time system performance provide an average delivery time of 2.511 milliseconds and a maximum delay time of 26.436 milliseconds.

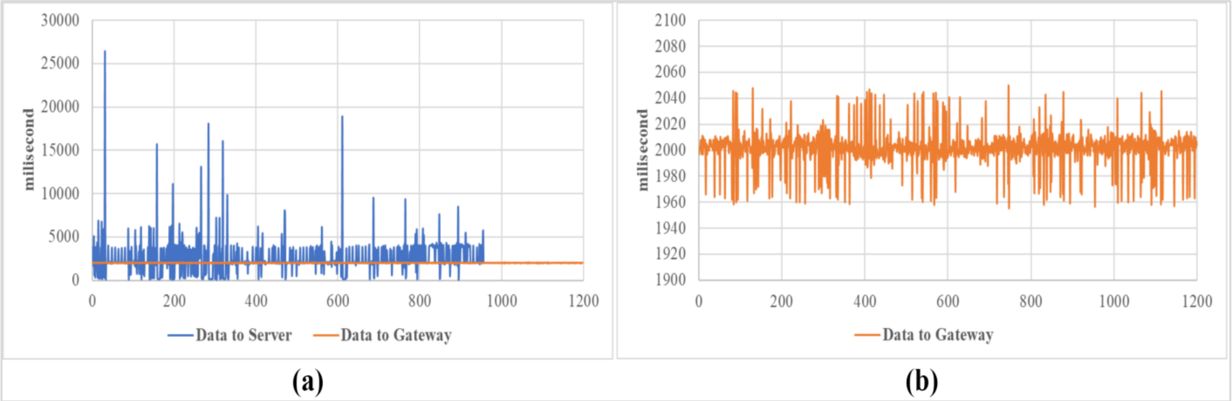


Figure 17 Oxycon real-time telemetry test production capacity 5 Lpm (a) Data transfer to the server that occurs request time out; (b) Sending data in serial communication to the gateway

Next, we integrated Oxycon data and Oximeter data during ongoing therapy on telemedicine applications. For performance testing of the application, we used performance monitoring tools provided by Firebase. Integrating the performance monitoring software development kit (SDK) on the mobile application makes these tools available. Due to the mobile application being created by Flutter and Firebase, these tools are natively supported. The performance monitoring feature provides a dashboard to gain insight into the application's performance. From the dashboard, we can analyze data such as the application's loading time from various Android device models.

In this study, we conduct application startup time tests and test for cold start. Cold start means the application still needs to be started or running in the background. Application startup times are crucial for users because users expect a fast and responsive application to load. An application with a lengthy startup time can lead to user dissatisfaction. From the Firebase performance dashboard, we have information that the loading time for android devices with Xiaomi Redmi Note 3 is 865ms for cold start. This device was first released in November 2015 with graphics processing unit (GPU) Snapdragon 650 and 3 GB of RAM. Android has a standard for a cold start of at most 5 seconds, which our application is far from it for the device that has been released for more than five years.

The telemedicine system that has been tested is then tested on patients suffering from hypoxemia or athletes who need additional oxygen treatment. Oxygen treatment is needed when the patient runs into a condition of low blood oxygen levels, also known as hypoxemia. Untreated acute hypoxemia can lead to tissue hypoxia (low oxygen levels at the cellular level), organ dysfunction and death. The delivery of oxygen to cells also depends on cardiac output (cardiac output) and hemoglobin (Hb) to carry oxygen to the tissues. Oxygen therapy can improve oxygen delivery to cells by enhancing the amount of oxygen in the blood. The amount of oxygen in the blood was measured using pulse oximetry as SpO_2. On oxygen therapy, patients get oxygen supply with a higher concentration than free air (> 0.21). Oxygen delivery devices should be selected based on the patient's oxygen requirements, including nasal cannula, conventional mask, venturi mask, and mask with reservoir bag. If the patient requires a higher oxygen flow rate (>10–15 L/min) to reach the target SpO_2, and/or shows other signs of respiratory failure, use another rescue breather capable of providing higher oxygen flow and/or positive pressure can be considered. The rationale for the use of oxygen begins with the provision of minimal oxygen supplementation until the required SpO_2 target is achieved. Although avoiding hypoxemia is the main goal of oxygen therapy, it is important to remember that oxygen administration exceeding the need to achieve the target SpO_2 can be dangerous for the patient. Therefore, oxygen supplements and weaning should be carried out periodically. Check the quality of the oxygen source periodically, including oxygen concentration and flow or pressure output. The process of monitoring patient progress remotely can be realized as shown in the schematic in *Figure 18*. The Oxycon and Oximeter devices communicate with edge server devices using BLE communication. These devices send monitoring data every 3 seconds to the edge server. The edge server pre-processes the data and then sends it to the main server with encrypted data. After receiving the data, the mobile application that has been created displays information about the patient's condition during remote therapy.

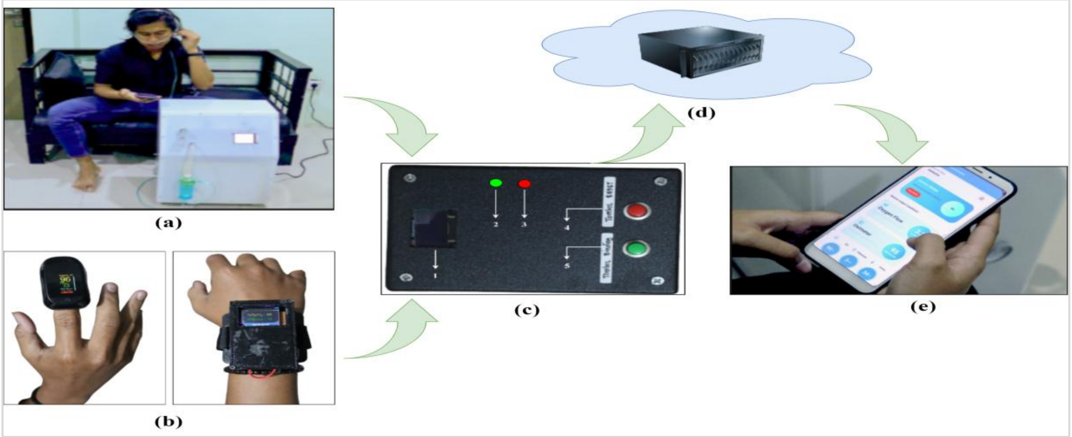


Figure 18 Remote therapy based on telemedicine process (a) Patient uses Oxycon; (b) Patient uses oximeter; (c) Edge server receive data from Oxycon and Oximeter; (d) Main server receive data from edge server; (e) Telemedicine mobile application

Our research has been functionally implemented for remote respiratory therapy by physicians. Our research is supported by our previous study in improving Oxycon's performance to produce 95% pure oxygen stably in environments with high air humidity [3]. A key concern in our study was real-time consistency in the medical telemetry process. Telemetry process that we conducted with internet network quality/quality of service (QoS) using AxencenetTools obtained an average delay value of 90.71 milliseconds, an average jitter value of 11.92 milliseconds, an average packet loss value of 3.90 (3%) and an average throughput value of 28.78 milliseconds (89%), then referring to the TIPHON standard category of wireless networks that we use are categorized with an average index of 3.5 (good). While the results of the real-time test of sending data that we did from the edge server device to the main server gave good results as previously explained.

Ten participants who suffered hypoxemia with a mean age of 25 were involved in the study. Our findings suggest that a man suffering from hypoxemia that didn't get supplementary oxygen after doing sport saturation measurements below 94% (p = 0.03). The non-improvement group presented with a lower mean—94 (93–96) % versus 96 (95–97) %, p=0.01 and minimum saturation—89 (86–92) % versus 92 (90–94) %, p=0.04. They also presented higher variations in saturation measurements; saturation amplitude was 9 (7–11) % versus 7 (4–8) %, p=0.03. The comparison of both study groups along with statistical values is specified in *Table 3*.

Table 3 Comparison of the improvement and non-improvement participant group

Parameter	Improvement	Non-improvement	p-value
Saturation amplitude, % median [inter quartile range]	7 [4–8]	9 [7–11]	0.03
Mean saturation, % mean	96	94	0.01
Minimum saturation, %, mean	92	89	0.04

5.Discussion

Our study objective was to create a SpO_2 therapy system by integrating a mobile oxygen concentrator with a smartphone app and telemedicine, enabling lung specialists to oversee and manage patient progress. The oxygen concentrator prototype of our previous study consistently delivered oxygen concentrations of up to 95% during treatment and could be controlled remotely. To develop the mobile application for this system, Flutter, an open-source framework supported by Google, was employed. Flutter enables high-speed performance and the development of visually appealing cross-platform applications using a single codebase. To address respiratory illnesses in patients, an algorithm was devised based on scientific literature, serving as the core design of the telemedicine application. The oximeter device used in the system can communicate through either Wi-Fi or BLE. Mobile oximeters can be employed to monitor SpO_2 levels in patients receiving oxygen therapy, but it's essential to consider the oximeter device's ergonomic and practical aspects. Avoiding excessive supplementary oxygen administration is crucial, making the determination of therapy duration a vital parameter to prevent adverse effects. The success of the SpO_2 therapy process relies on precise monitoring and control by lung specialists. This study underscores the necessity for an integrated SpO_2 monitoring system that fuses digital technology and medical devices to enhance patient care.

Our study underscores the significance of establishing a therapy duration parameter to prevent adverse effects stemming from excessive oxygen administration. It also addresses the imperative need for robust data security measures, encompassing encryption, authentication, and authorization, aimed at safeguarding patient confidentiality. Furthermore, the research recognizes the requirement for additional exploration into the integration of the mobile oxygen concentrator device with a smartphone application for pulmonologists to monitor patient conditions effectively. It emphasizes the potential advantages of telemedicine systems over conventional approaches and underscores the vital roles of patient data security management and community acceptance of telemedicine. The system incorporates several functionalities, including real-time monitoring of patient biometric data, historical data analysis, and the allocation of doctors for patient supervision based on sensor data. The study proposes future hardware enhancements, such as ensuring a stable internet connection and employing proficient microcontrollers to optimize data transmission efficiency. Additionally, it highlights the necessity for further investigation into potential biases in SpO_2 measurement across various skin tones and improving the accuracy of respiration rate estimation.

The implication of our study as potential of incorporating digital technology, including mobile Oxycon and telemedicine, to enhance patient care and treatment precision. This system enables the remote monitoring and control of SpO_2 therapy, empowering doctors to make precise treatment decisions. Integrating telemedicine technology has the potential to improve patient-centered care and self-care, particularly in lung transplantation. Telemedicine-based care solutions, such as telemonitoring and teleconsultation, offer practical approaches for patients and clinicians, particularly in the context of remote patient monitoring. Ensuring data security and privacy is pivotal in telemedicine system development, guaranteeing the safeguarding of patient information. Telemedicine is regarded as a pivotal component of future healthcare, promising potential benefits for upcoming generations. The study advocates for further research into community acceptance of telemedicine and the optimal practices for its implementation.

A notable constraint of our study is that we exclusively examined the impact of the telemedicine process on athletes who had engaged in strenuous physical activity as our research subjects. Logically, individuals who have undergone rigorous exercise are expected to encounter a reduction in SPO_2. To ensure more conclusive findings, it becomes imperative to conduct tests on hospital patients dealing with acute hypoxemia disease in future research endeavors.

A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

The main requirement is an Oxycon that can produce 95% pure oxygen and has flow rates in the range of 1-15 Lpm. Additionally, the developed oxygen concentrator is integrated with an IoT system to facilitate monitoring between device users and third parties, such as lung specialists. Monitoring the patient's health development helps avoid the negative impact of high SPO2 levels. Oxygen therapy is immediately administered to patients, including adults and children, with conditions such as respiratory disorders, sepsis (systemic infection) with hypoperfusion or shock, changes in mental status (reduced consciousness), and hypoxemia ($SpO_2 <$ 90% if the patient's hemodynamic condition is stable; $SpO_2 <$ 94% if the patient displays emergency signs with or without respiratory distress; $SpO_2 <$ 92-95% if the patient is pregnant).

In hardware development, there are several challenges when sending data from the sensor to the database, including an unstable internet connection and delays in the microcontroller's response during data transmission. These issues lead to delays in sending sensor data. Suggestions for improvement include addressing internet connectivity issues and selecting a more reliable microcontroller.

In software development, data security is a critical concern due to the sensitive nature of patient data stored in the information system. Ensuring data privacy is essential for user comfort. Data transmission from the user to the server must be encrypted using a secure protocol. Additionally, on the server side, authentication and authorization are implemented to restrict access to patient data, ensuring that only authorized individuals, such as the treating physician, can view the data. This requirement remains a key focus for ongoing system development.

The paper acknowledges the need for further research to address bias in SpO_2 measurements related to different skin colors and to enhance the accuracy of respiration rate estimation, particularly for rapid breathing patterns. Future work will prioritize resolving these limitations. This study aimed to evaluate the effectiveness of telemedicine systems compared to traditional methods. Future research will also explore patient data security management in telemedicine systems and assess the level of community acceptance of telemedicine.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Galang Adira Prayoga: Conceptualization, validation, writing-original draft, analysis and interpretation of results. **Emir Husni:** Supervision, conceptualization, writing-review and editing. **I Putu Satwika:** Data collection, analysis and interpretation of results. **Marta Diana:** Data collection, analysis and interpretation of results.

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Appendix I

S. No.	Abbreviation	Description
1	BLE	Bluetooth Low Energy
2	COVID-19	Coronavirus Disease 2019
3	ESP	Espressif System 32-bit
4	FURPS	Functionality Usability Reliability Performance and Security
5	GPU	Graphics Processing Unit
6	IoMT	Internet of Medical Things
7	IoT	Internet of Things
8	LCD	Liquid-Crystal Display
9	Lpm	Liter Per Minute
10	MAPE	Mean Absolute Percentage Error
11	OCS	Oxygen Concentrator Sensor
12	OIS	Oxycon Information System
13	OMS	Oral and Maxillofacial Surgery
14	Oxycon	Oxygen Concentrators
15	PI	Perfusion Index
16	PR	Pulse/Perfusion Rate
17	PSA	Pressure Swing Adsorption
18	QoS	Quality of Service
19	QR	Quick Response Code
20	RESTful API	Representational State Transfer Application Programming Interface
21	SRAM	Static Random Access Memory
22	SDK	Software Development Kit
23	SoC	System on a Chip
24	SpO_2	Oxygen Saturation
25	UART	Universal Asynchronous Receiver Transmitter
26	UCD	User Credential Database
27	UUID	Universal Unique Identifier
28	WBAN	Wireless Body Area Network
29	WLAN	Wireless Local Area Network