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Proportional Assist Ventilation Using a Disturbance Observer and Predictive Control

Kenji Ozaki, Kazutoshi Soga, Yutaka Ishikawa, Seiichi Shin, Seishiro Marukawa, Junko Yamauchi, and Magdy Younes

***Abstract*: This paper presents a general control representation for medically-proposed methods of mechanical ventilation, and then proposes an improved configuration with a disturbance observer and with a predictive control block against an existing Proportional Assist Ventilation (PAV) method. The trade-off relation between robust stability margin and responsibility has been shown using $\|S\|_\infty^{-1}$ in Nyquist diagrams and time-response results with our mechanical ventilator SSV-200 connected to our lung simulator (LUNGOO). Also, a clinical issue of expiratory asynchrony is compared between two methods with the same test construction. The actual clinical tests for these performances will be expected with a next new version of our SSV. We also present on-line identification methods for patient's airway resistance and respiratory compliance which are necessary for implementation of PAV. Animal test results and a few clinical test results of our techniques are also reported for these identification methods.**

I. Introduction

Mechanical ventilators typically deliver a variety of ventilation methods. Mandatory ventilation methods such as VCV (Volume Control Ventilation) and PCV (Pressure Control Ventilation) are necessary for patients without breathing efforts but are also optionally used for patients with spontaneous efforts [1]. Pressure Support Ventilation (PSV) was introduced in the early 1980s and is commonly used at present for patients with spontaneous breathing efforts [1]. PSV principally can synchronize patients' inspiration and expiration timing using triggering functions, but not strictly harmonize with patients' effort itself. Furthermore, when the time constant of the respiratory system is long, the ventilator cycle often extends well beyond patient's inspiratory effort (expiratory asynchrony [12] [13]). In 1992, PAV was proposed [2] with the concept of "proportionally amplifying patient's breathing effort". This method is theoretically superior to PSV in that the magnitude of assist delivered by the ventilator automatically adjusts in response to changes in breathing effort, and the ventilator cycle should also automatically terminate soon after patient's effort cease. In this paper, in Section III, some problems with the original method of PAV application are discussed, in particular the phenomenon called "Runaway" [2], [3]. In Section V, we present a new configuration for PAV delivery system using a disturbance observer to estimate instantaneous patient's inspiratory effort (P_{mus}) and having a predictive control block in which we can adjust robust stability margin and time responsibility of a patient-ventilator overall system. Furthermore in Section IV, results of on-line identification of patient's airway resistance and compliance are reported. These methods are indispensable for realizing PAV ventilation methods [4].

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II. Control Descriptions for Patient and Ventilator Relations

A. General Block Diagram

An example of a mechanical ventilator (SSV-200) and patient's respiratory system are illustrated in Fig. 1. Patient ventilator relation can be simply configured as in Fig. 2. The patient block is a control objective representing ventilation dynamics activated by a disturbance of a patient breathing effort pressure (P_{mus}) that is a virtual variable indicating global effect of respiratory muscles [5]. Also ventilator delivering pressure and/or gas flow acts as a manipulated variable of an output of a mechanical ventilator. We can see that the mechanical ventilator itself is a kind of control device

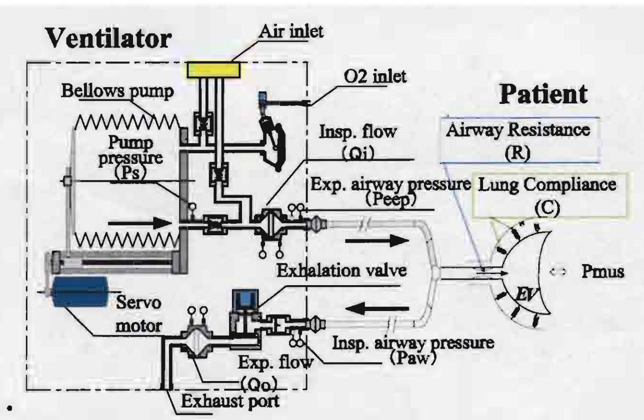


Fig.1 Schematic Diagram of Ventilator and Patients

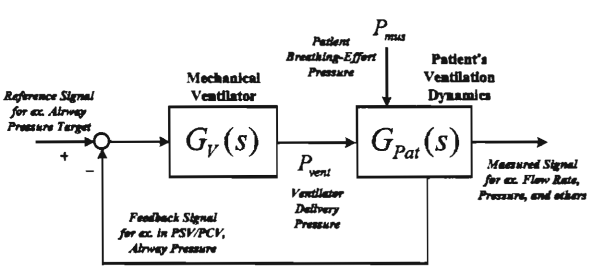


Fig. 2 Block diagram of patient and ventilator

in which adequate reference and feedback variables are used corresponding to different ventilation methods. For example in this figure, PSV or PCV is implemented with feedback and reference variables of the corresponding mode.

B. Block Diagram Representation of PAV method

In Fig. 1, patient's ventilation dynamics are normally represented by the following linear equation [3].

$$P_{vent} + P_{mus} = R \times Q + E \times V \qquad \cdots \qquad (1)$$

where, R is patient's airway resistance, E is respiratory elastance, Q is gas flow rate to a patient, and V is gas volume to the patient which is calculated as $\int Q dt$.

The proposed method for PAV delivery is to control ventilator delivery pressure (P_{vent}) according to the following equation [3] with an ideal condition of $G_V(s) \equiv 1$.

$$P_{vent} = K_{fa} \times Q + K_{Va} \times V \qquad \cdots \qquad (2)$$

where K_{fa} is a fraction of patient's resistance and K_{Va} is the same fraction of patient's elastance [2]. With the consideration of ventilator dynamics $G_V(s)$, an actual PAV configuration can be expressed as in Fig. 3 [6].

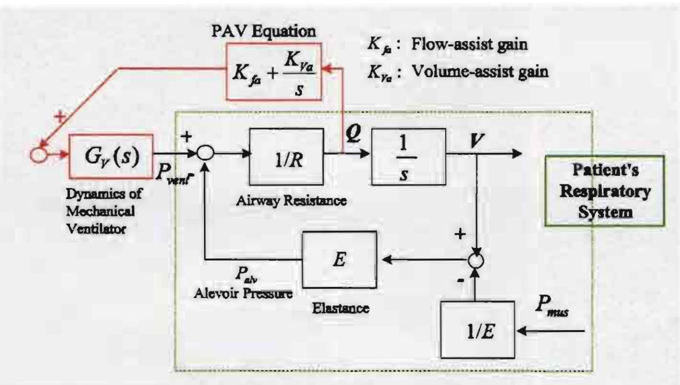


Fig. 3 Block diagram for original PAV

III. Features and Problems of Original PAV

From Fig. 3, the transfer function and the steady state gain of $\frac{Pvent}{Pmus}$ are calculated as follows:

$$\frac{P_{vent}}{P_{mus}} = \frac{G_c(s)e^{-\tau_c s} \times \frac{K_{fa}s + K_{Va}}{Rs+E}}{1 - G_c(s)e^{-\tau_c s} \times \frac{K_{fa}s + K_{Va}}{Rs+E}} \qquad \cdots \qquad (3)$$

$$\left.\frac{P_{vent}}{P_{mus}}\right|_{t\to\infty} = \frac{G_c(0) \times \frac{K_{Va}}{E}}{1 - G_c(0) \times \frac{K_{Va}}{E}} \qquad \cdots \qquad (4)$$

where, $G_V(s) = G_C(s)e^{-\tau_c s}$ according to our actual test results of SSV. $G_c(s)$ is a minimum-phase transfer function normally with $G_c(0)=1$. We can summarize features and problems of the original PAV implementation method as follows:

(a) The original PAV has a positive feedback mechanism, so it may become unstable. Even in ideal case of $G_C(s)e^{-\tau_c s} = 1$, $|Rs + E| > |K_{fa}s + K_{Va}|$ is a stability condition.

(b) Runaway phenomenon will happen when the stability condition is violated. As illustrated later in Nyquist plots, the runaway may happen with instability condition especially in low-frequency regions. This means that $E > K_{Va}$ at $s \to 0$ is more important condition to prevent runaway phenomena and also the identification of E is more important for actual use.

(c) According to equation (4), when $K_{Va} = \alpha E$, the steady state relation will be as follows:

$$\left.\frac{P_{vent}}{P_{mus}}\right|_{t\to\infty} = \frac{\alpha}{1-\alpha} \qquad \cdots \qquad (5)$$

α is so-called assist ratio in the original PAV. The main purpose of PAV is amplification of P_{mus} and it is achieved as hyperbola function of α. On the other hand, the dynamics of ventilator of $G_V(s)$ and the ratio between R and K_{fa} affect transient performance of proportional amplification.

(d) As mentioned above, with PAV, on-line identifications of E and R are indispensable. One author of this paper has proposed methods for such on-line identification [7], [8] and we have implemented these methods in SSV-200 and obtained good results for animal tests and also a few clinical tests [9].

IV. On-line R&E Identification Results

Space does not permit a detailed explanation [9] of these methods, (see Appendix-A,B for a brief graphical description) and hereinafter animal and clinical test results are reported:

A. Animal Test Results(see the photograph in Appendix-C)

We tested the performance of the SSV-200 ventilator and especially R and E identification performances with a beagle (10kg ♂) endotracheally intubated with 7mm I.D. tube, and generally anesthetized with continuous intravenous infusion of ketamine, midazolam, and a small dose of vecuronium, which kept its spontaneous breathing unsuppressed. Table 1 are identification results.

Table 1 Identification Results

	Success number	Success %	Mean	SD	CV
C	274	73.7	23.9	1.59	0.07
R	255	48.9	7.5	1.34	0.18

C=1/E (mL/cmH_2O); R: (cmH_2O/L/sec);

We have judged these identification results likely correct because a coefficient of variation (CV) value of C (lung compliance: C=1/E) is quite small and the identified resistance value is slightly bigger than the resistance of intubation tube (6.7cmH_2O/L/sec) which is the major component of resistance during ventilation with intubation.

B. Clinical Test Results

We have done clinical tests in some colleges of medicine and hospitals on 6 patients. We summarize the results in Table 2.

Table 2 Clinical Test Results

Patient	***R*** Identification		***C*** Identification	
	Success number	Mean value	Success number	Mean value
A	375	12.0	426	35.0
B	13	7.0	14	79.0
C	11	7.0	43	36.0
D	53	11.0	83	29.0
E	57	14.0	52	50.0
F	6	6.0	25	48.0

Unfortunately, we could not directly validate these results. However, a professor reported that they coincided with their clinical finding.

V. A NEW PAV CONFIGURATION

As already stipulated, the main purpose of PAV is "assisting patients by proportionally amplifying instantaneous breathing effort", as reflected in a calculated P_{mus}. Also we have realized on-line identification methods for patient's E and R during PAV ventilation. As a result, we propose a new PAV configuration shown in Fig. 4 which is a similar configuration with a predictive control. The features of this configuration are as follows:

(A) For simplification if we consider $G_m(s)\times e^{-\tau_m s} \equiv G_C(s)\times e^{-\tau_c s}$ (refer to Fig. 5), then the signal Q - $\hat{Q}$ has information of P_{mus} according to the configuration of Fig. 4. Actual patient flow and estimated patient flow will be denoted as follows:

$$Q = (P_{mus} + P_{vent})\frac{s}{Rs+E} \qquad \cdots \quad (6)$$

$$\hat{Q} = \frac{s}{\hat{R}s+\hat{E}} \times P_{vent} \qquad \cdots \quad (7)$$

We subtract (6) – (7) and unknown parameters of R, E would be equal to $\hat{R}$, $\hat{E}$ as an ideal case, then we get $\hat{P}_{mus}$ as follows:

$$\hat{P}_{mus} = \left(\hat{R} + \frac{\hat{E}}{s}\right)\left(Q - \hat{Q}\right) \qquad \cdots \quad (8)$$

Thus, we can obtain instantaneous estimates of P_{mus} with a PI calculation for the flow difference signal with a proportional and integral gain corresponding respectively to identified patient's respiratory resistance and elastance. For the next step, we obtain the transfer function and steady state gain from Fig. 4 as follows:

$$\frac{P_{vent}}{P_{mus}} = \frac{G_c(s)e^{-\tau_c s} \times \frac{K_{FG}s + K_{VG}}{Rs+E}}{1 + G_c(s)e^{-\tau_c s}\frac{K_{FG}s+K_{VG}}{Rs+E}\left(\frac{G_m(s)e^{-\tau_m s}}{G_c(s)e^{-\tau_c s}}\frac{Rs+E}{\hat{R}s+\hat{E}} - 1\right)} \qquad \cdots \quad (9)$$

$$\left.\frac{P_{vent}}{P_{mus}}\right|_{t\to\infty} = \frac{G_c(0)\times\frac{K_{VG}}{E}}{1 + G_c(0)\times\frac{K_{VG}}{E}\times\left(\frac{G_m(0)}{G_c(0)}\frac{E}{\hat{E}} - 1\right)} \qquad \cdots \quad (10)$$

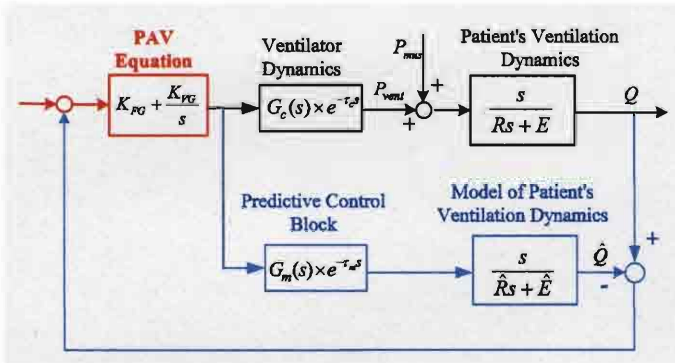


Fig. 4 New PAV Control Configuration

(B) The stability condition and dynamic characteristics can be designed and/or adjusted using a predictive control block $G_m(s)e^{-\tau_m s}$ comparing with the actual and measurable ventilator dynamic of $G_c(s)e^{-\tau_c s}$. The ability to have designable and/or adjustable block inside the control mechanism of a mechanical ventilator is the most important feature of our new configuration. This point has never been provided in the original PAV or other configuration, for example, only with a disturbance observer which we have already proposed as in Fig.5 [6].

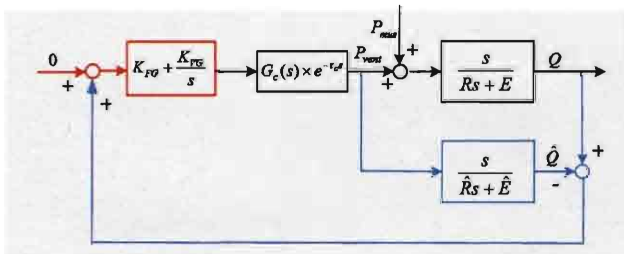


Fig. 5 A Configuration only with a disturbance observer

The features including robust performances with this control block $G_m(s)e^{-\tau_m s}$ are separately analyzed and reported in Section VI and VII.

(C) As an ideal case that $\hat{E} = E$: $G_c(s)|_{s\to 0} = G_m(s)|_{s\to 0} = 1$: and $K_{VG} = \beta \times \hat{E}$, the steady-state gain can be got as follows:

$$\left.\frac{P_{Vent}}{P_{mus}}\right|_{t\to\infty} = \beta \qquad \cdots \quad (11)$$

Thus, the linear amplification purpose of PAV is achieved at steady state in this configuration, which is a pure linear relation with β.

(D) In the proposed method, we can obtain a linear amplification with a negative feedback whereas with the original PAV positive feedback is used. This feature is closely related with the robust stability margin which will be explained in the following Section.

VI. Robust Stability and Dynamic Characteristics of the Proposed PAV Configuration

For the actual use of PAV, it is normal that patient's parameter R and E will change from time to time [3]. As a result, PAV method has a possibility of runaway phenomenon which is related to stability margin. On the other hand, time responsibility, or linear amplifying performance, is important for its purpose and also for minimizing expiratory asynchrony caused by the response delay of mechanical ventilator. Hereinafter, analysis and test results are compared between original and proposed PAV when patient's parameters differ from identified values.

A. Robust Stability Margins from Sensitivity Functions

We can calculate Nyquist plots using loop functions in eq. (3) and eq. (9) respectively for original PAV and proposed one. The robust stability margin can be calculated as eq. (12).

$$\|S\|_\infty^{-1} = \min_\omega |1 + L(j\omega)| \quad \cdots \quad (12)$$

This margin can be represented [10] as a circle radius contacting Nyquist plot with a center at (-1, 0) in the complex $L(j\omega)$ plain. In Fig. 6 and 7, several Nyquist plots and vectors corresponding to stability margins are shown for original and proposed PAV with $R > \hat{R}, E > \hat{E}$ or $R < \hat{R}, E < \hat{E}$ respectively.

For these calculations, we use the transfer function of mechanical ventilator of equation (13) as shown in several test results of the actual ventilator (SSV-200). Moreover, for adjustable control block, we use the following transfer function eq. (14) which is intentionally not same as the actual transfer function of eq. (13) especially neglecting delay time.

$$G_C(s)e^{-\tau_C s} = \frac{1}{1+0.024s}e^{-0.01s} \quad \cdots \quad (13)$$

$$G_m(s)e^{-\tau_m s} = \frac{1}{1+0.02s} \quad \cdots \quad (14)$$

Actual time responses using this predictive control block will be shown in the next Section. The following features can be deduced from these results of analysis in addition to the features mentioned in the preceding Section.

(E) As a matter of course, we have a wider stability margin with the negative feedback configuration shown in Fig. 6, and also even with the positive feedback shown in Fig. 7. In medical usage, this means a bigger margin for instability phenomena when patient's mechanical parameters change, for example, when airway resistance (R) increases by sputum accumulation or bronchoconstriction.

(F) In the original PAV, stability limit exists in low frequency region especially in ω=0. The terminology of "Runaway" may come from this fact. On the other hand in our proposed PAV, we need to take care of stability margin in high frequency region, in which we have an oscillative response in

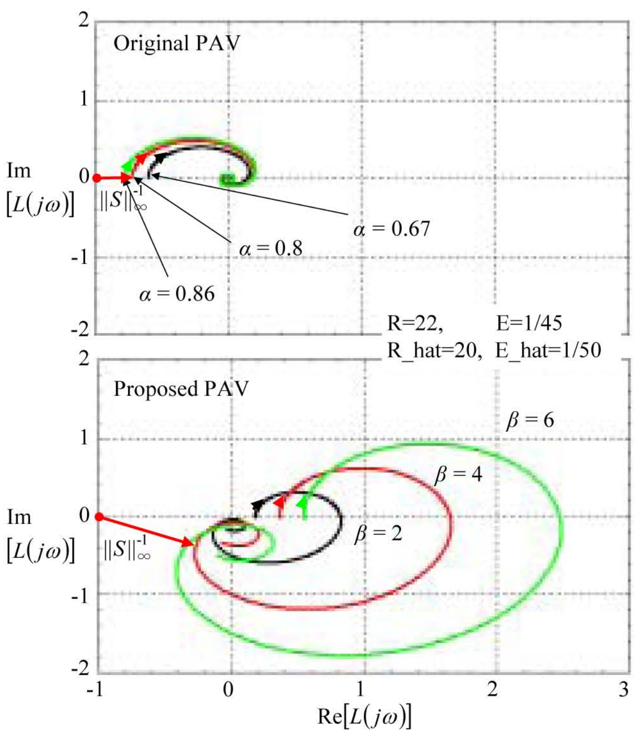


Fig. 6 Nyquist plots and $\|S\|_\infty^{-1}$ for $R > \hat{R}, E > \hat{E}$

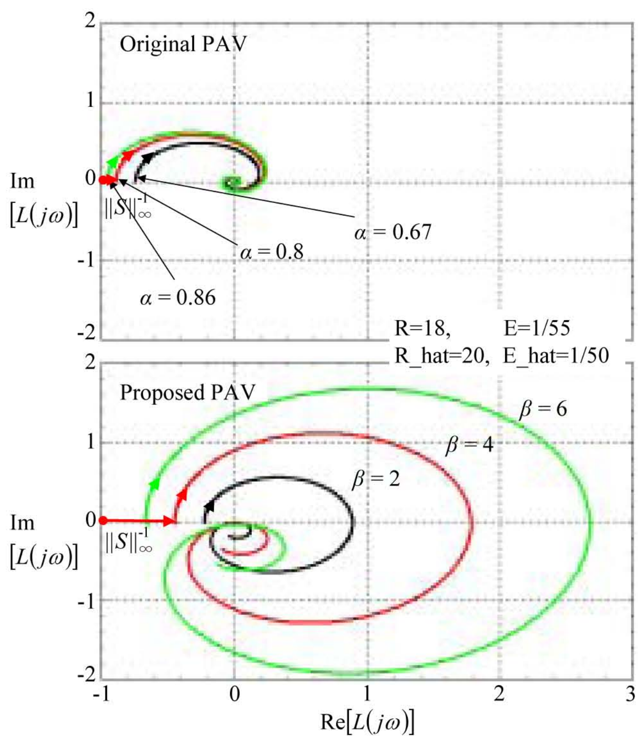


Fig. 7 Nyquist plots and $\|S\|_\infty^{-1}$ for $R < \hat{R}, E < \hat{E}$

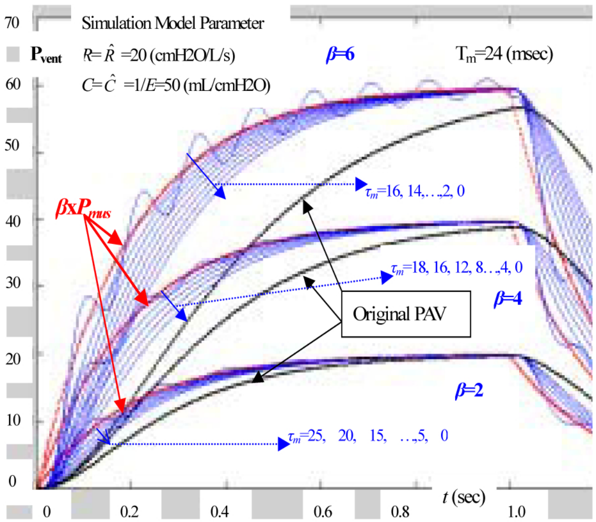


Fig. 8 Simulation tests for time-response (T_m=24, τ_m:variable)

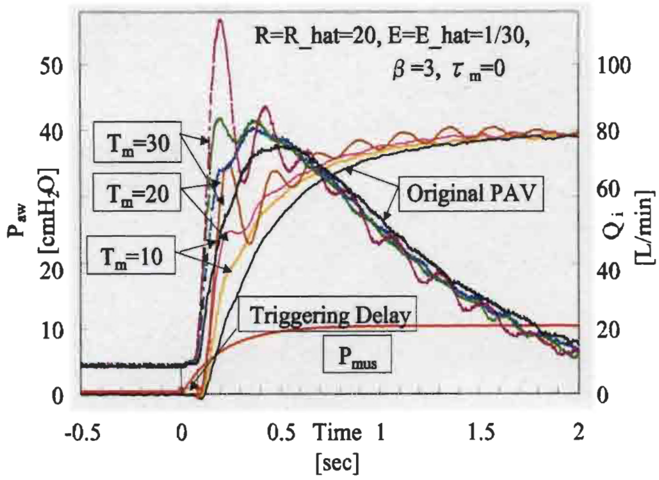


Fig. 9 Ventilator response comparison for two PAV methods

early stage of starting PAV assist, which can be seen in the next Section.

B. Time Response Performances

In addition to the improvement of robust stability margin, time response characteristics can be adjusted and also fairly improved in the proposed PAV. In Fig. 8, computer simulation results for original and proposed PAV are shown with three amplifying gains and with several control parameters in the proposed control block. Hereinafter for all kinds of time-response tests, we used the following time-function of P_{mus}:

$$P_{mus} = P_{mus\_Max}[1-\exp(-t/T_{mus})] \quad T_{mus} = 0.2(\text{sec}) \quad \cdots \quad (15)$$

After several simulations and Nyquist plot analysis with control parameter τ_m and T_m, and also respiratory parameter R and E, the following sets of adjusting parameters were found appropriate: τ_m=0 (msec) and T_m=20 (msec). We confirmed actual time response using our ventilator SSV-200 connected with our spontaneous breathing lung simulator LUNGOO [11] (refer photographs in Appendix C). This test arrangement is very close to an actual patient-ventilator configuration. Fig. 9 is a representative test result. According to these actual test results and Nyquist plot analysis, time-response and stability margin can be fairly improved with the proposed method, so that good robust performances have been got with these adjusting parameters.

VII. Patient-Ventilator Interaction - Expiratory Asynchrony Phenomena -

In partial support ventilation methods such as PSV and PAV, the synchronizing performance is closely related to the ventilation method itself and also to time response performance of the mechanical ventilator. Giannouli et. al. [12] have reported that with PSV, fairy big phase difference can be seen between patient's effort and response of ventilator and that these phenomena will not be likely happen with PAV. The mechanisms of expiratory asynchrony with PSV have been reported by Yamada [13]. Du et. al. [14] have reported that the response delay in mechanical ventilators can result in expiratory asynchrony also with PAV. We report comparison result of expiratory asynchrony phenomenon using SSV-200 and lung simulator LUNGOO. In LUNGOO, we can set P_{mus} as a time function (eq. (15)). Fig. 10 shows that the time difference (δT) between peak pressure of P_{mus} and zero-crossing of flow, which is the measure of expiratory asynchrony used in the literature [14], can be substantially decreased.

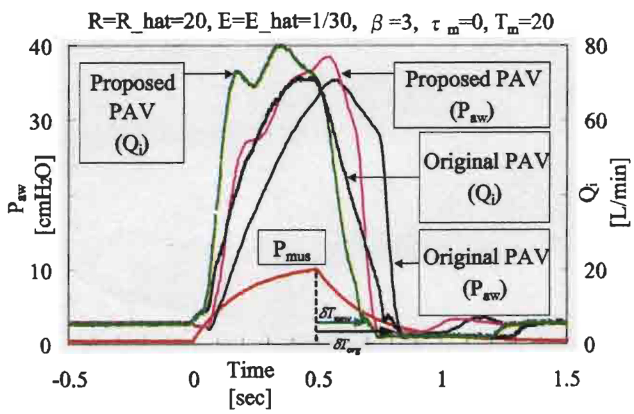


Fig. 10 Expiratory Asynchrony in two PAV methods

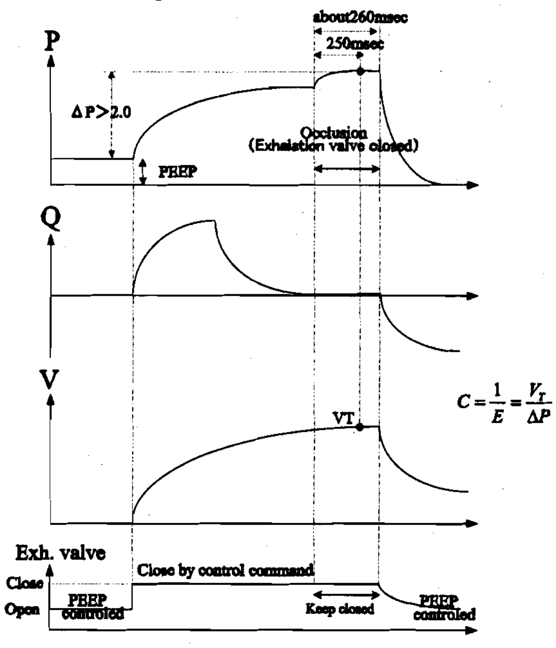
VIII. Conclusion

In this paper, we present a new configuration of PAV ventilation method using a disturbance observer and with a predictive control block. It is also shown that the proposed PAV method has an adjustable control block which can give a bigger stability margin and also much better time response including a less expiratory asynchrony. These features have been confirmed with computer simulations and/or with test construction using our mechanical ventilator and the lung simulator instead of real patients. Including these two points, we summarize that five points of our contributions from control application view points are: (a) using control technique we propose improved ventilation method; (b) we can have an adjustable predictive control block in our control configuration, which has never been provided in other ventilation configurations; (c) we also propose and evaluate robust performances with an intentionally different transfer function of this adjustable block comparing to the actual and measurable ventilation dynamics; (d) on-line parameter identification method of patient's respiratory system have been evaluated to be able to adopt in clinical usage; and (e) in association with these clarifications, we present a block diagram representation for patient-ventilator overall system. As a summary, we conclude that systematic control engineering approach is indispensable to develop and design a good mechanical ventilator.

Appendix

Appendix-A: Graphical Explanation of C Identification

Refer to the following figure and calculation formula of "C" written in this figure.



Appendix-B: Graphical Explanation of R Identification

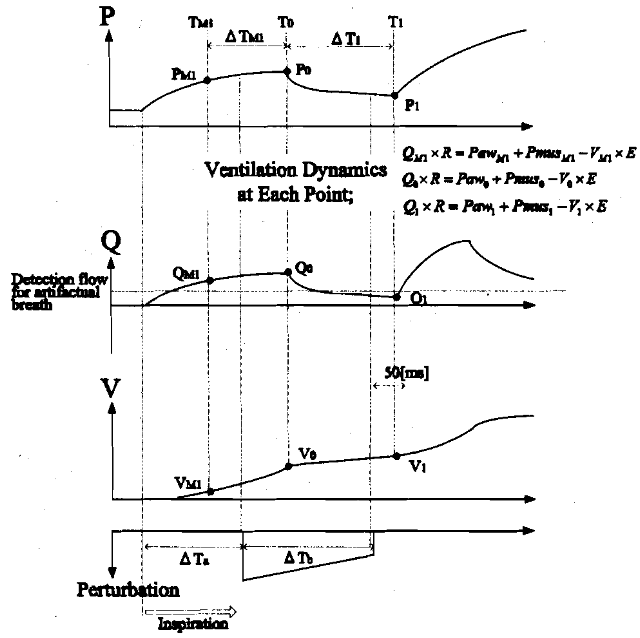
During starting phase of PAV assist, a special occlusion pulse is put. The resistance "R" can be estimated with the flow and pressure variance with the following procedures: At each point, ventilation dynamics can be represented with equations shown in the figure. If we take two subtracts for the three dynamics and add resulting two equations, we obtain:

$$(\Delta Q_1 + \Delta Q_{M1})R = (\Delta Paw_1 + \Delta Paw_{M1}) + (\Delta Pmus_1 - \Delta Pmus_{M1}) - (\Delta V_1 + \Delta V_{M1})E \quad \cdots \quad \text{(A1)}$$

If we assume P_{mus} will change monotonously, we obtain:

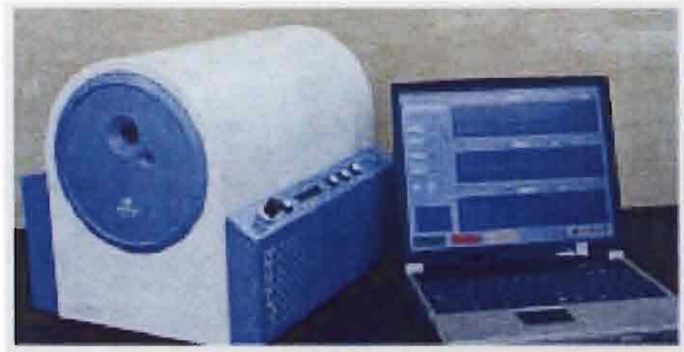
$$(\Delta Q_1 + Tr \times \Delta Q_{M1})R = (\Delta Paw_1 + Tr \times \Delta Paw_{M1}) - (\Delta V_1 + Tr \times \Delta V_{M1})E \quad \cdots \quad \text{(A2)}$$

where, we put as $T_r = \Delta T_1 / \Delta T_{M1}$. If we use identified result of E in this equation, we can get estimated value of R.



Appendix-C: Photographs

Photograph of SSV-200



Photograph of LUNGOO

Photograph of animal test surroundings with SSV-100 (Prototype ventilator)

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