IMPROVEMENT OF THE TRANSIENT ANSWER OF THE PRESSURE AND FLOW CONTROL SYSTEM IN MECHANICAL VENTILATION OF THE LUNGS

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Abstract. *The Acute Respiratory Distress Syndrome (ARDS) is a type of respiratory failure whose treatment involves mechanical ventilation. The prognostic depends on the precision of the mechanical ventilator control system, because overshooting and long settling time of the pressure and flow control system can generate discomfort and risks to the patient with ARDS. The objective of this work is to numerically simulate the techniques of control PID and Fuzzy to determine which, amongst the studied ones, presents the best transient answer. Considering this, a lung model for a patient with ARDS and a mathematical model for the mechanical ventilator are chosen to be the system's plant. The analysis of results concludes that Fuzzy logic presents more safety and comfort to the patient in general.*

Keywords. *Control, PID, fuzzy, lung ventilator, transient response.*

1. INTRODUCTION

The main symptoms of ARDS, Acute Respiratory Distress Syndrome, are the low concentration of oxygen in the blood, difficulties to breathe and accumulation of excessive fluid in the alveoli visible by thorax x-ray (Antoniazzi, 1998), as it can be observed in the Fig. 1, that shows two x-rays - healthy lung [1] and lung with ARDS [2].

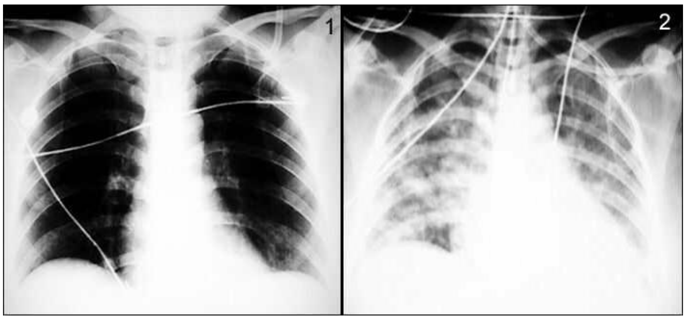

Figure 1. X-ray of a Healthy Lung [1] and a Lung with ARDS [2] (Barbas, 2003)

ARDS is always a consequence to some aggression to the lung or other part of the body as trauma or sepsis (Fernandes, 2001), aggravating the critical patient situation, taking him or keeping him in a Intensive Care Unit (ICU).

The mechanical ventilation can contribute to reduce the mortality caused by this illness, therefore, if correctly applied, it minimizes the pulmonary effects found in patients with ARDS. However, to ventilate a lung with ARDS can unchain different physiological effects, so, the ventilatory strategy can protect the lungs and minimize the inflammatory effects or can even increase the pulmonary injury.

One of the resources applied in the treatment of ARDS is the alveolar recruitment, that consists of maneuvers to make available the collapsed alveoli to gaseous exchange. Carried through the pulmonary ventilator, the maneuvers demand adequate reply of control not to be deleterious instead of beneficial. According to lung specialists, the overshoot and the settling time of flow control and pressure systems in pulmonary ventilators cause discomfort and risks to the patient with ARDS.

In this work, a comparison is presented between two control techniques for pulmonary ventilators, analyzing the transient parameters, overshooting, rise time and settling time. The first technique, more conventional, is based on the proportional, integrative and derivative gains (PID) in relation to the system and the reference error. The second technique, Fuzzy, searches to reproduce the human thinking in the system control.

2. PHYSIOLOGY

The respiratory system is the set of structures involved in the gaseous exchange with the environment, see Fig. 2. It can be divided in two parts: airways, pipes that lead air between the atmosphere and the lungs, and the alveoli, in which the gaseous exchange properly said occurs.

Alveoli are small cavities formed by flattened epithelial cells, with about 0.25-0.5 mm in diameter, highly irrigated by blood capillaries with which the gaseous exchange is made. It's estimated that each lung has 300 million alveoli, determining an exchange surface of $70m^2$.

There are two types of alveolar cells: type I (90% of the alveolar surface) allows the diffusion of gases and type II (10% of the alveolar surface) produces surfactant, a lipoprotein mixture that reduces the superficial tension of the liquid that involves the alveoli. This substance assists the alveoli expansion, therefore if there is any problem with the production of this substance, or if there is water inside the alveoli, the superficial tension of the water or the absence of enough surfactant can create a great tension in the alveoli causing them to collapse (close).

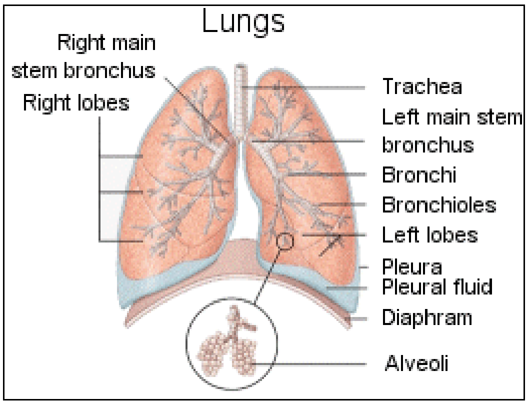

Figure 2. Respiratory system

3. RESPIRATORY MECHANICS

In this section, the parameters that quantify or characterize the pulmonary ventilation are presented (Guyton and Hall, 1997).

The increase of the pulmonary volume during the inspiratory phase causes an expansion of the lungs and, consequently, of the thoracic wall, distending the elastic structures of the respiratory system. Likewise to a system of springs, this elastic structure will exert a contrary and proportional force to the deformation, in turn proportional to the inspired volume. The lungs and thorax expansibility is called compliance (C), being expressed by the increase of volume in the lungs (V) for each unit of pressure increase (P), being the usual unit L/cmH_2O:

$$C = \frac{V}{P} \tag{1}$$

Smaller the pulmonary compliance, smaller will be the volume placed in the interior of the lungs for each cmH_2O in a given pressure variation. Or still, a bigger insufflation pressure to generate the same current volume will be necessary.

Respiratory resistance is defined as the set of opposing forces to the gaseous flow in the airways related to its anatomical structure. The resistance offered by the respiratory system (R) is mainly caused by the friction between air and the airways, being defined in function of the difference of pressure between the mouth and the alveoli (ΔP) and the air flow generated through it ($\dot{V}$):

$$R = \frac{\Delta P}{\dot{V}} \tag{2}$$

4. MECHANICAL VENTILATION

The mechanical ventilation has the objective to assist totally or partially the ventilatory activity of the patient. The basic components of a pulmonary ventilator are: a flow valve, a exhalation valve, pressure and flow transducers for monitor the system.

The way for which a ventilator manages the know mixture of gas to the patient is nominated ventilatory mode. Each mode defines how the controlled variables will behave during its functioning (pressure, volume, flow or time) as well as the algorithms that will be used to initiate or to finish the inspiratory and expiratory phases. The main characteristic of the Volume Controlled Ventilation is the maintenance of a specific known curve of flow during the inspiratory phase to keep a constant delivered volume, independently of the values of resistance and compliance of the respiratory system. In the other hand, the main characteristic of the Pressure Controlled Ventilation is the dependence between the respiratory mechanics of the patient and the inspiratory flow and volume, because the main goal is to keep a constant pressure in the circuit during the inspiratory phase.

4. ARDS

The Acute Respiratory Distress Syndrome (ARDS) is a type of pulmonary insufficiency. When alveoli are damaged, some collapse and lose their ability to receive oxygen. With some alveoli collapsed and others filled by fluid, it becomes difficult for the lungs to absorb oxygen and get rid of carbon dioxide. Within one or two days, progressive interference with gas exchange can bring about respiratory failure requiring mechanical ventilation.

Due to the alveolar collapse and pulmonary edema, a reduction of the compliance of the respiratory system occurs. Moreover, the bronchia constriction by the inflammatory process causes an increase of the resistance. In the Tab. 1, average values of compliance and resistance collected in articles and books are presented.

Table 1. Values of Compliance and Resistance for individuals – healthy, intubated and with ARDS.

	Compliance (mL/cmH_2O)	**Resistance ($cmH_2O/L/s$)**
Healthy	100 to 130	0.6 to 2.4
Intubated	35 to 50	More than 6
ARDS – Gattinoni et al, 1998	39	10.5

In the initial phase of ARDS, it is possible to identify a point of inferior flexion (Pflex-inf) when a graph of pressure by inspired volume is traced, meaning that a great population of alveoli is recruited (opened for ventilation) at this moment, with consequent increase of the pulmonary compliance. In Fig. (3), there is a graph of pressure by volume of a healthy patient and one with ARDS.

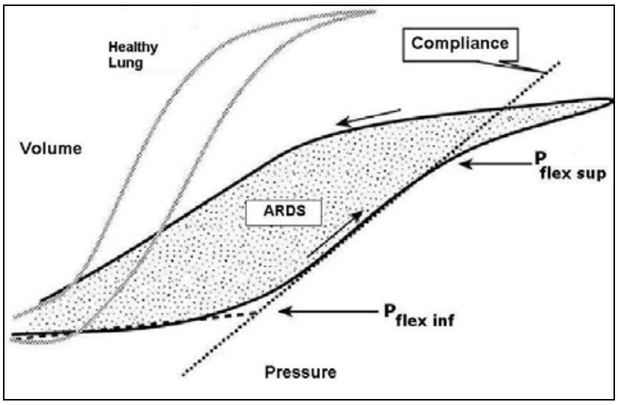

Figure 3. Pressure-Volume curve, Healthy Lung and with ARDS

4.1 Alveolar Recruitment

The pulmonary ventilation in ARDS first demands a maneuver of alveolar recruitment, that consists of a high-pressure application in the airways to open collapsed alveoli. The alveolar recruitment in ARDS presentes the following advantages: better oxygenation of the patient, better distribution of the current volume, better efficiency of the PEEP (Positive End Expiratory Pressure) in keeping the alveoli open.

The pressures can be raised until 6kPa (60cmH2O) in Pressure Controlled Ventilation, with PEEP up to 4,5kPa (45cmH2O). As it can be noticed, the high-pressure values must be precisely generated by the pulmonary ventilator, not generating overshooting peaks that can cause barotraumas (a harmful expansion of the lung of the patient). On the other hand, the ventilator cannot have a very slow constant of time, for this would imply in an also slow rise of the alveolar pressure, and so the application time is depleted without the pressure to enlist the alveoli has been effectively reached.

5. LUNG MODEL

There are diverse proposals of respiratory systems modeling in literature, based on different theories. For this study, it is desirable that the possibility of different states (properties) for the two lungs exists, beyond the variation of the compliance value (non linearity) in a simple way, to facilitate the application of different control techniques. Thus, it was decided to use the model represented in the Fig. (4) that considers different compliance values for the two lungs.

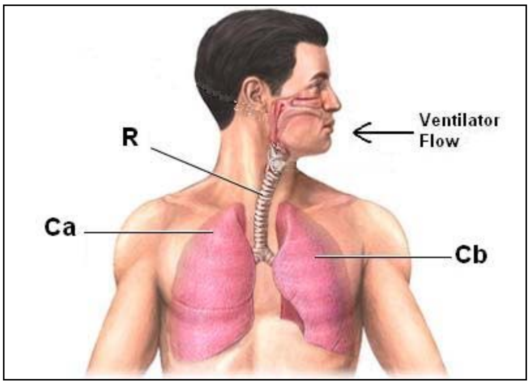

Figure 4. Model of Two Lungs

The proposed equation is based on the development by Bonassa (2003):

$$P_{VA} = R \cdot \dot{V} + \frac{V}{C} + PEEP \tag{3}$$

Being P_{VA} - the corresponding pressure to the superior air way of the patient, which can be monitored by the ventilator; PEEP - Positive End Expiratory Pressure adjusted by the operator and other parameters previously defined. The pressure in the lung A is dependent of its compliance and its volume:

$$P_A = \frac{V_A}{C_A} + PEEP \tag{4}$$

The flow for each lung is a balance of its compliances:

$$\dot{V}_A = \dot{V} \cdot \frac{C_A}{C} \tag{5}$$

Being C the addition of the compliances of the two lungs (C_A and C_B). The same logic is repeated for lung B.

The expiration is a free process, proportional to the difference of pressure between the lung and the external environment, restricted by the resistance of the airways.

6. LUNG VENTILATOR MODEL

The modeling of lung ventilator was presented as a critical point of this work. As the objective is to test different control techniques for one determined behavior of the ventilator + patient system, the experimental modeling of the plant was not considered. Moreover, as the study object is a ventilator for an ICU bed, it only has interest in the flow valve (proportional) and in the exhalation valve, that create the conditions of alveolar recruitment (keeping the airway pressure as desired).

The research on lung ventilator models was made in three fronts: conventional literature, internet and contact with researchers of different control groups, that already had carried through projects related to the artificial ventilation. However, it was not possible to find a model that was convenient to this study in particular.

Thus, the model was gotten from Ogata (1998) and refers to a hydraulical valve. This model corresponds to a flow valve of a low pressure pulmonary ventilator that only controls the standards of pressure and flow and not the mixture of gas sent to the patient. Thus, the flow of this valve follows the equation:

$$\dot{V} = K \cdot \sqrt{(P_{ent} - P_{VA})x} \tag{6}$$

Being K - the constant of the valve, 0.002; Pent - the pressure in the valve entrance, 20kPa (200cmH2O) and x - the opening of the valve orifice, allowing values between 0 and 12mm. The exhalation valve was considered ideal and capable to keep the pressure in the patient air way equal to PEEP during all the expiratory phase.

The system flow valve + lung of the patient was validated simulating the ventilation ways: controlled by volume and controlled by pressure available in literature (Bonassa, 2003). The parameters of the Eq. 6 had been also based on the article of Tassaux et al (1998).

7. STUDY CASES

Two study cases will be presented in this article. The first one (case I) considers the Pressure Controlled Ventilation, with inspiratory pressure relative to the alveolar recruitment of 40cmH_2O. The inspiratory time was limited to 1 second, for the focus is the transient regimen of the cycle, but maneuvers of alveolar recruitment can be longer than that. The resistance of the airways is 10cmH_2O/L/s, the compliance of the lung A is 0.02L/cmH_2O, the compliance of the lung B, 0.01L/cmH_2O (global compliance of the system 0.03L/cmH_2O), values very close to the ones that Gattinoni and collaborators (1998) gotten experimentally.

In the second case (case II), the compliance of lung B vary from 0.005L/cmH_2O to 0.01L/cmH_2O when the pressure of the respective lung reaches 18cmH_2O. The other parameters had been kept equal to case I.

The cases had been simulated in a discrete way, to preserve the non-linearities of the flow valve and of the lung. The discretization period was defined in 0.02s. The analysis of the transient regimen will be made through the following concepts:

- maximum overshooting (M): maximum peak value of the pressure curve divided by the final value of the steady response, results in percentage, according to Eq. 7.

$$M = \frac{P_{\max imum} - P_{reference}}{P_{reference}} \tag{7}$$

- Settling time: required time so that the response curve values are inside of an interval of 2% of its final value.
- Rise time: required time so that the response curve reaches 90% of the reference adjusted value.

8. PID CONTROL

The output of PID controller for the actuator is calculated from the proportional, integrative and derivative answer in relation to the error of the system (difference between the reference value and the measured value) of the variable that is intended to control. In a discrete form, the following formula is implemented (Palm III, 1983):

$$x(u+1) = x(i) + \left(kp + \left(\frac{ki \cdot \Delta t}{2}\right)\right) \cdot e(i) + \left(\left(\frac{ki \cdot \Delta t}{2}\right) + kp - \left(\frac{2 \cdot kd}{\Delta t}\right)\right) \cdot e(i-1) + \left(\frac{kd}{\Delta t}\right) \cdot e(i-2) \tag{8}$$

Being x – control variable (displacement of the flow valve), e - error between the adjusted reference and the measured value, kp - proportional gain, ki - integral gain, kd - derivative gain, Δt - interval of discrete time.

The gains had been defined by the method of the attempt and error resulting in proportional gain equal to 0.16, the integrative 0.735 and derivative, 0.0022. In the Fig. 5, block diagram of the described PID controller.

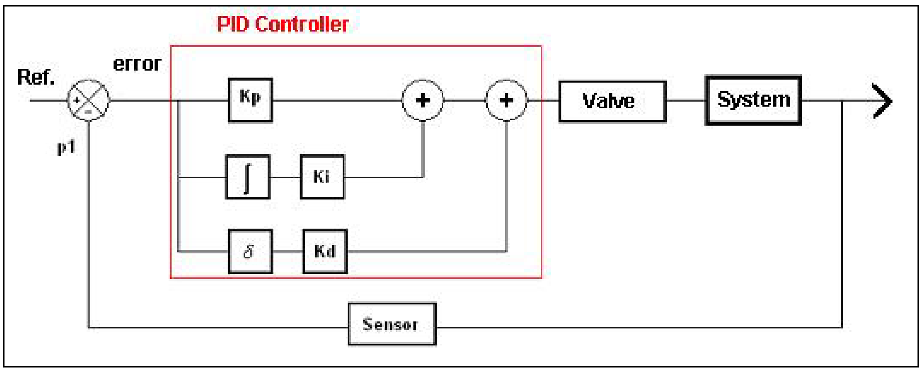

Figure 5. Block diagram of PID Controller.

9. FUZZY CONTROL

"The Fuzzy control is a methodology to represent, manipulate and implement the human heuristical knowledge of how to control a system." (Passino and Yurkovich, 1998). The Fuzzy logic imitates the human reasoning, as it allows that each input value of the controller and output value for the actuator are classified as linguistic variables, such as "close", "superior", "high", "low", etc. After the classification, the variable is submitted to a rules set that determines the performance of the system.

In the Fig. 6, there is the Fuzzy Controller block diagram, indicating the variables that will be described next.

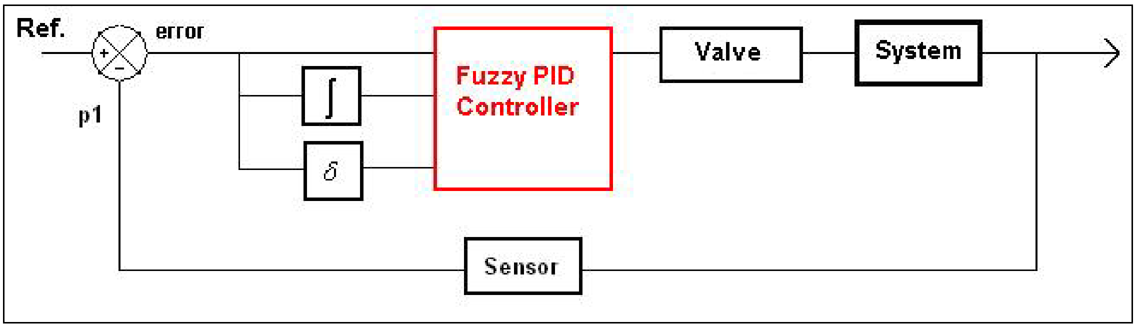

Figure 6. Block diagram of Relative PID Fuzzy Controller.

For this study, were considered control inputs: the relative error of the system, the variation and the integral of this error, being thus the controller called Relative Fuzzy PID. The relative error ($\bar{e}$) is defined discrete by the following form:

$$\bar{e}(i) = \frac{Pref - P_{VA}(i)}{Pref - PEEP} \tag{9}$$

Being Pref - adjusted pressure as reference by the user, P_{VA} - the airway pressure of the patient in each discrete instant and PEEP - positive pressure in the end of the expiration adjusted by the operator.

The variation (deviation) of the error follows the equation:

$$\delta e(i) = e(i) - e(i-1) \tag{10}$$

Being $\delta e(i)$ - variation of the error in a given instant of time, e(i) - error in a given instant of time, e(i-1) - error in the previous instant.

The integral error is defined as:

$$\sum e(i) = \sum e(i-1) + e(i) \cdot \Delta t \tag{11}$$

Being $\sum e(i)$ - discrete integral of the error (sum) in a given instant of time, $\sum e(i-1)$ - discrete integral of the error in the previous instant, e(i) - error in a given instant of time and Δt - interval of the system discretization.

Five linguistic variables had been attributed to the relative error and its variation (very negative, negative, zero, positive, very positive) and 3 linguistic variable for its integral (negative, zero, positive).

The output variable of the Fuzzy controller is the variation of the opening in the flow valve, on the basis of 9 linguistic variables (to open completely, to open much, to open, to open little, to keep position, to close little, to close, to close much, to close completely), to guarantee a gradual behavior for the valve.

10. SIMULATION

The simulations had been made in a discrete form, with time interval of 0.02s (50Hz), using the Scilab software. In case I, the patient airway pressure overshooting, as it can be seen in the Fig. 7, reaches a value of 15.6% above the desired control value, with relative Fuzzy PID controller, the occurred overshooting is only 0.8%, see Fig. 8. As the compliance of each lung is kept constant, the alveolar pressures are the same in each instant of time for the two lung compartments.

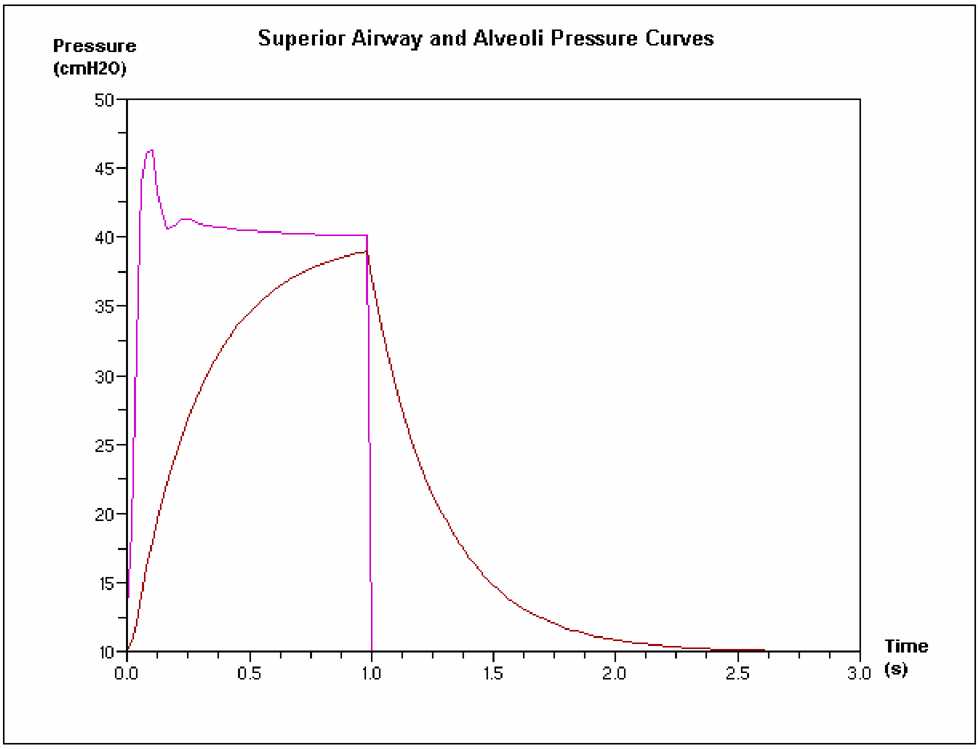

Figure 7. Case I. Pressure in the Superior Airway (purple curve), in the Lung A (C_A=0.020L/cmH_2O, red), in Lung B (C_B=0.010L/cmH_2O, coincident with lung A) with PID controller.

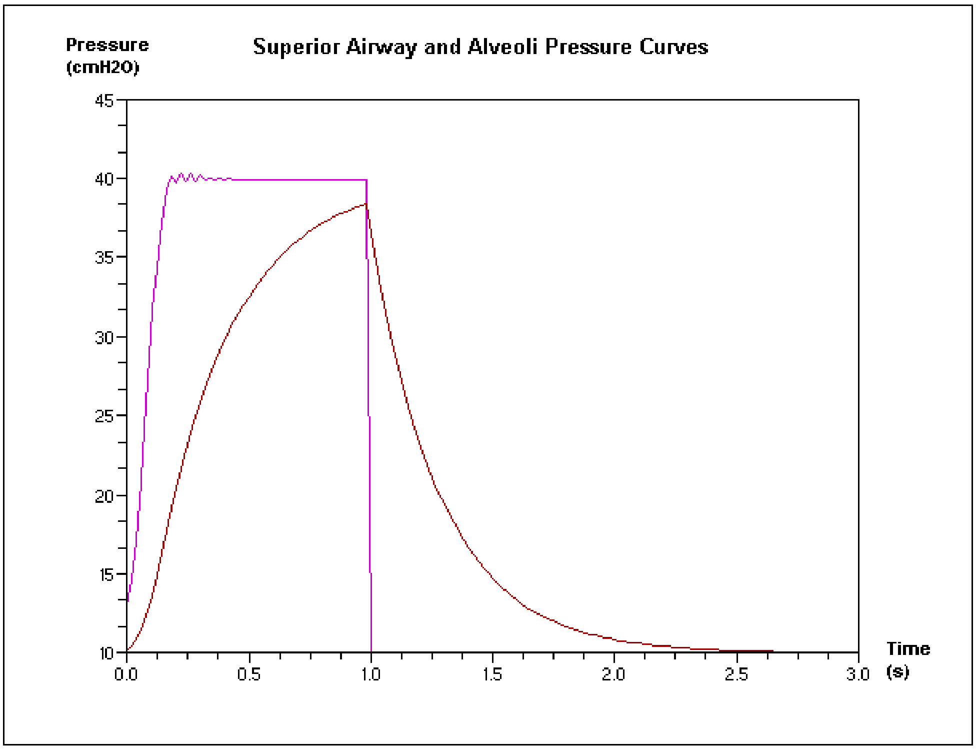

Figure 8. Case I. Pressure in the Superior Airway (red curve), in the Lung A (C_A=0.020L/cmH_2O, purple), in Lung B (C_B=0.010L/cmH_2O, coincident with lung A) with relative Fuzzy PID controller.

In case II, for the PID controller, the Fig. 9 presents the graph of pressure for the system. The system overshooting in this case was 17.9%, with peak pressure of 47.17cmH_2O, rise time of 0.06s and settling time of 0.32s.

As the compliance of compartment B is modified during the cycle, it does not have equalization of the pressures between the lungs, because the volume transference phenomenon (pendleluft) between them was not considered.

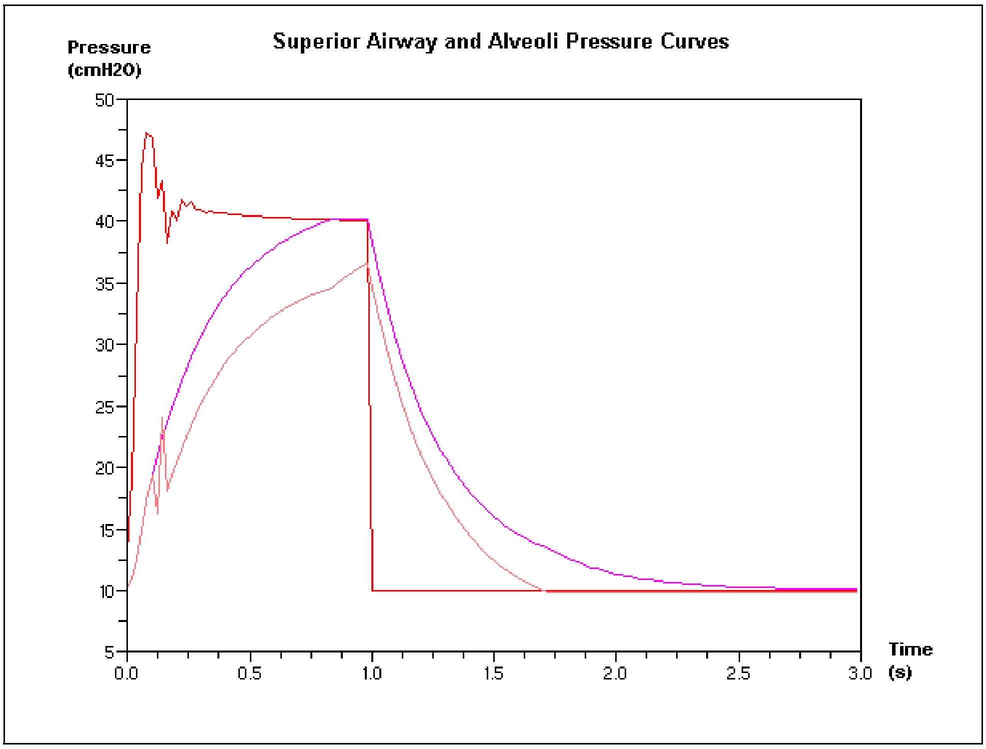

Figure 9. Case II. Pressure in the Superior Airway (red curve), in the Lung A (C_A=0.020L/cmH_2O, purple), in Lung B (variable C_B, light pink) with PID controller.

For the relative Fuzzy PID controller, the result of the simulation is presented in the Fig. (10), also relative to the pressure. Overshooting got limited at 9.6%, the rise time increased for 0.14s and the settling time practically remained equal in 0.3s.

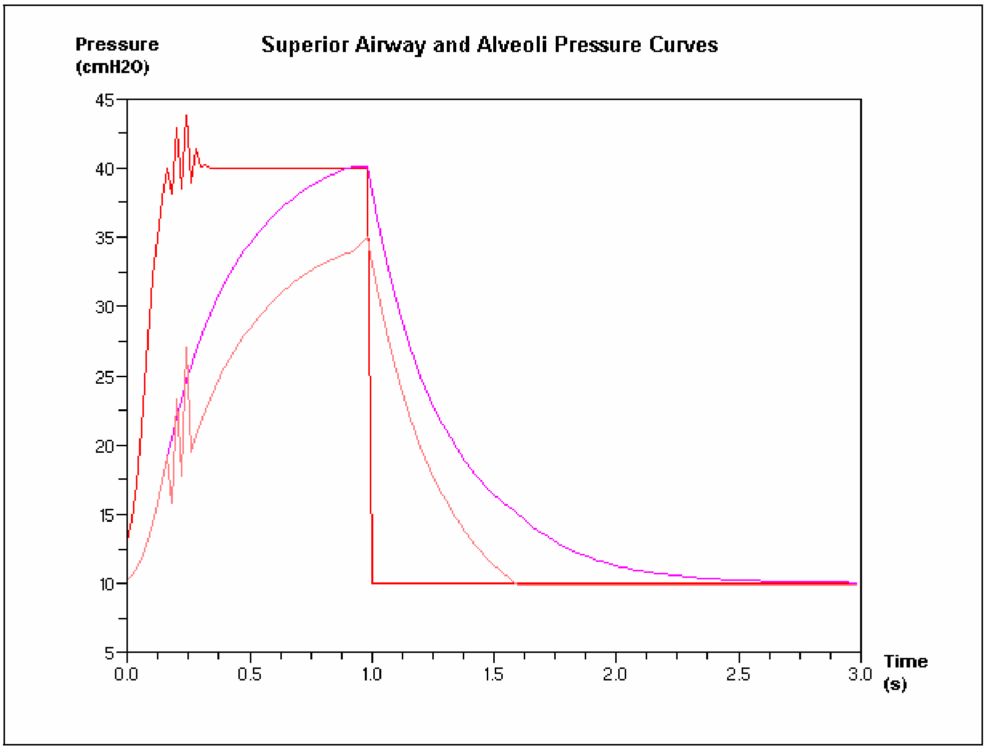

Figure 10. Case II. Pressure in the Superior Airway (red curve), in the Lung A (C_A=0.020L/cmH_2O, purple), in Lung B (variable C_B, light pink) with a relative Fuzzy PID controller.

The oscillation in the curve of pressure B in the inspiratory phase is due to the way as the compliance variation was imposed to the system in case II.

11. RESULTS ANALYSIS

Table 2 and Tab. 3 presents a compilation of the transient index for the case studies I and II, respectively.

Table 2. Case I. Transient Index for PID and relative Fuzzy PID controllers.

Case I		
Controller / Parameters	PID	Relative Fuzzy PID
Overshooting	15.6%	0.8%
Settling Time (s)	0.34	0.16
Rise Time (s)	0.06	0.14

Table 3. Case II. Transient index for PID and relative Fuzzy PID controllers.

Case II		
Controller / Parameters	PID	Relative Fuzzy PID
Overshooting	17.9%	9.6%
Settling Time (s)	0.32	0.3
Rise Time (s)	0.06	0.14

Case I shows clearly how the Fuzzy theory can contribute to improve transient aspects of the system reply. Overshooting was 20 times lesser for PID Relative Fuzzy controller (0.8%) in relation to the conventional PID (15.6%), also occurring a reduction in the settling time (PID - 0.34s, relative Fuzzy PID - 0.16s).

In case II, the compliance variation of lung B and the consequent behavior variation of the system had effected in the system by the great oscillation of the control variable (pressure in the airway), what justifies the high values of overshooting. Even so, the relative Fuzzy PID controller presented practically the half of the value for overshooting, for the same reply settling time. The settling time was relatively long for both the controllers because of the variation of compliance in lung B, that occurs between the instants 0.12s and 0.16s for PID controller and between 0.18s and 0.26s for relative Fuzzy PID.

In the two presented cases, the rise time for relative Fuzzy PID was more than the double of the conventional PID.

12. CONCLUSION

In this article, it was decided to present the model of the ventilator + patient system with the biggest number of details: high inspiratory pressure, 2 lungs with different compliances, compliance of one of the lungs variable with the pressure. In the complete work referred to this article, five other case studies with different parameters for the considered model of ventilator and lung had been simulated, beyond using more three controllers based on the Fuzzy logic: PD, PI and PID, with classic definitions of error, variation and integral.

Systemically, Fuzzy controllers had presented smaller overshooting than the PID controller, as evidenced for the two cases presented in this article. The settling time for case I, in which it did not have variation of the system properties, was also better for Fuzzy controller.

The rise time of PID controller was smaller than Fuzzy controllers, showing that this last one is slower to create brusque variations in the valve opening, as required when the error is very big. This characteristic is, however, a direct implication of the set of rules created for this simulation, i.e., it can be improved inside of the Fuzzy logic.

The Fuzzy logic, used in the controller, is constructed on the basis of the system knowledge, that in this case corresponds either to the dynamic behavior of the ventilator valves, as to the patient. In this project, the characteristics of Fuzzy controller had been determined either by the authors' knowledge of the system obtained from available literature as well as by cycles of attempt and error, intending to reach an ideal behavior. Thus, with more complete and extensive information of medical specialists, it is possible to improve Fuzzy controller still more, having as direct implication the improvement of the transient parameters, as well as other control parameters.

The model of the system applied in this study is theoretic, and, even validated by the literature, it still does not correspond to a real ventilator connected to a real patient. It is possible to refine the ventilator model, considering the behavior of the pressure sensors, the hysteresis and the inertia of the flow valve, the expiratory valve and maintenance of the PEEP by means of the control, among others points. The pulmonary modeling also can be refined in a way that critical behaviors of the lung - collapse, hysteresis, recruitment - can be simulated in a more realistic way.

However, with the preservation of its nonlinear characteristic by discretization and incorporation of variable respiratory properties, the simulations made had allowed a qualitative and quantitative analysis of the transient reply of the flow control system, allowing the conclusion that the Fuzzy logic can have better performance than conventional PID controller, providing better safety and comfort to the patient.

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14. RESPONSIBILITY NOTE

The authors are the only responsible for the printed material included in this paper.