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Computerized Decision Support Systems for Mechanical Ventilation

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1. Introduction

In the USA alone, there are between 44,000 and 98,000 injuries resulting from medical errors each year (Kohn et al., 2000). The financial costs associated with serious injuries and mortalities resulting from medical errors are between 17 and 29 billion USD per year in the USA alone (Kohn et al., 2000) while the human costs of such incidents cannot be measured in financial terms. Expecting too much from clinicians results in inevitable rises in medical errors. This is particularly true in chaotic environments such as the hospital ICU settings where large amounts of medical data needs to be processed in a relatively short time and medical decisions can often make the difference between life and death.

Computerized decision support and knowledge-based expert systems can be used as helpful tools to clinicians in healthcare in general, and to the ICU intensivists in particular. There can be no doubt that a clinician provided with an efficient decision support system is better equipped to make complex medical decisions in time than a physician who does not have access to such resources.

Among various treatments used in the ICU settings, mechanical ventilation is an essential technology to treat many different illnesses and is relatively costly. Without this treatment most major surgical operations could not be performed and many respiratory illnesses could not be treated successfully. This life saving treatment costs about 1500 USD per day in the ICU settings and it has been reported that the average hospital cost for an ICU patient on mechanical ventilation is more than twice the average cost for an ICU patient not requiring this treatment (Dasta et al., 2005). It has further been reported that about two thirds of hospital costs for treatment of patients on mechanical ventilation are spent on about one third of patients who receive this treatment for an extended period of time of more than 96 hours amounting to about 16 billion USD annually in the USA alone (Zilberberg et al., 2008).

These data demonstrate the fact that the high cost of mechanical ventilation is bound to increase significantly if patients are not provided with proper treatment, and as a result, the duration of the treatment is unduly increased. This analysis is beside the point that when mechanical ventilation is prolonged due to non-optimal or inappropriate treatment, many medical complications such as ventilator associated pneumonia may result, which can significantly increase the mortality and morbidity rates of patients on this medical treatment. Effective decision support systems for mechanical ventilation can improve the

treatment and expedite weaning from the ventilator and thereby significantly and positively impact both the quality and the cost of healthcare for patients who need this kind of treatment.
This chapter provides an overview of different methodologies employed in the design of computerized decision support systems for mechanical ventilation. These will include model-based technologies, rule-based methods, some combinations of the two techniques, as well as some major variations that are applied within the two distinct methodologies. The chapter further provides a brief overview of various decision support systems that have been presented to date for mechanical ventilation and a brief discussion of future trends in this technology.

2. An overview of different methodologies used in decision support systems for mechanical ventilation

Intelligent decision support systems (IDSSs) for mechanical ventilation can be designed as expert advisory systems or can also be used for automatic control of ventilation or weaning (Tehrani & Roum, Nov. 2008). These systems are designed to take patient's ventilatory data, process the data, and determine appropriate treatment options for the patient by using different methodologies. The required input data to these systems can be provided automatically by monitors and sensors, or if the system is an open-loop advisory tool without any capability to control the ventilator automatically, some or all of the input data can be provided manually by the clinician. Figure 1 shows a schematic block diagram of an IDSS for mechanical ventilation.

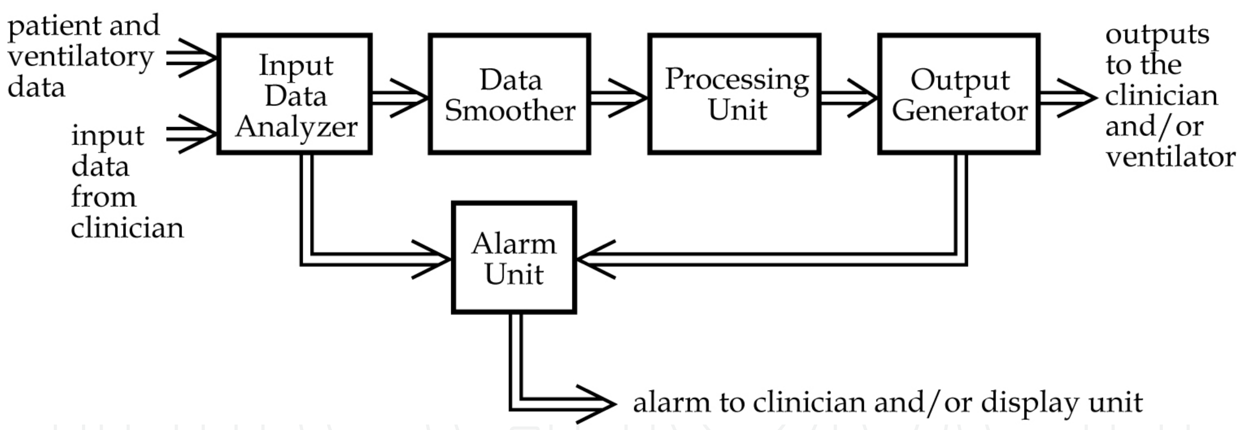

Fig. 1. A schematic diagram of an IDSS for mechanical ventilation.

As shown in this Figure, the input data from the clinician and the patient's physiological and ventilatory data are provided to an Input Data Analyzer that verifies the validity of the input data by comparing it to predefined acceptable ranges. This unit detects artifacts and corrects or discards erroneous data. It can also be used to remove noise from the ventilatory signals. The validated data is then transferred to a Data Smoother unit which is designed to prevent abrupt or inappropriate changes in the ventilatory parameters. The outputs of this unit are provided to a Processing Unit that determines the optimal treatment options for the patient. The outputs of this unit are communicated to the clinician by using a graphical display unit and if the system is designed to control the ventilator automatically, these outputs are applied to the ventilation system. In this process, if any of the patient's

measured data or the computed parameters of the system fall outside predefined safe ranges, alarms are activated and communicated to the clinician by using an Alarm Unit.
The methods used by the Processing Unit differ greatly among various IDSSs and are based on the types of the inputs, the patient groups that the system is designed for, whether the system is based on established treatment protocols, physiological models, or a combination thereof, and also whether the system is an advisory tool or is for automatic control of the ventilator as well. An overview of various methodologies that are employed in the IDSSs for mechanical ventilation will be followed next.

2.1 An overview of different information processing and control techniques used in IDSSs for mechanical ventilation

An IDSS for mechanical ventilation receives various patient and ventilatory input data and processes that information by using many various techniques to determine the treatment options for the patient. A number of IDSSs developed to date use initial data validation and smoothing techniques to detect artifacts, validate the input data, and prepare data for further processing. These techniques include temporal abstraction techniques to select and process the input data in some of the more recent technologies.
The inputs required by IDSSs differ greatly based on the type of the system and the patient groups that the system is designed for. These inputs may include the following data types:

1. The patient's medical problems and data such as patient's gender, age, weight, height, ideal body weight, and body temperature
2. The patient's cardiovascular data such as heart rate, stroke volume, cardiac output, systolic and diastolic blood pressures
3. The patient's blood gas information and the rate of change of the data
4. The patient's respiratory mechanics data (e.g. respiratory resistance and compliance) and the rate of change of the data
5. The set and measured ventilatory parameters such as tidal volume, respiratory rate, minute ventilation, peak inspiratory pressure, fraction of inspired oxygen (F_{IO2}), the positive end-expiratory pressure (PEEP), the inspiratory to expiratory time ratio, the rate of change of these data, along with the set alarm levels on the ventilator for maximum and minimum pressure and volume
6. Additional patient parameters for use in a physiological model of the patient's respiratory system if such models are used in the structure of the IDSS

Table 1 shows different main categories of IDSSs for mechanical ventilation. As shown in this table, the structure of these systems can be divided in three basic categories: (a) rule-based, (b) model-based, (c) rule-based combined with model-based.
The systems that are rule-based use established clinical protocols and guidelines to determine the patient's ventilatory parameters. In model-based systems, the treatment options are decided based on simulation of a physiological model of the patient. However, there are some rule-based systems that determine the ventilatory treatment options based on statistical models and those are quite different from IDSSs whose structures are based on the patient's physiological models. Finally, there are systems in which clinical guidelines are used in combination with physiological models and the basic structure of those are referred to as rule-based + model-based in Table 1.
The IDSSs for mechanical ventilation use various mathematical and control procedures to determine and control their outputs. The techniques used in various IDSSs include classic

as well as fuzzy control technologies. Many of these systems can be used in several ventilatory modes while some others are designed to be used in specific ventilation modes such as synchronized intermittent mandatory ventilation (SIMV) or pressure support ventilation (PS). Some systems are for use in the management phase of ventilation while several other systems are for use in the weaning phase of treatment only. Still, there are some IDSSs that can be used in a number of management and weaning modes of the treatment. Depending on their intended phases of ventilation treatments, IDSSs can be used for regulation of patient's blood gases, expediting weaning, or a combination of these factors. Furthermore, in addition to providing advisory guidance to clinicians, several systems can also be used to control the ventilator automatically in one or more ventilatory modes and treatment phases.
These systems also vary in their applications and patient groups that they are designed for. The patient groups served by different IDSSs can be based on patients' illnesses or on their age groups. There are systems that are designed for patients suffering of acute respiratory distress syndrome (ARDS) or chronic obstructive pulmonary disease (COPD) only, while others are to be used for a wider range of disease conditions. Some IDSSs are designed for adult and pediatric patients while several other systems are developed for neonate patients only. Still, there are a few systems that can be used for both adult and neonatal patient populations.

Main characteristics	**Available variations**		
Basic structure	Rule-based	Model-based	Rule-based + Model-based
Applicable ventilation mode	Single mode (e.g., PS)	Multiple modes	
Type of technology	Open-loop (advisory)	Open-loop (advisory) + Closed-loop (automatic)	
Patient group	Adults	Neonates	Adults + Neonates
Disease condition	ARDS	COPD	Various disease conditions

Table 1. Main categories of IDSSs for mechanical ventilation.

2.2 An overview of various IDSSs for mechanical ventilation

Table 2 lists the IDSSs developed to date for mechanical ventilation in a chronological order. The major features of these systems and the patient groups that they are intended for are listed in this table.
The early IDSSs for mechanical ventilation were developed in mid 1980s for adult patients. These systems were rule-based and used clinical guidelines and protocols to determine or critique ventilatory treatment options for patients (Fagan et al., 1985; Miller, 1985). Around the same time, another system was developed for treatment of neonates that was also based on set clinical guidelines (Carlo et al., 1986).
In late 1980s, another rule-based system for closed-loop adjustment of the length of mandatory breaths in the intermittent mandatory ventilation (IMV) mode was introduced

that used the measured pressure in the patient's endotracheal tube to make its determinations (Hernandez et al., 1988). Later, another rule-based system for management of ventilation weaning was presented (Hernandez-Sande et al., 1989).

Around the same time, another computerized system for treatment of adult patients suffering of ARDS was introduced (Sittig et al., 1989). This system used clinical guidelines to treat ARDS patients in several ventilator modes including assist/control (AC), continuous positive airway pressure (CPAP), pressure-controlled-inverted ratio ventilation (PC-IRV), IMV, and positive pressure ventilation with extracorporeal carbon dioxide removal ($ECCO_2R$). This was followed by the introduction of another rule-based system that used statistical models of different patient groups to determine ventilatory settings (Rudowski et al., 1989).

Another rule-based system for weaning patients from mechanical ventilation was presented a few years later (Tong, 1991). At about the same time, another computerized system for ventilatory treatment of premature neonates was introduced (Arroe, 1991). This system was rule-based and was developed for use in the volume control mode of ventilation.

A computerized system for closed-loop control of weaning for adult patients was presented at about the same time (Strickland & Hassan, 1991). This rule-based system used the patient's measured oxygen saturation, respiratory rate, and minute ventilation data to control the rate of ventilation in the SIMV mode. If the rate could be sufficiently reduced while the measured patient data remained acceptable, the system then decreased the pressure support level until the patient was ready for extubation.

Soon afterwards, another rule-based system for closed-loop control of weaning for adult patients was introduced (Dojat et al., 1992). This system used the patient's measured respiratory rate, tidal volume, and the end-tidal pressure of carbon dioxide as inputs, and if these data remained in a predefined "comfort zone," the level of pressure support was automatically and incrementally reduced to wean the patient from the ventilator.

A computerized system for ventilation of adult patients was presented later (Rutledge et al., 1993). This system used a physiological model of the patient rather than clinical rules to determine ventilator parameters. No results were reported to show the performance of this model-based system.

Another computerized system for ventilator treatment of adult patients was presented a few years later (Shahsavar et al., 1995). This system was based on clinical rules and could be used as an expert system in the management and weaning phases of ventilation.

About one year later, another IDSS for ventilation treatment of neonates was presented (Miksch et al., 1996). This system was rule-based and used temporal abstraction techniques to prepare and process the input data. This system used arterial blood gas data, the interval of data, and the qualitative trends of data to process the inputs and determine ventilatory treatments. No results were presented to show the performance of this system.

Several years later, a closed-loop system for weaning patients from mechanical ventilation was introduced which used fuzzy logic control procedures (Nemoto et al., 1999). This rule-based system created fuzzy sets based on patient's measured heart rate, tidal volume, respiratory rate, and arterial oxygen saturation to determine the pressure support level provided by the ventilator during weaning.

Another IDSS that was based on a physiological model of the patient was presented several years later (Rees et al., 2006). A simplified model of respiratory mechanics and mathematical models of oxygen and carbon dioxide transport were used in this system to simulate the effects of changing some of the ventilatory parameters such as F_{IO2} on the patient's blood gases. This system could not simulate the effects of some other ventilatory parameters such as the PEEP level on patient's blood gases.

IDSS	Basic structure	Type of technology	Applicable ventilation modes	Patient group/disease condition
Fagan et al., 1985	Rule-based	Open-loop	Multiple modes	Adults
Miller, 1985	Rule-based	Open-loop	Multiple modes	Adults
Carlo et al., 1986	Rule-based	Open-loop	Volume control	Neonate RDS patients
Hernandez et al., 1988; Hernandez-Sande et al., 1989	Rule-based	Open-loop + Closed-loop	IMV, Weaning	Adults
Sittig et al., 1989	Rule-based	Open-loop	Multiple modes	Adult ARDS patients
Rudowski et al., 1989	Rule-based	Open-loop	Multiple modes	Adults
Tong, 1991	Rule-based	Open-loop	Weaning	Adults
Arroe, 1991	Rule-based	Open-loop	Volume control	Neonate RDS patients
Strickland & Hassan, 1991	Rule-based	Closed-loop	SIMV+PS, Weaning	Adults
Dojat et al., 1992	Rule-based	Closed-loop	PS, Weaning	Adults
Rutledge et al., 1993	Model-based	Open-loop	Multiple modes	Adults
Shahsavar et al., 1995	Rule-based	Open-loop	Multiple modes	Adults
Miksch et al., 1996	Rule-based	Open-loop	Multiple modes	Neonates
Nemoto et al., 1999	Rule-based	Closed-loop	PS, Weaning	Adult COPD patients
Rees et al., 2006	Model-based	Open-loop	Multiple modes	Adults
Tehrani, 2007; Tehrani & Roum, Apr. 2008; Tehrani & Abbasi, 2009	Rule-based + Model-based	Open-loop + Closed-loop	Multiple modes, PS, Weaning	Adults + Neonates
Tehrani, 2009; Tehrani & Abbasi, 2010	Model-based	Open-loop	Multiple modes	Adults + Neonates
Lozano-Zahonero et al., 2011	Rule-based	Open-loop + Closed-loop	Multiple modes	Adult ARDS patients

Table 2. A list of IDSSs for mechanical ventilation and their main features

About a year later, another computerized system for ventilation treatment was introduced (Tehrani, 2007). This system used clinical rules and guidelines, but many of its rules were adaptive and were derived on the basis of physiological models. Application of the system however did not require the simulation of physiological models of oxygen and carbon dioxide transport of the patient. This system incorporated the features of a closed loop ventilation technique known as Adaptive Support Ventilation (ASV) (Tehrani, 1991; Tehrani 2008), but augmented that system by adding many features including control of F_{IO2}, PEEP, and weaning. This system used patient's ventilatory and physiological data to control a wide range of ventilatory parameters including minute ventilation, tidal volume, respiratory rate, the inspiration to expiration time ratio, F_{IO2}, PEEP, and the pressure support level for spontaneously breathing patients. This system could be used as an open-loop advisory tool as well as a closed-loop system for automatic control of the ventilator in various ventilatory modes for both adult and neonate patient groups (Tehrani & Roum, April 2008; Tehrani & Abbasi, 2009).

At about the same time, a model-based IDSS for critiquing mechanical ventilation treatments was introduced (Tehrani, 2009). This system was based on physiological models of the human respiratory system for adults (Fincham & Tehrani, 1983), and neonates (Tehrani, 1993). The purpose of this model-based system was to provide a tool to the clinician to predict the effects of changing ventilatory parameters on the patient's blood gases. The system could simulate the effects of changing a wide range of ventilation parameters including minute ventilation, tidal volume, respiratory rate, F_{IO2}, PEEP, and pressure support level in different modes of ventilation on patient's blood gases. This system could be used for adults as well as neonate patients (Tehrani, 2009; Tehrani & Abbasi, 2010) for critiquing mechanical ventilation treatments. This open-loop advisory system could be used alone or with another computerized expert system. It could be used as a tool to assist the clinician to choose an appropriate ventilation treatment option for patients by predicting the outcomes of different treatment options at bedside.

Around the same time, another rule-based IDSS which employed fuzzy control procedures to adjust the respiratory rate of mechanically ventilated patients was presented (Lozano-Zahonero et al., 2011). In this system which was tested on adult patients suffering of ARDS, the arterial carbon dioxide partial pressure (P_{aCO2}) of the patient was used as the input parameter to the IDSS. Fuzzy rules derived from clinical experts' opinions and guidelines were used to determine the required respiratory rate of the patient based on his measured P_{aCO2} level.

The list of the systems provided in Table 2 represents a wide range of IDSSs for mechanical ventilation treatments. However, this list is not meant to be exhaustive and does not include some similar systems that have been developed to this date.

2.3 Summary comparison of IDSSs for mechanical ventilation

A comparison of the strengths and/or the main features of the systems listed in Table 2 is provided in Table 3. As can be seen, most of IDSSs developed to date for mechanical ventilation are rule-based, one is rule-based, but many of its adaptive rules are derived from physiological models, and several other systems are based on physiological models.

Some IDSSs use artifact rejection/correction techniques, smoothing processes, and data abstraction techniques to validate and smooth the input data. In addition to providing treatment advice to clinicians, several IDSSs can also be used for closed-loop control of ventilation and/or weaning, while others are strictly open-loop knowledge-based advisory systems.

System	Rule-based	Model-based	Adaptive rules	Use of data abstraction techniques	Appl. to multiple vent. modes	Open-loop	Closed-loop	Appl. to var. pat. groups/ dis. cond.
Fagan et al., 1985	√				√	√		√
Miller, 1985	√				√	√		√
Carlo et al., 1986	√					√		
Hernandez et al., 1988; Hernandez-Sande et al., 1989	√					√	√	√
Sittig et al., 1989	√				√	√		
Rudowski et al., 1989	√				√	√		√
Tong, 1991	√					√		√
Arroe, 1991	√					√		
Strickland & Hassan, 1991	√					√	√	√
Dojat et al., 1992	√			√		√	√	√
Rutledge et al., 1993		√	N/A		√	√		√
Shahsavar et al., 1995	√				√	√		√
Miksch et al., 1996	√			√	√	√		
Nemoto et al., 1999	√		√			√	√	
Rees et al., 2006		√	N/A		√	√		√
Tehrani, 2007; Tehrani & Roum, Apr. 2008; Tehrani & Abbasi, 2009	√	√	√	√	√	√	√	√
Tehrani, 2009; Tehrani & Abbasi, 2010		√	N/A		√	√		√
Lozano-Zahonero et al., 2011	√		√		√	√	√	

Table 3. Comparison of the key features of IDSSs for mechanical ventilation.

The number of ventilatory parameters that these systems can control or simulate, the modes of ventilation they can be used for, their control structures, and the patient groups or disease conditions that they can address, are also quite different for various IDSSs as discussed above.

3. Concluding remarks and future trends

In brief, if an IDSS for mechanical ventilation is easy to use and can provide helpful information to the clinician, it can be a useful aide to the intensivist for determining appropriate ventilation treatments for his patients. This is due to the fact that despite the application of a number of automatic control systems for mechanical ventilation (Tehrani, 2008), the majority of advanced ventilators are still open-loop controlled devices in which some or all of the main ventilatory parameters are manually set by an intensivist. Therefore, an expert IDSS can serve as a helpful advisory tool to the clinician to set the patient's ventilatory parameters.

The following features can be important in establishing the reliability and flexibility of an IDSS for mechanical ventilation (the first feature has a higher impact on a system's reliability while the other features mostly affect an IDSS's flexibility):

1. Having sufficient safeguards for data validation and artifact detection and correction
2. Applicability to a wide range of ventilatory modes
3. Capability to determine and/or simulate a wide range of ventilatory parameters
4. Applicability to various patient groups
5. Applicability to various disease conditions

Therefore, if a system has a high level of reliability and can be regarded as reasonably flexible, it can be concluded that it may be more easily and readily used by ICU clinicians.

Also, critiquing systems based on physiological models that can provide additional information to clinicians by predicting different treatment outcomes can provide more insight to clinicians and be helpful to them in choosing more appropriate treatment options for their patients. These systems can be used alone or in combination with other IDSSs to set ventilatory parameters for patients.

At the end, it may be noted that the trend of mechanical ventilation is towards more automation. Therefore, IDSSs that in addition to providing treatment recommendations in an advisory capacity can also be used for automatic control of ventilation or weaning, may be more desirable for use by clinicians and find more applications in the years to come.

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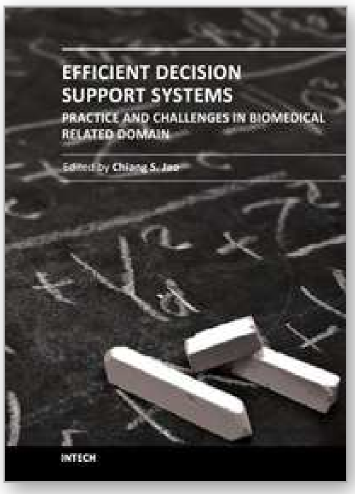

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This series is directed to diverse managerial professionals who are leading the transformation of individual domains by using expert information and domain knowledge to drive decision support systems (DSSs). The series offers a broad range of subjects addressed in specific areas such as health care, business management, banking, agriculture, environmental improvement, natural resource and spatial management, aviation administration, and hybrid applications of information technology aimed to interdisciplinary issues. This book series is composed of three volumes: Volume 1 consists of general concepts and methodology of DSSs; Volume 2 consists of applications of DSSs in the biomedical domain; Volume 3 consists of hybrid applications of DSSs in multidisciplinary domains. The book is shaped decision support strategies in the new infrastructure that assists the readers in full use of the creative technology to manipulate input data and to transform information into useful decisions for decision makers.