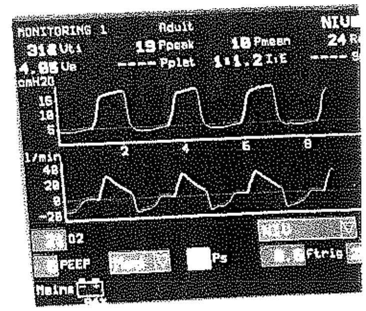
Current Trends in Automated Mechanical Ventilation



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From the iron lung to neurally adaptive pressure control, ventilation has come a long way. What does the future hold?

Fifty years ago, Saxton and Myers[1] described a servomechanism that automatically adjusted end tidal carbon dioxide partial pressure during mechanical ventilation by regulating the negative pressure of an iron lung. Their rationale was quite simple and just as valid today:

> "... proper alveolar ventilation cannot be assured by standardizing pressure settings on respirators because the physical characteristics of the lungs and thorax differ from patient to patient ... ."

Subsequent to the iron lung era, ventilators were developed that more reliably supported the patient's gas exchange needs by connecting directly to the trachea using an artificial airway. As predicted by the equation of motion for the respiratory system,[2] there were only two directions that new ventilator development could take: volume control (preset tidal volume and inspiratory flow) or pressure control (preset inspiratory pressure and inspiratory time). Volume control offers the advantage of maintaining consistent gas exchange in the face of changing respiratory system mechanics, while pressure control offers the advantage of better ventilator-patient synchrony and the ability to limit the risk of overdistention and ventilator-induced lung injury (VILI). Nevertheless, the safety and efficacy of an individual ventilator connected to an individual patient still rely on the appropriateness of a variety of operator-controlled settings. Thus, the forces driving improved ventilator performance are aimed at 1) meeting more of the patient's needs (eg, increased comfort and decreased time on the ventilator) rather than merely supporting gas exchange; 2) doing less harm with the ventilator (improved safety and quality outcomes); and 3) increasing efficiency of health care professionals by decreasing bedside workload associated with patient monitoring and ventilator adjustment.

The Need for Better Ventilators

Physiological Needs. Even if we restricted our discussion to only one disorder, such as acute respiratory distress syndrome (ARDS) and only one ventilator setting (tidal volume), we would still find that ventilator management is a complex issue. We know that small tidal volumes are better for ARDS patients than large ones,[3] but we also know that one-size tidal volume does not fit all patients.[4] And we know the disease is a dynamic process[5] causing changes in respiratory system mechanics that result in the need to continually adjust tidal volume.

Of course, meeting all of the patient's ventilatory needs also requires consideration of ventilator-patient synchrony. Failure to do so allows the possibility of asynchrony, which can decrease patient comfort, delay weaning, and even cause harm.[6] To get an idea of the added complexity of ventilator management when including the need for synchrony, we can categorize various types of asynchrony in terms of the phases of a breath (Table 1). All of these sources of asynchrony provide opportunities for improvement by means of more responsive hardware and more intelligent software.

Quality and Safety Needs. To err is human. In the United States, the number of patients who die from medical errors is equivalent to one airplane crash every day of the year.[7] More people die from medical errors than from highway accidents, breast cancer, or AIDS.[8] The speed of ventilator technology development has outpaced the medical profession's ability to educate staff. One major medical device watchdog organization has reported, "We continue to receive reports of hospital staff misusing ventilators because they're unaware of the device's particular operational considerations."[9] The Joint Commission reports the following on its Web site:[10]

> "As of January 2002, the Joint Commission has reviewed 23 reports of deaths or injuries related to long term ventilation—19 events resulted in death and four in coma. Of the

Table 1. Types of ventilator-patient asynchronies classified by the phases of an assisted breath

1. **Phase I (transition from expiration to inspiration)**
   - Inappropriate trigger sensitivity
     - Too high, resulting in auto-triggering
     - Too low, resulting in missed patient efforts
   - Inappropriate trigger delay (time lag from start of inspiratory effort to start of inspiratory flow delivery from the ventilator)
2. **Phase II (inspiration)**
   - Inappropriate tidal volume
     - Too high, resulting in increased risk of lung damage
     - Too low, resulting in patient double triggering
   - Inappropriate inspiratory time
     - Too long, resulting in patient trying to force expiration
     - Too short, resulting in patient double triggering
   - Inappropriate inspiratory flow during a volume controlled mandatory breath, resulting in shifting of work from ventilator to patient (ie, airway pressure decreases as muscle pressure increases)
   - Inappropriate pressure rise time during pressure control
     - Too short, leading to pressure overshoot and dyspnea
     - Too long, leading to peak flow being too low resulting in dyspnea
   - Inability of patient to exhale during a pressure controlled mandatory breath, resulting in discomfort and possible premature cycling and alarm
   - Increased inspiratory resistance (eg, wet or soiled heat and moisture exchanger, HME), causing increased work of breathing
3. **Phase III (transition from inspiration to expiration)**
   - Inappropriate cycle threshold, resulting in inspiratory time too long or short or failure to cycle
4. **Phase IV (expiration)**
   - Expiratory time too short, resulting in gas trapping, autoPEEP, and missed patient trigger efforts
   - Increased resistance through expiratory circuit (eg, wet bacteria filter or HME), causing gas trapping and missed patient trigger efforts

23 cases, 65 percent were related to the malfunction or misuse of an alarm or an inadequate alarm; 52 percent were related to a tubing disconnect; and 26 percent were related to dislodged airway tube. A small percentage of the cases were related to an incorrect tubing connection or wrong ventilator setting. None of the cases were related to ventilator malfunctions. As the percentages indicate, ventilator-related deaths and injuries are often related to multiple failures that lead to negative outcomes. The majority of the cases occurred in hospital Intensive Care Units (ICUs), followed by long term care facilities and hospital chronic ventilator units."

Results of root cause analysis of the 23 cases reported to The Joint Commission are shown in Table 2. A shocking proportion (87%) of causes involve inadequate training on the part of ventilator operators. If the knowledge cannot be assured at the bedside, then perhaps a solution is to build more automation and intelligence into the ventilator. Indeed, one ventilator manufacturer makes this bold statement in its advertising literature: "Any medical instrumentation that requires constant input from a human operator is obsolete."

Efficiency Needs. In the United States, the majority of the workload associated with mechanical ventilator management falls on the respiratory care profession. However, while the number of jobs for RTs is expected to increase in the foreseeable future, the number of people entering the field has been declining for some time. National trends suggest a growing percentage of unfilled RT posi-

Table 2. Results of Joint Commission root cause analysis of 23 cases

Staffing	
Inadequate orientation/training process	87%
Insufficient staffing levels	35%
Communication breakdown	
Among staff members	70%
With patient/family	9%
Incomplete patient assessment	
Room design limits observation	30%
Delayed or no response to alarm	22%
Monitor change not recognized	13%
Equipment	
Alarm off or set incorrectly	22%
No alarm for certain disconnects	22%
Alarm not audible in all areas	22%
No testing of alarms	13%
Restraint failure (escape)	13%
Distraction (environmental noise)	22%
Cultural (hierarchy/intimidation)	13%

Adapted from The Joint Commission, Preventing ventilator-related deaths.

has recently reviewed the reasons why clinicians resist adopting new practices despite clear evidence for change.[19] These include fear of failure, excessive workload, lack of trust in change recommendations, lack of emotional investment due to noninvolvement in development of change policies, and simple intellectual inertia. Some argue that practice guidelines are "cookbook medicine" that results in treating all patients the same way regardless of the need for individualized care. Others make a much stronger case (in my opinion) for reducing practice variation and uneven patient outcomes by using "adequately explicit" computerized protocols.[20] Mechanical ventilators are an excellent medium for such computerized protocols.

Science Fiction or Future Fact

The real challenge in control of ventilation is defining and measuring the appropriate feedback signals. If we stop to consider all the variables a human operator assesses, the problem looks insurmountable. Not only does a human consider a wide range of individual physiologic variables, but there are also the more abstract evaluations of such things as metabolic, cardiovascular, and psychological states. Add to that the various environmental factors that can affect operator judgment, and we get a truly complex control problem.

What might the future evolution of mechanical ventilators yield? I think the ideal control strategy would have to start out with basic tactical control of the individual breath. Next, the addition of longer-term strategic control would permit adaptation to changing load characteristics. Mathematical models could provide the basic parameters of the mode, while expert rules would place limits to ensure lung protection. Next, sensors would inform the ventilator of relevant physiologic data (eg, end tidal gases, blood gases, Po_1, heart rate, blood pressure, cardiac output, functional residual capacity, etc). Fuzzy logic[21] in the ventilator's computer would then interpret the data to establish the patient's immediate condition. This information is passed on to a neural network that would then select the best response to the patient's condition. The neural network would ideally have access to a huge database comprising both human expert rules and actual patient responses to various ventilatory strategies. This arrangement would allow the ventilator to not only learn from its interaction with the current patient but also learn from and contribute to the database. The database and this ventilator could be networked with other intelligent ventilators to multiply the learning capacity. Finally, in 2055, VentNet becomes self-aware and takes over the world (just kidding). ■

Editor's note
References are available with the online version at www.rtmagazine.com

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