IMPLEMENTATION AND ASSESSMENT OF A NOVEL MECHANICAL VENTILATORY SYSTEM FOLLOWING A NOISY VENTILATION REGIME

Marcus Henrique Victor Júnior*, Luiz Alberto Forgiarini Junior**, Toru Miyagi Kinjo***,
Marcelo Britto Passos Amato**, Takashi Yoneyama* and Harki Tanaka****

* Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil
** Faculdade de Medicina da Universidade de São Paulo, São Paulo, Brazil
*** Magnamed, São Paulo, Brazil
**** Universidade Federal do ABC, Santo André, Brazil

e-mail: marcus.henrique.victor.junior@gmail.com

Abstract: The growing interest in variable mechanical ventilation, known as noisy ventilation, motivated this work. The aim of which was to develop and test the new system, firstly on a bench setup and after in vivo. The first setup consisted of a mechanical ventilator, a mechanical lung simulator, a calibrated measuring device and a personal computer implementing the routine responsible for the noisy regime. The experiments were valuable to assess the behaviour of the new system and verify its use in vivo. Besides, an algorithm was developed to perform parameter estimation of the artificial respiratory system comprised of a mechanical lung simulator and air ways. The estimated parameters were: compliance, resistance and positive end-expiratory pressure (PEEP). To evaluate the correctness of the algorithm the parameters were adjusted directly on the bench system. The compliance was adjusted on the mechanical lung simulator, the resistance adjusted in the air ways and the PEEP adjusted on the mechanical ventilator. The assessment was based on the comparison between adjusted and estimated values. In the in vivo experiment conducted in an animal Intensive Care Unit (ICU) a pig was utilized. To perform noisy ventilation, the mechanical ventilator and the computer were utilized. Data were collected and analysed with the developed algorithm. The novel noisy ventilation system was found to be satisfactory in terms of its performance and its use in vivo showed that it can improve the respiratory system based on comparisons between estimated parameters and other outcomes such as blood gas, ultrasonography and electrical impedance tomography.

Keywords: noisy ventilation, respiratory care, mechanical ventilator, parameter estimation, respiratory system model.

Introduction

During respiratory failure, some procedures such as intubation and invasive mechanical ventilation may be life saving [1]. The general aim of mechanical ventilation is to provide adequate gas exchange support, while not damaging the respiratory system. This technique is one of the most important life support tools in the ICU [2]. However, it may also be harmful by causing Ventilator Induced Lung Injury (VILI) and other undesirable effects [3].

There is a growing interest in the development [4] and use of variable mechanical ventilation [5] performing variable volume and variable pressure controlled ventilation. The reasons are that this technique can improve lung functions and reduce lung damage in experimental Acute Lung Injury (ALI) models when compared to standard mechanical ventilation. Moreover, variable tidal volume ventilation would improve lung mechanics and gas exchanges [6].

Online estimation of respiratory system mechanics [7] at the bedside is a diagnostic tool to follow the mechanical conditions of the mechanically ventilated patients in the ICU. Different methods have been developed to calculate the volume-dependent dynamic compliance, which may provide information to identify over-distension and recruitment without the need of obtaining the static pressure-volume curve [8]. Most of these methods are based on the linear first-order equation of motion [9].

This work concerns the development and test of a novel system for mechanical ventilation. The system is based on a mechanical ventilator and an embedded platform utilizing a digital processing unit, which in the present case is a personal computer in view of its facility for the development of software routines. A computational routine was developed to drive the mechanical ventilator in a noisy ventilation regime. Further, to assess the respiratory system under test an estimation parameter algorithm was developed to estimate parameters of compliance, resistance and PEEP. Firstly, the whole system was tested in a bench setup and after was tested in an animal ICU with a pig.

Materials and methods

Development of noisy ventilation system – To perform the noisy ventilation a system based on a mechanical ventilator and a personal computer was used. The routine implemented in the personal computer was responsible for controlling the mechanical ventilator and ensuring that the correct behaviour was being performed. The routine was responsible for sending commands to the mechanical ventilator and reading parameters from it. Coupled with the system, a calibrated measuring device was used to assure and compare the readings from the mechanical ventilator and the calibrated device. These three pieces of equipment worked together to execute the noisy regime for further assessment. Figure 1 depicts the system described when a mechanical lung simulator was coupled with the system.

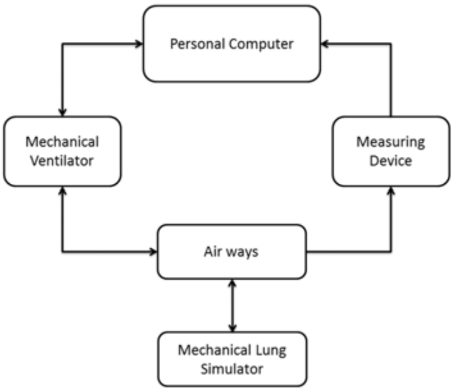

Figure 1: Overview of the developed system.

Data Acquisition – Data were collected from the mechanical ventilator and the measuring device. Values of flow and pressure were sent to the computer every 20 milliseconds by the mechanical ventilator and every 6 milliseconds by the measuring device and they were stored in the memory for further analysis. The values were indexed by a time tag for each pair of flow and pressure. The data of volume were obtained by integrating the data of flow, after signal processing. It is important to notice that the curves of flow, pressure and volume are the basis for the data analysis.

Filtering and Cycle Detection – Before beginning analysis, data should be filtered and split into breathing cycles. These tasks were performed utilizing a Finite Impulse Response filter (FIR) and cycle detection, following the concepts of respiratory physiology.

A low pass filter was designed to cut off noise at 1.66Hz, since the breathing frequency was between 12 and 20 cycles per minute (0.2Hz – 0.33Hz). The FIR was chosen, because it has good properties such as phase linearity at pass band and stability, although a computational power is required. In this case, there was no problem with computational complexity as this resource was more than adequate.

Cycle detecting was performed with data of flow, after filtering. A detection algorithm was built, knowing that flow becomes positive during the inspiratory period. A rising edge of 1mL/s was utilized to detect each new cycle. All transitions which exhibit this edge indicate a new cycle mark. As the data of flow have some noise, a robust algorithm was developed to deal with this condition, to avoid false cycle detections and further erroneous analysis. Figure 2 shows samples of flow (both raw and filtered) as well as the performed cycle detection.

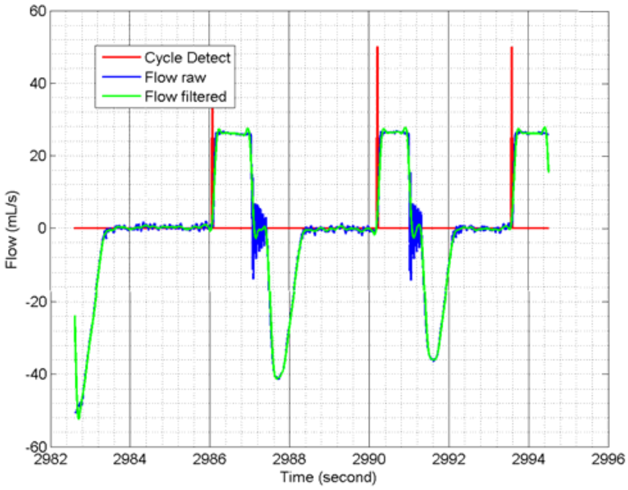

Figure 2: Data of flow. Filtering and cycle detection.

Modelling – The respiratory system can be modelled as shown in Equation (1) [9].

$$P = PEEP + R.\dot{V} + \frac{V}{C} \qquad (1)$$

where, P is the total pressure, $PEEP$ is the positive end-expiratory pressure, R is the resistance of air way, C is the compliance, V is the volume and $\dot{V}$ is the air flow.

Parameter Estimation Method – The Equation Error Method (EEM) was used to provide the parameter estimation. This method is based on the principle of least squares. The EEM minimises a quadratic cost function of the error in the equations. It is assumed that states, their derivatives and control inputs are available or accurately measured. The method is relatively fast and simple, and applicable to linear systems. For a system described by the state Equation (2), with initial conditions x(0) = x_0, the equation error can be written as Equation (3).

$$\dot{x} = Ax + Bu \qquad (2)$$

$$e(k) = \dot{x}_m - Ax_m - Bu_m \qquad (3)$$

Subscript ‘m’ denotes ‘measured’ data. Rewriting Equation (3),

$$e(k) = \dot{x}_m - A_a x_{am} \qquad (4)$$

Where subscript ‘a’ denotes ‘augmented’ matrix, as follows,

$$A_a = [A \quad B], \qquad x_{am} = \begin{bmatrix} x_m \\ u_m \end{bmatrix} \qquad (5)$$

In this case, the cost function is given by Equation (6),

$$J = \frac{1}{2}\sum_{k=1}^{N}[\dot{x}_m(k) - A_a x_{am}(k)]^T[\dot{x}_m(k) - A_a x_{am}(k)] \quad (6)$$

Then, the estimator is given as [10],

$$\hat{A}_a = \dot{x}_m(x_{am}^T)(x_{am}x_{am}^T)^{-1} \quad (7)$$

Application of EEM on Model – Given Equations (1) and (5), they can be rearranged as follows,

$$\dot{V} = \frac{P}{R} - \frac{1}{RC}V - \frac{PEEP}{R} \quad (8)$$

So,

$$\dot{V} = \begin{bmatrix} \frac{1}{R} & -\frac{1}{RC} & -\frac{PEEP}{R} \end{bmatrix} \begin{bmatrix} P \\ V \\ 1 \end{bmatrix} \quad (9)$$

$$A_a = \begin{bmatrix} \frac{1}{R} & -\frac{1}{RC} & -\frac{PEEP}{R} \end{bmatrix}, \quad x_a = \begin{bmatrix} P \\ V \\ 1 \end{bmatrix} \quad (10)$$

Combining Equations (7) and (10), A_a can be easily obtained and the parameters of compliance, resistance and PEEP calculated.

Ethical Committee Approval – The project was approved in the Ethical Committee of Faculdade de Medicina da Universidade de São Paulo, 055/13.

Pig preparation – The animal was a female pig, breed Landrace, 27 kg weight. It was anesthetized and submitted to controlled mechanical ventilation. The animal was sedated during all experiment. It had been intubated and it had gotten a cystostomy and some vascular accesses for drugs administration. An acute lung injury model was applied, through depletion of surfactant.

Hardware and Software – The proposed noisy ventilation regime was implemented and tested using a mechanical ventilator, provided by Magnamed, model Oxymag - emergency and transport pulmonary ventilator [11]. The measuring device, provided also by Magnamed, was model Ventmeter - lung ventilator certification system [12]. The mechanical lung simulator, Michigan Instruments®, was an adult mechanical lung simulator model 5601i [13]. The dedicated software used to develop the routines was Labview® and the software utilized to perform data analysis was Matlab®.

Results

Assessment of the developed system – To assess the developed system a bench test was performed as is depicted in Figure 1. The convergence time and the error were analysed. Convergence time is the amount of time or breathing cycles in which the system reaches an acceptable error between volume commanded and volume executed. The error is described in Equation (11). For all trials, the convergence time remained under 15 breathing cycles, approximately 75 seconds, and the error remained under 8%.

$$error = \left|\frac{volume\ executed - volume\ commanded}{volume\ commanded}\right| \quad (11)$$

Parameter estimation – Since the data were collected, the algorithm could estimate the parameters. Trials with the mechanical lung simulator were conducted to evaluate the estimated values. For compliance, three values were adjusted: 40, 50 and 60 (mL/cmH_2O). The estimated values of mean and standard deviation were: 40.6±0.8, 50.0±0.9 and 59.8±1.0, respectively. For resistance, the adjusted value was 50 (cmH_2O.s/L) and the estimated mean and standard deviation were 49.3±7.3. For PEEP, four values were adjusted: 0, 5, 10 and 15 (cmH_2O). The estimated values of mean and standard deviation were: 0.2±0.2, 5.7±0.2, 10.6±0.2 and 15.6±0.2, respectively.

Pig experiment – In the trial with the pig, the same devices were utilized except the measuring device and mechanical lung simulator. Performing noisy ventilation, a Normal Distribution was utilized, whose parameters of mean equal to 135 (mL), as the tidal volume, and standard deviation of 25% of the mean. Figure 3 shows the estimated parameters for the pig. In this trial, after all other related procedures, a noisy regime was performed (Noisy 1) followed by a standard regime (Standard) and another noisy regime (Noisy 2), each one lasted 30 minutes. These three stages are easily perceived in Figure 3, since the noisy curves are intercalated by a much smoother curve.

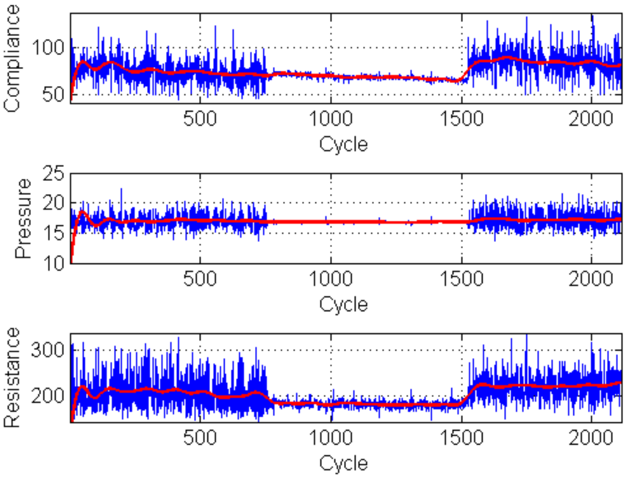

Figure 3: Parameter estimation during trial with pig.

Also, blood gases were measured during the trial, at instants of 0, 5 and 30 minutes, of each of the three stages. The obtained values are shown in Table 1.

Discussion

The characteristics of convergence time and error were evaluated and showed reasonable outcomes. The measuring device was valuable in this stage, since it is a calibrated device and should point out any mismatching between mechanical ventilator measures and measuring device.

Table 1: Blood gas. The values of partial pressure are in (mmHg) and the instants are in minutes.

Stage\Instant	**0**	**5**	**30**
	PCO_2/PO_2	PCO_2/PO_2	PCO_2/PO_2
Noisy 1	91.0/494	90.0/424	102.0/427
Standard	91.8/460	91.6/379	126.0/408
Noisy 2	91.1/409	88.6/482	86.9/479

The parameter estimation showed good matching between adjusted and estimated values. In this stage, the mechanical lung simulator was valuable because it is a device whose compliance can be adjusted and it has known mechanical properties. The value of resistance could be adjusted mechanically, putting the chosen resistance in the air ways. The value of PEEP was regulated by the mechanical ventilator. All estimated values exhibited statistics close to the adjusted values.

During the experiment with the pig, as the system and the algorithm were proven to be working, the estimated parameters could be confronted with blood gas. The mechanical parameters showed that the compliance improvements can be correlated with a better state of respiratory system in an ALI model, since the PEEP remained almost constant during the trial and the resistance could be changed due to other factors. The blood gas showed that the stages with noisy regime have better outcomes in relation to higher concentrations of Oxygen gas and lower concentrations of Carbon dioxide gas.

Conclusion

The assessment of the developed system showed that the system has the necessary capabilities to execute noisy regime. The system is expected to be used in vivo with a large number of samples, initially in animals, with a view to better understanding the benefits of noisy ventilation in patients, by evaluating the parameters studied and performing cross relations between other results such as blood gas, ultrasonography and electrical impedance tomography.

Acknowledgements

The authors would like to thank the engineers from Magnamed. Also, we would like to thank Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for research grant 303450/2013-4.

References

[1] Moerer, O. Weaning from mechanical ventilation: Which strategies are useful? Anaesthesiology Intensive Therapy, 2013; 48 (10): 640-647.

[2] Kuchnicka, K.; Maciejewski, D. Ventilator associated lung injury, Anaesthesiology Intensive Therapy, 2013; 45 (3): 164-170.

[3] Cordioli R.L.; Akoumianaki E.; Brochard L. Nonconventional ventilation techniques, Current Opinion in critical care, 2013; 19 (1): 31-37.

[4] Fernandez, J.; Miguelena, D.; Mulett, H.; Godoy, J.; Martion-Torres, F. Adaptive support ventilation: State of the art review, Indian Journal of Critical Care Medicine, 2013; 17 (1): 16-22.

[5] Gama de Abreu, M.; Beda, A.; Spieth, P.M.; Handzsuj, T.; Pelosi, P.; Carvalho, N.C.; Koch, E.; Koch, T. A novel adaptive control system for noisy pressure-controlled ventilation: a numerical simulation and bench test study, Intensive Care Medicine, 2010; 36 (1):164-168.

[6] Suki, B.; Arold, S.P.; Mora, R.; Lutchen, K.R.; Ingenito, E.P. Variable Tidal Volume Ventilation Improves Lung Mechanics and Gas Exchange in a Rodent Model of Acute Lung Injury, American Journal of Respiratory and Critical Care Medicine, 2002; 165 (3): 366-371.

[7] Albanese, A.; Karamolegkos, N.; Haider, S.; Seiver, A.; Chbat, N. Real-Time Noninvasive Estimation of Intrapleural Pressure in Mechanically Ventilated Patients: a Feasibility Study, 35th Annual International Conference of the IEEE EMBS, 2013; July.

[8] Zhao, Z.; Guttmann, J.; Moller, K. Assessment of a volume-dependent dynamic respiratory system compliance in ALI/ARDS by pooling breathing cycles, Physiological Measurement, 2012; 33: 61–67.

[9] Diong, B.; Nazeran, H.; Nava; P.; Goldman, M. Modelling Human Respiratory Impedance, IEEE Engineering in Medicine and Biology Magazine, 2007; Jan/Feb: 48-55.

[10] Girija G, Raol JR, Singh J. Modelling and parameter estimation of dynamic systems. London: The Institution of Engineering and Technology, 2004.

[11] Oxymag. Magnamed. Available from: http://www.oxymag.com.br/

[12] Ventmeter. Magnamed. Available from: http://www.ventmeter.com.br/

[13] Mechanical Lung Simulator Model 5601i. Michigan Instruments. Available from: http://www.michiganinstruments.com/shop/test-lung-products/item/adult-and-infant