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Research article

Design of Volume Control Type Portable Mechanical Ventilator

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A B S T R A C T

This research addresses the critical need for affordable, portable ventilators, particularly for patients with respiratory distress, including those with COVID-19. These devices are essential for initial patient care during transport to hospitals. This project focuses on developing a volume-controlled ventilator that adheres to fundamental medical standards, enabling precise adjustments of tidal volume (VT), I/E ratio, and respiratory rate (RR). The ventilator utilizes an Arduino Mega 2560 controller to manage a solenoid valve, which regulates airflow for inspiration and expiration. Tidal volume, the volume of air delivered per breath, is adjustable between 50ml and 805ml, with selectable increments of 5ml to 20ml. The solenoid valve's activation controls the inspiration phase, allowing for adjustable inspiration times from 0.25 to 3.8 seconds. Conversely, deactivation facilitates expiration, with adjustable expiration times from 0.75 to 6.3 seconds. This precise control over respiratory parameters aims to provide effective and adaptable respiratory support, enhancing accessibility to crucial medical interventions.

1. INTRODUCTION

The development and production of medical devices in the form of ventilators continue to be carried out to help patients heal during the SARS-CoV-2 Virus pandemic, which causes COVID-19. According to the World Health Organization (World Health Organization), about 80 percent of people with the Coronavirus can recover without requiring special treatment, but 1 in 6 people experience serious pain and difficulty breathing and cause damage to the lungs, for the fundamental purpose using ventilators is to encourage and increase oxygen levels to the lungs, thus, allowing the healing of the lungs, and at the same time reduce the risk of errors diagnosis [1].

Cheap and portable ventilators are needed in mass disaster emergency response conditions [2]. In addition, it is used for patients who travel to the main hospital by medical vehicle (ambulance) [3].

2. PROBLEM DESCRIPTION

Mechanical ventilators have noninvasive and invasive functions. Patients with milder symptoms may be given a breathing apparatus or "non-invasive" ventilation in the form of a facemask, nose mask, or mouthpiece that allows compressed air or a mixture of gases to be pushed into the lungs [5], while people with respiratory failure are given a breathing apparatus or "invasive" ventilation in the form of a tube or tube inserted into the windpipe/tracheostomy [6]. Based on these problems, the purpose of this design is to build an invasive function portable ventilator with a mandatory ventilation mode [7]. The type of ventilation is oxygen volume control (O_2).

The basic ability of a mechanical ventilator clinically is to have a Tidal Volume, Respiratory Rate, Inspiratory/Expiration Time Ratio, and carbon dioxide (CO2) removal mechanism [4].

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The ventilator design focuses on the design of the oxygen volume control system and the actual timing system of inspiration and expiration. Improper administration of air volume and pressure will cause damage to the lungs (barotrauma and volutrauma) [7].

3. METHOD

3.1. Tool Performance Requirements

The manufacture of this ventilator still refers to the standards that have been set clinically. Table 1 shows the parameters that must be met.

Table 1. Volume Control Ventilator Performance Standard [8]

Settings	Range	Accuracy
Tidal Volume	0-800 ml	± 40 ml < 10 %
PIP	0-40 cmH_2O	± 0.5 cmH_2O
PEEP Valve	5-20 cmH_2O	± 0.5 cmH_2O
Respiratory Rate	8-40 BPM	As needed

Tidal volume is the volume of air supplied to the patient each cycle of respiration [9]. Tidal volume administration produces pressure on the lungs, namely Peak Inspiratory Pressure (PIP). PIP is the maximum pressure of air in the lungs.

Then it takes a positive end-expiratory pressure (PEEP) setting. PEEP is the final expiratory positive pressure required to keep the alveoli open; so that the process of oxygen absorption can take place to flow to the blood [10].

In addition to tidal volume and PEEP, parameters that can be adjusted according to patient needs are respiratory rate and I/E ratio. Respiratory rate is the average breath per minute (BPM), while I/E ratio is the ratio of inhalation and exhalation time, the ratio value is 1:1-1:5 [8].

3.2. Hardware Design

Before designing a ventilator, first conduct a literature study to find out the basic concepts of ventilators and human breathing processes. The following are the results of the ventilator design in Figure 1.

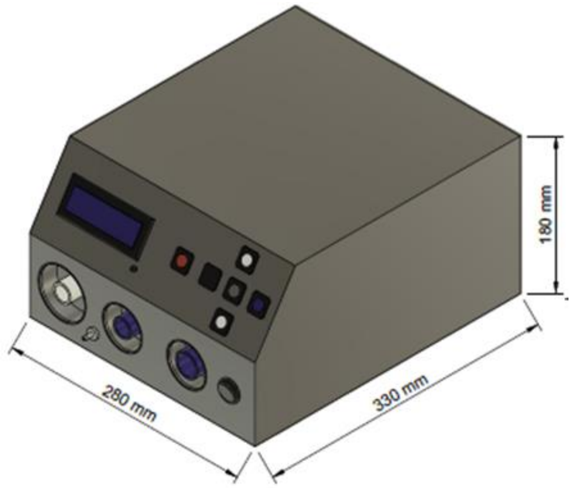

Figure 1. Ventilator design results

The design scheme of the inner hardware of the ventilator is shown in Figure 2.

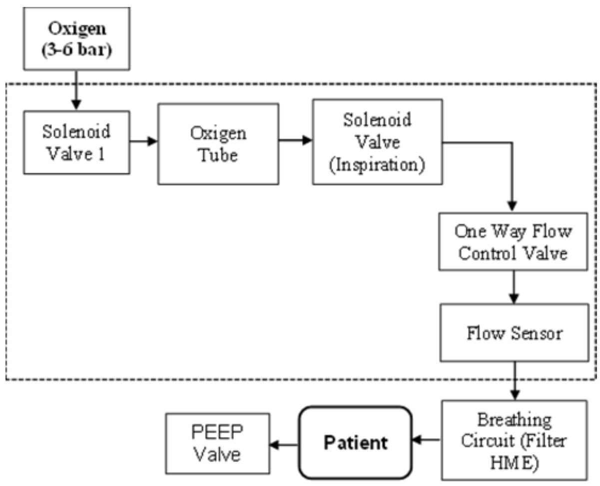

Figure 2. Ventilator block diagram

The electronic devices used consist of Arduino ATMega2560, solenoid driver, pressure sensor, orifice flow meter, membrane push button, and LCD display. Then for power supply, use a 12 Volt 12 Ampere Battery. For the needs of 5 Volt DC voltage, an additional module in the form of a DC Buck Converter is used. The scheme of the ventilator control system is shown in Figure 3.

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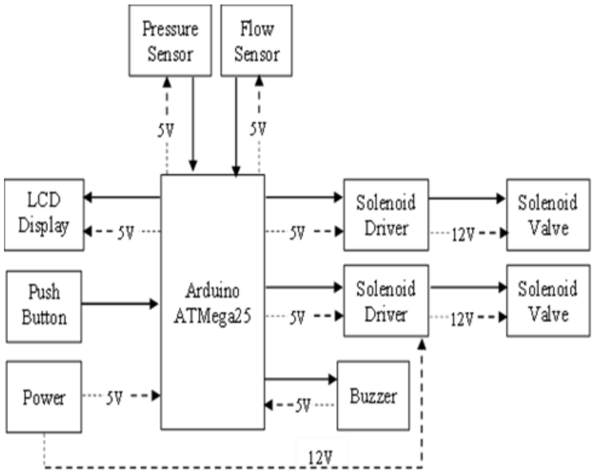

Figure 3. Control system block diagram

3.3. Ventilator Support Equipment

Equipment used to support the design and design of ventilators are:

- Solenoid valve

The solenoid valve in Figure 4 is a valve drive whose working principle uses an electromagnetic system that will drive the piston on the steering valve, so that it can direct the gas fluid [11]. The solenoid valve used works with a voltage of 12 Volt DC.

Figure 4. Solenoid valve

- Microcontroller Module

Microcontroller is a device that functions as an input and output controller on a ventilator. Arduino Mega 2560 is used to control the opening and closing of the solenoid valve. In addition, the ability to handle many sensors and actuators with large and complex quantities, the physical shape of the microcontroller module can be seen in Figure 5.

Figure 5. Arduino Mega 2560

- Pressure Sensor

MPX5010 series pressure sensor can measure pressure from 0-101 cmH_2O (0.2-4.7 Volt DC Output). Activating the MPX5010 sensor in Figure 6, does not require external power, but instead uses the data line on the microcontroller used [12].

Figure 6. Pressure sensor

3.4. Basic Design Concepts

Built ventilators work on the basis of air volume control. The control center used is Arduino ATMega2560. The controller will regulate the volume of air (O_2) given to the patient through the components of the solenoid valve 1. The solenoid valve will open when given an electric voltage of 12 Volt DC, so that compressed air will enter the tube, then the inspiration solenoid valve will be active and air has flowed to the patient through the breathing circuit. To obtain a more accurate volume of oxygen, one-way flow control is used. Then the I/E ratio and respiratory rate will be applied to the inspiration solenoid valve; so that the actual time of the inspiration and expiratory phases can be adjusted.

3.5. Test Methods

The test is carried out to determine the tidal value of the volume and the actual I/E ratio. The volume of air supplied by the Ventilator is measured manually based on the displacement of liquid in the measuring glass/tube. The air on the Ventilator has flowed into a measuring cup filled with water, and air pressure pushes water out of the measuring cup, so that an air volume value is obtained. Measurements are made in the inspirational and expiratory phases.

Furthermore, for testing the accuracy of the actual time of the inspiration phase and expiratory phase measured using an oscilloscope. The oscilloscope displays the voltage signal on the solenoid valve within a certain time range. Measurements were made on solenoid valve 1 for tidal volume regulation and inspiration solenoid valve for inspiration phase regulation and expiratory phase.

4. DISCUSSIONS

4.1. Ventilator

The results of the ventilator design are shown in Figure 7. The image consists of the outside of the ventilator and the inside of the ventilator. The ventilator made has dimensions of 330 cm long, 280 cm wide and 18 cm high. The ventilator made consists of 5 main parts, namely:

- The component box is made of PVC material as a holder of ventilator components (1).
- The control panel consists of 6 membrane switches that are used as buttons to change parameter values according to patient needs and activate the ventilator. LCD screen that serves to display parameter values including flow and pressure (2).

Figure 7. Ventilator

- The control system consisting of a microcontroller (3) and a solenoid driver (4) is shown in Figure 8.

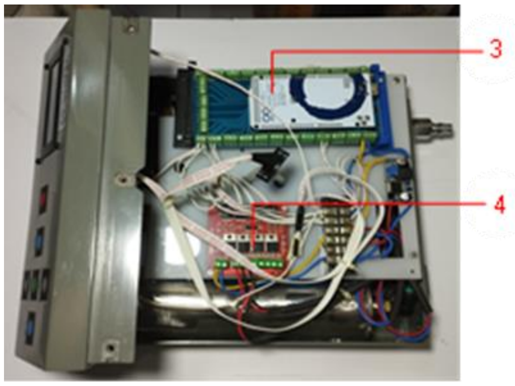

Figure 8. Microcontroller

- The power supply consists of a 12 Volt DC (5) switching power supply, an on-off switch, and a step -down buck converter that serves as an electrical source and regulator for the ventilator.
- The air volume control mechanism consisting of a stainless steel tube with a capacity of 800 ml, a solenoid valve (6) and away flow control valve is shown in Figure 9.

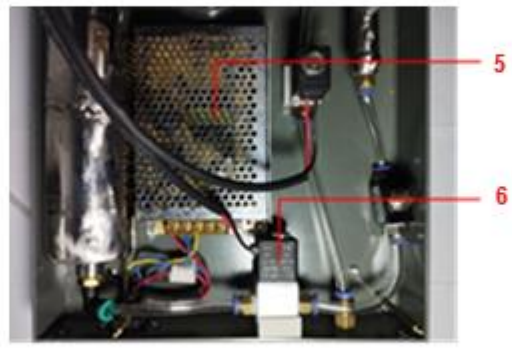

Figure 9. Power supply and air volume control

4.2. Testing

Tests carried out in the form of measurements on ventilator parameters as follows:

4.2.1. Respiration Cycle

The respiration cycle on a ventilator is one phase of inspiration time plus one phase of expiratory time. Inspiration and expiration time are obtained based on the setting of the number of inhalations/frequency of breaths and the ratio of inhalation/exhalation time. The actual time of the respiration cycle is calculated based on the respiratory rate (RR) value:

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$$I/EA = (60\ sec / RR) / (I + E) \qquad (1)$$

where, I/EA is the actual time of inspiration and the actual time of expiration in seconds. Then 60 seconds is the time of the respiration cycle. I is the ratio of inspiration, and E is the ratio of expiration [6]. The equation is then used in the programming of the ventilator created. The calculation data is shown in Table 2 with the arameter p value, namely RR 15 BPM and I/E ratio 1: 1 - 1: 5.

Furthermore, to determine the timeliness of the respiration cycle on the inspiring solenoid valve, measurements were made using an oscilloscope. The oscilloscope displays the voltage signal on the solenoid valve for a certain time. Solenoid valve 1 for tidal volume adjustment and solenoid valve inspiration for inspiratory phase and expiratory phase.

The results of measuring the actual time of inspiration and expiration using the oscilloscope are shown in Figure 9 and 10. The ventilator parameters are RR 15 BPM and I/E ratio 1: 1 and 1: 2.

Table 2. Actual time of breath cycle (RR 15 BPM).

***RR* (BPM)**	***I/E Ratio***		**Time(s)**	
	I	E	I_A	E_A
15	1	1	2.00	2.00
15	1	2	1.33	2.67
15	1	3	1.00	3.00
15	1	4	0.80	3.20
15	1	5	0.67	3.33

Table 2 shows the actual time of inspiration (I A) 2 seconds and the actual time of expiration (EA) 2 seconds. After measurement, a signal is obtained on the oscilloscope as shown in Figure 10.

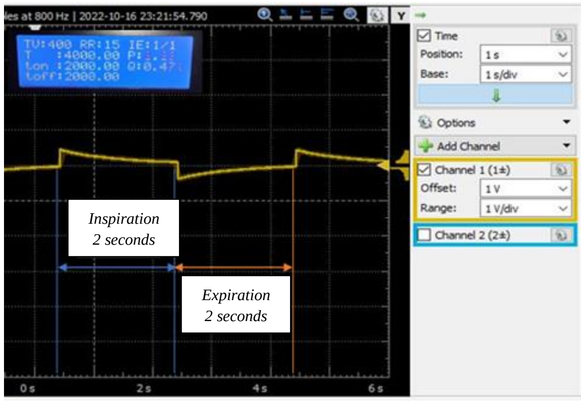

Figure 10. Measurement of the actual time of the respiration cycle

Figure 11 shows the actual time of inspection of 1.33 seconds and the actual time of expiration of 2.67. The measurement results show the same time value.

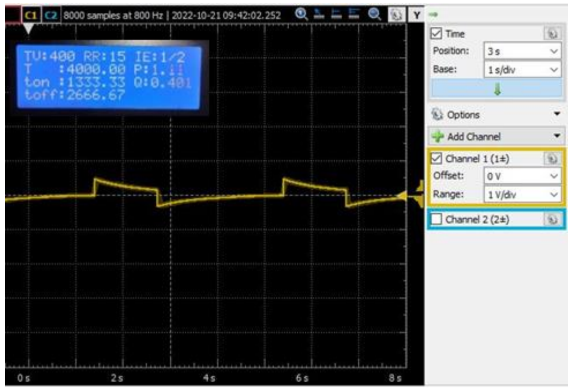

Figure 11. Respiration cycle with I/E ratio 1:2

4.2.2. Tidal Volume

The ventilator built has a volume control system through the activation of solenoid valve 1 and volume limitation with the use of stainless steel tubes with a maximum capacity of 800 ml. When the solenoid valve is active, pressurized air will enter the tube. The value of the incoming air volume is based on the length of opening time of the solenoid valve. The opening time range of the solenoid valve starts from 0.1 seconds to 0.74 seconds. Air will be inserted into the stainless steel tube when the expiration process occurs. The measurement results in Figure 12 show the process of activating the solenoid valve for refilling the ventilator tube. The solenoid valve is active for 0.2 seconds.

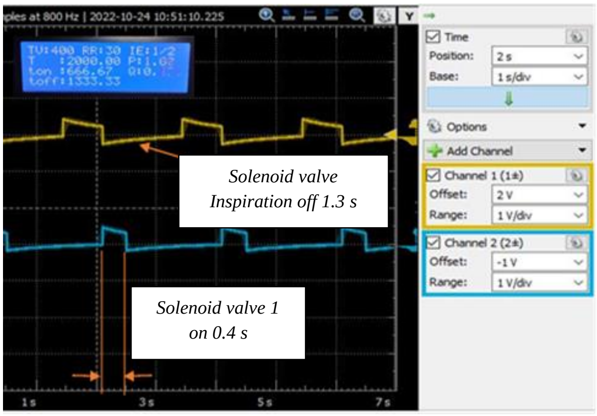

Figure 12. Solenoid valve 1 active, I/E 1:1, 15 BPM.

Based on the process of activating solenoid valve 1, volume measurements are carried out with measuring cups in containers containing water. Measurements were made at compressor air pressure of 6 bar, paremeter I/E ratio 1: 1 and RR 20 BPM, so that the time of the solenoid valve inspiration off is 1.5 seconds. The activation time range of solenoid valve 1 (On) is 0.1 seconds - 0.74 seconds. The increase in activation time of solenoid valve 1 is 0.02 seconds. The following are the results of measurements made in Figure 13.

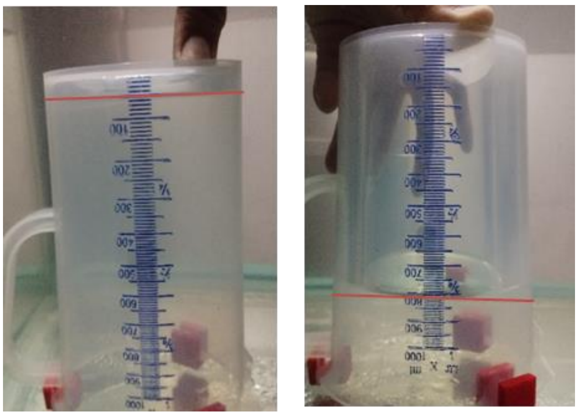

Figure 13. Measurement of ventilator exhaled air volume, (a) 0.1 seconds 50 ml (b) 0.74 seconds 805 ml

Based on the measurement results, there is an increase in volume every 0.02 seconds by 20 ml - 40 ml. Measurements are repeated until the highest volume value is obtained.

The overall data of tidal volume (VT) measurements are shown in the graph of Figure 14. Tidal volume measurement results were obtained which were 50 ml - 805 ml. When the I/E ratio and Respiratory Rate parameters are changed, the Tidal Volume remains the same, the difference is the inspiratory flow rate/minute ventilation. Inspiratory flow rate is the speed of air flow that is flowed in one minute to meet the needs of air volume in the respiration process. To obtain the value of airflow velocity requires the value of tidal volume and inspiration time, if the inspiration time is 1 second and the tidal volume is 400 ml, then the airflow speed is 24 l / minute. For adults under normal circumstances requires an inspiratory flow rate of 30-40 l/min [13].

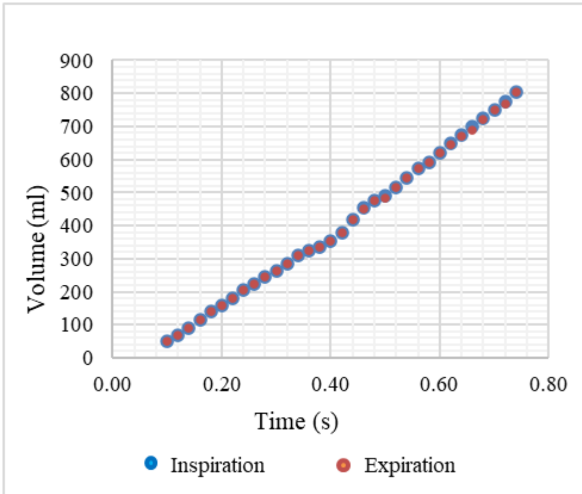

Figure 14. Tidal volume

The administration of tidal volume to patients is adjusted to the ideal body weight, generally 6-8 kg/ml ideal body weight [14]. If the patient is obese, the patient's height is the basis for determining tidal volume.

Tidal volume data obtained based on the activation of the inspired solenoid valve is then used in the programming process for adjustments to the ventilator's LCD display.

4.2.3. Pressure Inspiration

Inspiratory pressure is the final pressure of air (O_2) in the lungs (test lung) or often called peak inspiratory pressure (PIP). The limits of PIP values can be seen in Table 1. PIP values are limited to a maximum of 40 cmH_2O. The following graph in Figure 15 shows the overall pressure measurement results.

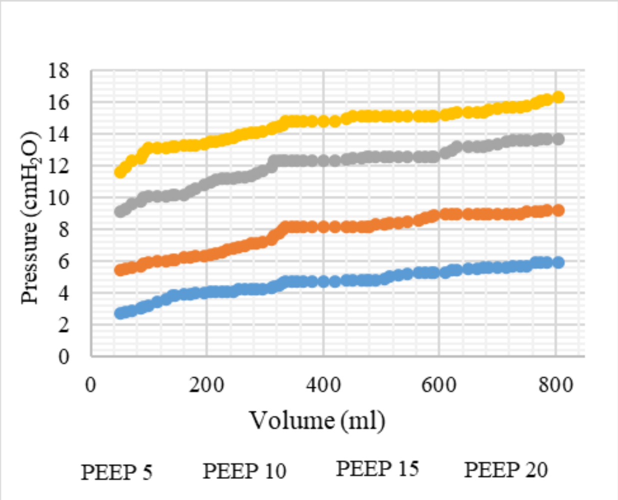

Figure 15. Pressure and volume

Based on the graph of Figure 15, a minimum PIP value of 2.7 cmH_2O (50 ml) and a maximum PIP of 16.3 cmH_2O (805 ml) were obtained. The pressure value will change when the PEEP valve (positive end expiratory pressure) is set at the position of 5 cmH_2O - 20 cmH_2O. The PIP value obtained is in accordance with the medical mark, namely a pressure of less than 40 cmH_2O, but the PEEP value obtained is not in accordance with the settings in PEEP valve. The PEEP valve is set manually. Here are the PEEP values obtained in the graph of Figure 16.

The medical standard PEEP value is 3 cmH_2O - 5 cmH_2O and under certain conditions a higher value is needed if the patient has acute lung disease (Acute Respiratory Distress Syndromee), which is about 7 cmH_2O - 11 cmH_2O [15]. Based on the graph, the PEEP valve setting that can be used is only at the position of 10 cmH_2O - 20 cmH_2O, where the PEEP value is obtained which is 2.9 cmH_2O - 10.9 cmH_2O.

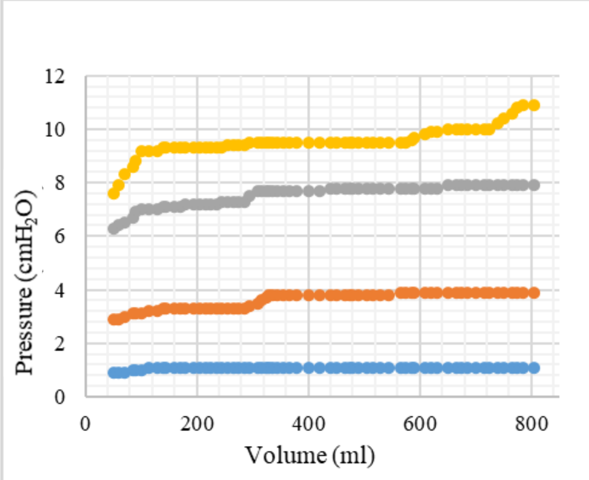

Figure 16. Pressure and PEEP

The PEEP value is also influenced by the tidal value of volume and expiration time, if the expiration time is longer then the PEEP value will be lower.

5. CONCLUSION

The ventilator is built using an Arduino Mega 2560 microcontroller as the control center and a solenoid valve as output. The respiration cycle can be applied to the solenoid valve, if the solenoid valve is active then, the inspiration process takes place, the actual inspiration time can be set from 0.25 seconds - 3.8 seconds. Conversely, if the solenoid valve is not active, the expiration process takes place. The actual expiration time can be set from 0.75 seconds - 6.3 seconds. To ensure the timing of inspiration and expiration is right according to control, measurements are taken using an oscilloscope. The measurement results do not obtain errors or time differences. Then the volume produced by the ventilator can be set from 50 ml - 805 ml, with an increase in volume of 5 ml - 20 ml per 0.1 seconds. The volume is obtained from the activation time of solenoid valve 1, the activation time range is 0.1 seconds - 0.74 seconds, with an increase in time of 0.1 seconds. Solenoid valve 1 will be active (open) when the expiration process takes place and the incoming air is accommodated in a stainless steel tube with a maximum capacity of 800 ml. Then the peak inspiratory pressure (PIP) value is a maximum of 16.3 cmH_2O and the positive value of end expiratory pressure (PEEP) can be set from 2.9 cmH_2O - 10.9 cmH_2O.

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