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Research article

Model-free volume and pressure cycled control of automatic bag valve mask ventilator

Cong Toai Truong[1], Kim Hieu Huynh[1], Van Tu Duong[1,2,*], Huy Hung Nguyen[1,3], Le An Pham[4], and Tan Tien Nguyen[1,*]

[1] National Key Laboratory of Digital Control and System Engineering (DCSELAB), HCMUT, VNU-HCM
[2] The Department of Mechatronics, Ho Chi Minh City University of Technology, VNU-HCM
[3] Faculty of Electronics and Telecommunication, Saigon University, Vietnam
[4] Grant and Innovation Center (GIC), University of Medicine and Pharmacy, Ho Chi Minh city

* **Correspondence:** Email: dvtu@hcmut.edu.vn, nttien@hcmut.edu.vn.

Abstract: Ventilators are drawn to many researchers during the Covid-19 pandemic because it's essential equipment that's accustomed to treat severe Covid-19 patients. In low-income countries, there's a shortage of pricy respiratory devices resulting in exceeding the provision of taking care of Covid-19's patients in ICU. This paper attempts to design and implement an appropriate respiratory device referred to as a bag valve mask (BVM) ventilator for those who are Covid-19 patients in medical care, those patients have a requirement of safe transport and also palliative care. The BVM ventilator comprises a man-made manual breath unit (AMBU) bag and paddles for squeezing the AMBU bag which is popular in medical aid settings. The BVM ventilator is required to travel airflow through the system to the patient's lung with the specified volume for every breath cycle within a threshold air pressure. Since the AMBU bag is straightforward to be deformed over time, it's difficult to get mathematical modelling for constructing a reliable controller. Therefore, a model-free control (MFC) control approach is utilized successfully to style a controller for our BVM ventilator model with a PEEP valve and a HEPA filter. Some experimental scenarios are administered to gauge the effectiveness of the proposed controller for the BVM ventilator to control the airflow and control air pressure mode.

Keywords: mechanical ventilator; bag valve mask system (BVM); low-cost ventilator; volume control timed cycle

1. Introduction

Covid-19 pandemic emerged Wu-Han province, China at the top of 2019 has broken out throughout the globe that is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [1–6]. The pandemic has competent many stages and lots of varieties of virus generations [7,8] that threaten global health. According to WHO data, the quantity of infected people is 174,502,686 and also the number of deaths is 3,770,361 within the world (until June 11, 2021) [9].

Coronavirus has transmission atypical modes as oral (in the shape of respiratory droplet nuclei), food-borne/water-borne transmission, skin contact, smoke exhaled from a smoker [10], and quickly damage the patient's health [11]. The foremost difficult thing is that the incubation takes place silently, and therefore the symptoms are very almost like the common flu. The main symptoms of Covid-19 patients are fever, shortness of breath, cough, and fatigue. Other symptoms that are less prevalent include muscle aches and pain, nasal, congestion, sore throat, runny nose chills, which are sometimes accompanied by frequent shaking headache, and loss of smell or taste [12].

The Covid-19 is capable of causing highly significant infections in humans, leading to highly hazardous conditions such as pneumonia, acute respiratory distress syndrome (ARDS), sepsis, and superinfection [13] as triggered by a cytokine storm. The cytokine storm could be a form of acute hyperinflammatory reaction that may cause serious illness in a very type of situations, including viral infections, malignancy, sepsis, and multi-organ failure. Intensively ill patients with Covid-19 who experience cytokine storms are thought to possess a poor prognosis and a higher mortality rate. The event of varied severe signs of the Covid-19 in SARS-CoV-2 infected patients appears to be influenced by cytokine storm: acute respiratory distress syndrome, thromboembolic disorders like acute ischemic strokes, and myocardial infarction induced by major artery blockage, encephalitis, acute kidney damage, and vasculitis [14–16]. In keeping with several of the research, roughly 15–30% of the Covid-19 infected patients developed severe and required ECMO device assistance [17]. Meanwhile, all countries within the globe, particularly developing ones, have an issue in terms of the amount and distribution of ECMO. Long-term plans include equipment distribution, ECMO user training, staffing, ECMO planning, and resource allocation [18]. The Covid-19 pandemic has caused essentially in the medical device industry (especially low-income countries [19–21]), such as protective equipment (PPE), testing kits, sophisticated equipment like life-saving mechanical ventilators [22], and X-ray machines [23]. Significantly, the time overload is experienced by doctors and nurses who work in the emergency resuscitation sector [24,25]. In some cases, the inter-and intrahospital transport [26] of critically ill patients is requiring ventilator assistance [27] or portable ventilators to be used for transportation since some existing studies have been demonstrated that the utilize of a manual AMBU might result in negative effect owing to erratic breathing [28]. Furthermore, as aforementioned, ECMO machines require a well-trained clinician to operate, thus the addition of a simple ventilator to resolve overcrowding of accident and emergency unit as the ways to decrease pressure for the medical sector.

Several efforts to create a low-cost, simple of use, transportability ventilator [29–36] in medical aid sectors were presented. However, the patients experience acute respiratory failure which causes fluid leakage to their lungs. This ends up in being extremely difficult breathing thereby require to treat using complex functionality mechanical ventilators. Meanwhile, simple low-cost ventilators which provide time-cycled tidal volume assist control mode or pressure-cycled are well-suited for unconscious patients whose compliance of lungs are kind of like that of the healthy persons' lung but cannot spontaneously breathe. Thus, the necessity for a BVM ventilator for safe transportation and palliative care is prominent in the Covid-19 outbreak. Besides that, the therapy for patients is established while utilizing a BVM ventilator in comparison to commercial ventilators are identical with fundamental control modes (volume control, pressure control). Thus, the treatment creates for patients effective safety, avoids infecting Covid-19 patients at the primary care level. The first aid is to assist transport the patient moreover in provide hospice care (if any). If the patient is transported correctly, and early weaning from mechanical ventilation will reduce cytokine storm, reducing mortality as in developed countries. Additionally, the BVM ventilator has short training times for hospital staff who can make good use of it timely at the first care level.

This paper presents the controller design for a bag valve mask (BVM) ventilator inspired by [37]. The study question: which one amongst ventilator controller models relevant to the BVM ventilator for safe and effective in Covid-19 patients. Our study objectives: establish and preliminary test the ventilator controller model for the BVM ventilator that can provide tidal volume assist control within the boundaries of pressure to avoid barotrauma. So as to regulate the tidal volume reaching the desired set volume, an airflow sensor is installed on the airway to feedback the airflow over time. The tidal volume is achieved by integrating the airflow continuously with time after each breath cycle. A pressure sensor is attached to the Luer lock port of a HEPA filter to monitor the air pressure whether exceeds the utmost allowable pressure. Moreover, the usage of the airflow and the air pressure sensors enable it to trigger the alarms operational. Several scenarios are carried out to evaluate the performance of the bag valve mask ventilator with an artificial test lung.

2. Materials and methods

2.1. Overall system description

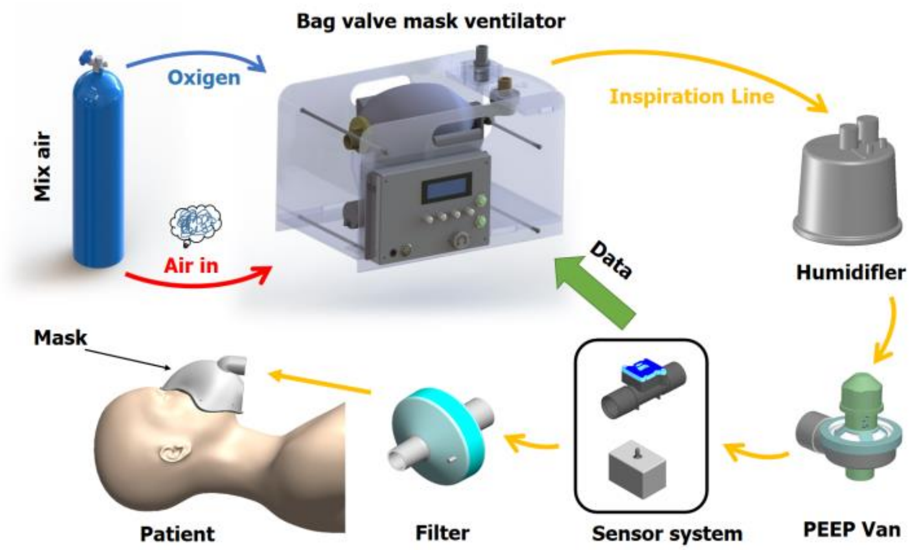

Figure 1. Breath circuit configuration.

Figure 1 describes the breath circuit configuration with the usage of a BVM ventilator. The

BVM ventilator delivers oxygen/air mixture from the oxygen hose through a humidifier, sensory system, and a HEPA filter to the patient wearing a mask. The working principle of the bag valve mask ventilator relies on squeezing rhythmically an artificial manual breath unit (AMBU) bag with two paddles. The humidifier is utilized to humidify and warm up the oxygen/air mixture before delivery to the patients' lungs through respiratory tubes. The positive end-expiratory pressure (PEEP) valve plays a key role that permits it to keep the remaining pressure of the patients' lungs positive continuously. The PEEP valve is adjustable easily by a knob.

To avoid barotrauma caused by exceeding maximum pressure, the PEEP valve should be placed as close to the patients' lungs as possible. The BVM ventilator is developed to operate under the following requirements:

Tidal volume: The desired volume of oxygen/air mixture is required to deliver to the patients' lungs for each breathe. The value of tidal volume depends on the bodyweight of the patient and is commanded by the clinicians. A tidal volume of 350 to 700 ml must be provided by the BVM ventilator. The tidal volume is $6 \div 8$ ml/kg for lungs without injury [38].

Positive end-expiratory pressure (PEEP): At the end of the expiratory phase, a positive air pressure above atmospheric pressure must be maintained in the airway to keep unstable lung units from collapsing [39]. The PEEP value is in the range of $5 \div 15$ cmH_2O [40].

Peak inspiratory pressure (PIP): The highest allowable airway pressure is applied to the patients' lungs during the inspiratory phase. An increased PIP ends up in a rise of volume. The PIP value is adjusted to correspond to the lung compliance and small tidal volumes.

Plateau Pressure: The airway pressure of the bag valve mask ventilator is measured at the end of the inspiratory phase with an inspiratory hold maneuver on the BVM ventilator in the range of 0.5 to 1 second [41].

Respiratory Rate: The number of breaths is taken per minute. The bag valve mask should provide in the range of $12 \div 40$ breathes per minute (BPM) depending on the ages and lung status of patients [42].

Inspiratory - Expiratory ratio: The ratio known as I:E ratio is defined as inspiratory phase time/expiratory phase time. The expiratory phase lasts twice as long as the inspiratory phase in typical spontaneous breathing. The BVM ventilator should provide in the range of 1:2–1:4 [43].

Flow rate: The maximum airflow corresponding to the desired tidal volume is delivered to the patients' lungs by the BVM ventilator. The flow rate should be titrated to meet the inspiratory demands of patients. For most patients, the maximum flow rate of 60 L/min is adequate [44].

Trigger Sensitivity: This function enables for assist control mode of the BVM ventilator by means of detecting the patients' effort correlating with pressure trigger sensitivity. A pressure trigger sensitivity is set in the range of $-1 \div -3$ cmH_2O. A breath is called a triggered breath when a negative pressure on inspiratory effort is greater than the set sensitivity.

Pressure waveform: The BVM ventilator provides the ramp function of the pressure waveform as shown in Figure 2. At the inspiration, the airway pressure is ascending to reach the PIP value. Then, there is a holding time to achieve the Plateau pressure. At the expiration, the airway pressure is descending to obtain the PEEP value. The baseline of the pressure waveform is increased by adding the PEEP. For any pressure sensitivity trigger, it can be detected in the expiration.

Flow CC: The BVM ventilator provides the flow waveform with a square wave in the inspiration, and the flow is descending in the expiration as shown in Figure 2. Since the BVM ventilator does not support the expiratory tube, the flow in expiration is unmeasurable.

Alarm triggers: The BVM ventilator must be triggered for alarms by the following conditions: (i) The airway pressure exceeds the allowable maximum pressure; (ii) The minimum pressure does not achieve; (iii) The desired angle of the paddles does not achieve; (iv) The PEEP value does not achieve; (v) The load current of the DC motor exceeds the allowable threshold.

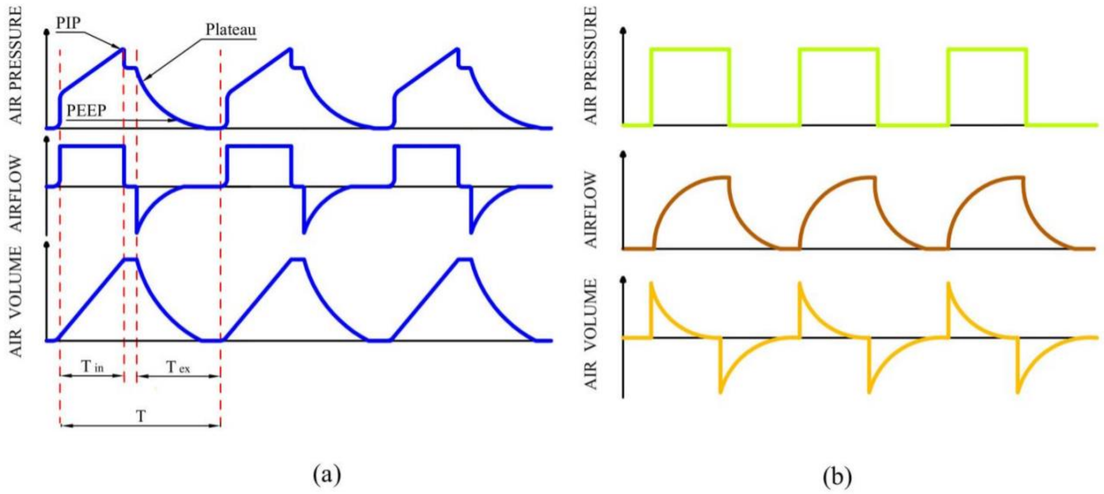

Figure 2. System response in volume–controlled mode (a) and pressure–controlled mode (b).

Figure 2 illustrates the waveform of the tidal volume, the airflow, and the air pressure in volume-controlled (VC) mode and pressure-controlled (PC) mode [45]. It can be seen from the graph that in VC mode, the airflow includes a waveform during the inspiratory phase. Thus, the tidal volume is a variable depending on the airflow constant and the inhalation time. The air pressure is a dependent variable that goes up during the inhalation and reaches its maximum at the end of the inspiration [46]. On the other hand, in terms of PC mode, the preset air pressure waveform encompasses a square profile. The airflow increases rapidly initially before an exponential drop afterward.

2.2. Bag valve mask ventilator

Figure 3 illustrates the BVM ventilator consisting of a lightweight chassis, two paddles, an AMBU bag for adults, a 12V 60W DC motor equipped with a 13 ppr quadrature encoder, and 1/262 planetary gearbox, inspiratory tubes, and electric controller equipped with a sensory system. The sensory system consists of an airflow sensor (SFM3020) to measure the flow in the airway, an air pressure sensor (SSCDANN001PGAA5), and three limit switches to detect the limit stroke and the home position of the paddles. Two paddles are powered by the DC motor directly through gear transmission.

The quadrature encoder is utilized to measure the rotational displacement of the paddles. The airflow sensor measures the flow traveling over the inspiratory tubes, thereby it is integrated through time spent to derive the volume delivered to the patients' lungs. The air pressure sensor is employed to measure the pressure in respiratory tubes relying on the compliance of the patients' lung. The desired tidal volume is reached by the commanded stroke on the rotational displacement of the paddles. Meanwhile, the air pressure relies on the rotational velocity of the paddles in the squeezing phase. The tidal volume, respiratory rate, I:E ratio, PIP, and PEEP are displayed on a graphical LCD and set by the control knob.

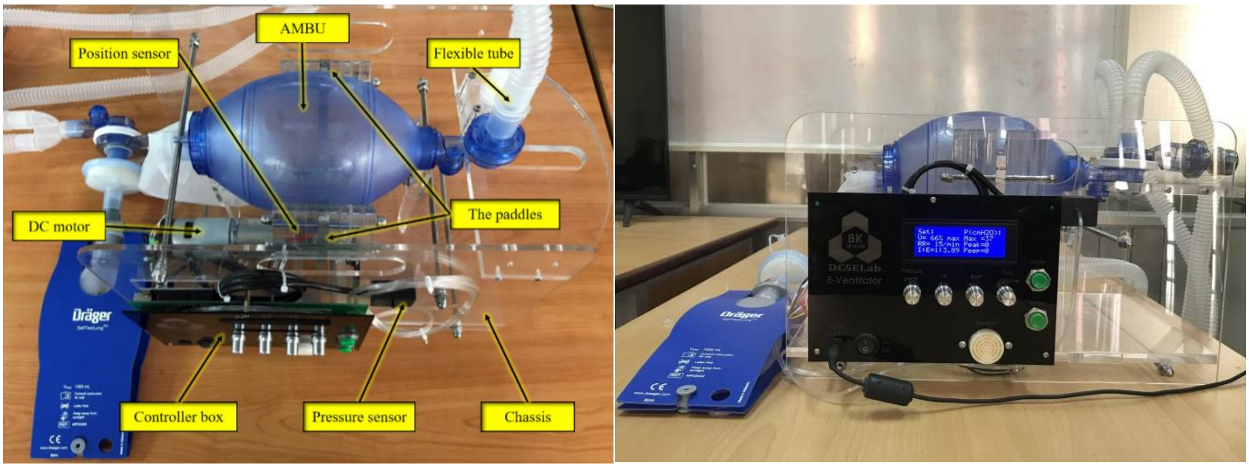

Figure 3. Structure of bag valve mask ventilator.

The process of the BVM ventilator is started by first pressing a “home/start” button to reach the initial position of the paddles known as “home” position recognized by hitting the home limit switch. The clinicians can set and monitor appropriate respiratory parameters through four control knobs and the graphical LCD display. Then, the BVM ventilator squeezes the AMBU bag for the first respiratory cycle by second pressing the “home/start” button. In the first squeezing, the paddles try to reach the specified angle akin to the required tidal volume concerning an experimental trajectory of tidal volume with relevance the paddle’s squeezing angle. The tidal volume can be adjusted by controlling the paddle’s angle. The breathing rate can be ascended by increasing the frequency of squeezing the paddles.

The actual tidal volume is controlled to reach the desired tidal volume through a piecewise controller for the DC motor of the BVM ventilator which can be expressed by:

$$u(t) = \begin{cases} u_{in}(t) & if \quad t \le T_i \\ u_{hold}(t) & if \quad T_i < t \le T_i + T_h \\ u_{ex}(t) & if \quad T_i + T_h < t \le T_e \end{cases} \tag{1}$$

where $u(t)$ is the supply voltage for the DC motor of the BVM ventilator called the piecewise controller, $u_{in}(t)$ is the sub-controller in the inspiration, $u_{hold}(t)$ is the sub-controller in the holding time, $u_{ex}(t)$ is the sub-controller in the expiration, T_i is the inspiratory time, T_e is the expiratory time, and T_h is the holding time to derive the plateau pressure. The parameters of the BVM ventilator are illustrated in Table 1.

Table 1. The parameter of the Bag Valve Mask System.

Parameters	Values
Overall dimensions	400 × 250 × 250 mm
Mass of BVM	5 kilograms
Respiration rate	6–40 BPM
Tidal volume	350–700 ml
Pressure	1 to 40 cm water (accuracy range ±0.7 cmH_2O)
Maximum working pressure limit (MWPL)	10 to 40 cmH_2O
Modes	Volume-controlled modes, Pressure-controlled modes
I:E	Adjustable (suggested 1:2)
Range PEEP	≤15 cmH_2O

3. Controller design

3.1. Model free control

It is clear to see that the BVM ventilator needs to be installed correctly to ensure adequate ventilation for the patient. In addition, the BVM ventilator is equipped with non-reusable parts such as a nonrebreathing valve [47] that might vary the BVM system model for each patient. Furthermore, for each respiratory breath cycle, the AMBU bags' elasticity is a slightly time-variant factor, thus, it is difficult to obtain a system model which represents the dynamic behavior of the BVM ventilator accuracy. Therefore, a free model control can be a suitable approach for the controlling of BVM ventilator. The unknown mathematical model could be expressed by an ultra-local model [48]:

$$y^{(\nu)} = F + \alpha u \tag{2}$$

where ν is the derivative order of y defined as the system output and could be selected by the practitioner; $\alpha \in R$ is a non-physical constant parameter and it should be chosen by the practitioner such that αu and F have the same magnitude; u is a saturated control input which is fed to an amplifier to drive the DC motor; the control input u has value ranging from −1 to 1 with minus sign defined as reverse rotation; F represents the unexplicit parts of the plant as well as various disturbances, the estimation of F comes from u and y which is expressed in Eq 13.

For $\nu = 1$, it can deduce that $y^{(\nu)} = \dot{y}$, and Eq 2 becomes:

$$\dot{y} = F + \alpha u \tag{3}$$

Approximate F by a constant function $\hat{F}$ in a short interval time, Eq 3 becomes:

$$\dot{y} = \hat{F} + \alpha u \tag{4}$$

A control approach [48] is employed to a controller named Intelligent Proportional (iPI) which control law is given as follows:

$$u = -\frac{\hat{F} - \dot{y}_d + K_P e + K_I \int e}{\alpha} \tag{5}$$

where $\dot{y}_d$ is the derivative of the reference signal; $e = y - y_d$ is defined as the error between the output signal and the reference signal; K_P is the proportional gain constant; K_I is the integral gain constant; $\hat{F}$ is the online estimation value of F. It should be emphasized that there were three iPI controllers corresponding to three stages in-breath: inspiratory, holding and expiratory. Therefore, u in Eq 2 is specifically expressed in Eq 6.

$$u(t) = \begin{cases} u_{in}(t) & if \quad t \le T_i \\ u_{hold}(t) & if \quad T_i < t \le T_i + T_h \\ u_{ex}(t) & if \quad T_i + T_h < t \le T_e \end{cases}$$

$$u_{in}(t) = -\frac{\hat{F}_i - (\dot{y}_d)_i + (K_P)_i e_i + (K_I)_i \int e_i}{\alpha_i}$$

$$u_{hold}(t) = -\frac{\hat{F}_h - (\dot{y}_d)_h + (K_P)_h e_h + (K_I)_h \int e_h}{\alpha_h} \tag{6}$$

$$u_{ex}(t) = -\frac{\hat{F}_e - (\dot{y}_d)_e + (K_P)_e e_e + (K_I)_e \int e_e}{\alpha_e}$$

To be more specific, $u_{in}(t)$, which is applied in the inspiratory phase, drives the system output known as the tidal volume in VC mode to track the desired volume ramp reference and as the air pressure in PC mode to track the desired pressure rectangular reference; $u_{hold}(t)$, in holding phase, is desired to keep the paddles fixed at the stopping angle of the inspiration and $u_{ex}(t)$, in expiratory phase, returns the paddles back to its homing position in preparation for a next squeezing cycle.

According to the algebraic parameter identification technique introduced in [49,50], by taking Laplace transform for Eq 4, it yields:

$$sY = \frac{\hat{F}}{s} + \alpha U + y_0 \tag{7}$$

where y_0 is the initial condition in the interval time $[t - L, t]$; ϕ is a constant parameter.

Differentiating Eq 7 with respect to s, it becomes:

$$Y + s\frac{dY}{ds} = -\frac{\hat{F}}{s^2} + \alpha\frac{dU}{ds} \tag{8}$$

Multiplying both side by $\frac{1}{s^2}$ to get rid of derivatives with respect to time:

$$\frac{Y}{s^2} + \frac{1}{s}\frac{dY}{ds} = -\frac{\hat{F}}{s^4} + \alpha\frac{1}{s^2}\frac{dU}{ds} \tag{9}$$

Considering the following relation:

$$\frac{c}{s^\alpha}, \alpha \ge 1, c \in C \leftrightarrow c\frac{t^{\alpha-1}}{(\alpha-1)!} \tag{10}$$

$$\frac{1}{s^{\alpha}}\frac{d^{n}}{ds^{n}}Y(s) \leftrightarrow \frac{(-1)^{n}}{(\alpha-1)!}\int_{0}^{t}(t-\tau)^{\alpha-1}\tau^{n}y(\tau)d\tau \tag{11}$$

Applying Eq 10 and Eq (11 in order to take inverse Laplace transform for Eq 9 in the interval time $[t-L,t]$, it yields:

$$\int_{t-L}^{t}(L-\tau)y(\tau)d\tau - \int_{t-L}^{t}\tau y(\tau)d\tau = -\hat{F}\frac{L^{3}}{3!} - \alpha\int_{t-L}^{t}(L-\tau)\tau u(\tau)d\tau \tag{12}$$

Therefore, $\hat{F}$ of Eq (5 can be determined by:

$$\hat{F} = -\frac{6}{L^{3}}\int_{t-L}^{t}[(L-2\tau)y(\tau) + \alpha\tau(L-\tau)u(\tau)]d\tau \tag{13}$$

By applying trapezoidal integral for the approximation of $\hat{F}$, when the grid spacing uniformly, for a domain L discretized into N equally spaced panels:

$$\Delta\sigma = \frac{L}{N} \tag{14}$$

Then F could be digitally implemented by using the following approximation of the integral (with T is the sampling time):

$$\begin{aligned} &-\frac{6}{L^{3}}\int_{t-L}^{t}\big((L-2\sigma)y(\sigma) + \alpha\sigma(L-\sigma)u(\sigma)\big)d\sigma \\ &\approx -\frac{6}{L^{3}}\Delta\sigma\left(\left(\sum_{k=1}^{N-1}(L-2\sigma_{k})\,y_{k}(T)\right) + \alpha\left(\sum_{k=1}^{N-1}\sigma_{k}(L-\sigma_{k})\,u_{k}(T)\right)\right) \end{aligned} \tag{15}$$

By substituting Eq 5 into Eq 3, it yields

$$\dot{e} + K_{P}e + K_{I}\int e = F - \hat{F} \tag{16}$$

During one sampling interval, F is approximated to be equal to the constant parameter $\hat{F}$, therefore Eq 16 becomes:

$$\dot{e} + K_{P}e + K_{I}\int e = 0 \tag{17}$$

F does not appear anymore in Eq 17, thus, the unknown parts and disturbance of the system disappear. The tuning of K_P, K_I affects directly the system response. Thus, K_P, K_I should be well selected in order to ensure a good tracking response while satisfying mechanical limits, i.e.:

$$\lim_{t\to\infty} e(t) = 0 \tag{18}$$

3.2. Experiment selecting α

According to Eq 2, α could be determined by evaluating the correlation between $y^{(\nu)}$ and u_{in}. The relation is shown as following:

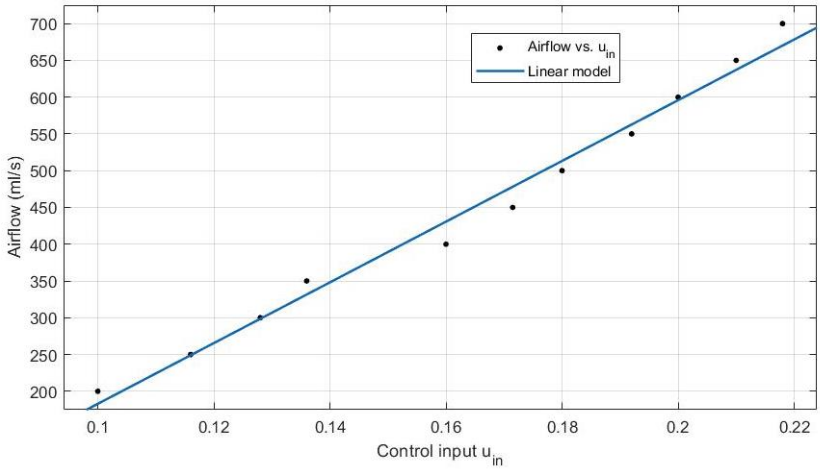

Figure 4. Characteristic of control signal with respect to airflow.

Correlation of the control signal $u_{in} - Airflow$ is expressed as the following linear model (95% confidence bound) with a correlation coefficient $R \approx 0.9847$ $(a = 4128,\ b = -229.8)$:

$$Airflow = a.u_{in} - b \tag{19}$$

Therefore, α is chosen to be equal to $(\alpha = a)$, the actual results of volume iPI control for the ramp desired air volume is shown in Figure 5.

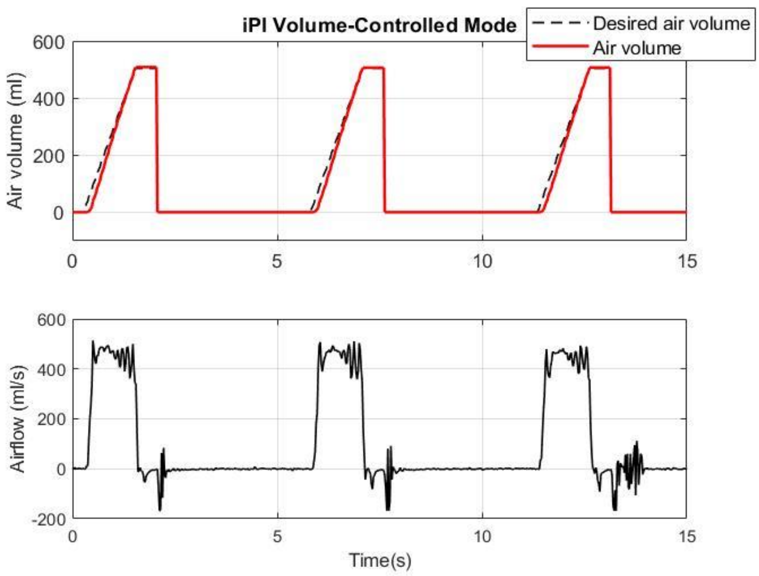

Figure 5. Volume response of volume-controlled mode for iPI controller.

4. Experimental result

To validate the effectiveness and controllability of the BVM ventilator operated with the proposed controller, two experiments in PC mode and VC mode are carried out. The airflow travels over the respiratory circuit to the artificial test lung by squeezing the AMBU bag with paddles. System parameters for digital implementation of iPI control are given as follows $v = 1,\ L = 250$ milliseconds, and the sampling time $T = 25$ milliseconds.

4.1. Volume-controlled mode

In the first scenario, the BVM ventilator is evaluated in VC mode with the desired tidal volume (500 ml), PEEP (5 cmH_2O), respiratory rate (20 BPM), I:E ratio (1:2), and PIP is controlled to be limit less than 40 cmH_2O. System parameter for digital implementation of iPI control is given as $\alpha = 4128,\ K_P = 2000,\ K_I = 3500$.

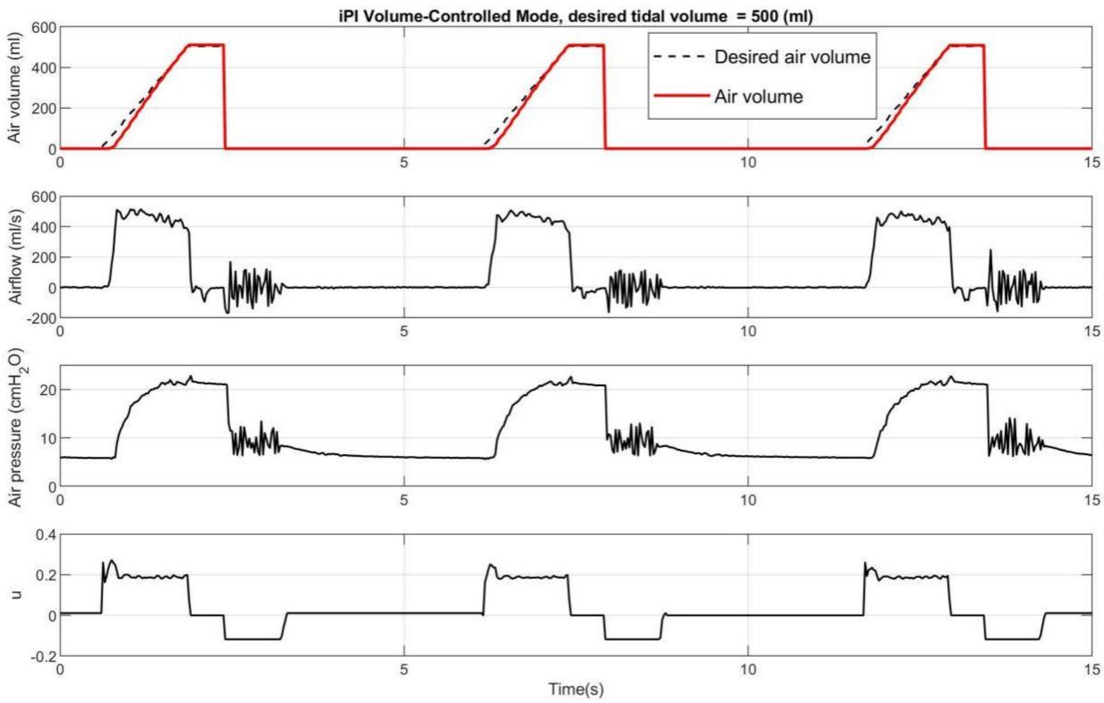

Figure 6. System response in VC mode.

Figure 6 illustrates the air volume response of the BVM ventilator under the control of iPI controllers for the desired volume ramp reference for three breath cycles. In VC mode, the airflow attempt to track a constant airflow during inspiration while the air pressure is a dependent variable [21]. To be specific, it depends on airflow rate, tidal volume, the circuit of patients, and lung characteristics. The theoretical waveform of air volume, airflow, and air pressure in VC mode is shown in Figure 2a. Although there was a quite long settling time, the tidal volume reaches its desired value at the end of the inspiratory phase. In short, the iPI controller provides good tracking of the tidal volume concerning the desired volume ramp reference.

4.2. Pressure-controlled mode

In the second scenario, the BVM ventilator is evaluated in PC mode with PEEP (5 cmH_2O), respiratory rate (16 BPM), I:E ratio (1:2), and the desired air pressure (20 cmH_2O). System parameter for digital implementation of iPI control is given as $\alpha = 2.75,\ K_P = 18.5,\ K_I = 0$.

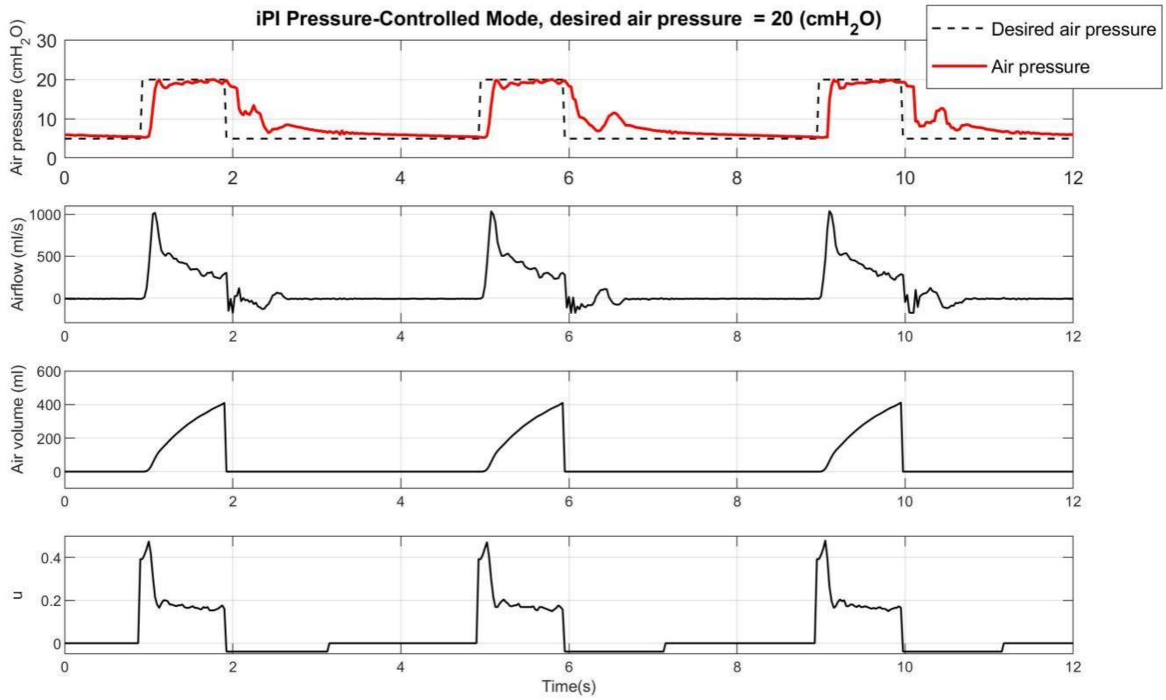

Figure 7. System response in PC mode.

Figure 7 represents a quite good tracking of the air pressure to the desired air pressure. The waveform of the air volume, the airflow, and the air pressure are theoretically shown in Figure 2 (b). During PC mode, clinicians can adjust the air pressure to track a theoretical waveform. The airflow is driven by the pressure gradient [21] and it provides a unique profile that reaches its maximum value at the beginning of the inspiratory phase before slowly reducing its value for the rest of the inspiration. Bearing a resemblance to the theoretical waveform, the value of airflow increased dramatically before decreasing gradually with a tidal volume of approximately 400 ml. The settling time of the proposed controller was quite large, and there was chattering at the beginning of the expiratory phase due to the physical behavior of the BVM ventilator.

5. Conclusions

This paper has considered the matter of controlling a bag valve mask (BVM) ventilator which is portable, simple, and low cost to use for near-death or non-Covid-19 patients in shortage of respiratory devices. The BVM ventilator model is not only assumed to track the desired control terms in both volume-controlled and pressure-controlled modes by the proposed controller but also includes PEEP valves and HEPA filter. Our distribution differs from the conventional method is to develop the proposed controller based on performing stability analysis without explicit knowledge of BVM ventilator structure. Additionally, the proposed controller can adapt to the time-variant characteristic of the AMBU bag to provide a reliable response. The experimental results of the BVM ventilator evaluated with an artificial test lung showed that the proposed controller has applicability to apply for BVM ventilators. It implies that the BVM ventilator is capable of safely and effectively utilize for Covid-19 patients after the next medical testing process.

For the following work, the BVM ventilator will be validated on a suitable WET Lab (University of Medicine and Pharmacy at Ho Chi Minh city) with an animal test in the medical process. Experiments on large animals like buffalo, pigs, sheep, and others can be used to evaluate the BVM ventilator. Animal object (as shown in Table 2) is going to submit to general anesthesia and instrumented. After being anesthetized, all parameters of the experimental animal objects' survival are observed until stable. After stabilizing, the animal object is tested with the BVM ventilator. For each scenario, we experiment with different PEEP parameters, then we proceed to provide parameters for the BVM ventilator and monitor it for 120 seconds after changing to control the BVM ventilator's parameters for the animal object. For the next scenario, the animal object is respiration on the BVM ventilator within 30–60 minutes to evaluate the BVM ventilator operated under volume/pressure control mode. Experimental details will be presented in the following study.

Table 2. System limit parameters for experiment

Parameters	Values
Animal object	Buffalo/pig/sheep
Animal mass	45–55 kg
Condition of health	Normal (no congenital respiratory illness)
Tidal volume	350–400 ml
Airway pressure range	1 to 40 cm water (accuracy range ±0.7 cm water)
Modes	pressure-controlled modes
Inspiration:Expiration (I:E) Ratio	1:2
Respiratory rate	25–40 breaths/min
Air overflowing pressure	Adjustable (0–15 cmH_2O)

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Conflict of interest

The authors have declared no conflict of interest.

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