Detection of Oxygen Levels (SpO2) and Heart Rate Using a Pulse Oximeter for Classification of Hypoxemia Based on Fuzzy Logic

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ARTICLE INFO

Article history:

Received November 03, 2021
Revised March 18, 2022
Accepted April 04, 2022

Keywords:

Fuzzy Logic;
Heart Rate;
Hypoxemia Classification;
Oxygen Levels;
Pulse Oximeter

ABSTRACT

This study made the digital system to perform screening (early prediction) of Hypoxemia using MAX30102 sensor with the fuzzy value from SpO2 level and heart rate. This research also uses the Internet of Things (IoT) system to gather data from devices to the cloud. Hypoxemia is a lack of oxygen in the blood flowing in the body. Hypoxemia conditions in the body due to lack of oxygen levels in the blood will cause an increased heart rate. Hypoxemia conditions that are not immediately recognized cause damage to cells, tissues, and organs. Hypoxemia is an essential condition because information about oxygen levels in the blood is closely related to health conditions. In this project, researchers built a Hypoxemia early detection system. From the research results, it is found that the accuracy rate of the system to detect hypoxemia is 80%, with 60% sensitivity and 100% specificity. Based on the experiment, this research is able to help screening detection (early prediction) of Hypoxemia.

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1. INTRODUCTION

Happy Hypoxia is a condition that has been a topic of discussion a few times ago because it is called a symptom that someone has COVID-19 [1]. Hypoxia is a term used to describe a condition when the oxygen level is insufficient in the body [2]. Usually occurs due to insufficient oxygen concentration in the blood, otherwise known as Hypoxemia [3]. These conditions will cause an increase in heart rate [4]. Mostly, hypoxemic patients will complain of being breathless [2].

Hypoxemia is a symptom of various diseases, such as Hypercholesterolemia [5], Asthma [6], GERD [7], Anxiety Disorder [8], and others. If not immediately known, Hypoxemia can cause damage to cells, tissues, and organs such as the brain and even heart failure [2]. So, Hypoxemia is important to know because it is very closely related to health conditions and can be detected by measuring SpO2 levels and heart rate.

There is some previous research that is related to this research. In 2014, a study was conducted to detect heart rate and blood oxygen levels (SPO2) using a photoplethysmograph-based pulse oximeter [9]. A study also used a pulse oximeter to detect arrhythmia. The research also uses IoT technology and can connect to an android application [10]. Another research uses MAX30102 and Optical camera communication to detect heart rate and oxygen level for a real-time monitoring system [11]. The research also used MAX30102 and fuzzy logic to detect Hypoxic Symptoms [12]. Based on the research before, there is no research that integrates MAX30102, fuzzy logic, IoT system, and android application for monitoring and detecting Hypoxemia.

This research develops a non-invasive system to perform screening (early prediction) for Hypoxemia. The detection system is made using Fuzzy Logic by utilizing two parameters: heart rate (bpm) and SpO2 level, which were detected using the MAX30102 sensor. This research uses the MAX30102 sensor because high sensitivity for detecting pulse oximeter and heart rate and can be used for wearable health purposes [12]. This research will use the IoT concept to make historical data save in the cloud. IoT is a technology that connects several devices via an internet connection to the cloud [13]. IoT uses the internet to send data from the physical world to the cloud using a specific protocol [14]. In the health sector, the Internet of Things is designed to help health workers by providing complete information about patient diseases and can respond to changing health conditions in a timely manner [15]. IoT generates data from one or more sensors from the physical world [16]. The data generated from the sensor will analyze using specific techniques, and the result can display on all devices that connect to the IoT system [17]. The prediction results generated by the system in this research will later be saved to Google Firebase. Besides being displayed on the LCD, it will also be displayed via the Android application that connects to the IoT system. This system will help make it easier for the user to see the predicted results from the hypoxemia analysis carried out by the system.

2. METHOD

This study began with the process of reviewing research papers discussing Hypoxemia. The first research by [4] stated that when the SpO2 level will decreases and the heart rate will increase to compensate for the lack of oxygen but has a problem developing a system that can be used to screen for hypoxemia. Table 1 and Table 2 are value grouping from SpO2 and Heart Rate.

Second research by [9] found the value of the SpO2 level and the heart rate using a pulse oximeter based on a photo plethysmograph which is a non-invasive technology using a light source or a photodetector on the skin's surface to measure circulator volume variation so the results could be grouped based on its categories.

The research conducted by [4] and [9] was then developed to process data on SpO2 levels and heart rate to detect Hypoxemia. So this research implemented a fuzzy system that will process the value of SpO2 and heart rate to detect Hypoxemia using sensor a pulse oximeter MAX30102, which is a non-invasive sensor that can detect SpO2 levels and heart rate integrated into one chip, that consists of two LEDs combination, photodetector, optimal optics, and low noise analog signal processing, then connected to a microcontroller for data processing [18]. The Fuzzy Logic approach has advantages in human cognitive traits, especially in concept formation, pattern recognition, and decision making in uncertain or unclear environments [17][19].

Table 1. SpO2 Value Grouping [4]

SpO2 (%)	Status
95 – 100	Normal
91 – 94	Mild
86 – 90	Moderate
<85	Severe

Table 2. Heart Rate Value Grouping (HR) [4]

Age	Heart Rate (BPM)	Status
Minimum 15 years	< 60	Bradycardia
Minimum 15 years	60 - 100	Normal
Minimum 15 years	> 100	Tachycardia

2.1. General System Process

Fig. 1 and Fig. 2 are architecture and flowchart from the proposed system that describes the process of Hypoxemia detection. The MAX30102 sensor will work when a finger is attached to the sensor. The sensor is connected to the Arduino UNO microcontroller for data processing. The value of SpO2 levels and the heart rate (bpm) will be processed using Fuzzy Logic to obtain Hypoxemia predictions. The results of measuring the value of SpO2 levels and heart rate will be displayed on the LCD. If the system is connected to the internet, then the ESP8266 module as a Wi-Fi module will send the data to Google Firebase in JavaScript Object Notation (JSON) format, and the results are also displayed on the Android Application. According to [20] research, the database provided by Google Firebase is much more efficient in speed than SQLite.

2.2. Fuzzy Logic Model and Design

Fuzzy Logic is a technique used to replace the uncertainty of a question with multiple answers [21]. One of the Fuzzy modeling methods is the Sugeno Fuzzy Inference System. The process has three architectures or workflows: Fuzzification, Inference, and Defuzzification [22]. The fuzzification process will change the crisp data into membership degrees. In this study, the fuzzification process was used to determine the fuzzy input variable; the heart rate (bpm) and the oxygen saturation in the blood (SpO2).

The SpO2 membership function uses a trapezoid shape and shoulder curves like Fig. 3. When the SpO_2 value is less than 85% is included in the severe membership function, SpO_2 values 86% to 90% are included in the moderate membership function, SpO2 discounts 91% to 94% are included in the mild membership function, and SpO_2 values of more than 95% are included in the standard membership function.

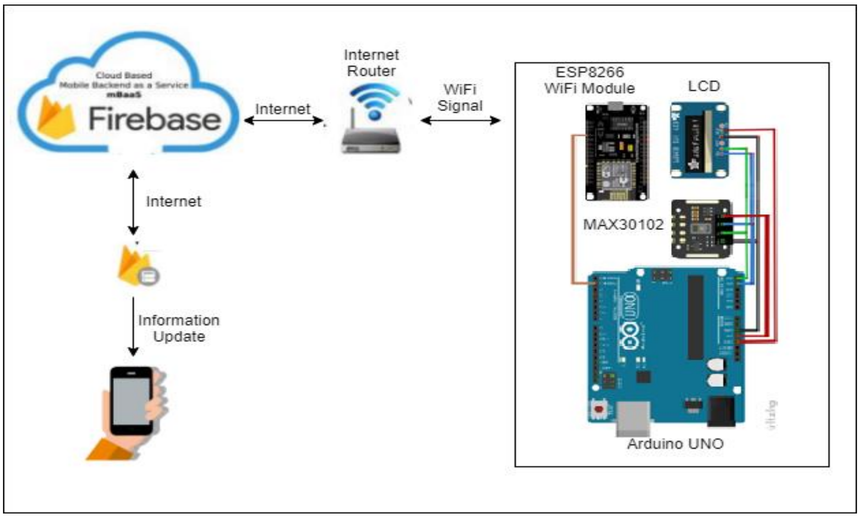

Fig. 1. System Architecture

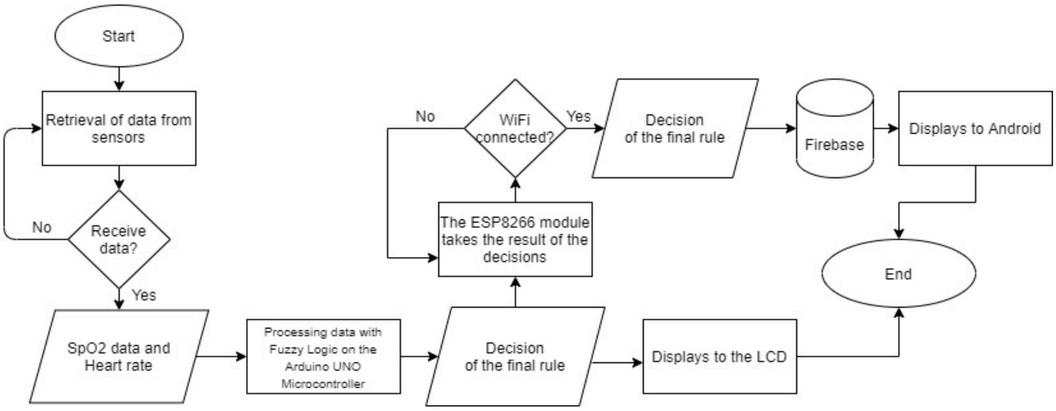

Fig. 2. System Flowchart

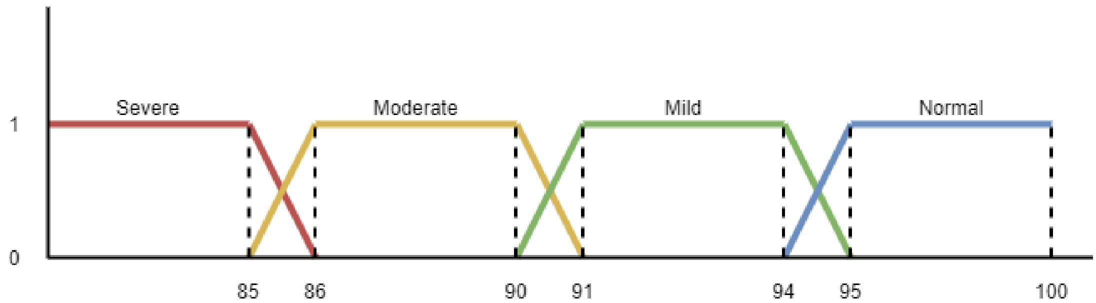

Fig. 3. Membership of SpO2

1. Normal

$$\mu(x) = \begin{cases} 1 & ; 95 \le x \le 100 \\ \dfrac{x-94}{95-94} & ; 94 \le x < 95 \\ 0 & ; x < 94 \end{cases} \quad (1)$$

2. Mild

$$\mu(x) = \begin{cases} 0 & ; x < 90 \\ \dfrac{x-90}{91-90} & ; 90 \le x < 91 \\ 1 & ; 91 \le x \le 94 \\ \dfrac{95-x}{95-94} & ; 94 < x \le 95 \\ 0 & ; x > 95 \end{cases} \tag{2}$$

3. Moderate

$$\mu(x) = \begin{cases} 0 & ; x < 85 \\ \dfrac{x-85}{86-85} & ; 85 \le x < 86 \\ 1 & ; 86 \le x \le 90 \\ \dfrac{91-x}{91-90} & ; 90 < x \le 91 \\ 0 & ; x > 91 \end{cases} \tag{3}$$

4. Severe

$$\mu(x) = \begin{cases} 1 & ; 85 \le x \\ \dfrac{86-x}{86-85} & ; 95 \le x < 86 \\ 0 & ; x > 86 \end{cases} \tag{4}$$

Where x is Input value that will be converted to a Fuzzy number

The heart rate membership function uses the shoulder curve and triangular curve membership function like Fig. 4. When a heart rate value less than 60 bpm is bradycardia, a heart rate value of 60 bpm to 100 bpm is standard, and a heart rate value of more than 100 bpm is tachycardia.

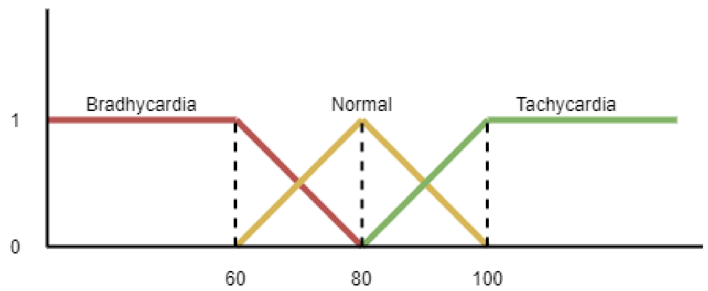

Fig. 4. Membership in Heart Rate

1. Bradycardia

$$\mu(x) = \begin{cases} 1 & ; x \le 60 \\ \dfrac{80-x}{80-60} & ; 60 < x \le 80 \\ 0 & ; x > 80 \end{cases} \tag{5}$$

2. Tachycardia

$$\mu(x) = \begin{cases} 1 & ; x > 100 \\ \dfrac{x-80}{100-80} & ; 80 < x \le 100 \\ 0 & ; x \le 80 \end{cases} \tag{6}$$

3. Normal

$$\mu(x) = \begin{cases} 0 & ; x < 60 \\ \frac{x-60}{80-60} & ; 60 \leq x \leq 80 \\ 1 & ; 91 \leq x < 94 \\ \frac{100-x}{100-80} & ; 80 < x \leq 100 \\ 0 & ; x > 100 \end{cases} \quad (7)$$

Where x is Input value that will be converted to a Fuzzy number

The Sugeno model uses a simpler membership function. Each output produced by a crisp value is represented on a singleton, with a degree of membership of 1 (one) at a single crisp value and 0 (zero) on all other crisp values [23]. The Membership singleton of Hypoxemia Prediction from this research can see in Fig. 5.

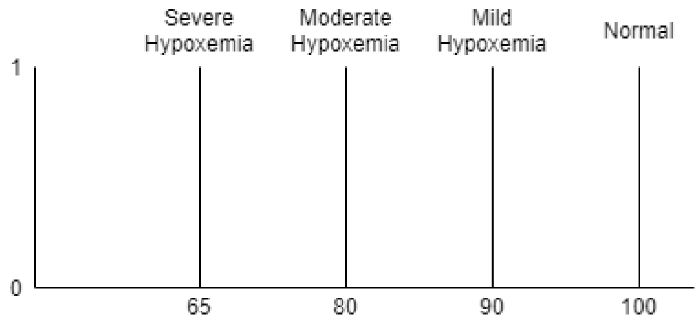

Fig. 5. Membership Singleton of Hypoxemia Prediction

In determining the prediction of Hypoxemia using the Sugeno Order-Zero method, namely:

$$If\ (x_1\ is\ A_1) \cap (x_2\ is\ A_2) \cap \ldots \cap (x_n\ is\ A_n)\ then\ z = k \quad (8)$$

Where x_n is Input Variable and A_n is Category

The inference is the process of converting Fuzzy input to Fuzzy output using if-then rules. The implication function is a logical structure consisting of a set of premises and conclusions. The implication function is useful for understanding the relationship between the inference and the conclusion. The implication function is the IF statement x is A THEN B is y, where x and y are scalars, and A and B are Fuzzy sets. At this stage, the rules used in the Fuzzy system will be determined. The rule can see in Table 3.

Table 3. The fuzzy membership set that will be formed into rules

SpO2	Heart rate (HR)	Prediction
Normal	Bradycardia	Normal
	Normal	Normal
	Tachycardia	Mild Hypoxemia
Mild	Bradycardia	Mild Hypoxemia
	Normal	Mild Hypoxemia
	Tachycardia	Moderate Hypoxemia
Moderate	Bradycardia	Moderate Hypoxemia
	Normal	Moderate Hypoxemia
	Tachycardia	Severe Hypoxemia
Severe	Bradycardia	Severe Hypoxemia
	Normal	Severe Hypoxemia
	Tachycardia	Severe Hypoxemia

Determination of these rules is formed based on predetermined criteria with an appropriate assessment of the object. After the rules are formed, the next step is to determine the membership value (α) according to the Fuzzy regulations created using the minimum implication function. In the minimum implication function, the AND (intersection) operator is used.

1) IF (SpO_2 is Normal and HR is Bradycardia), THEN Normal
2) IF (SpO_2 is Normal and HR is Normal), THEN Normal

3) IF (SpO_2 is Normal and HR is Tachycardia) THEN Mild Hypoxemia
4) IF (SpO_2 is Mild and HR is Normal) THEN Mild Hypoxemia
5) IF (SpO_2 is Mild and HR is Bradycardia) THEN Mild Hypoxemia
6) IF (SpO_2 is Mild and HR is Tachycardia) THEN Moderate Hypoxemia
7) IF (SpO_2 is Moderate and HR is Normal) THEN Moderate Hypoxemia
8) IF (SpO_2 is Moderate and HR is Bradycardia) THEN Moderate Hypoxemia
9) IF (SpO_2 is Severe and HR is Tachycardia) THEN Severe Hypoxemia
10) IF (SpO_2 is Severe and HR is Normal) THEN Severe Hypoxemia
11) IF (SpO_2 is Severe and HR is Bradycardia) THEN Severe Hypoxemia

The composition of the rules is the overall conclusion by taking the maximum level of membership from each consequent application of the implication function and combining all the findings of each direction to obtain the Fuzzy solution area.

Defuzzification of determinism is the process of converting the output-fuzzy from the inference system into crips. Defuzzification in Sugeno's Fuzzy Inference System uses a weighted average formula.

$$WA = \sum_{i=1}^{N} \frac{\alpha_{i.} z_i}{\alpha_i} \quad (9)$$

Where WA is weighted average value, α_i is α predicate to i, z_i is consequent to i, i is sequence of data; N is amount of data.

3. RESULTS AND DISCUSSION

Before testing for Hypoxemia prediction, the MAX30102 sensor is calibrated to determine the value of Root Mean Square Error (RMSE). If the RMSE value is smaller (close to 0) means, the prediction results are more accurate [24]. Testing is done by comparing the measurement results with the MAX30102 sensor with three factory-made pulse oximeters, tested on a total of 10 people classified as adults (18 years - 59 years) and seniors (67 years). Ten people are enough to represent a sample of the population. The sensors are simultaneously attached to the four fingers of the tested person. In turn, each was tested for 30 seconds, and each person was tested ten times.

$$\text{RMSE} = \sqrt{\frac{\sum_i^n (actual\ value - predict\ value)^2}{n}} \quad (10)$$

Where RMSE is Root Mean Square Error, i is sequence of data, and n is The amount of data.

From the results of the calibration test in Table 4 and Table 5, all the RMSE values obtained were less than 3.5%. Based on research [25], if the RMSE value of a pulse oximeter is less than 3.5%, the sensor has fairly good accuracy and can be used for testing.

The test aims to determine whether the system has been created to be able to detect hypoxemia. The test is carried out by the method of sensitivity, specificity, and accuracy testing will be calculated. Two terms generally used in medical and epidemiological research are sensitivity and specificity [26]. Sensitivity is the capacity of the test to demonstrate which person is ill in the entire population is ill. Specificity is the capacity of the test to show which individuals are healthy than those who are genuinely not ill [26]. Sensitivity and specificity test methods have previously been carried out in research by [27][28].

The result from the android application and the hardware can see in Fig. 6 and Fig. 7. The android application and firebase will log all data related to this research. The parameter that is logging is SpO_2 and Heart Rate sensor value. The result of prediction is also shown in the application and firebase.

This testing scenario takes five people who have a history of disease in which one of the symptoms is hypoxemia, that is GERD, schizophrenia, asthma, gastritis, and hypercholesterolemia [5][6][7][29][30] and also five healthy people. The test was carried out for 30 seconds for each person.

Table 4. SpO_2 Calibration Results

Age Classification	RMSE value when the system is compared to -		
	Pulse Oximeter I	Pulse Oximeter II	Pulse Oximeter III
Adult (18 years - 59 years)	0.55% – 1.37%	0.89% – 1.76%	0.93% – 2.61%
Elderly (67 years)	0.94%	0.83%	1.71%

Table 5. Heart Rate Calibration Results

Age Classification	RMSE value when the system is compared to -		
	Pulse Oximeter I	**Pulse Oximeter II**	**Pulse Oximeter III**
Adult (18 years - 59 years)	2% – 3%	1.67% – 3.1%	1.52% – 2.97%
Elderly (67 years)	2.28%	2.55%	2.26%

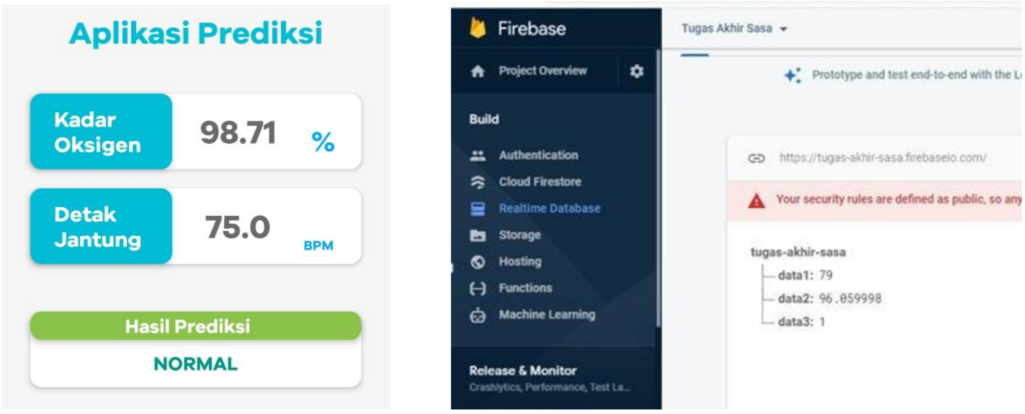

Fig. 6. Android application and Data logging in Firebase

Fig. 7. Device Hardware

$$\text{Sensitivity} = \frac{true\ positive}{true\ positive + false\ negative} \times 100\% \tag{11}$$

$$\text{Specificity} = \frac{true\ negative}{false\ positive + true\ negative} \times 100\% \tag{12}$$

$$Accuracy = \frac{(Total\ Data - Invalid\ data)}{Total\ Data} \times 100\% \tag{13}$$

After testing in Table 6, the results of the tests that have been carried out are two people who have invalid test status. The development of the sensitivity value calculation is 60%, the specificity value is 100%, and the accuracy is 80%.

In the Hypoxemia detector's testing results in Table 6, two people are not detected to have hypoxemia: people who have GERD and Asthma. GERD is a condition of esophageal damage caused by increased stomach acid. Hypoxemia in GERD patients occurs when the acid comes in contact with the esophagus or even gets into the lungs. In [7], it was explained that the severity of GERD affects hypoxemia. It is stated that the more severe the GERD is experienced, the more frequent recurrences of hypoxemia will be. Based on interviews with GERD patients, it is known that the disease has been present for one year. The patient is currently undergoing therapy to get better with the frequency of relapses about once in two months. It results in hypoxemia not being detected by the detection system.

Meanwhile, in the interviews with asthma patients, it was found that patients routinely took Asthma medication at a dose of 20-40 mcg twice a day. According to [31], the level of medication adherence will affect the frequency of relapse in asthma patients. When the test was carried out, the patient was in a healthy condition, so the instrument did not detect the Hypoxemia condition.

Table 6. SpO2 Value Grouping

No	**Gender**	**Age (years)**	**History of Disease**	**Indicated Hypoxemia**	**SpO2**	**HR**	**Prediction**	**Comparison of Disease and Prediction**
1	Woman	21	GERD	Yes	97.60	91	Normal	Invalid
2	Woman	21	Skizofrenia Paranoid	Yes	91.99	90	Mild	Valid
3	Woman	40	Asthma	Yes	96.88	62	Hipoksemia	Invalid
4	Woman	55	Gastritis/Maag	Yes	93.79	63	Normal	Valid
5	Woman	67	Hyper-	Yes	93.83	68	Mild	Valid
6	Man	21	cholesterolemia	No	95.93	67	Hipoksemia	Valid
7	Woman	38	Normal	No	98.83	90	Mild	Valid
8	Woman	55	Normal	No	97.03	69	Hipoksemia	Valid
9	Woman	22	Normal	No	99.34	74	Normal	Valid
10	Woman	21	Normal	No	99.44	80	Normal	Valid
			Normal				Normal	
							Normal	
							Normal	

The sensitivity test aims to determine the effectiveness of the tool to identify a disease. From the test results, the results obtained from the calculation of the sensitivity are 60%. It occurs because the test population is too small; namely, only five people have a history of the disease and the five tested. Some people do not relapse, resulting in a sensitivity percentage value of only 60%.

The specificity test aims to show which individuals are not suffering from pain from honestly not. The specificity value obtained from the test is 100%. The detection system is made to detect individuals who do not experience hypoxemia from five healthy individual populations. The total accuracy value obtained from the test results is 80%, with two test results invalid from the whole test population.

Because hypoxemia is closely related to COVID-19, suggestions for further research is testing should also be done on COVID-19 patients because COVID-19 is a topic that is always being researched. Currently, the case of COVID-19 in Indonesia has not shown a substantial decrease. There are still quite a number of cases in some areas, like East Java and South Sulawesi [32].

4. CONCLUSION

In this study, Fuzzy Logic Inference System Sugeno models can process data SpO2 and heart rate quite well. Based on the results of the tests and analyzes that have been carried out, it can be concluded that the Hypoxemia detection system using the MAX30102 sensor based on Fuzzy Logic can be used to perform screening Hypoxemia with sensitivity is 60%, the specificity is 100%, and the accuracy is 80%.

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