MJS-NVIC/con/009-10/01/NJCC 6.4.16-20.2002
NJCC, 08.2002, p.16-20. Editor: J. Kesecioglu
Vol. 6, No.4

$P_{0.1}$-control mode ventilation

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Received and accepted for publication april 2002

Summary. The main limit of conventional modes of mechanical ventilation is represented by the absence of automatic servo-controlled loop to directly control the patient's respiratory effort. One index to monitor the patient's workload is represented by the Po.1. Po.1 is the drop in airway pressure in the first 100 ms of an inspiratory effort against the occluded airway opening, when the occlusion takes place at the end of the expiratory time that is at the end-expiratory volume The Po.1-control mode remains an experimental mode of ventilation, but the investigation into servo-controlled modes makes the patient-ventilator interaction more and more advanced. The idea to close the loop of a servo-controlled system with Po.1 is ambitious, even if supported by many scientific evidences on the complex relationship between Po.1 and patient inspiratory effort. The Po.1-control mode and its limitations are discussed in this manuscript.

Introduction

The main limit of conventional modes of mechanical ventilation is represented by the absence of automatic servo-controlled loop to directly control the patient's respiratory effort. Therefore the clinician has to manually modify the setting of ventilator to follow the changes in time of ventilation needs and in the mechanical properties of the patient chest wall-lung complex. Indeed, the current studies in closed-loop controlled modes of mechanical ventilation try to indicate the best index or indices to close the loop to control and optimise the respiratory workload of the ventilated patient.

In the present article, we shall briefly mention the principles of patient-ventilator interaction during mechanical ventilation and the indices commonly used to monitor the respiratory effort of the patient and we will deeply analyse the $P_{0.1}$-controller mode, an automatic closed-loop based on the continuous monitoring of $P_{0.1}$. Moreover, we will discuss the principles of operation the possible applications with the limits and future developments. The $P_{0.1}$-controlled was implemented and studied on an experimental workstation made with an Amadeus ventilator by Hamilton Medical (Bonaduz, CH).

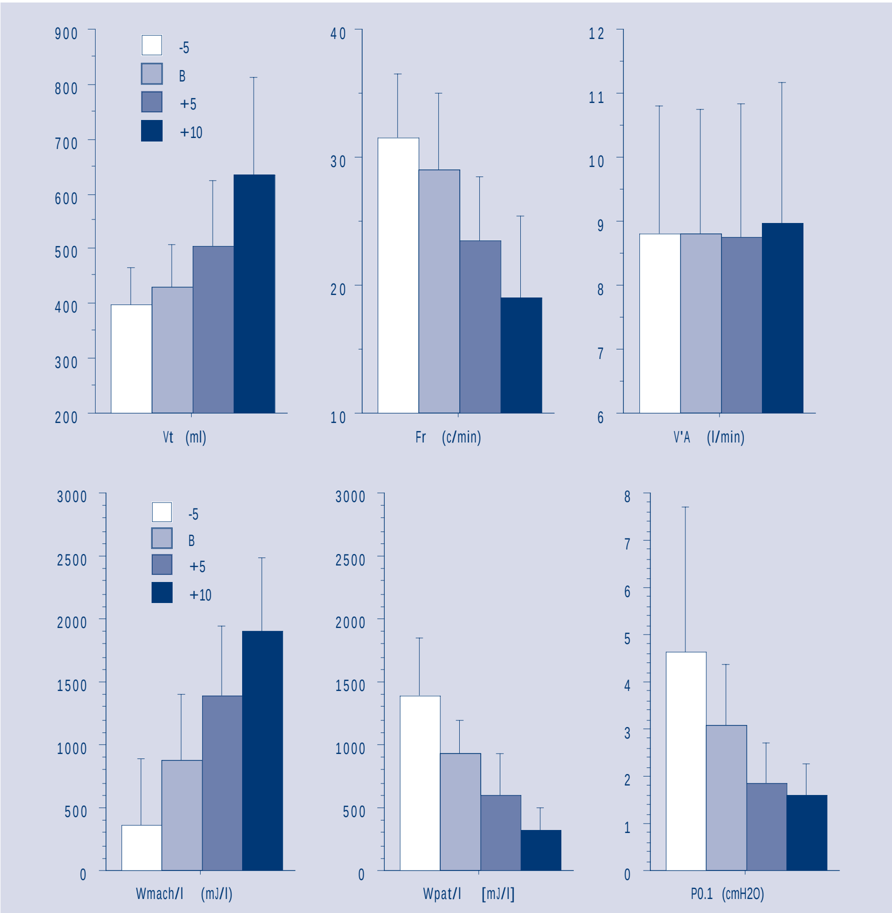

Fig. 1. Steady state response (mean ± SD) of 8 patients with acute respiratory failure to 4 different pressure support ventilation levels: pressure support was decreased by 5 cmH_2O (-5), and increased by 5 cmH_2O (+5) and 10 cmH_2O (+10) from the baseline setting (B). Increasing pressure support levels were associated with increasing tidal volume (VT), decreasing respiratory frequency (Fr), unchanged alveolar ventilation (VA), decreasing work per liter performed by ventilator (Wmach/l), decreasing work per litre performed by patient (Wpat/l) and decreasing $P_{0.1}$. (Reprinted by permission from Respiratory Care Clinics of North America, G.A. Iotti, 2001 Vol 7, number 3)

Patient-ventilator interaction during mechanical ventilation

In mechanically ventilated patients, the factors involved in promoting the ventilation are grossly represented by the patient (respi-

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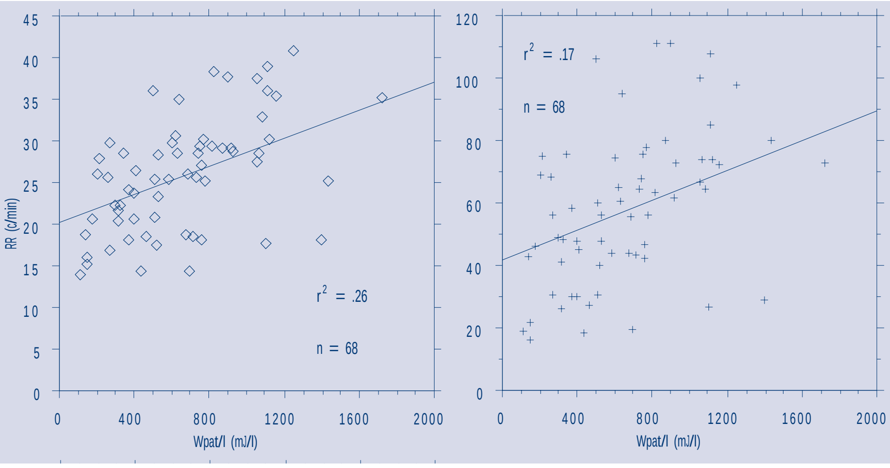

Fig. 2. Relationships between patient's work of breathing per liter (Wpat/l) and respiratory rate (RR) and rapid shallow breathing index (RR/VT, expressed as cycles/min/l), and P0.1 in 17 patients with acute respiratory failure, each one assisted at 4 different pressure support levels, in steady state. (Reprinted by permission from Respiratory Care Clinics of North America, G.A. Iotti, 2001 Vol 7, number 3)

ratory impedance, respiratory muscles) and by the ventilator (pressure generated by the ventilator). A very simple model of patient-ventilator interaction is represented by the total controlled modes of mechanical ventilation, when the patient is paralysed and the ventilation is completely guaranteed by the ventilator: the pressure generated is used to counterbalance the passive load of airways, thorax and lungs and the clinician externally controls the adequacy of the ventilation, instead of the physiologic respiratory centres of the patient. In this case the effects of the changes of ventilator controls made by the clinician are rather obvious, as well as it is directly predictable how to correct the hypo or hyperventilation. The real interest in optimising the closed-loop controlled modes regards the partial modes, for instance pressure support ventilation [1, 2, 3] or assisted controlled ventilation [4,5] and synchronized intermittent mechanical ventilation [6] in which the respiratory centres and respiratory muscles of the patient actively interact with the ventilator, resulting in a modulation of the effort of the patient changing in time.

In pressure support ventilation [7], the total workload of ventilation is shared between the patient and the ventilator, but the clinical challenge is to precisely define the extent of workload left to the patient, with the danger to finally give a too low or too high support of pressure. In most cases, the clinician initially sets a given level of pressure support in the aim to maintain arterial $PaCO_2$ and pH within the "normal" ranges; later on, the adequacy of the setting must be verified and eventually corrected. In any case the changing in time of the ventilation needs are really very frequent and the clinician intervention is rarely immediate and precise. Generally, the clinician knows that the increase in pressure support generates a decrease in patient's effort, respiratory rate, and work of breathing, but he does not directly know the entity of this decrease (Figure 1). We can conclude that the criteria of the adequacy of patient ventilation in pressure support is essentially the CO_2 clearance and the oxygenation, with the risk to underestimate the real workload left to the patient (respiratory muscles fatigue or derecruitment).

To overcome the limit represented by the clinical judgment the solution is to equip the modern ventilators with closed-loop control, based on reliable indices of patient's workload.

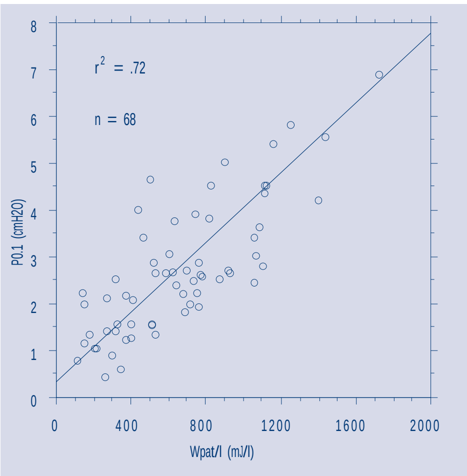

Fig. 3. Relationships between patient's work of breathing per liter (Wpat/l) and P0.1 in 17 patients with acute respiratory failure, each one assisted at 4 different pressure support levels, in steady state. (Reprinted by permission from Respiratory Care Clinics of North America, G.A. Iotti, 2001 Vol 7, number 3)

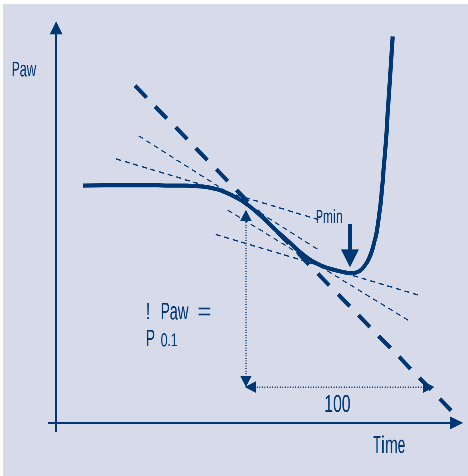

Fig. 4. Method for the automatic measurement of P0.1 (P0.1 cont) based on pressure-trigger related mini-occlusion. On the basis of the flow signal, the mini-occlusion period is identified. Within this period, the minimum value (Pmin) of the real time airway pressure is identified. From the Pmin point, Paw is analyzed backwards for its slope (dashed lines) and the maximum slope is identified (thick dashed line). P0.1 is calculated from the maximum slope, as the drop in Paw corresponding to a time of 100 ms. (Galbusera C, Palo A, Iotti G, et al. Relationship between P0.1 and inspiratory work of breathing during pressure support ventilation (PSV). Am Rev Respir Dis 1993; 147: A876)

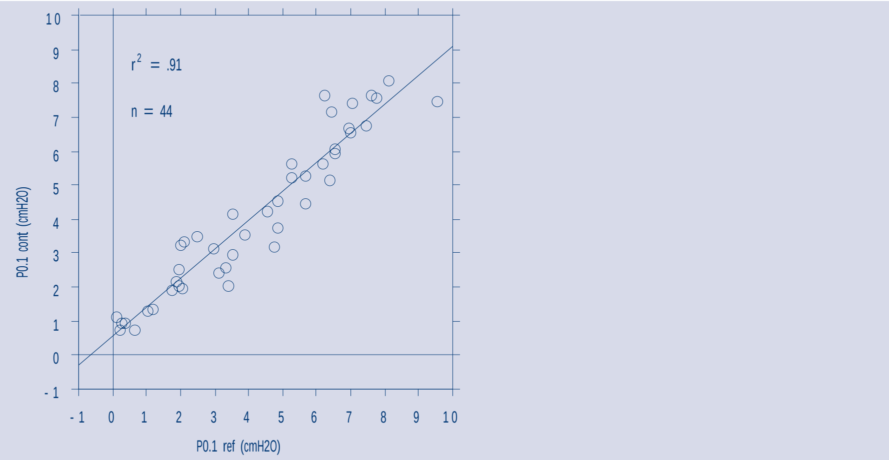

Fig. 5. Relationship between data from automatic continuous measurement of P0.1 (P0.1 cont) based on pressure-trigger related mini-occlusion (average of 180 consecutive breaths) and reference P0.1 measurement by formal end-expiratory occlusion (average of 3 maneuvers). (Reprinted by permission from Respiratory Care Clinics of North America, G.A. Iotti, 2001 Vol 7, number 3)

Indices of patient's workload during partial ventilatory support

The measure of the respiratory work of breathing [8] (pressure-time product or pressure-volume product) represents the gold standard for the evaluation of the patient's workload in assisted modes. Nevertheless, whatever the method used, it's time consuming, invasive and very unstable when continuously measured. These limits [9.10] make the index not suitable to be employed in the closed-loop controlled modes.

Respiratory rate (RR) and the derived index "rapid shallow breathing" (RR/V_T) [11] have been considered simple indices to clinically judge the patient's workload and to take decisions about the removal of the mechanical support.

The RR has been used to direct a closed-loop mode called mandatory rate ventilation (MRV), implemented on some ventilators (Cesar and Horus, Taema).

All these parameters show a correlation with patients respiratory workload at different levels of pressure support (PS) [12], but they cannot be considered the optimal choice to guide a closed-loop, since their poor correlation with the reference standard measure of the work of breathing [13,14]. (Figure 2)

Another index to monitor the patient's workload is represented by the $P_{0.1}$. $P_{0.1}$ is the drop in airway pressure in the first 100 ms of an inspiratory effort against the occluded airway opening, when the occlusion takes place at the end of the expiratory time that is at the end-expiratory volume [15,16]. This pressure drop is totally independent from the mechanical properties of the respiratory system and not influenced by voluntary reactions, when strictly considered in the time of the 100 ms. $P_{0.1}$ represents the pressure generated by the complex of the respiratory muscles and can be used as an index of the respiratory effort developed by the respiratory muscles [17].

Furthermore, $P_{0.1}$ shows a good correlation with the respiratory work of breathing [18,19,20] (Figure 3) and can be proposed as the optimal parameter to drive a closed-loop controlled mode.

The $P_{0.1}$ measurement is commonly performed by an end-expiratory occlusion manoeuvre and by the activation of the end-expiratory occlusion function in mechanically ventilated patients: the measurement so performed is necessarily discontinuous and not suitable for driving a close-loop controller. A possible solution relies on an automatic breath-by-breath measurement of $P_{0.1}$: to obtain a continuous measurement of $P_{0.1}$ it is possible to exploit the mini-occlusion phase associated with the opening delay of the inspiratory valve when a pressure trigger is present [21,22,23]. Even if this time delay is generally shorter than 100 ms in the majority of modern ventilators, it is possible to obtain a measure of $P_{0.1}$ since the pressure decays according to a given linear slope. The procedure described in the present article is based on an algorithm which identifies the mini-occlusion period on the airways flow signal, isolates the part of the curve to be processed, identifies the maximum slope of the pressure drop and finally calculates $P_{0.1}$ from this slope [24,25]. (Figure 4,5)

$P_{0.1}$ control mode: into details

The system is based on the simultaneous control of the patient inspiratory effort and of the tidal volume and it uses pressure support ventilation as the basic ventilation mode. The Po.1-controller combines two different controllers:

- The $P_{0.1}$-controller, which controls the patient's inspiratory effort
- The volumetric controller to maintain adequate ventilation. This latter is not based, as usual, on the tidal volume, which doesn't represent a reliable parameter to close a loop, but on the alveolar volume (VA, equal to the difference between tidal volume and dead space [26,27]), which really means the effective ventilation for the CO_2 removal.

The $P_{0.1}$-controller works automatically adjusting the level of the pressure support (PS) in the aim to reach the preset target of $P_{0.1}$ and VA (Figure 6).

The $P_{0.1}$-controller has been implemented on an experimental workstation on Amadeus ventilator (Hamilton Medical), equipped with a mainstream capnometer and two computers for the breath-by-breath analysis and the closed loop.

Many parameters of the respiratory pattern were monitored on a breath-by-breath basis, such as tidal volume (derived from flow), VD and VA (derived from expired CO_2-volume diagram). In practice, the user sets a value of $P_{0.1}$ target (between 1 and 5) and the controller progressively compares the target and the actual value of $P_{0.1}$, monitored on a breath-by-breath basis as described above. If the actual $P_{0.1}$ is higher than the target, the controller reacts with a decrease in PS level for the next breath, or an increase in the opposite case. The user also sets a target value of VA, within fixed limits for safety reasons: the minimum VA target is equal to one series dead space, and hence the minimum VT is equal to twice the series dead space. The controller automatically adjusts the level of PS by comparing the target VA with the actual at any breath: if the actual VA is higher than the target, the controller decreases the PS level, if it's lower the controller increases the PS level.

The closed loop is finally performed by merging the $P_{0.1}$-controller and the VA controller, and the result is that at any breath the target of $P_{0.1}$ and of VA corresponds to a point which lies in one of the four quadrants defined by the controller targets. Only in two quadrants, one and four, the command of the two controllers is consistent for both the two $P_{0.1}$ and VA controller: in quadrant "1" the command is increase PS, and in quadrant "4" is decrease PS. In the others quadrants the command of the each controller are discordant: in quadrant "2" the $P_{0.1}$ has the priority and the command will be to increase PS level, while in quadrant "3" the VA controller has the priority and the response will be to increase the PS level. The PS level changes are limited within 1 cmH_2O per each breath, the user sets the maximum limit of pressure support, while the minimum value set by the controller is equal to PEEP.

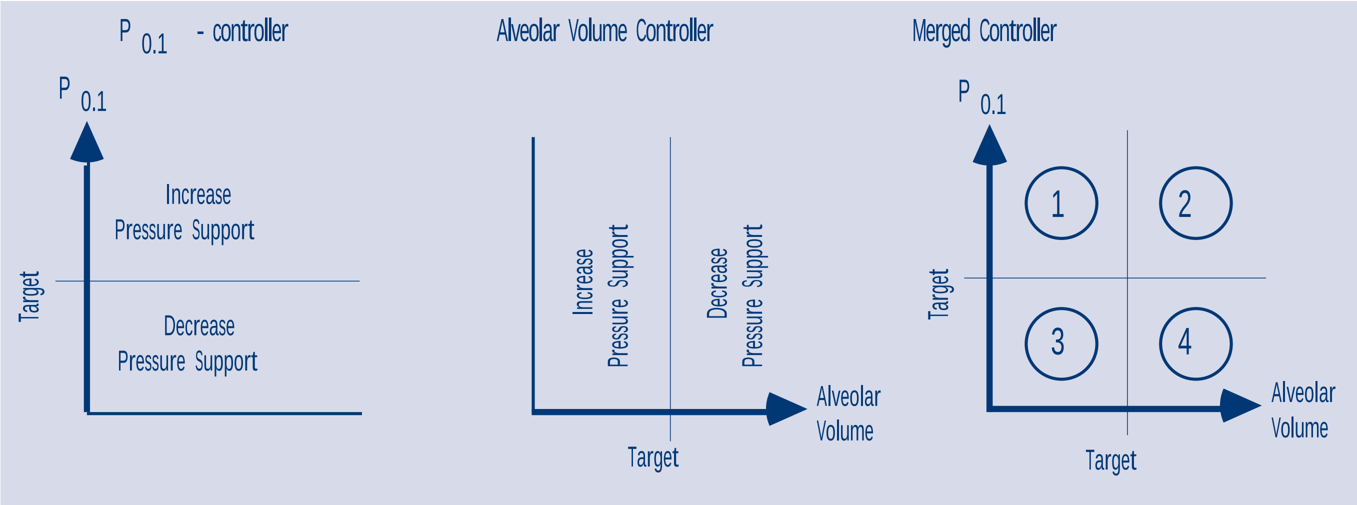

Fig. 6. Structure of the P0.1 control mode (from Iotti GA, Brunner JX, Braschi A, et al. Closed-loop control of airway occlusion pressure at 0.1 second (P0.1) applied to pressure-support ventilation: algorithm and application in intubated patients. Crit Care Med 24: 771-779, 1996, with permission).

Present applications and limits of $P_{0.1}$-controller mode

In a previous article [28], we showed the data relative to the application of the $P_{0.1}$-controller in ventilated patients (Figure 7): the $P_{0.1}$–VA controller was able to guarantee the maintenance of the patient inspiratory effort at a preset level (the target), avoiding the risk of hypoventilation. The final work of the controller depends on the relative prevalence of $P_{0.1}$ or VA controller, in according to the user set target. Hence, the $P_{0.1}$-controller mainly works as a stabilizer of the spontaneous patient's activity simultaneously avoiding the hypoventilation when the user sets a minimum value of VA target; in case of setting of very high VA target, the controller will mainly act as a stabilizer of the tidal volume, while avoiding unneeded waste of respiratory work of breathing.

The stabilization of the respiratory effort of the patient suggests the use of the $P_{0.1}$-controller for the automatic compensation of changes in those factors, which affect the patient workload, such as the respiratory impedance, the CO_2 exchange efficiency, the metabolic rate and others. In this context, we showed the capability of the $P_{0.1}$-controller [29] to counterbalance the changes in workload caused by different types of humidifier devices. In this study we used three different types of humidifiers, the hot-water humidifier, a high-resistance high-volume HME and a low-resistance low-volume HME, which determine different conditions of workload and ventilation requirements because of different apparatus resistance and different deadspace. Under these conditions, the $P_{0.1}$-controller was able to stabilize the spontaneous respiratory activity of the patient, and to counterbalance the mechanical effects of the devices on the respiratory workload.

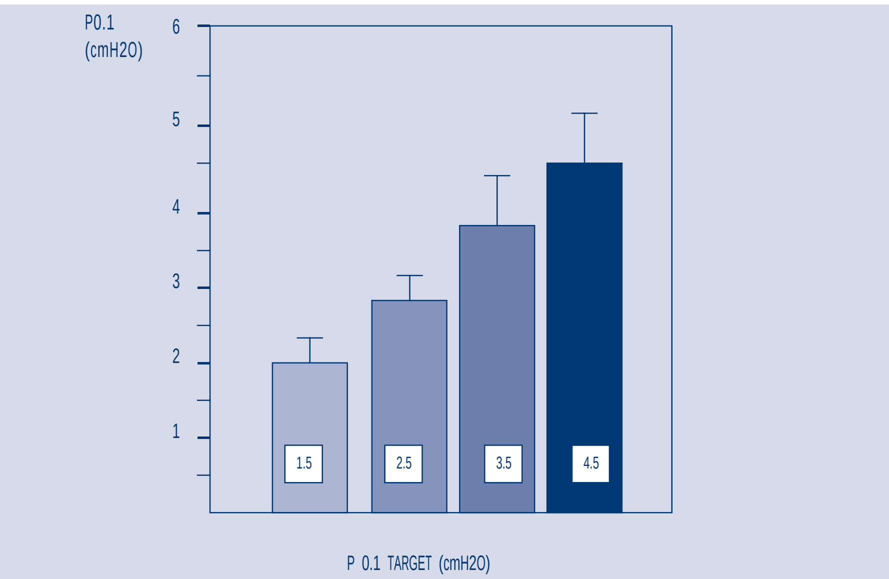

Fig. 7. Steady state values of P0.1 (mean ± SD) in 8 patients during ventilation with the P0.1-control mode, set at 4 different targets of P0.1 for each patient (plotted from data from Iotti GA, Brunner JX, Braschi A, et al. Closed-loop control of airway occlusion pressure at 0.1 second (P0.1) applied to pressure-support ventilation: algorithm and application in intubated patients. Crit Care Med 24: 771-779, 1996, with permission).

Another possible application of the $P_{0.1}$-controller is the weaning from mechanical ventilation, even if the controller has not been conceived for this purpose. If we want to reach the progressive weaning from the ventilator, we will set a target of $P_{0.1}$ near the normality, for example 2 cmH_2O (a value consistent for weaning) and a VA target adequate to avoid hypoventilation. The $P_{0.1}$-controller will progressively reduce the PS needed to reach the target, until the weaning process is performed when the ventilation requirements are consistent with. During this period, at any worsening of the patient the controller will respond with a further increase of PS level. Another possibility to use the controller for the weaning process consists in forcing the muscular capability of the patient by setting a high $P_{0.1}$ target, obviously avoiding the risk of hypoventilation and of muscular deterioration. In this case the selection of the $P_{0.1}$ target value is rather simple, since it can be derived from the literature [30,31,32,33].

Actually, the use of the controller in this field is only theoretical, since its technical features are not safe for the long period of time needed for weaning purposes.

The $P_{0.1}$-controller is an experimental mode of ventilation and it has not been yet implemented in a ventilator commercial version, because of some important limits discussed below.

In cases of prolonged fits of cough [34] the $P_{0.1}$-controller responds with progressive increase in PS level since coughing is associated with very high level of $P_{0.1}$. The only protective intervention is to set an adequate upper limit of pressure limit alarm.

The inappropriate increase in PS level is due by the absence of an automatic detection of cough, and theoretically can be solved by introducing a more sensitive $P_{0.1}$ filtering.

Another limitation of this system is represented by the lack of alveolar ventilation guarantee. As it has been conceived, the $P_{0.1}$-controller can prevent hypoventilation derived from ineffective and low tidal volume and apnea, but not from excessively high respiratory rate, since it has no control on the respiratory rate. A possible solution is to merge the $P_{0.1}$-controller with the volumetric controller used in adaptive support ventilation mode (ASV) [35], a new mode of ventilation recently implemented on the Galileo ventilator by Hamilton Medical.

Finally, the $P_{0.1}$-controller mode can be only applied when a pressure trigger is present, not with flow trigger. Under this condition, it's impossible to apply our method for the automatic and breath-by-breath measurement of $P_{0.1}$, since the flow triggering is associated with no pressure drop after the inspiratory effort performed by the patient to trigger the inspiration. When the patient triggers a breath in the presence of flow-triggering a change in airflow occurs during the first 100 ms of non-occluded inspiration (V0.1). Since this measurement is affected by changes in resistance and compliance, a possible solution is the intermittent conversion from the flow trigger to pressure trigger with no continuous flow, for instance, for one breath every few minutes. This pressure-triggered breath will furnish a measure of $P_{0.1}$ to compare the measure of $V_{0.1}$ obtained in the previous flow triggered breath. This method is actually under investigation [14].

Conclusions

The $P_{0.1}$-control mode still remains an experimental mode of ventilation, but the investigation into servo-controlled modes makes the patient-ventilator interaction more and more advanced. The idea to close the loop of a servo-controlled system with $P_{0.1}$ is ambitious, even if supported by many scientific evidences on the complex relationship between $P_{0.1}$ and patient inspiratory effort. The technical limitations of the system discussed above, actually contraindicate its set-up in a ventilator commercial version.

References

1 Azarian R, Lofaso F, Zerah F, et al. Assessment of the respiratory compliance in awake subjects using pressure support. Eur Respir J 1993 ;6:552-558
2 Foti G, Cereda M, Banfi G, et al. End-inspiratory airway occlusion. A method to assess the pressure developed by inspiratory muscles in patients with acute lung injury undergoing pressure support. Am J Respir Crit Care Med 1988; 14:650-653
3 Iotti GA, Braschi A, Brunner JX, et al. Respiratory mechanics by least square fitting in mechanically ventilated patients: applications during paralysis and during pressure support ventilation. Intensive Care Med 1995; 21:406-413
4 Marini JJ, Capps JS, Culver BH. The inspiratory workload of breathing during assisted mechanical ventilation. Chest 1985; 87:612-618
5 Marini JJ, Rodriguez M, Lamb VJ. The inspiratory workload of patients-initiated mechanical ventilation. Am Rev Respir Dis1986; 134:902-909
6 Marini JJ, Smith TC, Lamb VJ. External work output and force generation during synchronized intermittent mechanical ventilation. Effect of machine assistance on breathing effort. Am Rev Respir Dis 1988; 138:1169-1179
7 Brochard L. Inspiratory pressure support. Eur J Anesthesiol 1994;11:29-36
8 Iotti GA, Braschi A. Measurement of respiratory mechanics during mechanical ventilation. Rhäzüns, Switzerland, Hamilton Medical Scientific Library, 1999
9 Blanch PB, Banner MJ. A new respiratory monitor that enables accurate measurement of work of breathing: a validation study. Respir Care 1995; 39:897-905
10 Petros AJ, Lamond CT, Bennett D. The Bicore pulmonary monitor. A device to assess the work of breathing while weaning from mechanical ventilation. Anaesthesia 1993; 48: 985-988
11 Yang KL, Tobin MJ. A prospective study of indexes predicting the outcome of trials of weaning from mechanical ventilation. N Engl J Med 1991; 324: 1445-1450
12 Zakynthinos SG, Vassilakopoulos T, Daniil Z, et al. Pressure support ventilation in adult respiratory distress syndrome: short-term effects of a servo-controlled mode. J Crit Care 1997;12: 161-172
13 Fabry B, Haberthur C, Zappe D, et al. Breathing pattern and additional work of breathing in spontaneously breathing patients with different ventilatory demands during inspiratory pressure support and automatic tube compensation. Intensive Care Med 1997; 23: 545-552
14 Shikora SA, Benotti PN, Johannigman JA. The oxygen cost of breathing may predict weaning from mechanical ventilation better than the respiratory rate to tidal volume ratio. Arch Surg 1994; 129: 269-274
15 Whitelaw WA, Deenne J-P. Airway occlusion pressure. J Appl Physiol 1993; 74: 1475-1483
16 Whitelaw WA, Derenne J-P, Milic-Emili J. Occlusion pressure as a measure of respiratory center output in conscious man. Respir Physiol 1975; 23: 181-199
17 Foti G, Cereda M, Banfi G et al. End-inspiratory airway occlusion. A method to assess the pressure developed by inspiratory muscles in patients with acute lung injury undergoing pressure support. Am J Respir Crit Care Med 1997; 156: 1210–1216
18 Derenne JPh. P0.1: about the relevance of the 100 milliseconds. Intensive Care Med 1995; 21; 545-546
19 Galbusera C, Palo A, Iotti G, et al. Relationship between P0.1 and inspiratory work of breathing during pressure support ventilation (PSV). Am Rev Respir Dis 1993; 147: A876
20 Iotti G, Braschi A, Galbusera C. - P0.1, breathing pattern and pressure support ventilation. Intensive Care Med 1996; 22: 1131
21 Brenner M, Mukai DS, Russell JE, et al. A new method for measurement of airway occlusion pressure. Chest 1990; 98: 421-427,
22 Kuhlen R, Hausmann S, Pappert D, et al. A new method for the P0.1 measurement using standard respiratory equipment. Intensive Care Med 1995; 21: 554-560
23 Fernandez R, Benito S, Sanchis J, et al. Inspiratory effort and occlusion pressure in triggered mechanical ventilation. Intensive Care Med 1988; 14: 650-653
24 Galbusera C, Olivei M, Hanneman U, et al. Evaluation of a method for continuous P0.1 measurement during mechanical ventilation. Am J Respir Crit Care Med 1999; 159: A366
25 Palo A, Olivei M, Iotti G, et al. Prima realizzazione della misura continua della P0.1 in ventilazione artificiale. Validazione ed applicazioni. Acta Anaesth Italica 1992; 43: 382-392
26 Fletcher R. Deadspace, invasive and non-invasive. Br J Anaest 1985; 57: 245-249
27 Wolff G, Brunner JX, Weibel W, et al. Anatomical and series dead space volume: concept and measurement in clinical praxis. Appl Cardiopulm Pathophysiol 1989; 2: 299-307
28 Iotti GA, Brunner JX, Braschi A, et al. Closed-loop control of airway occlusion pressure at 0.1 second (P0.1) applied to pressure-support ventilation: algorithm and application in intubated patients. Crit Care Med 1996; 24: 771-779
29 Iotti GA, Olivei MC, Palo A, et al. Unfavorable mechanical effects of heat and moisture exchangers in ventilated patients. Intensive Care Med 1997; 23: 399-405
30 Fernandez R, Cabrera J, Calaf N, Benito S. P0.1/PIMax: an index for assessing respiratory capacity in acute respiratory failure. Intensive Care Med 1990; 16:175-179
31 Murciano D, Boczkowski J, Lecocguic Y, et al. Tracheal occlusion pressure: a simple index to monitor respiratory muscle fatigue during acute respiratory failure in patients with chronic obstructive pulmonary disease. Ann Intern Med 1988; 108: 800-805
32 Sassoon CS, Mahutte CK. Airway occlusion pressure and breathing pattern as predictors of weaning outcome. Am Rev Respir Dis 1993- 148: 860-866
33 Sassoon CS, Te TT, Mahutte CK, Light RW. Airway occlusion pressure. An important indicator for successful weaning in patients with chronic obstructive pulmonary disease. Am Rev Respir Dis 1987; 135: 107-113
34 Iotti GA, Brunner JX, Braschi A, et al. Closed-loop control of airway occlusion pressure at 0.1 second (P0.1) applied to pressure-support ventilation: algorithm and application in intubated patients. Crit Care Med 1996; 24: 771-779
35 Iotti GA, Olivei MC, Braschi A. Short introduction to the new mode Adaptive Support Ventilation (ASV). Min Anest 65 1999 ;(suppl 1): 719-723
36 Hannemann U, Brauer M, Olivei M, et al. New method for P0.1 evaluation without interruption of inspiratory flow delivery by continuous flow ventilators. Am J Respir Crit Care Med 1998; 157: A850