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Development of Measuring Instruments for Lung Vital Capacity and Human Respiratory Rate Based on Fiber Optic Sensors

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ABSTRACT

The development of measuring instruments for vital lung capacity and human respiratory rate based on the fiber-optic sensor has a system consisting of a laser diode as a light source, optical fiber as a waveguide, and OPT101 as a photodetector. This research consists of three stages: hardware design, software design, and data analysis. Each component used is tested and then tested on the entire system to determine each component's performance when used together. In the software system, the analog signal in the form of voltage from OPT101 is converted into an ADC value by an analog-to-digital converter. Based on the ADC value obtained, the threshold value is determined as the threshold for reading the respiratory rate. The number of ADC values during the measurement of vital lung capacity is then converted to volume. Testing of measuring instruments is carried out by comparing the results of instruments developed with a standard medical measuring device. The results of the tests and analyses that have been carried out have obtained an accuracy value of 92.62% for the measurement of vital lung capacity, 95.14% for the measurement of respiratory rate, and 92.62% for the measurement of the respiratory rate of variations in activity.

1. INTRODUCTION

The lungs are organs of the human body that primarily function as a place for exchanging oxygen and carbon dioxide (Lim, 2006). Various disorders of the lungs as a respiratory system, such as pneumothorax or chronic obstructive pulmonary disease, are ranked as the third cause of death in the world based on data compiled by the WHO (World Health Organization) in 2019 so that the health of lung function is very important to know (Organization, 2019). The health of lung function can be understood by measuring the vital lung capacity and the respiratory rate, which helps diagnose, detect, and treat various disorders of the respiratory system (Umara et al., 2021). Measure vital lung capacity using a spirometer to determine the maximum volume of air that can be exhaled in one breath after ultimate inspiration (Wanger et al., 2005). Respiratory rate measurement is done manually by counting the number of movements up and down the chest cavity in one minute (Wheatley, 2018).

So far, optical fiber, which is one type of cable that functions as a transmission medium, has been developed into a sensor because it has advantages such as very fast measurement response, high sensitivity, high precision, high accuracy, immunity to electromagnetic interference, immune to electromagnetic radiation, lightweight, strong, and more resistant to harsh environments (Idachaba et al., 2014; Yin et al., 2017). Some of the developments that have been made include Suraya (2018) developing a respiratory monitoring system based on changes in physical parameters using an optical fiber with an SMS (Singlemode-Multimode-Singlemode) structure. The sensor is placed crosswise on the mat and is positioned in the center of the participant's back. The measurement results of this tool are caused by the pressure applied to the back during inspiration and expiration, but if the participant moves, it will affect the measurement results.

Optical fiber as a sensor with the extrinsic method has been used to develop a respiratory rate-measuring instrument. This instrument can still be developed to measure other lung functions (Ikhsan & Harmadi, 2019). Unni et al. (2020) developed a measuring device for vital lung capacity using a fiber optic sensor. The balloon will accommodate the exhaled air. The balloon expansion that has not hit the flexible strip has not been able to calculate the essential lung capacity. The balloon expansion that has not hit the flexible strip has not been able to calculate the vital lung capacity.

Measurement of vital lung capacity and respiratory rate can help determine the health of lung function. Still, based on previous research, a measuring instrument capable of measuring vital lung capacity and the respiratory rate has not been developed in one device. Fiber optic sensor with extrinsic method is easier to design. The working principle of this tool in measuring vital lung capacity and respiratory rate is to sense changes in light caused by the movement of the membrane as a result of exhalation. The membrane used is made of latex. The movement of the membrane will reflect light coming from the optical fiber transmitter and re-enter the optical fiber receiver, and then be detected by the photodetector. The measurement results are real-time via liquid crystal display (LCD).

2. METHOD

2.1 Hardware Design of Measuring System for Lung Vital Capacity Measurement and Respiratory Frequency

The hardware design for measuring vital lung capacity and respiratory rate can be seen in Figure 1. The hardware consists of a sensor system with a light source from a laser diode, optical fiber FD 620-10 type step-index multimode as a waveguide, and OPT101 as a photodetector (Fidanboylu & Efendioglu, 2009). The optical fiber sensor uses an extrinsic method where the sensing process occurs outside the optical fiber without modifying the optical fiber structure (Sabri et al., 2015). The measurement results will be displayed on the LCD in real-time.

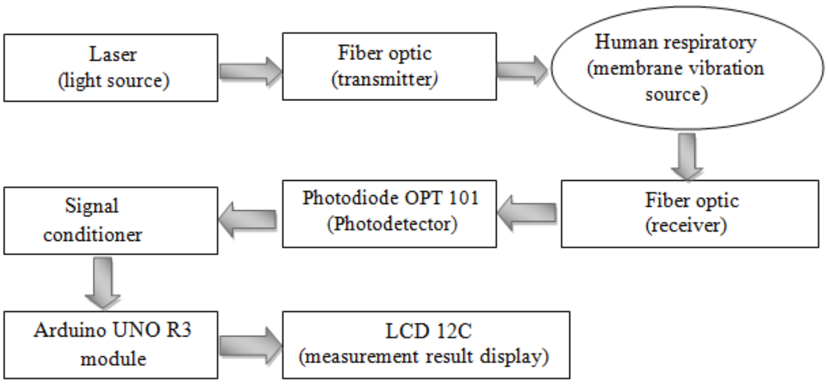


Figure 1. Hardware design for measuring vital lung capacity and respiratory rate.

2.2 Software Design for Lung Vital Capacity and Respiratory Rate Measurement

The software system's design aims to process the input signal from the optical fiber receiver, which is detected by OPT101 and then sent to the Atmega328 microcontroller contained in the Arduino UNO. The program design in this system uses Arduino IDE (Integrated Development Environment) software which is open source. The program is made using the C language, which is then embedded in the Arduino UNO module.

The programming flow chart for measuring vital lung capacity and respiratory rate can be seen in Figure 2. The output voltage obtained is processed into a decimal number by an analog-to-digital converter (ADC) and then converted into a vital lung capacity with units of mL and respiratory rate with breath per minute (bpm). The restored data obtained is displayed on the LCD.

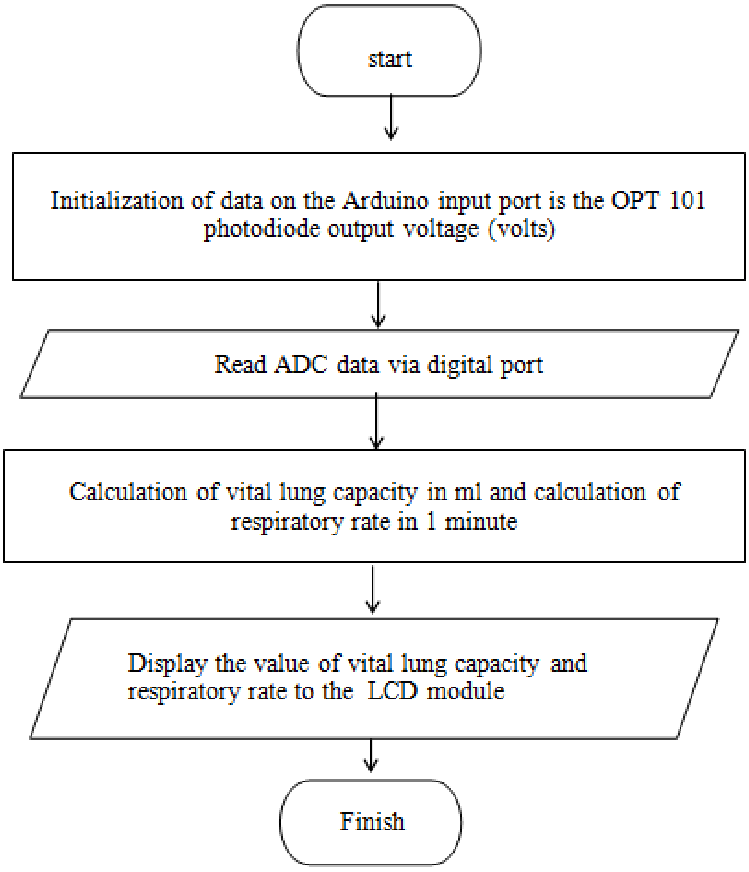


Figure 2. Flowchart of programming for measuring vital lung capacity and respiratory rate.

2.3 Data Analysis

Data analysis is a process to determine the level of accuracy and precision of a measurement system. Accuracy is a measure that shows how close the instrument reading is to the actual value (Santoso, 2017). The system's accuracy can be determined from the percentage error between the real and visible values. The error percentage in testing a measuring instrument can be determined by Equation (1) (Guang et al., 1995). The percentage accuracy of the measuring device is calculated using Equation (2)(Heidaryan, 2019).

$$\text{percentage error} = \left|\frac{Y_n - X_n}{Y_n}\right| \times 100\,\% \tag{1}$$

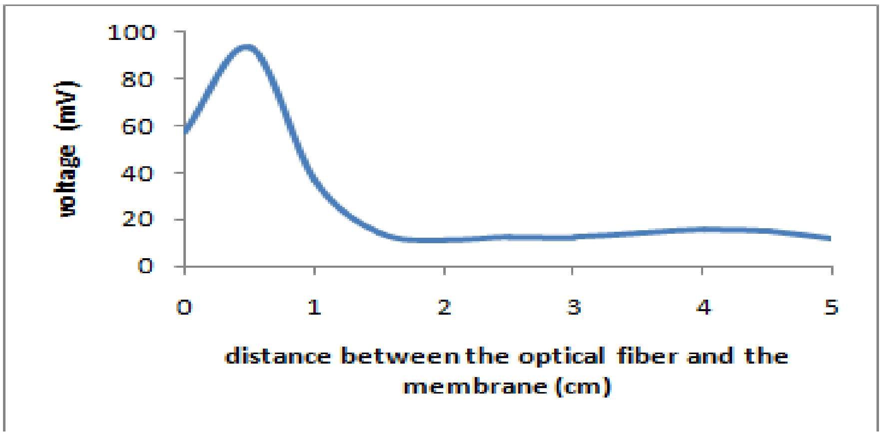
$$\text{percentage accuracy} = \left[1 - \left|\frac{Y_n - X_n}{Y_n}\right|\right] \times 100\,\% \tag{2}$$

Y_n is the actual value on the comparison instrument, and X_n is the value read on the measuring device. A spirometer is a comparison instrument for measuring vital lung capacity and manual calculations by calculating the up and down of the chest cavity as a comparison in measuring respiratory rate.

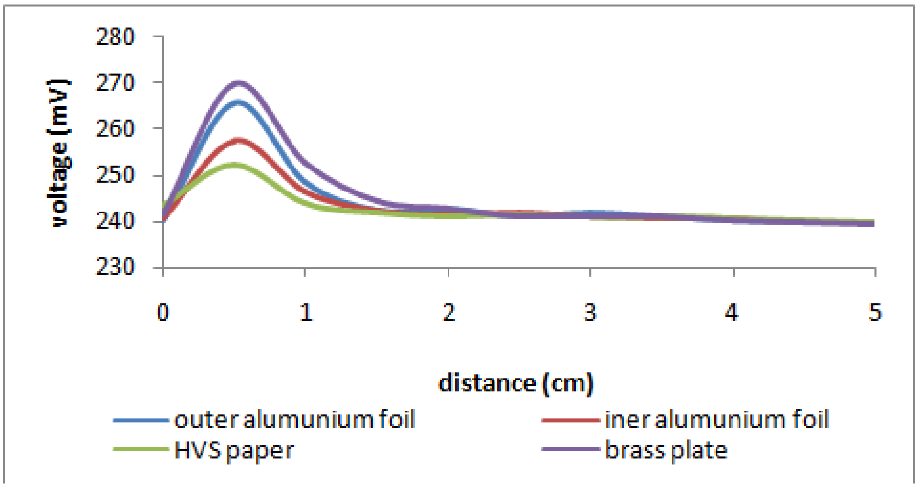
3. RESULTS AND DISCUSSION

3.1 Fiber Optic Sensor Characterization Results

The optical fiber sensor is characterized by varying the distance between the optical fiber and the membrane, with a distance variation of 0 cm to 5 cm. This characterization was carried out to obtain the relationship between the distance and the output voltage produced by the OPT101 photodetector. The membrane without a reflector has a low output voltage, so a reflector is needed to increase the resulting output voltage. The reflectors tested were aluminum foil, HVS paper, and brass plate with a thickness of 0.35 mm. The result of characterization is that the highest output voltage is obtained at a distance of 0.5 cm and is used as the distance between the optical fiber and the membrane in the development of the instrument. Previous research analyzed the micro-shift using a fiber optic sensor. The characterization results showed that the best distance between the optical fiber and the reflector was at a distance of ≤5cm (Saputro et al., 2014). The reflector that provides the highest output voltage is a brass plate of 270 mV, which is used as a reflector in tool development. Brass and copper have very similar optical properties. Both have good light-reflecting properties (Meier et al., 2007). Measurements were repeated five times. Figure 3 shows the results of the measurements.



(a)

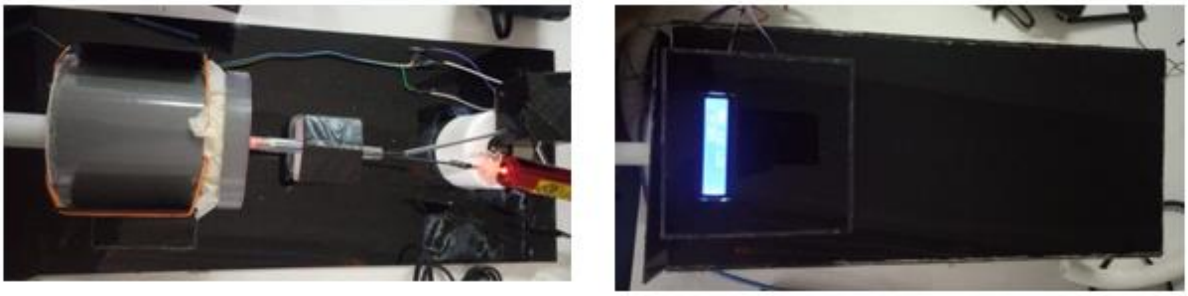


(b)

Figure 3. Distance relationship with voltage (a) without reflector and (b) with reflector.

3.2 Overall Measurement System Test Results

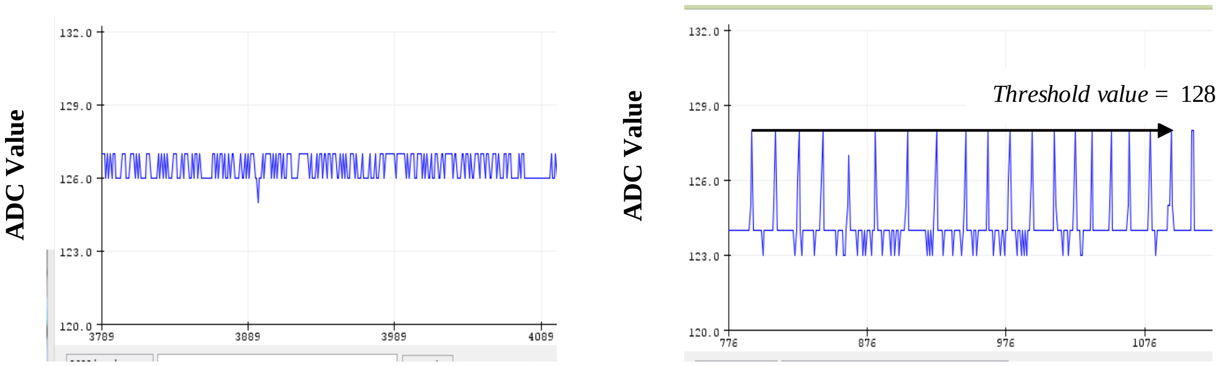
Tests are carried out to determine the performance of each system block when used simultaneously and to test the accuracy of the measuring instrument developed. The measuring instrument is operated with an input voltage of 5 volts. When the breath is exhaled, the membrane will vibrate according to the object's breathing and shift from its original. Then, the intensity of the light reflected by the membrane and received by the optical fiber receiver changes and affects the output voltage on the OPT101 photodetector. The physical form of the instrument can be seen in Figure 4.



(a) (b)

Figure 4. Physical form measuring instrument for vital lung capacity and respiratory rate (a) inside and (b) outside view.

In the measuring instrument programming process, the microcontroller processes the analog input signal generated by the OPT101 photodetector into an ADC value. When the device is not used, the ADC value tends to be constant with low-value fluctuations. When the device is used, it can be seen that the fluctuation of the ADC value is greater because the membrane vibrates due to breathing. The closer the membrane distance to the optical fiber receiver, the higher the graph formed on the serial plotter. On the other hand, if the distance from the membrane to the optical fiber receiver is further, the serial plotter graph will decrease (Ikhsan & Harmadi, 2019). The fluctuation of the ADC value can be seen in Figure 5.



Time (ms) Time (ms)

(a) (b)

Figure 5. Fluctuations in the ADC value of the OPT101 photodetector (a) before exhaling and (b) during exhaling.

Based on the ADC value, the threshold value used in the program can be determined as a working parameter of the measurement system. The threshold value is obtained based on the average fluctuation of the ADC value when the object usually breathes. The ADC value that reaches the threshold value is felt as a count of one breath. The result of the counting process for 1 minute is the respiratory frequency value displayed on the LCD in real-time in units of breaths per minute (bpm).

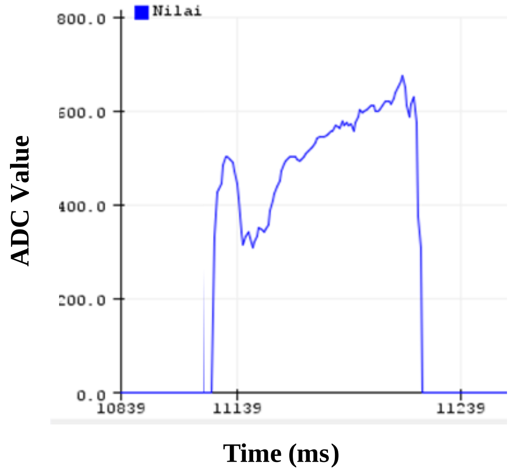


Figure 6. Fluctuations graph of ADC value when measuring vital lung capacity.

The vital lung capacity is calculated by calculating the number of ADC values during fluctuations and then converting it to the amount of vital lung capacity in mL. The magnitude of the multiplier in converting the ADC value into the volume is obtained by blowing air from the balloon into the developed device. The air volume in the balloon is calculated using the Equation for the volume of the ball. The air volume in the balloon is varied, and then the multiplier value is obtained by converting the total ADC value to a volume quantity of 0.09. Figure 6 shows the form of a graph measuring vital lung capacity**.**

3.3 Measurement Test Results

The final test of the measuring instrument was carried out to compare the values of the vital lung capacity and the respiratory rate of humans by measuring instruments developed using standard medical methods. The standard medical method used is to count the rise and fall of the chest cavity in 1 minute. Figure 7 shows a result comparison chart of respiratory rate measurements between measuring instruments developed with standard medical methods. Based on the analysis, the error percentage was 4.86%, with an accuracy percentage of 95.14%.

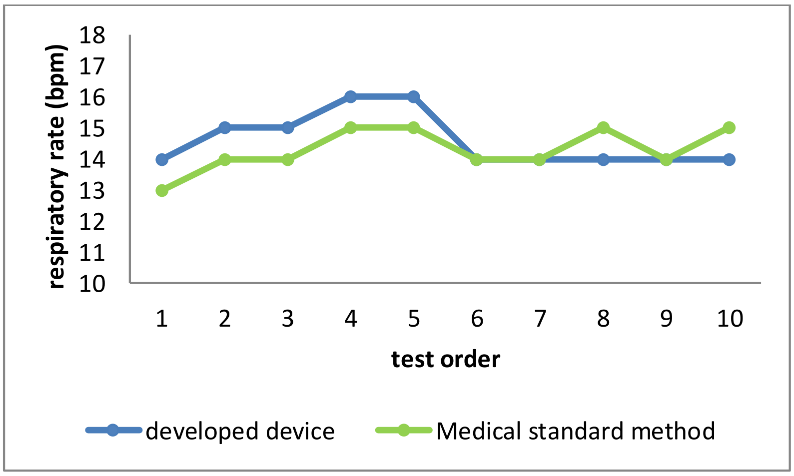


Figure 7. Measurement of human respiratory rate.

Testing the respiratory frequency with activity variations is carried out to determine the response of the measuring instrument when used with a fast breathing rhythm. The respiratory rate is influenced by body activity. The heavier the organ works, the higher the body's energy needs, so the quicker the person's respiratory rate (Damayanti, 2016). Figure 8 shows a result comparison chart of respiratory rate variations in activity measurements between measuring instruments developed with standard medical methods. Based on the analysis, the error percentage is 3.55%, with an accuracy percentage of 96.45%.

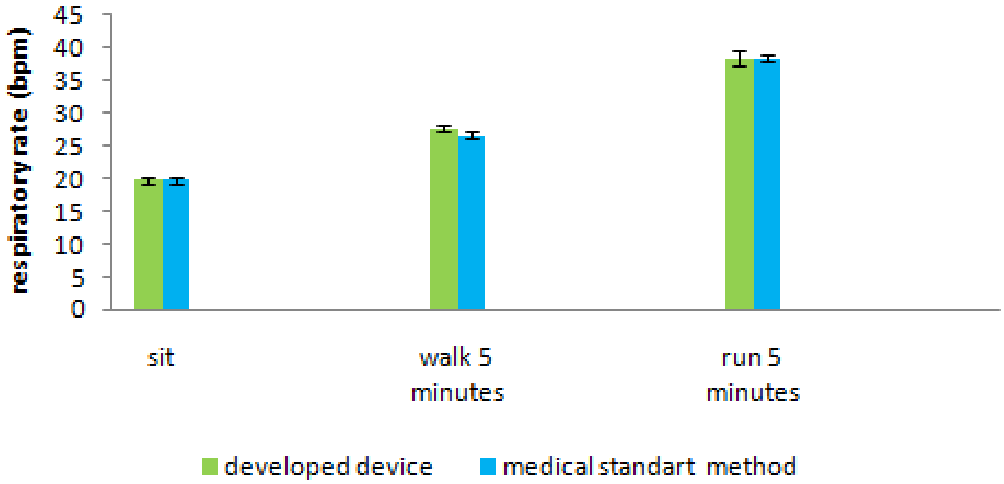


Figure 8. Results of measuring respiratory rate variations in activity.

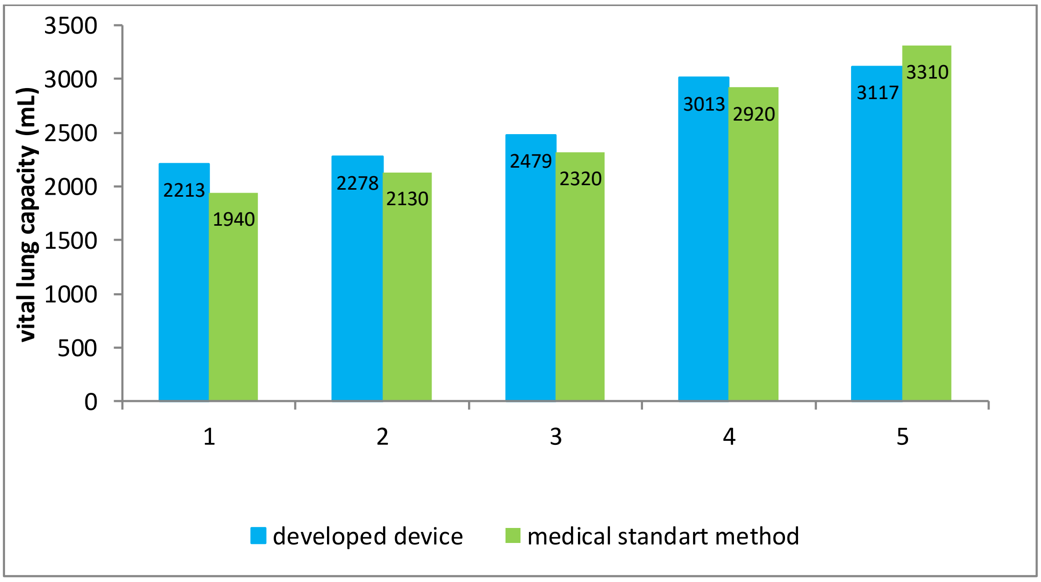


Figure 9. Measurement of vital lung capacity.

Measurement of the vital capacity of the lungs is carried out using a measuring instrument that was developed and then compared with the results of measurements using a spirometer as a medical standard measuring instrument. The measurement data can be seen in Figure 9. The five subjects' vital lung capacity of the 5 subjects measured had different lung capacities. Every human's vital lung capacity is influenced by age, sex, body mass, and ethnicity (Mead, 1980). The measured data compared are the data from measuring vital lung capacity with the largest volume of three repetitions.

The calculations gave the results of an average error percentage of 7.38% with an accuracy percentage of 92.62%.

4. CONCLUSION

Based on the research, testing, and analysis that has been carried out, it can be concluded that a measuring instrument for vital lung capacity and human respiratory rate based on fiber optic sensors using the extrinsic method has been successfully developed. The development of this measuring instrument uses a latex membrane with a brass chip reflector with a thickness of 0.35 mm at the optimal distance between the membrane and the optical fiber of 0.5 cm. The measuring instrument developed has an accuracy percentage of 95.14% for measuring respiratory rate, 96.45% for measuring the respiratory rate of activity variations, and 92.62% for measuring vital lung capacity.

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