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METHODOLOGICAL REVIEW

Intelligent decision support systems for mechanical ventilation

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Summary

Objective: An overview of different methodologies used in various intelligent decision support systems (IDSSs) for mechanical ventilation is provided. The applications of the techniques are compared in view of today's intensive care unit (ICU) requirements.
Methods: Information available in the literature is utilized to provide a methodological review of different systems.
Results: Comparisons are made of different systems developed for specific ventilation modes as well as those intended for use in wider applications. The inputs and the optimized parameters of different systems are discussed and rule-based systems are compared to model-based techniques. The knowledge-based systems used for closed-loop control of weaning from mechanical ventilation are also described. Finally, in view of increasing trend towards automation of mechanical ventilation, the potential utility of intelligent advisory systems for this purpose is discussed.
Conclusions: IDSSs for mechanical ventilation can be quite helpful to clinicians in today's ICU settings. To be useful, such systems should be designed to be effective, safe, and easy to use at patient's bedside. In particular, these systems must be capable of noise removal, artifact detection and effective validation of data. Systems that can also be adapted for closed-loop control/weaning of patients at the discretion of the clinician, may have a higher potential for use in the future.

Contents

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1. Introduction

Processing large volumes of patient data in the intensive care units (ICUs) of hospitals can be quite time consuming in an environment where timely decisions by the clinicians often make the difference between life and death. One of the ICUs' main tools, mechanical ventilation (an intervention for treating respiratory failure in critically ill patients), requires such processing of large volumes of data for effective therapeutic decisions. Computerized decision support systems can be useful in mechanical ventilation and other ICU interventions to help in the processing of this data and in making decisions based on those data to improve clinical outcomes.

In the past few decades, a number of intelligent decision support systems (IDSSs) for mechanical ventilation have been developed. One of the main factors giving rise to such developments has been the emergence of advanced mechanical ventilators. While these advanced machines have many added features and offer different outputs to respond to patients' needs, they have mostly remained open-loop controlled devices. Thus, the clinician is faced with various options to choose from. An IDSS would be a practical tool to help the clinician integrate the available data and make the right choice for the patient. Despite the apparent need for these systems and development of many technologies to address this need, IDSSs have not been commonly used in mechanical ventilation with the exception of a few that have been developed and implemented as closed-loop control systems (which, alone, do not qualify as advisory systems).

A number of reasons can be conceived for the infrequent use of these systems, such as (a) lack of accessibility, (b) no immunity to noise and erroneous data, (c) inadequate training for use of the systems, and (d) lack of implementation in commercial ventilators. Despite their infrequent use, many of these systems have been developed over the past few decades by a number of different research groups. Some of these systems have been evaluated by large multi-center groups, but have not yet been generally accessible for evaluation. The vast majority of these systems have not been implemented in commercial ventilators, and training for their use has been available to the personnel of the research groups only. However, considering the complexity of today's advanced ventilators, effective IDSSs would likely serve as handy tools for clinicians in the treatment and management of the ICU patients, the same clinicians who need to understand the underlying illnesses of patients, make important ventilatory treatment decisions, and set the complex ventilators to deliver such treatments in a timely manner.

In this article, the methodologies that are used in various IDSSs are discussed, an overview of available systems is provided, and a critical comparison of the techniques and their applications in relevant ICU settings is given. The systems discussed in this article span from 1985 to present. The literature on this subject has been searched and reviewed in order to acquire the details of the systems and their methodologies.

As will be discussed later in this article, IDSSs may also be used to expedite mechanical ventilator weaning, and that can have important impacts on both quality of patient care and the cost of mechanical ventilation treatment. Weaning from the ventilator, especially for patients who have had prolonged ventilation and are considered as "hard to wean," has always been a challenging task for the medical personnel [1—5]. Evidence suggests that timely extubation (removal of the endotracheal tube) with termination of mechanical ventilation significantly improves the treatment outcome and reduces the mortality and morbidity rates associated with prolonged mechanical ventilation, while reducing the high costs of mechanical ventilation and the ICU stay. At the same time, care must be taken not to proceed with weaning prematurely, since re-intubation (re-insertion of the endotracheal tube) and re-institution of mechanical ventilation after weaning can have detrimental consequences for patients. Many IDSSs are designed to address the problems associated with weaning patients from the mechanical ventilator.

Among the systems developed to date to assist in weaning, some are designed to automatically control the ventilator in a closed-loop mode. Although the closed-loop systems developed specifically for weaning patients are described in this article and a few commercially available closed-loop techniques are briefly discussed, the focus of this review is on decision support systems and not on closed-loop techniques for mechanical ventilation. A comprehensive review of closed-loop technologies developed to date for mechanical ventilation would require a much more detailed analysis of a wide range of techniques that is not within the scope of this article.

2. Overview of different design methodologies

IDSSs for mechanical ventilation can be designed to work with automatic sensors and a monitor system providing the input data directly and automatically to the system or without using such a monitor if the required input data is entered manually by the physician. Fig. 1 depicts the arrangement in which a sensor and monitor system can be used to provide the required data.

In this arrangement, the patient's input data and the settings on the ventilator as well as the respiratory parameters measured by the ventilator are monitored automatically, and provided to an intelligent system either continuously or at fixed and/or variable intervals. The clinician is able to observe the data, retrieve it, and query the system to receive advice on how to proceed with treatment and adjust the outputs of the ventilator. Alternatively, patient data and ventilatory parameters can be manually input into the system via the computer keyboard; in that case, automatic monitoring of data is not needed. If automatic monitoring of data is used, another alternative is to control the ventilator directly and automatically by the IDSS rather than by the physician. The broken lines labeled as "feedback control" in Fig. 1, represent the path through which the ventilator may be controlled by the system. In that case, the ventilator is said to be closed-loop controlled.

2.1. Basic structures and types of IDSSs

Fig. 2 shows a schematic block diagram of what a modern IDSS consists of. The input data, whether entered manually by the clinician or automatically supplied by a Sensors and Data Monitor unit, needs to be analyzed and validated at the beginning to remove noise and discard artifacts. The input data further undergoes smoothing processes before being supplied to the Information Processing and Control unit which in turn determines the next treatment option and the settings of the ventilator. The outputs of the unit are provided to the Output Generator which produces outputs for display to the clinician and/or to the ventilator. A Graphical Display unit accumulates patient data over time and an alarm unit is needed to alert the clinician of any error in the input data or any untoward condition detected in the patient. Within the main categories

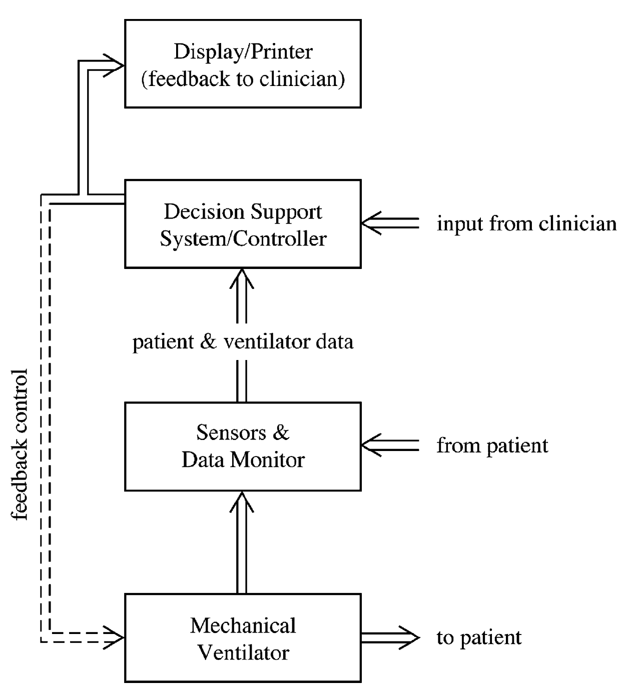

Figure 1 Block diagram depiction of an IDSS for mechanical ventilation. The broken lines labeled as "feedback control" represent the automatic supply of control signals to the ventilator in case the system is used to control the ventilator in a closed-loop manner.

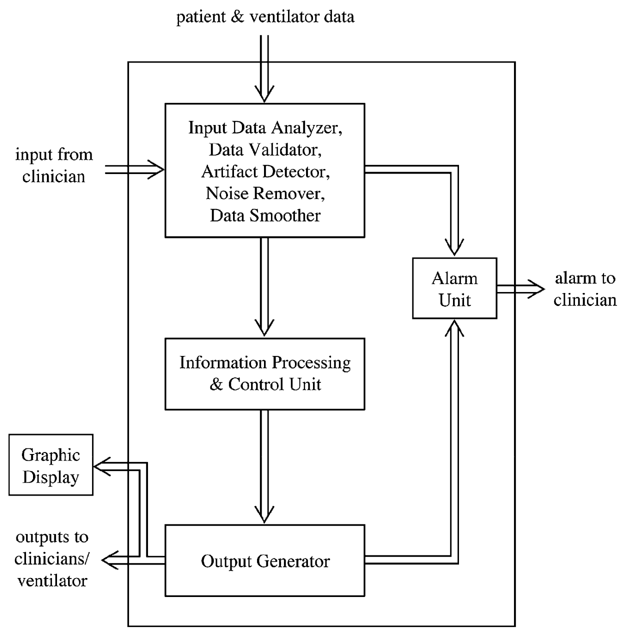

Figure 2 A schematic block diagram of an IDSS/controller for mechanical ventilation.

of IDSSs, there are various techniques used for data validation and analysis. The required input parameters of systems and their validation techniques are quite different depending on the structure and type of the system as will be discussed in the next section.

The basic structure of the Information Processing and Control unit of an IDSS can belong to any of the three basic categories: (a) rule-based, (b) model-based, and (c) rule-based combined with model-based. The majority of systems are rule-based, meaning that the system determines the optimal treatments for patients based on clinical and experimental guidelines and protocols. In contrast, model-based techniques are available in which the treatment methods are optimized by simulating a physiological model of the patient. Finally, there are also systems in which the rules used to determine the optimal treatment are based on a combination of the patient's physiological model as well as clinical guidelines.

IDSSs are also designed differently to optimize various parameters. Some are used to regulate patients' blood gases, some are designed to expedite the weaning procedure, and still others regulate patient parameters and reduce weaning time simultaneously.

There are also wide variations in the ventilatory modes and types of patients that different systems are designed for. Some are developed for treatment of specific respiratory profiles such as the acute respiratory distress syndrome (ARDS), and for optimal settings of a selected number of respiratory parameters. Others are designed for weaning patients in the synchronized intermittent mandatory ventilation (SIMV) and/or pressure support (PS) modes. Still others are designed for optimal setting of wider selections of respiratory parameters for various groups of patients in differing ventilatory modes.

Table 1 shows various categories of IDSSs. The first column of the table shows the main distinct characteristic of each category while the rows show the available options within that category.

2.2. The required inputs of IDSSs

In general, the input data for IDSSs falls into the following categories:

Table 1 Main categories of different IDSSs for mechanical ventilation

Key characteristics	Available alternatives		
Basis structure	Rule-based	Model-based	Rule-based + model-based
Applicable ventilation modes	Pressure support (PS)	SIMV or IMV + PS	Multiple modes
Patient types	Adults	Neonates	ARDS patients
Optimized parameters	Blood gases	Weaning time	Blood gases and weaning time
Type of technology	Open-loop (advisory)	Closed-loop (automatic)	Open-loop + closed-loop

- The patient's blood gas information either measured directly using arterial blood gas analysis (ABG), or measured by using indirect techniques such as pulse oximetry and end-tidal carbon dioxide monitoring, and the rate of change of such data.
- The respiratory mechanics data and the rate of change of such data.
- Set ventilatory parameters such as tidal volume, minute ventilation, respiratory rate, positive end-expiratory pressure (PEEP), the inspiratory-to-expiratory time ratio (I:E), inspiration time, pause time, fraction of inspired oxygen (F_{IO_2}), and peak inspiratory pressure.
- Measured ventilatory parameters such as minute ventilation, tidal volume, total respiratory rate, spontaneous respiratory rate, PEEP, the peak inspiratory pressure, and the rate of change of such data.
- Set alarm levels on the ventilator such as maximum allowed volume and pressure limits.
- Cardiovascular and hemodynamic parameters of the patient such as heart rate, stroke volume, cardiac output, systolic and diastolic blood pressures.
- Patient's medical problems and parameters such as body temperature, height, weight, and ideal body weight.
- Additional patient parameters related to any physiological model used.

The required input data depends on the basic structure of the system, the mode of ventilation, and the type of respiratory patients that the system is designed for. A number of the existing systems use data validation and smoothing techniques to exclude artifacts and some incorporate temporal abstraction techniques to select, validate and process the input data. The ability to remove noise, detect measurement artifacts, and validate the input data is a necessary requirement of any system for use in today's ICU settings. With the large amount of data accumulated for any ICU patient, it is practically impossible to prevent erroneous data entry to the system. In order to stop the propagation of such errors, validation algorithms need to be incorporated into the system. In addition, data abstraction and smoothing techniques are needed to prevent abrupt changes in the treatments offered. These features become even more important if the input data is provided by sensors and monitors to the system automatically.

3. Overview of IDSSs

Table 2 shows a listing of IDSSs developed to date along with their main features and applications. In order to provide an objective comparison, an overview of the characteristics of the systems is provided in this section.

The earlier IDSSs for ventilatory therapy were developed in 1980s. These systems were rule-based, open-loop advisory systems that were designed with fixed rules based on clinical guidelines. The first system, called Ventilation Manager (VM), used input data describing patient diagnosis, blood gas values, and hemodynamic parameters [6]. VM was used to wean postoperative patients. Another system, VQ-ATTENDING [7] took similar inputs but was designed to critique the physician's settings rather than provide treatment options. This system was implemented in LISP. Another rule-based advisory system was introduced in 1986 [8] which was designed to treat neonates with respiratory distress syndrome (RDS). The system made recommendations on whether to increase or decrease F_{IO_2}, PEEP, I:E, respiratory rate, and peak inspiratory pressure, on the basis of set clinical guidelines.

In the late eighties, a rule-based closed-loop system was developed to automatically adjust the length of mandatory breaths in the intermittent mandatory ventilation (IMV) mode by measuring the pressure in the patient's endotracheal tube and determining the strength of patient's spontaneous breaths based on that measurement [9]. A prototype of this system was designed as a closed-loop controller in the IMV mode for weaning the patients automatically from the ventilator. The system's software was written in 6502 assembly programming language. ESTER was another rule-based system developed in 1989 [10] that was designed as a weaning management system in the IMV mode. It was implemented using the LISP version of GENIE and ran on an IBM computer. The input data was provided by a respiratory support system as well as manually by the physician via the computer keyboard. ESTER was evaluated by treating both postoperative and ventilator dependent patients.

Around the same time another system, the computerized patient advice system (COMPAS), was introduced and was evaluated using several patients suffering from ARDS [11]. This was a rule-based system that used expert treatment protocols in five ventilatory modes. These modes were assist/control (AC), continuous positive airway pressure (CPAP), pressure-controlled-inverted ratio ventilation (PC-IRV), IMV, and low frequency positive pressure ventilation with extracorporeal carbon dioxide removal ($ECCO_2R$). COMPAS used a blackboard data base structure and a computerized clinical information system called HELP, which provided patient data to the system; data that was input by respiratory

Table 2 A list of IDSSs for mechanical ventilation

System's name and date	Developers	Basic structure	Applicable type of ventilation	Types of patients studied
VM (1985)	Fagan et al. [6]	Rule-based	Open-loop, modes not specified	Postoperative patients
VQ-ATTENDING (1985)	Miller [7]	Rule-based	Open-loop, modes not specified	Not specified
Not specified (1986)	Carlo et al. [8]	Rule-based	Open-loop, volume control	Neonates, RDS patients
Not specified (1988)	Hernandez et al. [9]	Rule-based	Closed-loop, IMV, weaning	Not specified
ESTER (1989)	Hernandez et al. [10]	Rule-based	Open-loop, IMV, weaning	Postoperative & ventilator dependent
COMPAS (1989)	Sittig et al. [11]	Rule-based	Open-loop, multiple modes	ARDS
KUSIVAR (1989)	Rudowski et al. [12]	Rule-based + statistical models	Open-Loop, modes not specified	Not specified
WEANPRO (1991)	Tong [13]	Rule-based	Open-loop, weaning	Cardiovascular, postoperative
Not specified (1991)	Arroe [14]	Rule-based	Open-loop, volume control	Neonates, RDS patients
Not specified (1991)	Strickland and Hassan [15]	Rule-based	Closed-loop, SIMV + PS, weaning	Postoperative patients
GANESH (1992)	Dojat et al. [16—20]	Rule-based	Closed-loop, PS, weaning	Patients with different medical problems
Not specified (1992)	Henderson et al. [21]	Rule-based	Open-loop, multiple modes	ARDS patients
VentPlan (1993)	Rutledge et al. [22]	Model-based	Open-loop, modes not specified	Not specified
Not specified (1993)	Strickland and Hassan [23]	Rule-based	Closed-loop, SIMV + PS, weaning	Patients with different medical problems
VentEx (1995)	Shahsavar et al. [24]	Rule-based	Open-loop, modes not specified	Patients with different medical problems
VIE-VENT (1996)	Miksch et al. [25]	Rule-based with temporal data abstraction	Open-loop, multiple modes	Neonates
Not specified (1999)	Nemoto et al. [27]	Rule-based fuzzy system	Closed-loop (design), PS, weaning	COPD patients
Not specified (2001)	McKinley et al. [28]	Rule-based	Open-loop, modes not specified	ARDS
ANFIS (2003)	Kwok et al. [29]	Rule-based, neuro-fuzzy system	Open-loop (F_{IO_2} adjustment only)	Patient simulation
Not specified (2006)	Rees et al. [30]	Model-based	Open-loop, modes not specified	Not specified
FLEX (2007)	Tehrani [31,32]	Rule based + model-based	Open-loop + closed-loop (design), multiple modes and PS, weaning	Patients with different medical problems

therapists, nurses, and other medical personnel. The recommendations of this system were provided to obtain and maintain acceptable blood gas values for patients. According to the reported results, the system recommendations were in agreement with those of the clinicians most of the time. One of the problems encountered in using this system was propagation of errors caused by erroneous data entry in the system which in turn caused a series of inappropriate treatment suggestions by the system.

The concept of another expert system called KUSIVAR was presented in 1989 [12]. This was a data driven system that used statistical models of different patient groups to predict patient responses to different ventilator settings. A prototype of the knowledge-based system was implemented by using the knowledge engineering environment (KEE) from Intellicorp which ran on an Explorer LISP-based workstation by UNISYS. The details of the statistical models used by the system were not provided and the results of evaluation of the prototype were not reported.

Another rule-based system called WEANPRO was introduced in 1991 [13]. This system was designed to help wean postoperative patients in the ICU. This knowledge-based system was developed by gathering advice from four domain experts amounting to 406 rules and ran on IBM compatible microcomputers. The input data, which included the blood gas values, the spontaneous respiratory rate and tidal volume, and the patients' hemodynamic parameters, were entered by the physician. WEANPRO then recommended new ventilatory settings based on the new and previous input data. According to the reported results, the number of blood gas measurements was reduced compared to the control group for the patients who were successfully weaned by using the system.

At the same time, a computerized expert system was presented for treatment of premature neonates [14]. The algorithm for this system was written in Turbo-Basic and designed to be used with a Siemens Servo 900A ventilator in the volume control mode. The system was rule-based and the rules were determined from clinical studies of respiratory insufficiencies in neonates. The inputs to the system included blood gas results and ventilator settings as well as the proposed changes in the settings by the physician. Using the inputs and the last six values of blood gases, the system recommended changes in the ventilatory settings, not as numerical values, but as a qualitative direction for those changes.

In 1991, a system designed for closed-loop control of the ventilator in weaning was introduced [15]. A laptop computer was interfaced with the ventilator and a pulse oximeter. The ventilation mode used was SIMV with pressure support. The computer system checked the patient's oxygen saturation, respiratory rate, and minute ventilation every 5 min. If all data was found to be in the satisfactory ranges, the system decreased the SIMV rate in increments of 2 breaths/min. When the SIMV rate reached 2 breaths/min, the system then started lowering the level of pressure support in increments of 4 cm H_2O every 5 min until the patient did not need any further ventilatory support. If any of the input data fell outside the satisfactory range in this process, the computer would return the patient's settings to the previous weaning level of support. The system was evaluated using nine postoperative patients following cardiac surgeries and all of them were successfully weaned.

In 1992 another knowledge-based system for mechanical ventilation was introduced [16]. This was a technique for closed-loop weaning of ventilated patients on PS mode. This system, called GANESH, was rule-based and used three input data: (a) respiratory rate, (b) tidal volume, and (c) the end-tidal partial pressure of carbon dioxide. The first two data were provided by the ventilator which was a Veolar Ventilator by Hamilton, and the end-tidal CO_2 partial pressure was measured and provided to a PC-based system by an end-tidal CO_2 analyzer. The system checked the input data periodically and if they were found to be in the specified "comfort zone," the patient was considered weanable and the level of pressure support provided by the ventilator was gradually reduced. The system was tested using 19 patients, of which 10 could be successfully weaned. Additional clinical evaluations of this technique were subsequently published in later years [17—20].

In another article in 1992, the performance of a different computerized decision support system for management of respiratory patients was discussed [21]. A computerized clinical information system, HELP, was used to provide patient data to the system which was used in multiple ventilatory modes including continuous positive pressure ventilation (CPPV), CPAP, PCIRV, and $ECCO_2R$. This rule-based system was used for management of the arterial oxygen saturation in ARDS patients.

Another ventilation management advisor, called VentPlan, was introduced in 1993 [22]. VentPlan calculated settings for F_{IO_2}, PEEP, tidal volume, and respiratory rate of the ventilator. Information regarding the patient's diagnosis was provided to a "belief network" which in turn calculated probability distributions for unmeasured patient parameters. Measured patient parameters, such as blood gas pressures, along with the probability distributions of unmeasured patient parameters generated by the "belief network" were combined to estimate the physiological parameters of a patient model by an empirical estimator. The estimated parameters were input into a patient model which simulated the effects of possible ventilatory settings, and a plan evaluator produced the highest ranked recommended settings based on the simulation results. VentPlan was based on physiological models rather than clinical rules. No results have been reported to show the effect of using this system in the care of ICU patients.

In 1993, a report of further clinical evaluations of a closed-loop system for weaning that was first introduced in 1991 [15] was published [23]. The system in this report was somewhat modified compared with the earlier version in the sense that it checked tidal volume instead of minute ventilation. Furthermore, although arterial oxygen saturation of the patient was still monitored, it was not used to control weaning. This new version of the system was evaluated using a group of 9 patients with complex medical problems. When, according to the physician's judgment, a patient was ready to be weaned, he/she was placed on the closed-loop system with the ventilator set in SIMV mode with pressure support. If the measured tidal volume and respiratory rate were found to be within acceptable ranges, the closed-loop system decreased the SIMV rate by 2 breaths/min every hour until an SIMV rate of 2 breaths/min was reached. Then the system reduced the pressure support level by 2 cm H_2O every hour if the total rate and tidal volume remained acceptable until the pressure support level was down to 5 cm H_2O, at which point blood gases were drawn and weaning was considered complete. This closed-loop system reportedly was able to wean 7 out of 9 patients successfully within the given time. None of the patients in the computer-controlled group had any adverse effect as a result of the treatment. Furthermore, according to the reported results, the closed-loop system required a lesser number of blood gas measurements, and it was more successful in weaning patients as compared to a control group.

The evaluation report of another knowledge-based decision support system called VentEx was presented in 1995 [24]. This rule-based technique took data such as patient age, weight, diagnosis, blood pressure, heart rate, blood gas pressures, and ventilatory settings (when applicable) to determine (a) whether ventilation needed to be started and the recommended mode of ventilation, (b) what changes in the settings of minute ventilation, respiratory rate, PEEP, and F_{IO_2} had to be made in the management phase of ventilation, and (c) whether the patient was ready to be weaned. Evaluation of this system was carried out by comparing the computer recommendations with those provided by physicians in different phases.

Another rule-based IDSS for ventilatory treatment of newborn infants was presented in 1996 [25]. This system called VIE-VENT used temporal data abstraction techniques [26] for data validation and interpretation and therapy planning. In the temporal abstraction process, the data points (e.g. arterial blood gases), the interval of data, and the expected qualitative trends of data were incorporated. This system was designed for use in the intermittent positive pressure ventilation (IPPV), IMV, and CPAP modes. No data was reported to show the efficacy of the system in the care of ICU patients.

In 1999, another rule-based system was introduced for weaning patients in the PS mode by using fuzzy logic [27]. This system created fuzzy sets using four inputs; heart rate, tidal volume, respiratory rate, and arterial oxygen saturation, to determine the pressure provided by the ventilator. The system considered the values of the input parameters as well as their rate of change to make its determination. This system was designed for the purpose of closed-loop control of weaning, but evaluations were done by retrospective comparison of system's recommendations with the physicians' orders.

The evaluation results of another computerized decision support system for treatment and weaning of ARDS patients were published in 2001 [28]. This rule-based system used information on the patient's blood gas pressures and allowed permissive hypercapnia to avoid barotrauma. Tidal volume was set based on patient's ideal body weight and adjustments were made to PEEP and F_{IO_2} for control of patient's oxygenation. If F_{IO_2} was less than or equal to 0.5 (50%), PEEP was sufficiently low, the blood pH was higher than an acceptable minimum, tidal volume was sufficiently large, and the respiratory frequency was lower than a predefined acceptable rate, then CPAP weaning trials were performed. The patient was considered as "weaned" if he/she tolerated 2 h of CPAP = 5 cm H_2O, and respiratory rate and blood pH remained acceptable.

ANFIS was the name of a rule-based system for control of F_{IO_2} that was introduced in 2003 [29]. In this system, the inputs were arterial partial pressure of oxygen, F_{IO_2}, and PEEP, and the output was a new value for F_{IO_2} setting. An adaptive neuro-fuzzy interface was used in the rule-based derivation of the output. The evaluations of the technique were done by simulations.

In 2006, an IDSS that was based on physiological models was presented [30]. Mathematical models of oxygen and carbon dioxide transport and a simplified model of lung mechanics were combined with penalty functions describing side effects of mechanical ventilation. The system used blood gas measurements and the physiological models to produce unmeasured model parameters and then used those parameters to simulate the effects of changing ventilatory settings on patient's blood gases. The system could be used to simulate the effects of some ventilatory settings such as F_{IO_2}, but the effects of changing PEEP and the I:E could not be simulated. The ventilatory parameters were input directly from the ventilator while the blood gas information was entered manually. The program software was written in JAVA. No evaluation results were reported for the system.

FLEX is the latest IDSS that was introduced in 2007—2008 [31,32]. This system uses knowledge-based as well as model-based rules to determine optimal settings of the ventilator. Application of this method does not require simulations of the physiological models of oxygen and carbon dioxide transport and consequently, many model parameters that would have otherwise been needed are not required. However, many of its rules are adaptive and derived based on physiological models and hypotheses. The system utilizes the ventilatory settings and measured ventilatory data which can be provided directly from the ventilator. The required patient data are airway resistance, ideal body weight, arterial oxygen saturation and body temperature. Other optional patient input data are dynamic compliance and either the arterial partial pressure of CO_2 measured by blood gas analysis or the end-tidal P_{CO_2} measured by using a gas analyzer. The monitored patient data can be input directly to the system or keyed in manually, depending on how the data is obtained. The system incorporates data validation and smoothing techniques and determines the new optimal settings of the ventilator to regulate blood gases and improve oxygenation, minimize the work rate of breathing, and expedite weaning. It can be used in volume control/assist or pressure control/assist modes as well as PS mode for weaning. This system is designed for use both as an advisory open-loop system and a closed-loop system for controlling the ventilator. The results of the study of the advisory version of the system have showed good agreement between the system's recommendations and clinical determinations, and the closed-loop version of the system has been implemented in an initial set up. A primary difference between this system and other rule-based technologies is that many of its rules are derived for individual patients and therefore, the same rules are not applied to all patients. The algorithm is written in Visual Basic and runs on a PC compatible system. FLEX is undergoing further evaluations at the present time.

4. Summary evaluation of IDSSs

Over the past few decades many IDSSs have been developed for mechanical ventilation. Most of the systems developed to date are rule-based while a few are based on patients' physiological models [22,30] and one derives many of its rules based on physiological models [31,32]. It is important to note that although model-based systems can be informative to the clinicians, those that require a large number of patient parameters as inputs, do not offer a feasible solution to patient's treatment at bedside and, thus, would not likely be used for that purpose. Table 3 provides a summary evaluation of the systems discussed in this article in view of today's clinical requirements.

Among different methodologies used in the design of various IDSSs, the potential utility of fuzzy logic in the analysis of physiological parameters and therapy determination was investigated in some systems [27,29]. However, this notion does not seem to have been explored sufficiently and deserves further evaluation in future research.

One area of development which needs to be strengthened is in the treatment of premature infants with mechanical ventilation. Nowadays, neonatal respiratory care is one of the most important and growing areas of respiratory treatment, due, in part, to the increasing survival rate of premature infants. Despite this, most of the systems developed to date are for adult patients only. A need for more reliable systems for neonatal treatment exists, and will likely be increasingly explored by researchers in this field.

It can be seen from Tables 2 and 3 that while most of the systems developed to date are open-loop advisory systems, some are designed for closed-loop control of weaning from the ventilator in the SIMV, PS and/or other modes of ventilation [9,15,16,23, 27,32]. This feature is of particular interest in view of the evolving technology of mechanical ventilation which seems to be towards more aggressive use of closed-loop control methods and automation. Validation and smoothing of the input data to prevent propagation of errors and incorrect or abrupt changes in the ventilator's outputs have also been of great concern and significance in the application of IDSSs, and in particular, in the utility of the systems that can be used for closed-loop control of weaning. Methods such as artifact detection techniques, graphical presentation of patient data and temporal data abstraction techniques have been employed in a number of systems to tackle the said problems. These methods may need further emphasis and expansion in the application of closed-loop weaning systems.

An important aspect of this research area is the relationship to automation of mechanical ventilation and its impact on commercially available ventilation modes. The concept of closed-loop control in mechanical ventilation is not new and has been in use in many forms and modalities for many years, particularly, in many assist control technologies that

Table 3 Summary evaluation of IDSSs for mechanical ventilation

Systems	Strengths/main features	Weaknesses/remarks
VM [6], VQ-ATTENDING [7], ESTER [10], COMPAS [11], KUSIVAR [12], WEANPRO [13], VentEx [24], VIE-VENT [25], ANFIS [29] and [8,14,21,28]	All are open-loop, rule-based systems. Some report use of data validation and abstraction techniques which are VM [6], and VIE-VENT [25]; one uses statistical models to anticipate patient response to treatment that is KUSIVAR [12]; three are designed for treatment of infants that are [8,14], and VIE-VENT [25]; one uses a neuro-fuzzy system that is ANFIS [29]	Use fixed rules. They cannot be used for closed-loop weaning; two are applicable to a single ventilatory mode that are ESTER [10], and [14]; one is used to adjust F_{IO_2} only that is ANFIS [29]; three are used to treat RDS patients only that are [8], COMPAS [11], and [14]; three do not report any clinical assessment results that are KUSIVAR [12], VIE-VENT [25], and ANFIS [29].
[9]	Rule-based, closed-loop system for weaning	Uses fixed rules, is restricted to IMV mode, lacks clinical assessments
[15], [23]	Rule-based, can be used for closed-loop weaning	Use fixed rules, are restricted to SIMV + PS mode
GANESH [16—20]	Rule-based, can be used for closed-loop weaning, uses data abstraction techniques	Uses fixed rules, is restricted to PS mode
VentPlan [22], [30]	Model-based open-loop systems, use physiological models of oxygen and carbon dioxide transport, can be informative to the clinician if used	Need many patient parameters, cannot be used for closed-loop weaning, lack clinical assessments
[27]	Rule-based fuzzy system, can be used for closed-loop weaning	Can be used for COPD patients only, is restricted to PS mode
FLEX [31,32]	Rule-based + model-based, does not need many patient parameters, can be used as an open-loop or closed-loop system for weaning, uses data validation and abstraction techniques, can be used for adults, pediatrics, and infants	Needs more extensive clinical assessments

Systems have been identified by their names and cited reference numbers, and are separated by commas. If a system has no specific name, only the cited reference number is listed.

are based on provision of mandatory minute volume [33]. However, three ventilation technologies stand out as more aggressive applications of closed-loop control in today's mechanical ventilation therapy. Those commercially available systems are two manufactured by Drager Medical, SmartCare and Proportional Pressure Support (PPS), and one by Hamilton Medical, Adaptive Support Ventilation (ASV).

SmartCare [34] utilizes a system for closed-loop weaning of respiratory patients in the PS mode first introduced in 1992 [16], which was briefly described in the preceding section.

Proportional pressure support or PPS is based on a patented method for closed-loop ventilation support of spontaneously breathing patients known as proportional assist ventilation (PAV) [35,36]. This technique is fundamentally a closed-loop weaning method and has no application as an open loop advisory system. In this technique, the rate and volume of gas flow from a ventilator to patient are measured continuously and the ventilator provides the applied pressure according to the equation $P = K_1V + K_2V^0$. In this equation, P is pressure supplied by the machine, V is the volume of gas, V^0 is the rate of gas flow, and K_1 and K_2 are parameters that determine the elastic and resistive components of pressure respectively. These parameters need to be chosen as fractions of the elastance and resistance of patient's respiratory system in order for the ventilator to be successful in assisting the patient and not to get into a run-away situation. This system is not based on provision of any mandatory minute volume and is only suitable for patients with some reasonable spontaneous breathing ability. Its inappropriate use may lead to serious consequences if the patient's effort is weakened over time, in case of rapid shallow breathing, apnea, or development of ventilatory leaks.

Adaptive support ventilation or ASV marketed by Hamilton Medical is a closed-loop ventilatory system in which target tidal volume and respiratory rate are continuously and automatically adjusted within safe limits, based on patient's changing requirements. In this technique, the respiratory mechanics data are continuously monitored and used to minimize the work rate of breathing. By using this system which is designed to stimulate natural spontaneous breaths during all phases of ventilation, every breath is synchronized with patient's spontaneous effort, and if there is no spontaneous breathing, the ventilator provides full ventilation to the patient. ASV is a patented technology licensed under US Patent 4,986,268 [37,38]. Since its development, more features have been added to the system for closed-loop control of additional ventilator's outputs [39,40]. However, those additional features have not been implemented in commercial ventilators to date.

A newly developed computerized decision support system for mechanical ventilation called FLEX [31,32], provides the main features of the ASV mode in addition to many other features to enhance the utility of the system in weaning as well as control of patient's oxygenation by adjusting PEEP and F_{IO_2}. FLEX is designed for use as an advisory system as well as a closed-loop control system for management and weaning of ventilated patients as discussed above.

The above-mentioned commercialized closed-loop technologies, ASV, SmartCare, and PPS have proven to be successful and are commonly used in clinical practice. This shows the utility and the potential impact of progressive research in this field which leads to provision of more effective and life-saving treatments to patients under critical care worldwide.

5. Concluding remarks

An important area of technology which is shaping the future of critical care is the ongoing rapid development of more reliable physiological sensors and monitors. The possibilities for closed-loop control of ventilation whose safety and effectiveness are intertwined and dependent on the reliability of physiological sensors are on the rise and it seems that the trend of ventilation is towards more aggressive automation. No doubt, intelligent, well designed, user friendly decision support systems may be quite helpful in improving the quality of respiratory care as well as reducing the high cost of such treatment. If a system is effective, safe, and easy to use, it can be helpful to reduce the work-load of medical personnel in the ICUs and can lead to better treatment decisions adopted for critically ill patients. Nonetheless, based on the increasing trend towards automation, one may also conclude that, in addition to processing data and providing recommendations, IDSSs can be adapted for certain ventilation modes for closed-loop control of weaning or management of patients. Thus, it is likely that IDSSs will be found to be of more use to clinicians in the years to come.

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