ПРИБОРОСТРОЕНИЕ, МЕТРОЛОГИЯ И ИНФОРМАЦИОННО-ИЗМЕРИТЕЛЬНЫЕ ПРИБОРЫ И СИСТЕМЫ

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Developing Algorithms and Programs for an Artificial Lung Ventilator

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In this paper algorithms and programs for an artificial lung ventilator were developed, which can be widely used, and especially now for COVID-19 patients. The aim of the work is to develop a software system for the microcontroller STM32L151ZDTx-LQFP144 of the portable ventilator Axion A-IVL-E-03, which allows operation in different modes of ventilation, graphical display of the respiration dynamics and prompt messages to the operator during operation using voice prompts and light signals. The developed lung ventilation algorithms provide periphery management and monitoring the correctness of their work, handle alarm status using a display, voice prompts and light indication. In this research, we will consider modes of artificial lung ventilation, the algorithms of work, and compare the existing analogues. Mathematical models have been proposed for pressure-controlled ventilation as a tool that allows the physician to understand the important interaction between patient input parameters (frequency, applied airway pressure and inspiratory ratio) and clinically important parameters (tidal volume, average volume of minute ventilation).

These mathematical models were applied and it was shown that they are a reasonable approximation of a complex process.

Keywords: microcontrollers, artificial lung ventilation, mathematical modeling, software tools, database systems, knowledge management, operating systems, distributed data processing.

INTRODUCTION

Artificial lung ventilation or mechanical lung ventilation is an integral part of medicine. No serious operation is complete without an artificial lung ventilation apparatus. Many diseases do not allow to live without an artificial lung ventilation apparatus, especially now at the period of COVID-19 pandemic. In some cases, artificial lung ventilation therapy helps people to breathe on their own again. Artificial lung ventilation apparatuses are used both in hospitals and in ambulances. This is a very important part of medicine, which is very closely related to pulse oximetry and capnography. Mechanical lung ventilation has changed significantly since the poliomyelitis epidemic. Ventilation apparatuses with negative pressure, used that time, were replaced by apparatuses with positive pressure. Analog displays have been replaced by digital ones. Nowadays almost all artificial lung ventilation apparatuses are now controlled by advanced computer algorithms, which allow doctors to change almost any parameter. Advances in ventilation technology have created a unique profession in the field of related medical services, a specialist in respiratory diseases, whose main function is to assist in the management of ventilation apparatuses and the intricacies of mechanical lung ventilation. Despite these significant advances, many of the physical principles that govern gas delivery during mechanical lung ventilation have remained the same. Mechanical lung ventilation is primarily a form of supportive therapy and does not cure the concerned disease. Mechanical ventilation should support two very important physiological goals: normalization of arterial blood as well as imbalance of the acid base by providing adequate ventilation and oxygenation using volumes and positive pressure, and reducing the patient's respiratory work by unloading the respiratory muscles in a synchronous manner. When establishing artificial lung ventilation, the primary violation of the patient’s respiratory exchange should be recognized. Patients whose main problem is hypoxemia, e.g., with congestive heart failure or acute respiratory distress syndrome (ARDS) will require more attention to ventilation parameters that improve oxygenation (proportion of inhaled oxygen FiO2), positive end expiratory pressure (PEEP), and mean airway pressure. In contrast, patients with hypercapnic respiratory failure, e.g., patients with acute exacerbation of chronic obstructive pulmonary disease (COPD), drug overdose, or neuromuscular disease, generally need to pay attention to ensuring adequate lung ventilation. There are also patients who are intubated only to protect the respiratory tract (e.g., cramps, altered mental status, and anesthesia). In such cases, mechanical lung ventilation is installed simply to maintain the patient's normal breathing capacity. Since many of these patients have relatively normal lungs, mechanical lung ventilation usually can be quickly stopped when the conditions violate the integrity of the airways to receive adequate treatment. In this research, we will consider the modes of artificial lung ventilation apparatuses, consider the algorithm of work, and compare existing analogues. In recent years, mathematical models have been proposed for pressure-controlled ventilation as a tool that allows the physician to understand the important interaction between patient input parameters (frequency, applied airway pressure and inspiratory ratio) and clinically important parameters (tidal volume, average volume minute ventilation). These models were used and it was shown that they are a reasonable approximation to a complex process.

ARTIFICIAL LUNG VENTILATORS

There is a growing demand for new technologies that can take on the function of a person’s lungs, from assisting an injured or recently transplanted lung to completely replacing a native organ. Artificial lung ventilators must be able to support gas exchange requirements for normal lung function. The device should maintain appropriate blood pressure, reduce injury to blood cells and minimize blood clotting and immunological response. Methods of parallel, sequential and venous double-beam cannula are currently proposed. Classic medical drama would be incomplete without a tense scene, of one person breathes for another to save his life. Currently, a mechanical lung ventilation is used with a wide range of methods, calculations and settings aimed at increasing its success. On the horizon, there is a mechanical or artificial lung, a device that is implanted in a person to support breathing. Number of people in need of a lung transplant is growing. Between 1997 and 2007, the number of candidates for lung transplantation increased by 11 % coupled with the huge gap between those who need a lung transplant and the number of available lungs, the demand clearly outweighs the supply. Only 18 % of 13,154 lungs from organ donors were transplanted in 2006. Where 81 % were not restored, due to discrepancy called the “poor organ function”. Thus, research was focused not only on the artificial lung as a replacement organ, but also on the artificial lung as a bridge to transplantation. Additionally, a successful artificial lung could be used as a supportive device after a transplantation or as additional support to mechanical ventilation [1–3].

Basic Principle

Venous blood always has a lower PaO_2 (40 mm Hg or 75 % saturated or 15 ml O_2/ 100 ml blood) and a higher $PaCO_2$ (46 mmHg) than respirable gas (PiO_2 150 mm Hg, $PiCO_2$ usually 0). Therefore, a partial pressure gradient displaces oxygen and CO_2 from pulmonary capillary blood. Ventilation is a process that mixes fresh respiratory gas with alveolar gas. If there is no ventilation at all, there will be no replenishment of oxygen and removal of CO_2. PaO2 will fall, and $PaCO_2$ will increase in the direction of venous O_2 and CO_2 tension. After the onset of apnea, CO_2 rises rapidly, and within 30 seconds, it is about 50 mm Hg, causing air hunger, like when holding the breath. The subsequent rate of increase in CO_2 voltage is much slower, about 15 minutes, to reach 80 mm Hg, because it dissolves very well. The rapid response of arterial CO_2 to apnea explains why it is such a good gas for our body to use as its primary ventilation control mechanism [4, 5]. In contrast, in the alveoli an oxygen reservoir can maintain an acceptable oxygen tension for about a minute. If the volume of the lung is sufficient, after a deep breath and, in particular, if the lung is filled with a partial oxygen pressure higher than usual, the acceptable voltage of the alveolar oxygen can last much longer. However, if the functional residual capacity FRC is reduced, oxygen consumption will increase or collapse may occur, and the benefits of “pre-oxygenation” will decrease markedly. If the ventilation is greater than necessary, the voltage of the alveolar gas will shift closer to the inhaled gas, i.e. the CO_2 level will be lower and the oxygen level slightly higher.

Inhaling: is an active process requiring muscular effort, 75 % of the diaphragm at rest; load on the intercostal muscles. Causes of effort when inhaling: drop in intrapleural pressure, drop in alveolar pressure, the pressure gradient from the mouth to the alveoli, the pressure gradient of the gas flow. Maximum inspiratory force is sometimes used as an indicator of effort; if <20 cmH_2O most patients have difficulty.

Exhaling: is a passive process due to the return of the lungs, relaxation of the inspiratory muscles, intrapleural pressure becomes less negative, alveolar pressure rises, pressure gradient from the alveoli to the mouth, and pressure gradient of the gas downwards supply.

Respiratory rate and I/E ratio: The normal respiratory rate is about 15 breaths/min, significantly increasing during exercise. The normal I/E ratio at rest and during sleep is 1/2 or less. At load, the I/E ratio is 1/1. Inhalation is usually an active process (requiring work). The exhalation is passive and usually lasts longer than the time required for inspiration, which leads to a period of no flow. With spontaneous breathing, breathing is minimized by reducing inspiratory time and reducing tidal volumes, which is enough to get rid of the CO_2 released [6–8].

Airway resistance: Limits the flow of gas through the respiratory tract, mainly due to airway diameter/ETT (fourth degree radius), where ETT means the endotracheal tube. The normal response to increased resistance is increased force, in conditions of increased airway resistance, slowing of breathing is better.

Intrapleural pressure: is 7.5 cm H2O at mid-chest level, due to the elastic recoil of the lung, opposite to the chest wall. It becomes more negative on inspiration. Less negatively in dependent areas of the lungs, reducing alveolar size.

Compliance: Static correspondence is an indicator of the stiffness of the lungs and chest wall, usually 50 ml/cm H2O in adults and proportionally less in children. Usually this occurs equally due to the correspondence of the lungs and chest wall (100 ml/cm H2O each). When considering the algorithms, the following modes were selected: PSV, IPPV, SIMV, and Resuscitation. These algorithms are the most commonly used by doctors, and areexplained in the following.

Pressure Support Ventilation (PSV)

The essence of this mode is ventilation with pressure support, i.e., the ventilator supports the patient's spontaneous breath. In response to a patient's respiratory attempt, the ventilator increases the pressure to the prescribed value and maintains inspiratory pressure at the set value throughout the inhalation and switches to exhalation when the flow decreases to the set percentage. All breaths in PSV mode are spontaneous, i.e., they are started and completed by the patient. In the PSV mode, doctors set, the support pressure, the positive end-expiratory pressure (PEEP), type of trigger used and its sensitivity, the flow rate curve, and flow percentage from the maximum possible [9].

- Trigger: The commonly used trigger is the flow-triggered ventilation and the pressure trigger. If no enough trigger sensitivity is set, the device will not recognize the patient's attempt to inhale and will not support his inhalation. However, the excessive sensitivity makes the device take a breath by false response of the trigger and take breaths that are not synchronous with the patient's respiratory activity.
- PEEP: positive end-expiratory pressure or baseline pressure is the pressure that the device always supports between breaths. If baseline pressure is atmospheric, this is ZEEP (zero end expiratory pressure or zero expiratory pressure).

Support pressure is the pressure created in the inhalation circuit that supports the patient's inhalation. Nowadays, in all modern devices, the support pressure is of the PEEP type. If the support pressure is set to zero, then the PSV will turn into continuous positive airway pressure CPAP. The curve of flow increase indicates the speed, i.e., how long with hardware inspiration, the flow reaches its maximum value. Mostly, the rate of pressure development can be set from 50 to 500 msec. When switching to exhalation, only a percentage of the flow is used as shown in Fig. 1.

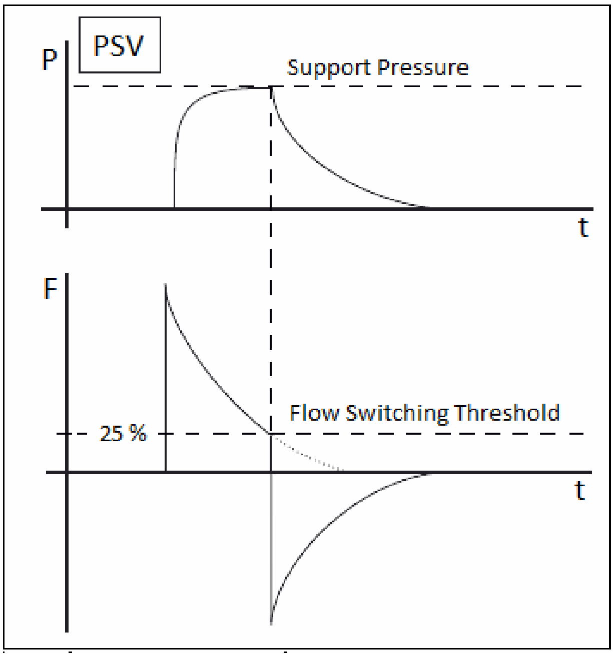


Fig. 1. Switching to exhalation in PSV mode

Threshold examples: the threshold for switching to exhalation in the flow mode is 25 % of the maximum inspiration flow, exhalation threshold is reduced to 10% of the maximum flow, and exhalation flow threshold is increased to 70 % of the maximum flow. The lower the percentage of switching to exhalation, the longer the breath and, accordingly, the greater the volume of breath. The first option is a standard default setting. Fig. 2 shows the examples described above. It is difficult to measure the value of the force that the diaphragm creates at the moment of patient`s breath in PSV mode. To do this, an esophageal pressure sensor (first manufactured by Dräger) should be installed. This sensor measures intrathoracic pressure surrogate with high reliability. However, the intrathoracic pressure does not fully reflect the force of the diaphragm muscles or the negative pressure that the diaphragm muscle will create in the chest at the moment of the patient's spontaneous breath. This is because as soon as the trigger works, the ventilator starts to fulfill its task of supporting pressure. It must begin to maintain the target pressure during the whole breath. In this case, the apparatus not only compensates for the rarefaction that happens to occur during inspiration during the expansion of the chest, but also creates the flow necessary to ensure the achievement of the target airway pressure of the patient. That is, the stronger the patient exhibits respiratory activity, the stronger the device must supply air to him in order to obtain a preset value of the support pressure [10–12]. The tidal volume in PSV mode depends on the quality of synchronization, correct support pressure, and correct switching to exhalation. We find that:

– High-quality synchronization of the ventilator with independent respiratory activity of the patient is one of the indicators of high-quality ventilation.

– The choice of the support pressure value determines not only the patient's comfort, but also the duration of mechanical ventilation, as well as the timing of recovery. Analysis of the results of monitoring the respiratory rate and tidal volume of the patient tells the doctor the way to optimize the ventilation mode setting. In mechanical ventilation, it is important not to try to use a particular patient in the general “averaged” scheme, but to take into account pathological conditions or variants of norm and individual characteristics each time [13–15].

– Under the correct switching from breath to exhalation, we show the setting of the breath duration acceptable for the patient. Among the five factors that determine the size of the tidal volume, we analyze the interaction of the three.

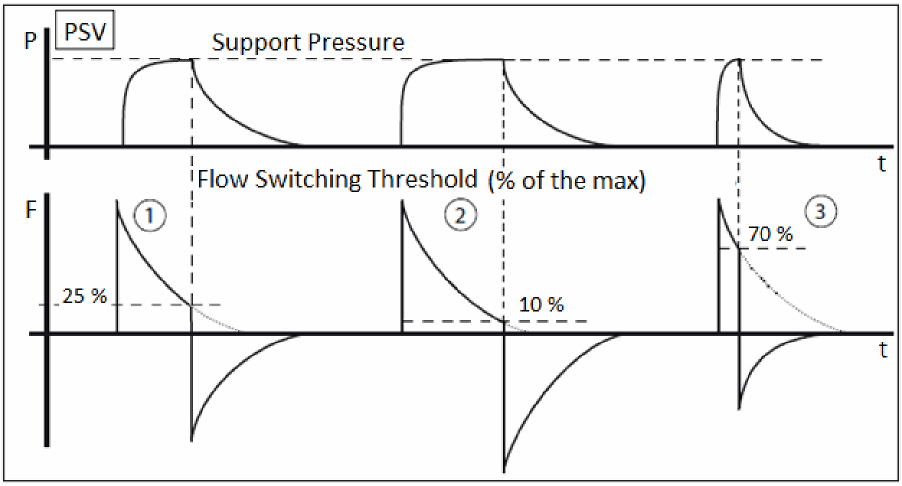


Fig. 2. Three different exhalation threshold examples

Main factors on which volumes depend are: different respiratory activity of the patient (Such as the frequency and depth of breathing), the patient's respiratory system state (i.e., compliance and resistance of the airways), the level of inspiratory support pressure, the rate of increase in flow, and the duration of inspiration to switch from inspiration to exhalation (depending on the percentage of the maximum flow).

Also, as a protection against apnea (stopping respiratory movements), the inclusion of air flow was pre-programmed if the patient's respiratory activity was not registered within ten seconds.

Intermittent Positive Pressure Ventilation (IPPV)

First introduced by Dräger as a ventilation mode with a template according to volume controlled continuous mandatory ventilation VC-CMV and with switching of time for exhalation according to time cycling. Fig. 3 shows a circuit that is similar to the one used in Evita series. The 2nd breath in the diagram shown does not differ at all from the 1st. The figure shows that the artificial lung ventilator increases airway pressure until it delivers the desired respiratory tract. P_{PLAT} is the plateau pressure, *PIP* is the peak inspiratory pressure, $1/f$ is the breathing cycle period, T_{insp} is the inhale time, T_e is the exhale time, Insp. pause is the inspiratory pause, and P_{AW} is the airway pressure. Immediately after the tidal volume is delivered, the flow stops. However, exhalation will begin only when the time allotted for the inhale of T_{insp} is over. At this point, the exhalation valve will open, after which the patient can exhale. The inspiratory time is divided into the inspiratory time, when the flow increases, and the second is the inspiratory pause. This provides an important insight into the operation of the two components of inspiratory time, such as the $P_{\max}$ or pressure limit option. The CMV modes are the volume controlled continuous mandatory ventilation VC-CMV and the pressure controlled continuous mandatory ventilation PC-CMV. The phase variables are:

– *Trigger:* The “CMV” mode has a time trigger, i.e., the ventilator always take breaths only on schedule. In many ventilators in this “CMV” mode there is one more trigger of the patient, where, the patient will be able to initiate a breath himself. It is a flow trigger or a pressure trigger. In order for the patient's trigger to work, a special time period is allocated before the scheduled inspiration starts. The breath that was initiated by the patient is called *assisted breath*. This breath does not differ in volume, pressure and duration from a *forced breath*. The “CMV” mode option with a patient trigger is also called *assisted-control ventilation* (A-C).

– *Limit inspiration*: or limit variable, when controlling the inspiration by pressure, the ventilator fulfills the prescribed pressure, i.e., the pressure limit is established upon the use of this breath control method. If inspiration is controlled by volume, the maximum inspiratory volume is set. If the ventilator controls the breath by volume, then it does not have the right to give more than what was established by the doctor. There are ventilators that provide when controlling the volume of inspiration to set the maximum pressure level or limit $P_{\max}$. If the device for the provided inspiratory time does not exceed the pressure limit, cannot deliver the set volume, then an emergency event is initiated that the volume is not delivered or a low volume is supplied, telling us to increase the inspiratory time or raise the pressure limit.

– *Switching from inspiration to exhalation cycle variables:* If the ventilator controls the inspiration by pressure “Pressure controlled continuous mandatory ventilation”, the transition is performed according to time “Time Cycling”. If the artificial lung ventilation apparatus controls the breath by volume, the transition is performed according to volume “Volume Cycling” or according to time “Time Cycling”.

– *Exhaling:* The limits of exhalation are determined by setting the expiratory time and the value of the PEEP level.

– *Conditional variables and control logic:* which in CMV mode is the amount of time that the patient’s trigger is activated, and the sensitivity of the trigger.

If the ventilator notices respiratory activity of the patient, then the apparatus switches to breath. If it does not see a patient's respiratory activity, then the breath is turned on according to the established schedule (time trigger).

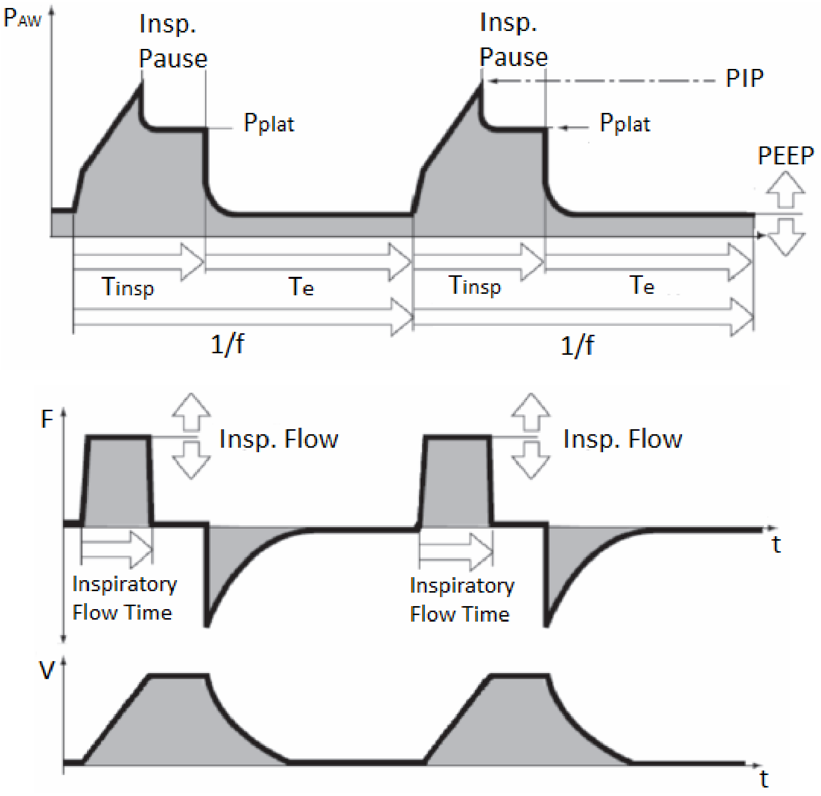


Fig. 3. Artificial lung ventilation apparatus increases airway pressure until it delivers the desired respiratory tract

Synchronized Intermittent Mandatory Ventilation SIMV

Constant flow VC as evolutionary stage. This version of SIMV has forced breaths in volume and transition to breathe using a time trigger and is synchronized with the patient's respiratory activity and spontaneous breaths in the intervals between forced breaths [16–18], as in PSV mode. *Forced breaths:* are controlled by volume, and switching to exhalation occurs in time. This mode has the ability to switch to a forced breath in time, i.e. a time trigger. *Spontaneous breaths*: have a flow or pressure trigger. If the support pressure value is set to zero, then the patient will produce spontaneous breaths as if it is the continuous positive airway pressure CPAP mode. The time trigger initiates a forced breath regardless of whether the patient has respiratory activity or it is absent. The effect of this trigger depends on the preset frequency of forced breaths. In this mode, the patient's trigger is usually triggered by flow or pressure. When the patient shows respiratory activity, that is, a flow or pressure sensor in the device initiates an inhalation, sends a signal to the algorithm to switch to breath. The doctor sets the sensitivity of the patient's trigger when setting the ventilation mode of the artificial lung ventilation apparatus. If the trigger sensitivity is too high, this leads to a false trigger, otherwise if too low the algorithm skips the patient's respiratory activity. The forced breath is triggered by a time trigger. Dividing the time into intervals allows the device to decide how to respond to a patient's respiratory attempt, Fig. 4. If the trigger reports an attempt to patient`s breath, then the device algorithm should include a forced breath or PSV breath, but always includes what is needed. To solve this problem, different time intervals are introduced for spontaneous and forced breaths.

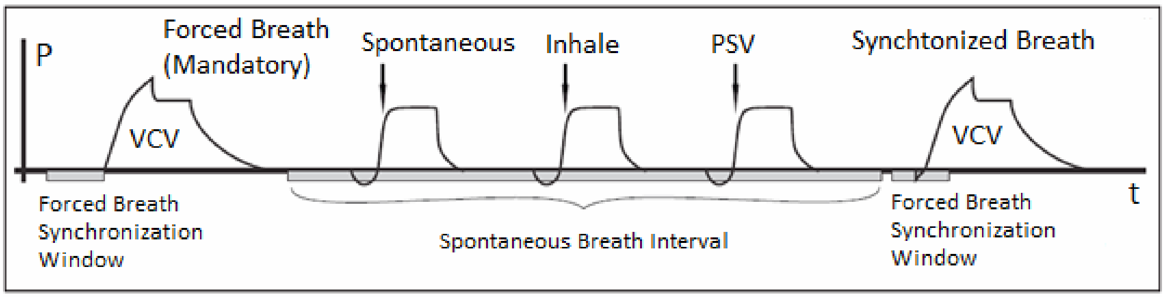


Fig. 4. Dividing the time into intervals

SIMV mode has a time interval for synchronizing forced breaths with patient activity. This timing interval is for forced breaths. The interval becomes available before the trigger starts a forced breath. Between the end of the forced inspiration interval, the time interval for spontaneous inspiration is delayed until the trigger triggers by time. If the patient's respiratory activity occurred during the synchronization interval, the device will switch to forced synchronized breath. If the patient does not have respiratory activity during the synchronization interval, then the trigger will work in time and the device will take a forced breath. In the third case, if the patient's respiratory activity is noticed during the interval between the windows for synchronized forced breaths, the device will support a spontaneous breath, i.e., a breath that is made according to the PSV mode. Fig. 5 shows this mode. This mode is preferred by doctors because of its versatility. If there is no patient respiratory activity, then it is indistinguishable from CMV-VC. If the doctor set the frequency of forced breaths to zero, then the regime turns into PSV. However, the most important distinguishing ability of this regimen is that it does not need to suppress the patient's spontaneous breathing and it is possible to smoothly change the degree of respiratory support. The disadvantage of the regime is that in its parameters pressure, flow and volume, forced and spontaneous breaths vary greatly. In the figure, you can verify these differences [19, 20].

Overview of analogues

Table 1 shows a comparison between the portable ventilator Axion A-IVL-E-03 and RITM 100 TMT, Aeros 4300, and A-IVL/VVLp-3/30. After analysis, the following tasks were identified:

– Develop lung ventilation algorithms, after studying the literature on most popular modes, such as auxiliary ventilation with pressure support, synchronized intermittent forced ventilation, intermittent ventilation with positive pressure, resuscitation.

– Provide peripheral management, after studying the information on keyboard, switches, and pressure, vacuum, airflow sensors, as well as speaker and LED control.

– Implement emergency handling, by monitoring the following emergencies stenosis (the set pressure threshold is exceeded), disconnection of the respiratory circuit (one of the reasons is the mask does not fit snugly with the patient), low battery, low pressure in the balloon (notifies of a low oxygen volume in the balloon), and pressure gauge hose error (pressure gauge hose was pinched).

– Develop a user interface, a clear and convenient interface, a driver for a 2.7-inch display has to be written, and realize the display of the obtained values from the sensors using a real-time graph.

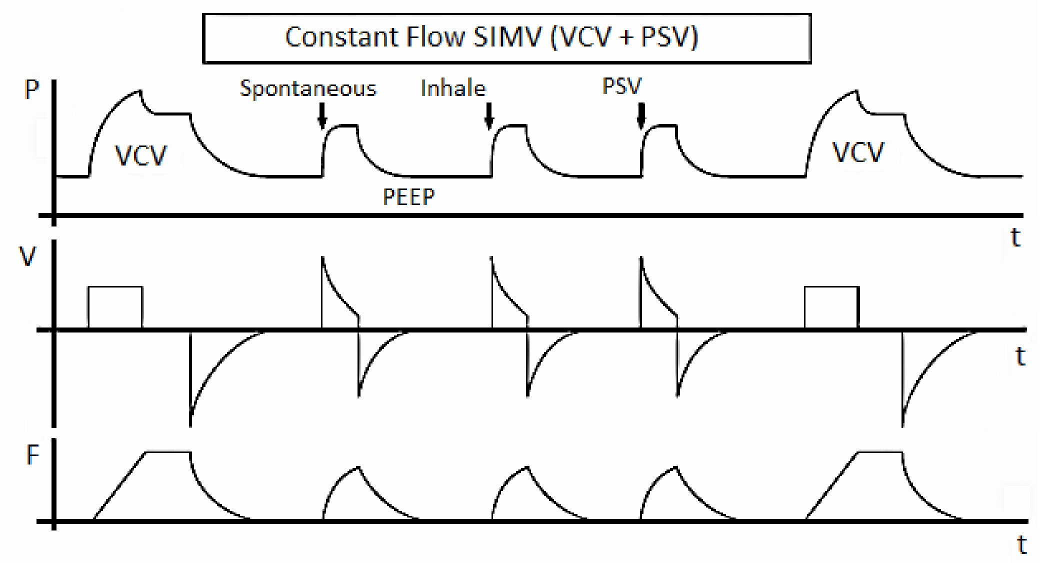


Fig. 5. SIMV mode

Comparison table

Name	A-IVL-E-03	RITM 100 TMT	Aeros 4300	A-IVL/VVLp-3/30
Manufacturer	LLC Concern «Axion», Russia	LLC «TMT», Russia	DIXION, China	LLC «Medprom», Russia
Modes	Modes of ventilation	IPPV, PSV, SIMV, Resuscitation, Oxygen therapy	CMV, ACMV	A/C, SIGH, SIMV, SPONT, Manual, PSV
Minute volume, l / min	0,5-30	0,5-25	0,5-15	0,7-15
Respiratory rate, 1 / min	10-80	5-80	4-99	10-40
Inhale / exhale	1:4-4:1	3:1-1:3	2:1-1:4	1:2
Ventilation pressure, mbar	0-50	0-60	0-60	15-50
Oxygen Concentration, %	100	50-100	48-100	60-100
Monitored parameters	Minute volume Respiratory rate Airway pressure Tidal volume Power indicator	Minute volume Respiratory rate Airway pressure Tidal volume	Tidal volume Minute volume Airway pressure Respiratory rate Power indicator	Airway pressure Ventilation modes Power indicator
Display, inch	2,7	5	–	–
Price, t.r. (thousand rubles)	85	200	275	95

FUNCTIONAL AND MATHEMATICAL MODEL

Functional model

The functional diagram is shown in Fig. 6. With the help of sensors, we obtain the respiratory circuit and the oxygen cylinder parameters. Data from the pressure sensor and vacuum sensor enters the controller using a serial peripheral interface SPI. The air sensor is analog and the data is converted using an analog-to-digital A/D converter.

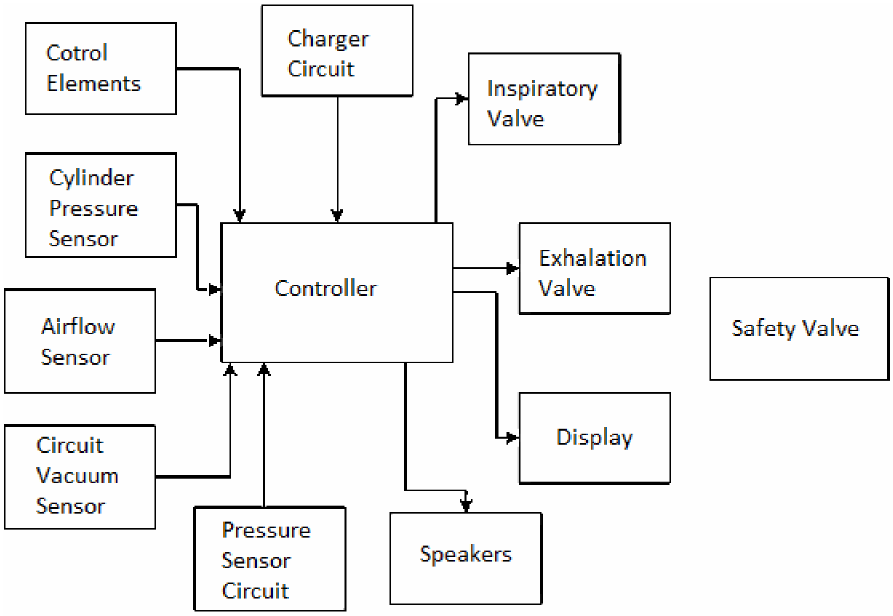


Fig. 6. Functional diagram

A battery charging program was developed on another controller, where all charging algorithms occur, and only the charge level comes to the main controller. With the help of the user interface the device modes are set. There is a keyboard with position selection, mode confirmation, exit button, manual mode button, disabling voice prompts button, and a button for turning the device on and off. With the help of dial switches, the time value and breath frequency per minute are selected. The regions indicated by a special color for different periods coincide with the color of the set values on the display, e.g., the child mode uses yellow color, on the display and the selected values are also tinted yellow. The controller also sends data to the display, about the current pressure, as well as the display of pressure and volume curves. Information about the mode operating time, the last selected mode, and the device's total operating time is displayed. Using the speaker, the device notifies the operator of possible emergency and voice prompts help in choosing the mode settings. The controller controls the inspiratory valve using pulse-width modulation PWM to more accurately supply the required calculated gas mixture flow. The exhalation valve opens when the patient exhales. Emergency handling, and a safety valve is included, responsible for venting hazardous pressure in the event of a circuit failure. An artificial lung that mimics the human lungs has also been used. The program was tested using an analyzer that monitors the level of oxygen, the frequency of breaths, pressure in the respiratory circuit, minute volume, the ratio of inspiration to expiration, and the display of curves.

Mathematical model

To describe the mathematical formulation of the problem, it is necessary to describe some important concepts in artificial ventilation:

Tidal volume: is a measure of one exhalation or a regular inspiration.

Inspired reserve volume IRV: maximum inspiratory volume at the end of a regular inspiration.

Inspiratory capacity IC: maximum inspiration volume following a regular exhalation:

$$IC = VT + IRV.$$

Total lung capacity TLC: air volume in the lungs at the end of the maximum inspiration.

Residual volume RV: the volume of air in the lungs at the end of the maximum exhalation.

Volume capacity VC: the volume of inspiration after the end of the maximum exhalation:

$$VC = TLC - RC.$$

Functional residual capacity FRC: the volume of air in the lungs at the end of a normal exhalation:

$$FRC = TLC - IC.$$

Expired reserve volume ERV: maximum expiratory volume at the end of normal exhalation.

Equation of motion or Newton's third law for the "ventilator - patient" system:

If the ventilator takes a breath in synchronization with the patient's breathing attempt, the pressure generated by the ventilator (P_{vent}) is summed up with the patient's muscular effort (P_{mus}) (left side of the equation) to overcome the elasticity of the lungs and chest and resistance to the air flow in the airways (right side of the equation):

$$P_{mus} + P_{vent} = P_{elastic} + P_{resistive} \text{ (m bars)};$$

$$P_{elastic} = E \cdot V \text{ (Elasticity} \times \text{Volume)};$$

$$P_{resistive} = R * V \text{ (Flow Resistance} \times \text{Volume)};$$

$$P_{mus}\left(mbar\right) + P_{vent}\left(mbar\right) = E\left(\frac{mbar}{ml}\right) * V(ml) +$$
$$+ R\left(\frac{mbar}{l} / \min\right) * V\left(\frac{l}{\min}\right).$$

Considering the proposed options for calculating the flow based on patient resistance and compliance. Artificial ventilation models are formed by balancing the pressure in the system:

$$P_{vent} + P_{resist} + P_{el} + P_{rest} = 0.$$

P_{vent} is the pressure applied by the ventilator, P_{resist} is the pressure to overcome the resistive losses inside and outside the lung, P_{el} is the pressure to overcome the elastic forces, since the lung is pumped and deflated, and P_{rest} is the residual pressure in the lung at the end of each inspiration cycle. It is expected, that the equation is assumed to be performed during each respiratory cycle $0 \le t \le t_i$. One cycle is divided into: inhale, $0 \le t \le t_{in}$, and exhale, $t_{in} \le t \le t_{ex}$. The main interest in these models is the volume noted by $V(t)$. The dynamics of the lung can vary between inhalation and exhalation. The specific model that can be obtained depends on the assumptions about P_{vent}, P_{resist}, P_{el} and P_{rest}. It is assumed that during inspiration $P_{vent} = P_{rest}$, and this type is called *permanent ventilation* or zero pressure PEEP ventilation. It is expected, that the pressure to overcome the elastic forces is proportional to the lung's volume, i.e., $P_{el} = V(t) / C$ during inhalation and exhalation. Here C is a constant called compliance. Other types of assumptions may be made for P_{el}, e.g., we can assume that $P_{el} = V(t) / C(V)$, where $C(V)$ is a linear function of V:

$$P = R_1Q + R_2Q.$$

Where P is the pressure, R_1 and R_2 are the resistance parameters, and Q is the flow for inhalation and exhalation:

$$Q = \frac{dV}{dt}.$$

Using this justification, we obtain the following system of differential equations for lung volume in one breath.

Inhale:

$$R_1\left(\frac{dV_{in}}{dt}\right) + R_2\left(\frac{dV_{in}}{dt}\right)^2 + \frac{V_{in}}{C} + P_{rest} = P_{ust}.$$

Exhale:

$$R_1\left(\frac{dV_{ex}}{dt}\right) + R_2\left(\frac{dV_{ex}}{dt}\right)^2 + \frac{V_{ex}}{C} + P_{rest} = 0.$$

Where V_{in} is the inspiratory volume, V_{ex} is the expiratory volume. Now we solve the equation based on the previous formulas:

$$\frac{dV_i}{dt} = \pm\sqrt{\left(\frac{R_1}{2R_1}\right)^2 + \frac{P_{ust} - P_{rest} - V_i/C}{R_2}} - \frac{R_1}{2R_2}.$$

We select the plus sign in the equation above so that $\frac{dV_i}{dt} \ge 0$. Then we can separate the variables and get the implicit equation for $V_i(t)$:

$$\ln\left(\sqrt{1 + \frac{4R_2}{R_1^{\,2}}\left(P_{ust} - P_{rest} - V_i/C\right)} - 1\right) +$$
$$+ \sqrt{1 + \frac{4R_2}{R_1^{\,2}}\left(P_{ust} - P_{rest} - V_i/C\right)} = -\frac{t}{CR_1} + a,$$

α is the integration constant.

$$a = \sqrt{1 + \frac{4R_2}{R_1^{\,2}}\left(P_{ust} - P_{rest}\right)} +$$
$$+ \ln\left(\sqrt{1 + \frac{4R_2}{R_1^{\,2}}\left(P_{ust} - P_{rest}\right)} - 1\right).$$

Substituting the value of α, we obtain an implicit solution to the initial equation:

$$\ln\left(\sqrt{1 + \frac{4R_2}{R_1^{\,2}}\left(P_{ust} - P_{rest} - V_i/C\right)} - 1\right) +$$
$$+ \sqrt{1 + \frac{4R_2}{R_1^{\,2}}\left(P_{ust} - P_{rest} - V_i/C\right)} =$$
$$= -\frac{t}{CR_1} + \sqrt{1 + \frac{4R_2}{R_1^{\,2}}\left(P_{ust} - P_{rest}\right)} +$$
$$+ \ln\left(\sqrt{1 + \frac{4R_2}{R_1^{\,2}}\left(P_{ust} - P_{rest}\right)} - 1\right).$$

EXPERIMENTS AND RESULTS

Fig. 7 shows the assembled pneumatic circuit according to which the apparatus works. At the inlet, there is a cylinder or tube with a pressure range from 2.7 to 6 bar, which is connected using a quick coupler. A pressure reducer regulates the inlet pressure to 2.7 bar, followed by a pressure sensor that monitors the drop in inlet pressure. The proportional valve is responsible for the prescribed level of flow. An ejector with a valve and a non-return valve, are responsible for suctioning, i.e., mixing pure oxygen with atmospheric air. The non-return valve does not allow the oxygen flow to exit the tube, but only to suck it. The airflow sensor calculates the volumes supplied by the device. A safety valve is needed in case of system failure. The exhalation valve opens when the patient exhales. The curves shown in Fig. 8 to 12 correspond to the experiment results obtained from the device's display. The device has an English interface that can be selected when it is turned on Fig. 13.

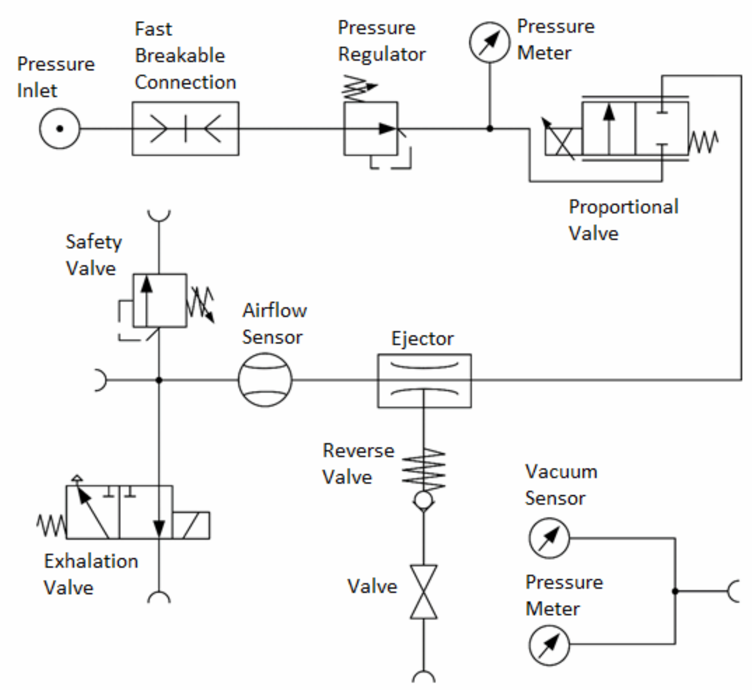


Fig. 7. Assembled pneumatic circuit

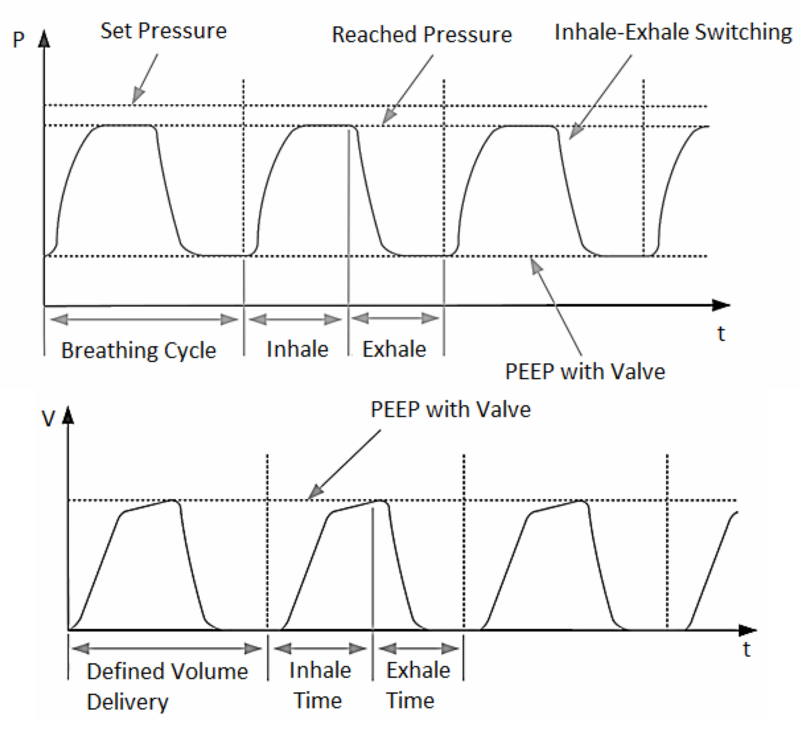


Fig. 8. IPPV experiment results. The curves obtained from the device's display

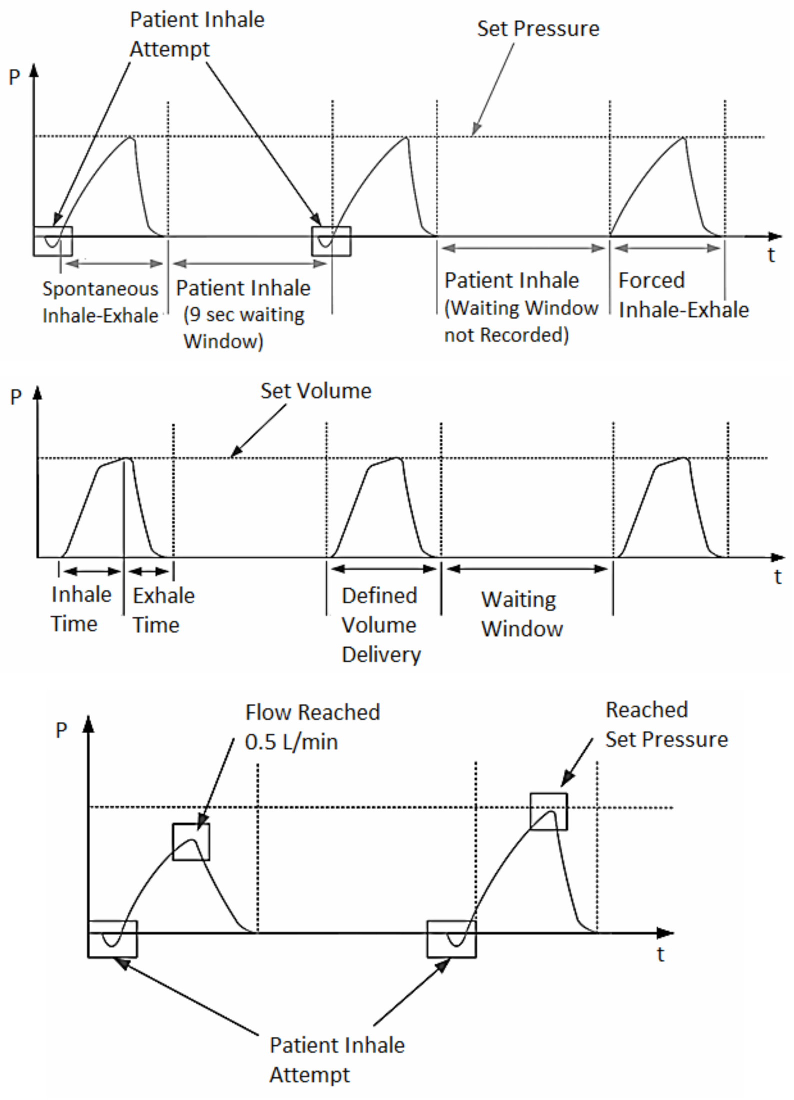


Fig. 9. PSV experiment results

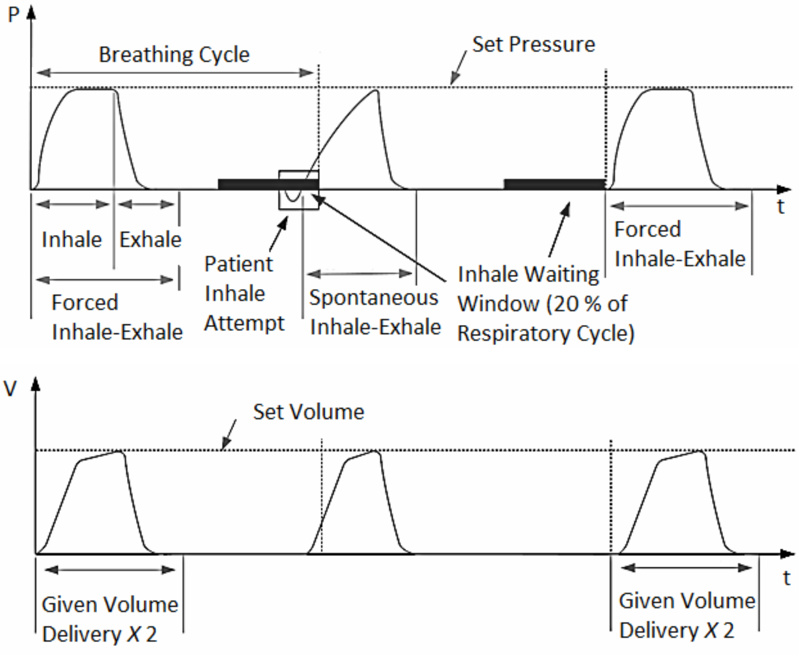


Fig. 10. SIMV experiment results

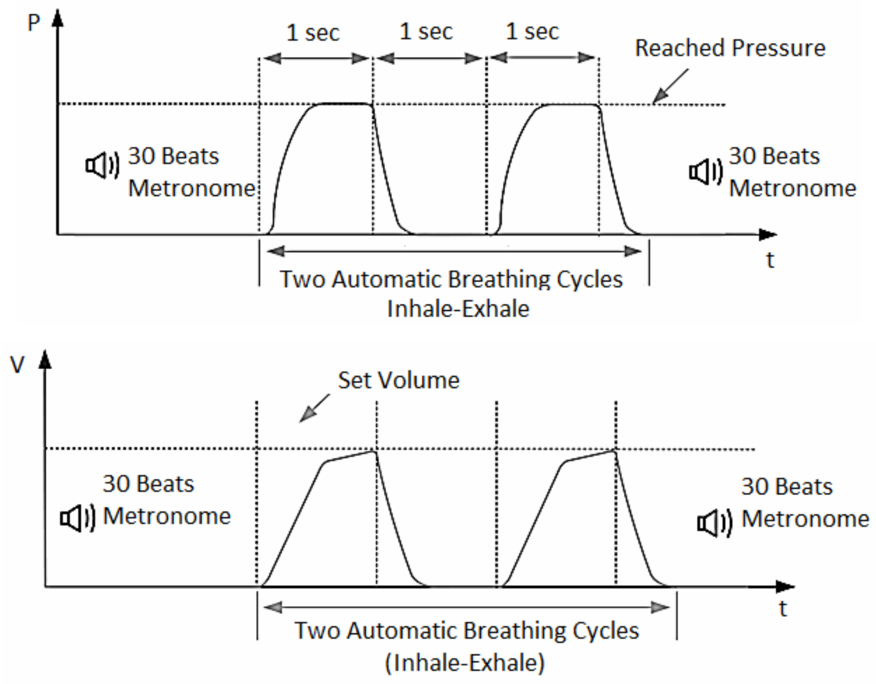


Fig. 11. REAN experiment results

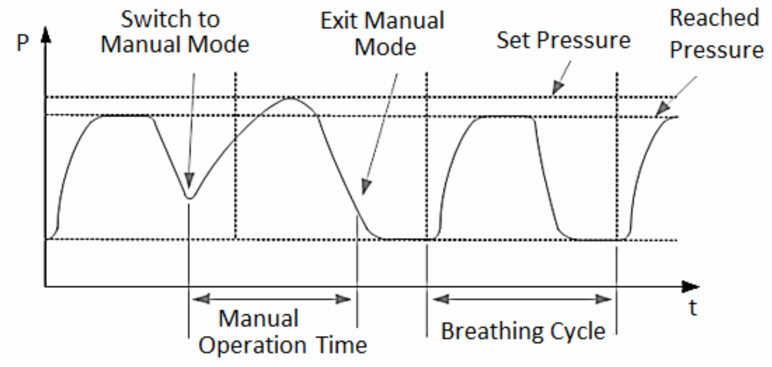
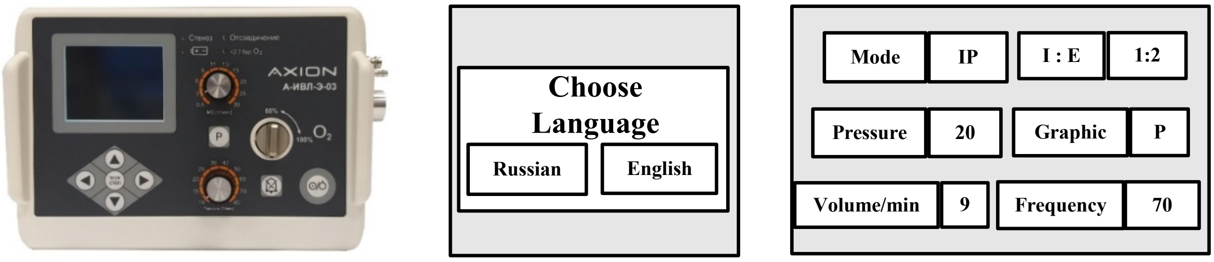


Fig. 12. Manual mode experiment results



Choose Language

Russian **English**

Mode	**IP**	**I : E**	**1:2**
Pressure	**20**	**Graphic**	**P**
Volume/min	**9**	**Frequency**	**70**

Fig. 13. Device appearance and user interface

Emergency handling programs were developed, where the display is repainted in a red area with a heading about emergency event. The LED starts flashing and a voice prompt starts giving advice. The alarm will work until it is turned off. The device will still try to give the air mixture to the patient.

1) Stenosis is the excess of a given level of pressure in the patient's respiratory circuit. When the pressure in the third respiratory cycle rises, this emergency occurs.

2) Disconnection of the respiratory circuit during the ventilation modes operation, if the pressure does not rise within 10 sec an emergency occurs.

3) Low pressure in the cylinder when trying to inhale, the pressure sensor in the cylinder detected a low-pressure value, after which this emergency situation is triggered.

4) Low battery level - if during operation of the device it receives a value corresponding to a low charge value, the device goes into this emergency situation. First there will be a warning, which will be repeated after ten minutes, then after two minutes the device will turn off.

5) Equipment malfunction when the device is turned on, if the device registers a malfunction of the pressure and air flow sensors.

After the device is turned on, and choosing the language, the operator can choose from the main menu the following settings: mode, pressure in the respiratory circuit, inhale-exhale ratio, type of displayed curve, volume per minute, and frequency. All parameters, except for mode and graphic, can be changed during the operation of the ventilation mode. The developed algorithms are shown on Fig. 14. In IPPV mode and all other modes the respiration parameters are calculated based on the values set by the operator in the main menu. The flow is calculated based on the pressure difference, using approximation, the level of pulse-width modulation PWM is selected. The calculated voltage level is applied to the inspiratory valve, after which the gas mixture immediately begins to flow. Emergency situations are handled such as low pressure in the balloon, maximum pressure level in the respiratory circuit is exceeded, and the respiratory circuit is disconnected. During the supply of the gas mixture, the device, using the airflow sensor, detects the presence of atmospheric air leakage. In case of leakage, the calculated data are corrected so as not to exceed the specified volumes. The selected graphic is displayed in real time, as well as the current pressure in the respiratory circuit. After applying the target minute volume or the end of the inspiration time, the device switches to the exhale mode. The exhalation valve opens, and the inspiratory valve delivers extremely low flow values to maintain PEEP. If the operator has chosen to exit the mode, the screen returns to the main menu, otherwise the next breath occurs. In the PSV mode, using vacuum sensor, expects a patient attempt of inhale. To protect against apnea, an algorithm was made that delivers air mixture every 9 seconds if no patient attempts have been detected. After the patient reaches a predetermined pressure level, the device switches the mode to exhalation. The exhalation valve opens and the inspiratory valve closes. In the SIMV mode the exhalation valve opens and the inspiratory valve turns off. At this time, a waiting window opens to try to allow the patient to inhale spontaneously. If there was no spontaneous inhalation, a new forced ventilation cycle begins. Otherwise it goes into spontaneous ventilation mode similar to PSV. If the operator has chosen to exit the mode, the screen returns to the main menu, otherwise the next breath takes place via SIMV, if there is no respiratory activity or if there is PSV activity. After selecting the Resuscitation mode using voice prompts and a metronome, 30 compressions are performed, after which the device switches to inhale, exhale, inhale. During the supply of the air mixture, emergency situations are also handled. If the operator selects exit, the screen returns to the main menu, otherwise the next compression cycle occurs. In the manual mode the mode ends when the operator releases the manual mode key. As a warning in all emergency events, a voice message is displayed, an audible alarm is also output, and using the LEDs and display, an error is reported to the operator. When stenosis or exceeding a predetermined pressure level occurs, the device receives the current pressure value, if the pressure is exceeded, the exhalation valve opens, and the inspiratory valve closes. When disconnection of the respiratory happens, the device receives the current pressure value, checks how long the low pressure in the breathing circuit lasts. In case of emergency, the inspiratory valve closes. When low battery, the device receives data from a digital-to-analog converter DAC. Compares values if the charge level is low the used warnings are triggered. If the power was not connected, the device will automatically turn off after 2 min. When low cylinder pressure, the device receives the current pressure value from the sensor in the oxygen cylinder. If the pressure is below 2.7 bar, an emergency occurs, the inspiratory valve closes. For reverse current, the calculation is based on the pressure difference. Then, the calculation is made using the approximation formula for flow and resistance. The device receives data from the ADC. Calculates current resistance and approximation. There is a calculation of volts and calculation of the final value of the PWM resistance. For receiving data from sensors, pressure sensors communicate via the SPI and receive data by sending ones and zeros to the chip select pin. The airflow sensor sends data to the ADC. When processing the matrix keyboard, low-level is sent to start polling the keys, using a timer. If the key is pressed for more than 100 ms, it is regarded as key pressing. Using the SPI, the device communicates with flash memory, reads the data. Through a configured DAC and DMA, voice messages and voice signals are played.

General algorithm
1. Turning on the device
2. Menu program execution
3. Selected mode program execution
4. Turning off the device

IPPV Mode
1. Respiration parameters calculation
2. Calculation of required gas flow
3. Supplying gas mixture
4. Emergency handling
5. Checking for gas mixture suction
6. Displaying data on the screen
7. Switch to exhale
7. If (inhale_attempt=spontaneous) = YES go to 1
8. Otherwise if ((inhale_attempt=spontaneous) = No) & (mode_exit=YES) exit SIMV mode
9. Otherwise go to 1

PSV Mode
1. Respiration parameters calculation
2. Waiting for patient inhale trial
3. Calculation of required gas flow
4. Supplying gas mixture
5. Emergency handling
6. Checking for gas mixture suction
7. Displaying data on the screen
8. Switch to exhale
9. If exit_current_mode = NO go to step 1
10. Otherwise if YES end PSV mode

SIMV mode
1. Calculation of the required gas flow
2. Supply gas mixture
3. Emergency handling
4. Checking for gas mixture suction
5. Displaying data on the screen
6. Switching to exhalation
7. If (inhale_attempt=spontaneous) = YES go to 1
8. Otherwise if ((inhale_attempt=spontaneous) = No) & (mode_exit=YES) exit SIMV mode
9. Otherwise go to 1

Resuscitation mode
1. Respiration parameters calculation
2. Compression start
3. Emergency handling
4. Inhale

Manual mode
1. Respiration parameters calculation
2. Emergency handling
3. Supplying continuous gas flow
4. If exit_current_mode = NO go to step 1
5. Otherwise if YES end manual mode

Handling stenosis emergency
1. Getting the current pressure level
2. Checking if current pressure is exceeded
3. If pressure_exceeded = NO go to 9
4. Otherwise if YES close inhalation valve
5. Open the exhalation valve
6. Output voice message
7. Display graphical message
8. LED signaling
9. End emergency handling

Handling detachment emergency
1. Get current pressure level
2. If (pressure < 1 mbar) = NO go to 9
3. Otherwise if YES and
   (Counter = 10 sec) = NO go to 2
4. Otherwise if (counter = 10 sec) = YES
   Close the inhalation valve
5. Open the exhalation valve
6. Output voice message
7. Display picture message
8. LED signaling
9. End of emergency handling

Handling low battery emergency
1. Receiving data from ADC
2. Data conversion
3. If (charge_level = low) = NO
   Display current level & go to 1
4. Otherwise If YES
   Output voice message
5. Display graphical message
6. LED signaling

Emergency treatment start low cylinder pressure
1. Receive data from pressure sensor
2. If (pressure=low) = NO go to 1
3. Otherwise if YES
   Open exhalation valve
4. Close inhalation valve
5. Output voice message
6. Display graphical message
7. LED signaling
8. End of alarm handling

Reverse current correction
1. Pressure difference calculation
2. Using approximation formula
3. Receiving data from ADC
4. Resistance calculation
5. Calculation of approximation by current
6. Calculation of voltage
7. Calculation of final PWM percentage
8. End of Algorithm

Fig. 14 (to be continued). The developed algorithms

Receiving data from sensors
1. Send low level feed on chip select line
2. Data acquisition
3. Waiting for transmission
4. Send high level on chip select
5. Process the received data
6. Deliver data to the required mode
7. End of algorithm

Keyboard matrix processing
1. Turning on the timer
2. Send low level on keyboard polling line
3. Waiting to get high level on the pin
4. If Button_pressed = NO go to 8
5. Otherwise if YES & if (Button_pressed_time > 100 ms) = NO go to 8
6. Otherwise if ((Button_pressed_time > 100 ms) = YES) then process the push
7. End of Algorithm

Sound playback
1. Send low level on chip select line
2. Send message to read flash memory
3. Receiving data
4. Send high level on chip select
5. ADC setup
6. Data matrix playback via DMA
7. End of Algorithm

Display
1. Send command to display
2. Transferring data to the display
3. Setting the cursor
4. Setting display orientation
5. Setting display color
6. Performing the required function
7. End of Algorithm

Fig. 14 (continued). The developed algorithms

CONCLUSION

Various literature about theory of artificial ventilation of the lungs, their features and normal function was studied, and lung ventilation algorithms such as PSV, SIMV, IPPV, resuscitation, were studied and implemented. Mathematical and physical aspects of artificial ventilation of the lungs were also analyzed. Functional schemes were constructed for further programming of the ventilator for dealing effectively with the problem. Programs that conform to all the tasks were written. The constant needs for effective life support with minimal risk and optimized comfort are and will be the main tasks of mechanical ventilation. The optimal ventilation strategy is an adaptive process aimed at treating an acute condition and either supporting gradual excommunication from the ventilator or adapting to the natural breaks of chronic diseases. Such an adjustment can improve results and comfort, reduce side effects and avoid prolonged ventilation with associated risks and costs. To achieve these goals, the development of our understanding in the field of pathophysiology, medicine and engineering should be combined with an interdisciplinary approach to completely solve the complex problem of artificial ventilation to further improve patient care.

References

1. Goryachev A.S., Savin I.A. *Asinkhronii i grafika IVL* [Asynchrony and ventilation schedule]. Moscow, Aksiom grafiks yunion Publ., 2018, 370 p. (in Russ.).

2. Chatburn R.L. [Fundamentals of mechanical ventilation]. Mandu Press Ltd, Ohio, 2003, p. 312 p.

3. Colice G.L. Historical perspective on the development of mechanical ventilation. Principles and Practice of Mechanical Ventilation. Third. Tobin MJ, editor. New York, McGraw Hill, 2013, pp. 3-41.

4. Satishour O.E. Mechanical ventilation of lungs. Moscow, Medical Literature Publ., 2006, 349 p.

5. Housley E., Louzada N., Becklake M.R. To sigh or not to sigh. Am *Rev Respir Dis*, 1970, vol. 17, pp. 611-614.

6. Goryachev A.S., Savin I.A. *Osnovy IVL* [Basics of mechanical ventilation]. Moscow, Medizdat Publ., 2009 (in Russ.).

7. Mezhirova N.M, V'yun V.V., Danilova V.V. *Azbuka iskusstvennoi ventilyatsii legkikh* [The alphabet of artificial lung ventilation]. Khar'kov, KhNMU Publ., 2014, 29 c. (in Russ.).

8. Bendixen H.H., Hedley-Whyte J., Laver M.B. Impaired oxygenation in surgical patients during general anesthesia with controlled ventilation. A concept of atelectasis. *N Engl J. Med*, 1963, vol. 17, pp. 991-996.

9. Marini J.J., Kirk W., Culver B.H. Flow resistance of the exhalation valves and PEEP devices used in mechanical ventilation. *Am Rev Respir Dis*, 1985, vol. 17, pp. 850-854.

10. Torok P., Majek M. Multilevel Ventilation: Theory and Simplified Mathematical Model. General Reanimatology Publ., 2008, p. 7.

11. [10] Paradokas P.J. Mechanical ventilation. Saunders, New York, 2008, 369 p.

12. Ashbaugh D.G., Bigelow D.B., Petty T.L., Levine B.E. Acute respiratory distress in adults. *Lancet*, 1967, vol. 17, pp. 319-323.

13. Tawflic Q.A. Liquid ventilation. *Oman Medical J.*, 2011, p. 9.

14. Weil M.H., Tang W. From intensive care to critical care medicine: a historical perspective. *Am. J. Respir Crit Care Med*, 2011, vol. 17, pp. 1451-1453.

15. Ashbaugh D.G., Petty T.L., Bigelow D.B., Harris T.M. Continuous positive-pressure breathing (CPPB) in adult respiratory distress syndrome. *J. Thorac Cardiovasc Surg*, 1969, vol. 17, pp. 31-41.

16. Tobin M.J. Principles and Practice of mechanical ventilation. The McGraw-Hill Companies, 2013, 443 p.

17. Drinker P., McKhann C.F. The use of a new apparatus for the prolonged administration of artificial respiration. *JAMA*, 1929, vol. 17, pp. 1658-1660.

18. Zapol W.M. Extracorporeal membrane oxygenation in severe acute respiratory failure. A randomized prospective study. *JAMA*, 1979, vol. 17, pp. 2193-2196.

19. Baker A.B. Artificial respiration, the history of an idea, 1960, p. 6.

20. Barach A.L., Eckman M., Ginsburg E. Studies on positive pressure respiration. *J. Aviat Med*, 1946, vol. 17, pp. 290-356.

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Разработка алгоритмов и программы для аппарата искусственной вентиляции легких

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Описаны алгоритмы и программы для аппарата искусственной вентиляции легких, которые обеспечивают различные режимы работы аппарата. Работа является актуальной в условиях пандемии COVID-19 в связи с возросшим спросом на данные устройства.

Цель исследования – разработка программного комплекса для микроконтроллера STM32L151ZDTx-LQFP144, используемого на переносном аппарате ИВЛ Axion A-IVL-E-03 и обеспечивающего работу в различных режимах вентиляции, графическое отображение динамики дыхания на дисплее и подачу оператору голосовых подсказок и световых сигналов во время работы. Разработанные алгоритмы также предназначены для управления периферийными устройствами и контроля правильности их работы, разрешения аварийных ситуаций с помощью дисплея, голосовых подсказок и световой индикации. Кроме того, в качестве инструмента, который позволяет врачу понять важное взаимодействие между входными параметрами пациента (частота, давление в дыхательных путях и степень вдоха) и клинически важными параметрами (дыхательный объем, средний объем минутной вентиляции), предложены математические модели вентиляции легких с контролируемым давлением. Реализация данных математических моделей показала их применимость для симуляции данных сложных процессов. Разработан удобный и интуитивно понятный графический пользовательский интерфейс.

В статье также приводится сравнение существующих аналогов с предложенными разработками.

Ключевые слова: микроконтроллеры, искусственная вентиляция легких, математическое моделирование, программные средства, системы баз данных, управление знаниями, операционные системы, распределенная обработка данных.

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