AUTOMATIC CONTROL OF MECHANICAL VENTILATION. PART 2: THE EXISTING TECHNIQUES AND FUTURE TRENDS

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Tehrani FT. Automatic control of mechanical ventilation. Part 2: The existing techniques and future trends.

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ABSTRACT. Objective. The major automatic techniques that are available in commercial ventilators are described and a discussion of the recently developed systems along with the future trends in the field is provided. **Methods.** The major available automatic control techniques for mechanical ventilation are analyzed and the future trends are discussed in view of today's ICU requirements and the recently developed technologies. **Results.** Several major automatic techniques are available in commercial ventilators at this time. Those techniques have been in use successfully and are accepted by clinicians. At the same time, more advanced techniques have been and continue to be developed by various researchers that are designed for more aggressive use of automation in control of ventilation and oxygenation in different phases of ventilatory treatment. **Conclusions.** Automatic control of mechanical ventilation can significantly improve patient care in the ICUs, reduce the mortality and morbidity rates associated with provision of inappropriate ventilatory treatments, and reduce healthcare costs. Development of more effective and robust systems that can have high noise immunity and provide effective treatment to patients automatically in different phases of treatment will likely gain increasing momentum in the years to come.

KEY WORDS. mechanical ventilation, automation, closed-loop control.

INTRODUCTION

Despite development of many automatic techniques for control of the main outputs of mechanical ventilators, the majority of the commercially available ventilators are still mainly open-loop controlled devices. As was mentioned in part 1 of this article, automation is used in many conventional modes of ventilation as well as a number of more recently developed modalities and techniques such as the volume-assured pressure support mode or the automatic tube compensation method.

In the volume-assured pressure support mode (VAPS), which is available in commercial ventilators (such as Bird 8400STi model), the first portion of the breath is pressure limited. In the 1st phase of the breath the controller determines whether the target tidal volume can be delivered, and if not, inspiration is continued according to peak flow setting to deliver the target volume. Automatic tube compensation (ATC) is a feature offered in many of today's advanced ventilators such as Evita XL and Evita 4 ventilators by Dräger Medical, the Nellcor Puritan Bennett 840 model, and the Avea ventilator by Viasys Healthcare, Inc. By using ATC, the ventilator compensates for the

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additional work of breathing due to the airway resistance of the endotracheal tube by application of automatic control. In this technique, the machine calculates the pressure drop across the endotracheal tube based on the measured flow and the properties of the tube that need to be provided by the clinician in advance. Some ventilators use this technology to compensate for the pressure drop across the tube during inspiration only, and some others use the technique in both the inspiratory and expiratory phases of respiration. ATC is designed to eliminate the imposed work of breathing due to tubing and facilitate weaning. These and many other techniques are used to improve mechanical ventilation treatment using various automatic control methods. However, as was explained in part 1 of this article, the term “closed-loop control” used here denotes systems in which some or all of the main ventilation targets are computed and controlled by using automatic feedback, and the term “protocol-driven” is used to denote systems that are automatically controlled by use of clinical protocols. With this understanding in mind, there are presently several major automatic modalities that are available in commercial ventilators. Those are pressure regulated volume control (PRVC) which is available in a number of commercial ventilators such as Maquet Servo-i model, SmartCare and proportional pressure support ventilation (PPS) options offered for Evita XL and Evita 4 ventilators by Dräger Medical, proportional assist ventilation (PAV) offered by Puritan Bennett 840 ventilator which is similar to PPS, adaptive support ventilation (ASV) available in ventilators made by Hamilton Medical, and neurally adjusted ventilatory assist mode (NAVA) which is provided by Maquet Servo-i ventilators. The following section will be focused on these ventilation technologies.

AN OVERVIEW OF THE EXISTING AUTOMATIC SYSTEMS

Adaptive support ventilation (ASV)

ASV is a patented closed-loop ventilatory mode marketed by Hamilton Medical. In this technique, tidal volume, V_t , and respiratory rate, f , are adjusted by the ventilator on a breath-by-breath basis. A schematic diagram of this system is shown in Figure 1.

In the ASV mode, the ventilator calculates the required minute ventilation based on the patient's ideal body weight and another input called %MinVol according to the following:

For adults

$$\text{Minute Ventilation} = \text{Ideal body weight} \times \% \text{MinVol} / 1000 \quad (1)$$

For pediatrics

$$\text{Minute Ventilation} = \text{Ideal body weight} \times \% \text{MinVol} / 500 \quad (2)$$

The ideal body weight in kg is used as a measure of the patient's normal ventilatory requirement, and the %MinVol input is adjusted by the clinician based on measured levels of patient's blood CO_2 pressure. The ASV algorithm uses respiratory mechanics data that are measured continuously to adjust f and V_t on a breath-by-breath basis. This automatic adjustment is done to minimize the work rate of breathing. The objective is to provide a natural and comfortable breathing pattern to the patient and thereby stimulate spontaneous breathing and expedite weaning. The ASV algorithm uses the following equation to calculate the optimum rate of breathing:

$$f = \frac{-1 + \sqrt{1 + 4\pi^2 RC_e \frac{(MV - f V_D)}{V_D}}}{1 + 2\pi^2 RC_e} \quad (3)$$

In the above equation, MV is minute ventilation (in l/min), V_D is dead space (in l), RC_e , the expiratory time constant, is the product of respiratory resistance and compliance which is measured by dividing expired tidal volume by the expiratory peak flow, and f is the computed optimal respiratory rate in breaths/min. Having calculated MV and f , the required tidal volume is calculated as MV/f . The algorithm checks the safety of the calculated values by comparing them to determined safe limits and adjusts them if necessary. The pressure applied by the ventilator above the set positive end-expiratory pressure (PEEP) is adjusted based on the measured respiratory dynamic compliance of the patient to deliver the calculated V_t . This pressure is also adjusted further if necessary to remain in the safe range. In the ASV mode, the expiratory time is prevented from falling too short to avoid build up of intrinsic PEEP. In this mode, mandatory breaths are provided by the machine if there is no spontaneous breathing, and if patient triggers the breaths, the machine provides added pressure support to deliver the required V_t .

The main advantage of ASV is taking into account the changing respiratory mechanics of the patient and customizing the treatment in response to those changes. The mainstay of the ASV algorithm is minimization of the work rate of breathing by using Equation 3 as discussed above. Otis and coworkers proposed a hypothesis in physiology in 1950 that respiratory frequency in mammals is optimized to minimize the breathing work rate [1]. This hypothesis which was not related to mechanical ventilation was contested by many and confirmed by some other physiologists for decades. Until in 1991, a new system for

Fig. 1. A schematic diagram of the ASV system.

automatic control of mechanical ventilation was introduced whose features included the use of a modified version of an equation by Otis et al. (Equation 3 above) to determine the optimal rate of mechanical ventilation [2, 3]. This was done to provide a natural breathing pattern to the patient, reduce the work load of breathing on the patient's respiratory muscles, stimulate spontaneous breaths, and help reduce the fight that develops between the machine and spontaneously breathing patients. ASV is based on one of the more simple embodiments of the patent introduced in 1991 [2], and has been licensed under that patent.

The shortcomings of ASV are that minute ventilation is not continuously adjusted by the machine, and PEEP and the fraction of inspired oxygen, F_{IO_2} , are not controlled automatically. Furthermore, although the system is designed to encourage natural breathing, it does not provide any automatic push for weaning if desired.

Neurally adjusted ventilatory assist (NAVA)

The principles of this new mode of ventilation were introduced several decades ago [4]. That early technique has been modified, enhanced and patented in recent years, and adapted in Maquet Servo-i ventilators [5, 6]. This system called NAVA is fundamentally different from other closed-loop or protocol-driven modalities in the sense that the closed-loop controller in this system is a part of the patient's brain. In this system, the electrical signals controlling respiration that are transmitted from the brain to the diaphragm through the phrenic nerves are used to drive the ventilator. The electrical activation signal to the diaphragm (Edi) is monitored by using electrodes mounted close to the distal tip of a nasogastric tube positioned in the lower esophagus at the level of diaphragm. The Edi signal is passed through filters to eliminate noise due to motion artifact, the ECG signals, and other sources. This signal is processed, amplified, and applied to the ventilator. The ventilator's output signal

which controls the level of ventilatory support is proportional to the Edi signal. In other words, the ventilator acts as an amplifier of the Edi signal where the amplification gain called NAVA level is manually and periodically adjusted by titration. If the noise is effectively removed from the Edi signal, the beginning and the end of every breath are controlled by the Edi signal, which results in synchrony between the patient's respiration and the ventilator. This synchronization is a significant advantage of NAVA. However, the NAVA level that adjusts ventilatory support is manually controlled. In this system, the ventilator either partially or fully replaces the respiratory muscles, and therefore, the long term effects of the system need to be investigated. NAVA can be used in patients with intact phrenic nerve drive and cannot be used if sedatives and neural depressants are given to the patient.

Pressure regulated volume control (PRVC)

PRVC is a ventilatory mode that has been available for many years. In this mode, the inspiratory pressure above PEEP is automatically adjusted by the machine to deliver a set tidal volume on a breath-by-breath basis. In PRVC, the peak inspiratory pressure above PEEP is calculated as V_t/C_{dyn} where C_{dyn} is the patient's respiratory dynamic compliance. This calculated pressure is checked and kept below a maximum safe value. The advantage of this mode is that the target volume is delivered by using the minimum inspiratory pressure and high airway pressures are prevented. The target V_t and respiratory rate are preset but the breathing rate is controlled by the patient if he/she triggers the breaths. This mode is available in many ventilators including the Maquet Servo-i model.

Proportional pressure support ventilation (PPS)

PPS is a ventilatory mode that is available in Evita 4 and Evita XL ventilators by Drager Medical. This system is

based on a patented technique known as proportional assist ventilation or PAV [7, 8]. This PAV mode is also available in Puritan Bennett 840 ventilators. It is a closed-loop weaning technique in which the pressure support applied by the ventilator is a function of the patient's spontaneous effort.

In this technique, the pressure applied to the patient's airway by the machine is given by:

$$P = K_1 V + K_2 V' \quad (4)$$

where V is the volume of gas inhaled by the patient, V' is the rate of gas flow to the patient, and K_1 and K_2 are parameters set by the clinician, which determine the elastic and resistive components of pressure support respectively. For this system to successfully assist patient's ventilation and weaning, K_1 and K_2 must be set as fractions of the elastance and resistance of the patient's respiratory system respectively. Otherwise, the system gets into a runaway situation. This system can best be analyzed as a zero input, non-relaxed state feedback system and not as a positive feedback system as assumed by others. Figure 2 shows a schematic block diagram of the system.

Since the initial airway pressure in the PAV system is generated by the patient effort and is not provided externally by the machine, it can be regarded as an initial state of the system which should be non-zero if the system should work. In other words, viewed as an engineering system, it should not be initially relaxed. Then the state variables of the system that are volume of the gas intake and the resulting flow of gas are used as feedback inputs to the PAV algorithm that in turn calculates the required level of pressure support. The following analysis shows how this system can provide a stable level of assistance to the patient.

Considering only the elastic component of pressure, if the volume of initial gas intake by the patient is V , and his or her respiratory elastance factor is K , then the elastic component of pressure initially developed by the patient is

KV . The ventilator generates an additional elastic pressure of $K_1 V$ in response. Therefore, the total elastic pressure applied to the patient airway rises to $V(K + K_1)$. This amount of pressure increases the volume of the patient's gas intake to a total of $V(K + K_1)/K$. This volume is then multiplied by the elastance factor of the PAV system, K_1 , to produce the total amount of elastic pressure support in the next step as:

$$P_{aw} = K_1 \left[\frac{V(K + K_1)}{K} \right] = K_1 V + K_1^2 \frac{V}{K} \quad (5)$$

If this iterative analysis is continued, it can be seen that the total elastic component of pressure added by the ventilator shown from one step of the iteration to the next will be:

$$K_1 V \rightarrow K_1 \left[\frac{V(K + K_1)}{K} \right] \rightarrow K_1 \left[\frac{KV + \frac{V(K + K_1)}{K} K_1}{K} \right] \rightarrow \dots \quad (6)$$

which can be rewritten as:

$$K_1 V \rightarrow K_1 V + \frac{K_1^2 V}{K} \rightarrow K_1 V + \frac{K_1^2 V}{K} + \frac{K_1^3 V}{K^2} \rightarrow \dots \quad (7)$$

Therefore, as the number of iterations, n , tends to increase, the total pressure applied to the patient's airway by the ventilator will be:

$$P_{aw} = K_1 V + \frac{K_1^2 V}{K} + \dots + \frac{K_1^n V}{K^{n-1}} \quad (8)$$

which can be rewritten as:

$$P_{aw} = K_1 V \left[1 + \frac{K_1}{K} + \dots + \left(\frac{K_1}{K} \right)^{n-1} \right] \quad (9)$$

If $K_1/K = \alpha$, and n tends to become large:

$$P_{aw} = K_1 V [1 + \alpha + \alpha^2 + \alpha^3 + \dots + \alpha^{n-1} + \dots] \quad (10)$$

As can be seen, there is a geometric series inside the brackets in Equation 10. This series is convergent only if $\alpha < 1$. In that case:

$$P_{aw} = \frac{K_1 V}{1 - \alpha} \quad (11)$$

For example, if $\alpha = 0.5$ (meaning that K_1 is half of the value of K), then:

$$P_{aw} = 2K_1 V \quad (12)$$

As can be seen, only if K_1 is less than K (i.e. $\alpha < 1$), then the series inside the brackets in Equation 10 above converges. In that case, the system is stable, and the total

Fig. 2. A schematic diagram of the PPS (or PAV) system.

elastic pressure provided by the ventilator will be a finite value proportional to the initial volume of gas intake of the patient. A similar analysis can be done on the resistive component of the airway pressure which yields a similar conclusion.

The above analysis shows how the PAV system works. It is clear that this state feedback system can only produce stable results if the elastic and resistive parameters of the system (i.e. K_1 and K_2) are chosen as fractions of the elastance and resistance of the patient's respiratory system. Therefore, these parameters need to be correctly measured in spontaneously breathing patients.

The PPS (or PAV) weaning system is designed for and helpful to patients whose spontaneous breathing efforts are reasonably strong. There is no guarantee for delivery of any mandatory minute volume in this system. Inappropriate use of this system may lead to serious consequences if the patient's spontaneous breathing activity weakens with time, and in case of development of shallow rapid breathing or ventilatory leaks.

SmartCare

In early 1990s several protocol-driven techniques for automatic control of weaning from mechanical ventilation which had considerable similarities were introduced [9–11]. SmartCare marketed by Drager Medical is based on one of those techniques [10]. The schematic diagram of this system is shown in Figure 3. As seen in this figure, this protocol-driven system that is designed for use in the pressure support mode (PS), takes three patient inputs: (i) the end-tidal pressure of carbon dioxide (P_{etCO_2}) (ii) tidal volume (V_t) (iii) respiratory rate (f).

The principal function of this system is to keep these three variables within a defined “comfort zone” and

reduce pressure support level periodically to wean the patient if his/her conditions remain acceptable. For respiratory rate to be acceptable, it should be between 12 and 28 breaths/min, tidal volume should be above 250 ml (or 300 ml if patient's weight is above 50 kg), and P_{etCO_2} should be below 55 mmHg (or 65 mmHg in patients with chronic CO_2 retention). When respiratory rate is between 28 and 35 breaths/min, but P_{etCO_2} and V_t are acceptable, pressure support level is increased by 2 cm H_2O . If respiratory rate goes above 35 breaths/min, pressure support is increased by 4 cm H_2O . If respiratory rate is below 12 breaths/min, pressure support is reduced by 4 cm H_2O . If V_t becomes too low or P_{etCO_2} increases, pressure support is raised by 2 cm H_2O . The system also takes into account the duration of time in which patient's conditions have remained acceptable in adjusting the pressure support level. Meaning that if the patient has been in the comfort zone longer, the system reduces pressure support level more aggressively during weaning. Occurrence of apnea causes the system to revert to assist/control mode.

In this protocol-driven system, the pressure support level is adjusted incrementally based on clinical rules and guidelines. However, although the guidelines are somewhat adjusted for different patient groups, they are fixed for individual patients within those groups and do not change as patient's conditions vary. Since the rules are fixed and the applicable mode is pressure support, provision of adequate ventilation cannot be guaranteed. In other words, increasing the level of pressure support when all breaths are patient triggered may not result in provision of adequate ventilation to the patient if his/her spontaneous effort weakens or in the presence of worsening obstruction of the airways.

DISCUSSION

The fact that several major automatic control techniques have been accepted and used by clinicians indicates the significance of automation in this field and the likely trends in the industry in the future.

Table 1 shows a summary comparison of the automatic techniques described above.

As discussed, PRVC is a closed-loop mode in which the pressure applied by the ventilator is automatically adjusted based on the patient's measured respiratory compliance. Other main respiratory parameters such as V_t , f , F_{IO_2} and PEEP are manually set by the clinician. PRVC is available, also in combination with other modes, in many commercial ventilators.

ASV, marketed by Hamilton Medical, is a closed-loop technique with a calculated minute volume target. It

Fig. 3. A schematic diagram of the SmartCare system.

Table 1. Comparison of the features of the major available automatic ventilatory modes

Name of the ventilation mode	Advantages/Main features	Disadvantages/Remarks
Adaptive support ventilation (ASV)	Patented closed-loop feedback technique. Automatically adjusts tidal volume and respiratory rate based on a calculated minute ventilation and measured respiratory mechanics to minimize the work rate of breathing. Can be used for full and assist ventilatory control. Provides pressure controlled ventilation to deliver a target tidal volume	Does not push for weaning. Minute ventilation is not adjusted continuously. PEEP and F_{IO_2} are manually controlled
Neurally adjusted ventilatory assist (NAVA)	Patented technique that uses the neural output of the patient's own closed-loop respiratory system. It can provide the patient with a comfortable pattern of breathing and synchronize the ventilator with the patient's respiratory system	Effective removal of the noise from the Edi signal due to various sources such as the ECG and motion artifact is essential. The NAVA level that controls the level of ventilation support needs to be periodically adjusted manually. PEEP and F_{IO_2} are manually controlled. The system cannot be used for all patients. While on this mode, sedatives given to the patient affect ventilatory treatment
Pressure regulated volume control (PRVC)	The peak inspiratory pressure above PEEP is automatically adjusted based on measured dynamic compliance of the patient's respiratory system. Minimum pressure is applied by the ventilator to deliver a set tidal volume	The peak inspiratory pressure is the only ventilatory parameter controlled automatically. Ventilation, f , PEEP and F_{IO_2} are manually adjusted
Proportional pressure support ventilation (PPS), (PAV)	Patented closed-loop state feedback system. Automatically adjusts the level of pressure support in the PS mode. Is designed to provide comfort to patient in weaning	Does not provide any guaranteed minimum ventilation. PEEP and F_{IO_2} are manually controlled. Can be used if patient's spontaneous effort is reasonably strong. Should be watched for ventilatory leaks
SmartCare	A protocol-driven automatic system for control of weaning in the PS mode. Automatically and incrementally adjusts the pressure support level based on measurement of respiratory rate, tidal volume, and P_{etCO_2} . If measured values are in the specified "comfort zone," it pushes for weaning by incrementally reducing the pressure support level	Uses fixed rules. The changes in respiratory mechanics do not affect the acceptable ranges of respiratory rate and tidal volume. Does not guarantee delivery of minimum ventilation. PEEP and F_{IO_2} are manually controlled

adjusts f and V_t continuously to minimize the respiratory work rate. In the absence of spontaneous breaths, it provides full ventilatory support using pressure control to the patient at a computed rate to deliver a computed tidal volume. If the patient triggers a breath, ASV augments the breath if necessary using pressure support to deliver the required V_t . Therefore, regardless of existence of spontaneous breaths, ASV is designed to deliver a certain volume of breathing gas to the patient using a respiration pattern close to the patient's own natural breathing pattern. In the ASV mode, although weaning can begin with the help of the machine but the ventilator does not provide automatic push for weaning when patient conditions

become favorable. The minute ventilation is not continuously adjusted and PEEP and F_{IO_2} are manually controlled.

SmartCare marketed by Drager Medical is an automatic protocol-driven technique for weaning patients in the PS mode. It is designed to adjust the level of pressure support provided by the ventilator automatically in order to keep the patient in a comfort zone. This system requires continuous measurement of P_{etCO_2} , V_b , and f . Despite its advantages, the rules used in this technique are fixed for different patient populations and do not change as the individual characteristics of patients vary. Changing respiratory mechanics do not affect the acceptable ranges

of f and V_t and there is no guarantee of delivery of any minimum minute ventilation to the patient if his/her spontaneous effort weakens over time and/or the patient's airway obstruction increases.

The PPS mode also marketed by Drager Medical, which is similar to the PAV mode offered by Puritan Bennett 840 ventilator, is a closed-loop weaning method for use in the PS mode. It is not a positive feedback system as assumed by some researchers. It is rather a zero-input, state feedback controlled system from an engineering standpoint, and that is why it does produce stable results under prescribed conditions as described above. The PPS system is designed to follow patient's breathing pattern and respond proportionately to the patient's effort. Proper application of this system requires correct measurement of volume, flow, and respiratory resistance and elastance in spontaneously breathing patients. The system is designed for patients who have reasonably strong spontaneous breathing activity. PPS does not have any mandatory minute volume built into it. Although it has apnea back up, it should be watched to make sure that the patient's spontaneous breathing is not weakened over time, and ventilatory leaks are not developed during treatment.

NAVA is a new system available in Maquet Servo-i ventilators. In this mode, the electrical signal that is originated in the patient's brain and transmitted through the phrenic nerves to the diaphragm, Edi, is detected by electrodes attached to a tube positioned in the esophagus. This signal is processed and applied to the ventilator. The main advantage of this system is the synchronization that results between the patient's respiratory system and the ventilator if the electrical noise mixed with the Edi signal is effectively removed. The gain of the ventilator called NAVA level which is multiplied by the Edi signal to control the level of ventilatory support needs to be manually and periodically adjusted. This system is not suitable for patients whose phrenic nerve activities have been affected by disease or surgical operations, and patients under sedation or central depressants. The long term effects of the use of this system have not been determined at this time.

When used properly, all the systems described above offer advantages to both patients and clinicians compared to more conventional modes of ventilation as described in the preceding sections. Despite their differences in design and function, they all require accurate monitoring of certain patient parameters/inputs and incorporate artifact detection techniques. With the development of more reliable physiological monitors and sensors, it is likely that more aggressive automatic modalities will be used in clinical settings in the future. Such systems would require more advanced and elaborate techniques for data validation and abstraction.

Many systems have been developed for automatic control of oxygenation and additional outputs of ventilators [12–24] as discussed in part 1 of this article. At present, while some techniques for closed-loop control of F_{IO_2} are under clinical investigations for the purpose of future commercialization, still several important outputs of mechanical ventilators including F_{IO_2} are not automatically controlled by any commercial ventilator. In two more recent systems that both incorporate the ASV features in addition to many added automatic features, closed-loop techniques are used to automatically control a wide range of ventilatory parameters such as f , V_t , minute ventilation, PEEP, and F_{IO_2} [23, 24]. One of these systems is particularly designed to control weaning when the patient's conditions are favorable [24]. In addition to the systems that employ protocol-driven techniques or classical closed-loop control methods, several other systems have been introduced that employ fuzzy control techniques to control different aspects of ventilation [25, 26]; a concept which does not seem to have been sufficiently explored to this date, and may be used more extensively in the future. The systems that are developed to use the patient's neural respiratory drive [5, 6] may be used more aggressively in the future, particularly with respect to breathing synchronization, and may need further automation enhancement with regard to provision of ventilatory support.

CONCLUSION

In today's ICU settings, the amount of data accumulated for any patient is quite large. ICU clinicians have to make important decisions for ventilatory treatments of their mechanically ventilated patients; decisions that need to be made by carefully reviewing the patients' underlying illnesses, the large amounts of clinical data, and by reviewing the features of the advanced ICU ventilators. Automatic monitoring of patient data has become possible through development of more advanced physiological monitors and the reliabilities and capabilities of such monitors are increasing with time.

Significant automatic modes for mechanical ventilation have been developed and are available in response to clinical demands as discussed above. These systems will likely need to be enhanced and the techniques employed need to be made more responsive to patients' changing requirements in future. If done safely and effectively, more advanced automation of mechanical ventilation will have the potential of considerably reducing the work load of ICU clinicians and improve the quality of care for patients. Consequently, such techniques will have the potential to reduce the mortality and morbidity rates

associated with inappropriate manual settings of ventilatory parameters and could significantly reduce the healthcare costs and the duration of the ICU stay in the years to come.

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