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Steven R Holets RRT and John D Davies MA RRT FAARC

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Movement of the mechanically ventilated patient may be for a routine procedure or medical emergency. The risks of transport seem manageable, but the memory of a respiratory-related catastrophe still gives many practitioners pause. The risk/benefit ratio of transport must be assessed before movement. During transport of the ventilated patients, should we always use a transport ventilator? What is the risk of using manual ventilation? How are PEEP and F_{IO_2} altered? Is there an impact on the ability to trigger during manual ventilation? Is hyperventilation and hypoventilation a common problem? Does hyperventilation or hypoventilation result in complications? Are portable ventilators worth the cost? What about the function of portable ventilators? Can these devices faithfully reproduce ICU ventilator function? The following pro and con discussion will attempt to address many of these issues by reviewing the current evidence on transport ventilation. Key words: portable ventilator; transport ventilator; manual resuscitator; manual ventilation. [Respir Care 2016;61(6):839–853. © 2016 Daedalus Enterprises]

Introduction

The transport of patients within the hospital setting is a common event that exposes patients to risks normally not

encountered in the stationary environment. Transport-related adverse events are common, with reported incidences as high as 68%.¹ Although most adverse events are minor, serious adverse events resulting in physiologic compromise requiring therapeutic intervention do occur, with re-

Mr Holets is affiliated with the Department of Respiratory Care, Mayo Clinic, Rochester, Minnesota. Mr Davies is affiliated with the Department of Respiratory Care, Duke University Medical Center, Durham, North Carolina.

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ported incidences ranging from 4.2 to 8.9%.^{1,2} Established recommendations to minimize the potential for adverse events include careful planning before transport as well as ensuring that the following are available: a monitor with defibrillator; resuscitation equipment and drugs; sufficient supplies of oxygen and batteries; a manual resuscitator with mask; a transport ventilator; and, most importantly, skilled personnel.^{3,4}

Pro: A Portable Ventilator Should Be Used in All In-Hospital Transports

Utilizing a transport ventilator is considered standard practice for ICU patients requiring high levels of ventilatory support.⁵ Manual resuscitators are routinely used during transfers from the operating room or emergency department, when transport duration is expected to be brief, and in patients requiring only partial ventilatory support. This is based mainly on the assumption that manual ventilation is safe and effective. However, as our awareness of the potential for lung injury from exposure to excessive stress and strain during controlled and spontaneous breathing expands,⁶⁻⁹ so has the concern over the potential dangers of manual ventilation. Although routinely used in the controlled environment of the ICU during procedures such as bronchoscopy and suctioning, manual ventilation is fraught with risks and has little place, except in an emergency, during the transport of the intubated patient.

Manual Ventilation Is Neither Safe nor Effective

Most respiratory practitioners would probably say they feel confident in their ability to provide safe manual ventilation. It is, after all, a fundamental skill requirement of resuscitation training and is performed almost daily in the care of the mechanically ventilated patient. Unfortunately, the inability of caregivers to accurately control tidal volumes (V_T) and airway pressures during manual ventilation has been demonstrated in a number of studies, which reveal just how potentially unsafe the technique actually is.

Lee et al¹⁰ undertook a simple study evaluating the tidal volume delivered by 114 individuals trained in basic life support using a 1.6-L manual resuscitator. Participants were instructed to deliver 1-s inspirations at a rate of 10 breaths/min using one-handed compressions, 2-handed compressions, and 2-handed half-compressions. Volumes were measured using a microspirometer connected to an adult endotracheal tube (size not described). Physical char-

acteristics of hand width, height, and grip power were also measured. The results showed that manual ventilation resulted in large variations in delivered tidal volumes (mean $\pm$ SD): one-handed compressions, 592 ± 117 mL; 2-handed compressions, 644 ± 144 mL; and 2-handed half-compressions, 458 ± 121 mL. There was no correlation between hand size or grip power and volume delivered. The authors concluded that their findings support previous studies indicating that manual resuscitators are not suitable devices for accurate ventilation.

A more recent study was undertaken by Turki et al¹¹ to determine the pressures generated during manual ventilation. A lung model simulating 4 different load conditions represented typical clinical scenarios: normal resistance (15 cm H₂O/L/s) and compliance (0.033 L/cm H₂O), high resistance (50 cm H₂O/L/s) and normal compliance (0.033 L/cm H₂O), normal resistance (15 cm H₂O/L/s) and low compliance (0.012 L/cm H₂O), and high resistance (50 cm H₂O/L/s) and low compliance (0.012 L/cm H₂O). Using an adult 1.8-L Hudson manual resuscitator (Hudson RCI, Temecula, California), 9 respiratory therapists were separately described 3 clinical scenarios and asked to manually ventilate the model per their discretion with no knowledge as to the aims of the study. The lung model was covered by a bed sheet, allowing observation of movement, but no pressure or volume displays of the model or recording device were viewable. Results revealed substantial differences between respiratory therapists and between the various loads, with pressures as high as 100 cm H₂O being generated. Male respiratory therapists produced higher peak pressures (91 ± 20 cm H₂O) than female respiratory therapists (56 ± 18 cm H₂O) under the high resistance normal compliance scenario. The authors noted that although high resistance may limit transmission of high pressures to the alveoli, reducing the risk of barotrauma in this group, tidal volumes of 0.3–0.8 L in the high resistance low compliance scenario would expose alveoli to pressures of 26–68 cm H₂O, well above the current recommended safe threshold of 30 cm H₂O. Differences in frequency and tidal volume were not significant between scenarios, leading the authors to conclude that minute ventilation was a perceived goal regardless of the consequential load from manual ventilation.

A study conducted by Godoy et al¹² examined the effects of oxygen flow rate on delivered tidal volumes and inspiratory pressures. Using a single compliance and resistance condition, 7 manual resuscitators were tested with oxygen flows of 1, 5, 10, and 15 L/min while the same person squeezed the device using 2 hands. Wide variations in delivered tidal volumes were observed between resuscitators. Increasing flows from 1 to 15 L/min resulted in a 99 and 48% increase in tidal volumes and a 155 and 105% increase in peak pressures in 2 of the devices. The authors attributed this to the location of the oxygen inlet, which at

Correspondence: Steven R Holets RRT, Mayo Clinic 200 2nd Avenue SW, Rochester, MN 55905. E-mail: holets.steven@mayo.edu.

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flows >5 L/min caused the patient valve to stick and gas to be directed toward the patient during exhalation.

Two studies have looked at the volumes and pressures generated during neonatal ventilation. Bassani et al¹³ examined the effects of technique on ventilation. One hundred seventy-two neonatal ICU care providers (medical doctors, registered nurses, and physiotherapists) were asked to ventilate a test lung set to simulate a 3-kg newborn, compliance 0.003 L/cm H₂O and resistance 200 cm H₂O/L/min using 5 techniques: one-handed using 5, 4, 3, or 2 fingers and 2-handed using 10 fingers in random order. A 300-mL self-inflating bag was used with a pressure-relief valve set at 40 cm H₂O. Acceptable ventilatory parameters were peak inspiratory pressure of 20–25 cm H₂O, tidal volume (V_T) of 24–30 mL, and frequency of 40–60 breaths/min based on what the authors described as standard neonatal ventilation guidelines. Regardless of profession or technique, 155 of 172 (88%) delivered excessive pressures (>25 cm H₂O), 127 (74%) delivered excessive volumes (>30 mL), and 49% delivered insufficient frequency (<40 breaths/min). The authors concluded that regardless of technique, ventilatory target ranges using manual ventilation are not routinely attained.

A study to determine whether an educational intervention would improve target tidal volume delivery under changing compliance conditions was conducted by Bowman et al.¹⁴ An ASL 5000 simulator (Ingmar Medical, Pittsburgh, Pennsylvania) was programmed to mimic a 3-kg infant with compliances randomly varying between low (0.5 mL/cm H₂O), normal (1.1 mL/cm H₂O), and high (1.8 mL/cm H₂O). Twenty-seven neonatal professionals were asked to manually ventilate at a rate of 40–60 while maintaining a V_T of 12–18 mL (4–6 mL/kg) using a flow-inflating bag with a 10-L/min gas source and a 160-mL self-inflating bag. Participants were allowed to practice while viewing the pressure and volume displays on the simulator. Baseline trials were then conducted during which participants were allowed only to view the pressure or the volume display separately as compliance changes occurred. Afterward, one-on-one education and guided practice sessions were conducted, followed by post-intervention trials. Trials were performed approximately 8 months later to evaluate whether skills had been retained. On-target V_T performance improved over baseline but was poor when using the self-inflating bag and only the pressure display, with a baseline mean of 6% (95% CI 3–11%) of breaths on target to 21% (95% CI 15–30%) after intervention ($P < .01$). Using the flow-inflating bag baseline, on-target V_T was achieved in 1% (95% CI 1–4%) of breaths and improved to 7% (95% CI 4–14%) following intervention ($P < .01$). With the use of the volume display baseline, on-target V_T was achieved in 84% (95% CI 82–87%) and 81% (95% CI 73–90%) of breaths after education ($P = .41$). Flow-inflated bag on-target breaths were 68% (95% CI

64–73%) at baseline and 73% (95% CI 67–80%) following intervention ($P = .13$). Retention testing revealed that skills had been lost with no differences between baseline values. The authors concluded that educational training did little to improve the resuscitator's ability to detect and adjust to changes in lung compliance and that the addition of a spirometer improved performance.

Evidence continues to accumulate underscoring the importance of limiting tidal volumes and airway pressures.^{15,16} Protective ventilation strategies incorporating the use of low tidal volumes and limiting airway pressures reduce the risk of ventilator-induced lung injury in all intubated patients at risk of injury and should be adopted as standard of care.¹⁷ The need to transport should not excuse noncompliance to these strategies, and as demonstrated, control of pressures and volumes during manual ventilation is simply not possible even under controlled conditions. The notion that experienced practitioners can safely provide manual ventilation during transport is simply based more on myth than fact.

Physiological Risks Associated With Manual Ventilation

The physiological consequences associated with hyperventilation and hypoventilation are well known.¹⁸ Respiratory alkalosis affects cardiac and cerebral vascular tone. Cardiac vasoconstriction may lead to coronary artery spasm, myocardial ischemia, arrhythmias, and tachycardia.¹⁹ Alkalosis induces cerebral vasoconstriction, decreasing cerebral blood flow by 40–50%.²⁰ Although used therapeutically in stroke victims to decrease intracranial pressure, inadvertently lowering CO₂ levels to <25 mm Hg may cause tetany and lead to further ischemic damage.²¹ Alkalosis should be avoided in patients with or at risk of ischemic injury because it causes a left shift of the oxyhemoglobin curve, reducing oxygen delivery to the tissues.

The physiological effects of hypoxia have been studied extensively.²² During transport, hypoxia-related adverse events have been associated with inadequate oxygen reserves, atelectasis, and patient agitation.⁴ Needless to say, oxygenation must be closely monitored during transport, and equipment must be used that can deliver high oxygen concentrations and adequate amounts of PEEP when clinically indicated.

The deleterious effects of hyperoxia on newborns are well recognized.²³ Exposure to high oxygen concentrations has also been shown to be detrimental in various adult patient populations.^{24,25} Cardiovascular responses to hyperoxemia include: reduced stroke volume and cardiac output, increased peripheral vascular resistance, and coronary artery vasoconstriction.²⁶ Oxygen toxicity from exposure to high levels of oxygen worsens lung function.²⁴ Decreased mucociliary transport, inflammation, pulmonary

edema, and fibrosis have all been attributed to hyperoxia. There is mounting evidence that oxidative stress from free radicals may exacerbate lung injury in patients already suffering from respiratory failure and that precise control of F_{IO_2} targeting adequate tissue oxygenation may be a better therapeutic strategy than the current focus on simply achieving high systemic saturations.^{27,28} Unnecessary exposure to high oxygen concentrations is unavoidable with manual resuscitation devices, which are specifically designed to deliver oxygen concentrations approaching 100%.

Real-life transport of the critically ill ventilated patient often requires navigation through a maze of hallways, elevators, and obstacles. Although the main responsibility of the respiratory therapist accompanying the patient is to maintain the airway and ensure that the patient is being properly ventilated, the respiratory therapist also assists with overseeing the monitoring of vital signs, recognizing alarms, and troubleshooting equipment problems, all while helping to maneuver a fully loaded transport cart that easily exceeds several hundred pounds. In this demanding environment, effectively compressing a manual resuscitator while maintaining a constant vigil on delivered volumes and pressures is unrealistic, and it is of little wonder that studies of manual ventilation during transport have revealed that patients experience significant changes in pH and P_{aCO_2} , resulting in potentially life-threatening adverse events.

One of the earliest studies of manual ventilation during transport was conducted by Braman et al²⁹ in 1987. They evaluated blood gases in 20 subjects being transported from a medical ICU with the use of a manual resuscitation bag. Results revealed that 14 of 20 (70%), experienced hypo- or hyperventilation, defined as a change in P_{aCO_2} of >10 mm Hg and pH >0.05 . P_{aCO_2} ranged from -18 to $+28$ mm Hg, and pH ranged from -0.17 to $+0.18$. Six subjects developed hypotension and arrhythmias. Evaluation of arterial blood gases (ABGs) in a subsequent group of 16 subjects transported using a home ventilator modified for transport found no significant change in P_{aCO_2} .

Gervais et al³⁰ compared the ABGs of 30 subjects during transport. Subjects were divided into 3 groups and were ventilated either manually with or without a spirometer to monitor exhaled volume or by a transport ventilator set to the same minute ventilation as was used in the ICU. Blood gases were drawn before the transport while on the critical care ventilator and upon completion. It was revealed that manual ventilation without monitoring resulted in significant decreases in P_{aCO_2} , from 41 ± 2 to 34 ± 2 mm Hg ($P < .05$), and a corresponding rise in pH over baseline. Their conclusions were that adequate blood gas variables can be achieved during transport, provided that minute ventilation is controlled, and that the addition of a spirometer to monitor tidal volumes is recommended during manual ventilation.

Hurst et al³¹ randomized 28 subjects to receive manual ventilation provided by a skilled respiratory therapist or via a transport ventilator with settings matching the ventilator used in the emergency department. Subjects were ventilated with one method to their procedural destination and crossed over to the other upon their return. Baseline heart rate, blood pressure, and ABG values obtained in the emergency department were compared with those taken upon reaching the initial destination and upon return to the emergency department or final location. Heart rate, blood pressure, and oxygenation were stable throughout the transport, regardless of the method of ventilation. During manual ventilation, hyperventilation resulted in significant increases in pH, from 7.39 ± 0.03 to 7.51 ± 0.2 , and a decrease in P_{aCO_2} from 39 ± 4 to 30 ± 3 mm Hg ($P < .05$). Two subjects in this group experienced supraventricular tachycardia, which the authors noted may be precipitated by respiratory alkalosis. Interestingly, transport times averaged only 9 ± 3 min, illuminating the fact that hyperventilation may occur even during relatively brief transport periods. The authors concluded that the use of a transport ventilator is preferred to manual ventilation during transport.

The use of capnography has been recommended for intubated patients during transport.³² Its use while manually ventilating during transport has also been shown to facilitate tighter control of ventilation³³; however, it does not protect against and, in the case of a high end-tidal CO_2 reading, may actually incite the practitioner to ventilate beyond safe thresholds.¹³ As described previously, keeping one's eye glued to a monitor while in the midst of transporting a patient is simply unrealistic. Transport ventilators allow stringent control of ventilation parameters, and their advanced monitoring and alarm capabilities provide the only means of truly accomplishing the main goal of protecting the patient.

Spontaneous Breathing During Transport

As described previously, not all patients needing transport require total ventilatory support. The administration of heavy sedation for the sole purpose of facilitating transport makes little sense and exposes the patient to the additional risks associated with apnea. Because the patient's breathing pattern may vary considerably, the device used should have the ability to provide consistent support and oxygen concentration under a variety of conditions. Of particular importance is the ability of the device to allow easy initiation of gas flow and expiration without undue resistance, because asynchrony in either instance increases work of breathing.^{34,35}

An early study by Hess et al³⁶ evaluated the inspiratory and expiratory imposed work of breathing and oxygen delivery of 11 manual resuscitators. A 2-chambered test

lung driven by a mechanical ventilator delivered low, moderate, and high ventilatory patterns. Pressure, flow, and volume signals were electronically recorded and integrated to calculate work in J/L. Oxygen flow of 15 L/min was connected to each resuscitator while an oxygen analyzer measured F_{IO_2} at the patient connection. Although exact details are beyond the scope of this discussion, findings revealed that all resuscitators caused an increase in imposed work of breathing during both inspiration and expiration. As the level of ventilation increased, imposed work increased significantly ($P < .01$) to as high as 0.965 ± 0.097 J/L. There was a significant difference between inspiratory and expiratory work ($P < .01$), which was magnified at higher levels of ventilation. Two of the resuscitators tested had built-in PEEP valves. The addition of 10 cm H_2O PEEP resulted in a further increase in imposed work during inspiration work of breathing of >1 J/L in both devices. This is due to the fact that, unlike transport ventilators that are PEEP-compensated, inspiratory flow is maintained through a manual resuscitator only by the patient generating a negative pressure gradient greater than the PEEP valve level. Additionally, only 7 of the 11 devices were able to deliver F_{IO_2} of >0.85 under the test conditions. The authors noted that the imposed work generated by manual resuscitators is 10–100-fold greater than that reported on ICU ventilators and concluded by recommending against the use of manual resuscitators during spontaneous breathing.

Although improvements in various models of manual resuscitators have alleviated some of the failings found in earlier devices,³⁷ studies continue to reveal the limitations of manual resuscitators.^{37,38} Maintaining consistent support and stable F_{IO_2} during spontaneous breathing is impossible with manual resuscitators, which are designed to allow unregulated entrainment of room air during high inspiratory demand and rely solely on the operator's ability to synchronize manual compressions with the patient's spontaneous efforts when partial support is warranted. Their use during spontaneous breathing has been shown both to be ineffective and to result in negative physiological consequences.^{38,39}

Transport Ventilators

The development of the transport ventilator was born out of the realization that manual ventilation was simply inadequate in many circumstances. The first transport ventilators were cumbersome ICU or home ventilators crudely adapted for the task and bolted to the transport cart. Early ventilators specifically designed for transport, although smaller than their ICU counterparts, suffered from severe shortcomings. The fluidics of pneumatically powered devices consumed considerable amounts of oxygen even when sitting idle. Electronic devices were hampered by the weight

and limited life of batteries available at the time. In a review of the publications on intrahospital transports, Fanara et al⁴ identified portable ventilators accounting for 22% of the adverse events caused by equipment factors. Battery life, running out of oxygen, inadvertent disconnections, and personnel not properly trained with the ventilator operation were cited as root causes. Fortunately, improvements in technology have alleviated many of these problems. Today's modern transport ventilators offer many of the same features found on ICU machines, including variable control of F_{IO_2} , multiple modes, and advanced monitoring and alarm capabilities. Selection of a transport ventilator should be based on matching anticipated ventilation requirements to ventilator capabilities.

There are literally dozens of devices marketed as transport ventilators. They range from simple gas-driven automated resuscitators that provide 100% oxygen and little more than crude control of rate and tidal volume and a pressure relief valve to sophisticated transported ventilators with a variety of modes and advanced monitoring and alarm capabilities. For in-hospital transport, the 2002 American Association for Respiratory Care Clinical Practice Guidelines recommend that a transport ventilator should have sufficient power for the duration of the transport, independent control of rate and tidal volume, ability to provide full support, deliver constant volume in the face of changing pulmonary impedance, provide a disconnect alarm, and be capable of providing PEEP and an F_{IO_2} of 1.0. Many newer generation transport ventilators surpass these recommendations and rival the performance of their ICU counterparts.

Two studies have looked at the performance of newer generation transport ventilators. Blakeman and Branson⁴⁰ conducted a thorough evaluation of 4 of the newest generation transport ventilators. They assessed V_T accuracy, triggering characteristics, battery duration, gas consumption, and F_{IO_2} stability under differing resistance, compliance, V_T , and rate conditions. They found that all of the ventilators were within the American Society for Testing and Materials standards of $\pm 10\%$ at a tidal volume target of 400 mL, but 3 of the 4 ventilators were outside of the $\pm 10\%$ acceptable range at a setting of 50 mL with ranges of 55.7 ± 1.4 to 58.2 ± 1.2 mL. Triggering pressure ($P_{I_{max}}$) varied from 0.32–1.72 cm H_2O with the fastest rise time settings to 0.34–3.29 cm H_2O with the slowest rise time. Gas consumption using a minute ventilation of 10 L/min varied from 9.2 to 16 L/min. The higher gas consumption was attributed to the bias flow during flow triggering. All ventilators delivered stable F_{IO_2} concentrations under the differing conditions, although one was unable to achieve a threshold of $\pm 5\%$ at higher F_{IO_2} settings with a maximal attainable F_{IO_2} of 0.919. Testing revealed a need for improvements in the ability to deliver smaller tidal volumes accurately; how-

ever, all ventilators performed well within the established requirements for adult transport.

Boussen et al⁴¹ evaluated 3 gas-driven and 5 turbine-driven ventilators under simulated passive and spontaneously breathing conditions. Ventilators were tested using volume-targeted and pressure support modes. Pressure support of 5 and 10 cm H₂O with and without PEEP of 5 cm H₂O were tested under high and low drive conditions. Turbine-driven models outperformed the gas-driven ventilators in tidal volume accuracy, triggering characteristics, and pressurization performance. In comparison with other studies, the authors found considerable improvement in V_T accuracy over older transport ventilators. Turbine-driven transport ventilators demonstrated performance comparable with that of ICU ventilators in the pressure support mode.

Magnetic resonance imaging (MRI) poses a unique challenge in terms of mechanical ventilation. Any piece of equipment containing metal can become a flying projectile if positioned too close to the imager and not properly secured. To maintain a safe distance, extended circuit tubing is routinely used on ventilators, adding to compressible volume loss and attenuating triggering sensitivity. Few transport ventilators are MRI-safe, and those available in the past have been pneumatically powered, with limited capabilities and alarms. Chikata et al⁴² recently compared the performance of older MRI-safe portable ventilators with that of an ICU ventilator. None of the MRI ventilators tested delivered tidal volumes within the American Society for Testing and Materials limits of $\pm 10\%$ under all conditions. At an F_{IO₂} setting of 1.0, variations in delivered F_{IO₂} were minimal, but it varied considerably at an F_{IO₂} of 0.60 (air mix). The peak pressure relief valve worked appropriately in all models, but PEEP deviated significantly from set values and between models. Although older generation MRI ventilators are equipped with audible pressure alarms, providing some level of safety monitoring, vital signs should also be continuously monitored. The newest MRI portable ventilators appearing on the market claim significant performance improvements in accuracy over those in the study by Chikata et al,⁴² with such additional features as an integrated gaussmeter, superior monitoring capabilities, and advanced modes.

Although the cost of a modern transport ventilator is considerably greater than that of a manual resuscitator, the difference has to be weighed against the additional costs related to injurious ventilation and hyperoxia that can occur during manual ventilation. Inappropriate tidal volumes have been identified as an independent risk factor contributing to increased mortality and length of hospital stay,^{16,43} and hyperoxia, for even short periods, has been shown to worsen outcomes and increase mortality in select patient populations.²⁵ With hospital reimbursement tied directly to patient outcomes, minimizing risks while improving

patient safety is a financial necessity. The average daily cost of a mechanically ventilated patient is estimated at \$4,000,⁴⁴ and the number of patients requiring prolonged ventilation alone is expected to exceed 600,000 by 2020.⁴⁵ Obviously, the increase in mechanical ventilation means that more patients will require transport. Although evidence is lacking, one can foresee that eliminating unnecessary exposure to the injurious effects associated with manual ventilation may result in sufficient savings to offset the cost of a transport ventilator.

Summary of the Pro Position

Modern transport ventilators are superior to manual ventilation in their ability to minimize the risk of ventilator-induced lung injury while maintaining ventilation goals through the control and continuous monitoring of tidal volumes and airway pressures. Precise control of oxygen concentration during controlled and spontaneous breathing reduces the risk of hyperoxia or hypoxia. Significant improvements in battery life and the ability to hot-swap batteries while in operation virtually eliminate power concerns, and the advanced monitoring and alarm capabilities found in today's transport ventilators eradicate the shortcomings of earlier models. It is of little wonder that their use has been endorsed by multiple professional organizations and should be considered the standard of care for all in-hospital transports. The time has come to abandon the antiquated and unsafe practice of manual ventilation.

Con: A Portable Ventilator Should Not Be Used in All In-Hospital Transports

Intrahospital transport of the critically ill patient is a difficult but essential part of patient management. It can be hazardous due to patient physiologic instability as well as overcoming logistical barriers. Logistically, a risk of adverse events can stem from inadequate training, inability of the clinicians to work as a team, and equipment maintenance and malfunction. An extremely important aspect of intrahospital patient transport is adequate ventilation during the process. Up until about 15 y ago or so, this was accomplished by manual ventilation performed by a respiratory therapist, nurse, or physician. This was carried out through the use of a manual resuscitation bag in which the parameters of ventilation were determined by the clinician. Recently, portable ventilators have been introduced with the aim of providing more consistent patient ventilation during transport as well as freeing up the clinician to help with other aspects of the transport. Today, portable ventilators are used for most of the intrahospital transports. The question to be answered is whether patient ventilation during all intrahospital transports should be done with a portable ventilator. Although manual ventilation is used commonly during resuscitation efforts and rapid re-

sponses, manual ventilation still has a place during patient transport.

Portable Ventilators

The introduction of portable ventilators has been a major technological advancement, but to be truly effective, they have to be reliable enough to deliver consistent ventilatory parameters in the face of changing lung mechanics. The United States Food and Drug Administration's approval of portable ventilators in 2001 has resulted in an increasing scope of their use during transport, especially as they become more sophisticated. According to the American Association for Respiratory Care guidelines, if a transport ventilator is used, it should have sufficient portable power supply for the duration of transport, have independent control of tidal volume and respiratory frequency, be able to provide full ventilatory support as in assist-control or intermittent mandatory ventilation (not necessarily both), deliver a constant volume in the face of changing pulmonary impedance, monitor airway pressure, provide a disconnect alarm, be capable of providing PEEP, and provide an F_{IO_2} of 1.0.³ It is of vital importance that each institution run a bench analysis of transport ventilators before purchase to make sure they can, in fact, meet these guidelines.

We need to be careful, however, in making the assumption that all transport ventilators are created equal. Transport ventilators are touted to be more efficient and consistent for patient ventilation during transport. However, it is important to point out that significant differences may still exist between the different types of portable ventilators. In a study by Zanetta et al,⁴⁶ the functionality of 5 different portable ventilators and 3 ICU-type ventilators used for transport was examined. The investigators created 3 different lung mechanic scenarios with a test lung: normal, ARDS, and obstructive disease. They found that V_T delivery, resistance to exhalation, and triggering sensitivity varied substantially among the different ventilators.⁴⁶ This was especially true with the portable ventilators. There were differences among the 3 ICU-type ventilators as well, but not to the same extent.⁴⁶ Chipman et al⁴⁷ evaluated 15 transport ventilators both on the bench (with varied lung mechanics) and in sheep weighing approximately 30 kg with normal lungs and then again in injured lungs. They found that all of the ventilators could ventilate healthy lungs.⁴⁷ However, V_T levels varied considerably in the face of decreased compliance and/or increased resistance to the point that the authors concluded that only 4 were able to ventilate the saline-lavaged injured lungs.⁴⁷ Also, a majority of the ventilators could not ventilate on battery power alone, and, like the V_T levels, battery duration and oxygen consumption varied considerably between devices.⁴⁷ The authors concluded that only 2 of the 15 transport ventilators would work appropriately when transport-

ing patients with high ventilatory requirements.⁴⁷ In a more recent bench study of 8 transport ventilators, Boussien et al⁴¹ evaluated their ability to deliver a set V_T under normal conditions, ARDS conditions, and obstructive conditions. The group also evaluated the performance of the triggering system and the quality of rise to pressure. They found that there were significant differences in V_T delivery. The error range was -5 to 53%.⁴¹ They also found that the turbine-based transport ventilators achieved better tidal volume delivery and trigger sensitivity than the pneumatic ventilators.⁴¹ Blakeman and Branson⁴⁰ examined the performance of 4 commonly used transport ventilators and found that there were significant differences in performance across a wide spectrum of operation, including triggering sensitivity, battery duration, F_{IO_2} stability, gas consumption, and V_T accuracy. The rise to pressure time also differed greatly. The devices that had the fastest rise time had the greatest pressure overshoot.⁴⁰ Clinically, this may be important because a rapid rise time setting may cause turbulent flow in the circuit, potentially overwhelming the patient. Setting the rise time too slow may result in a delay in reaching the set pressure or the possibility that the set pressure may not be reached at all. This would result in air hunger or flow asynchrony with an undue increase in the work of breathing. Perhaps the largest study to date was done by L'Her et al.⁴⁸ This group evaluated 26 different emergency and transport ventilators that were grouped into 4 different categories depending on sophistication: (1) ICU-like, (2) sophisticated, (3) simple, and (4) mass casualty. They examined V_T delivery with different respiratory mechanics and asynchrony index, among other things. Although the V_T values of the ICU-like and the sophisticated ventilators were within a 10% accuracy range, there will still be substantial differences among the devices in every category.⁴⁸ They were also affected to a certain degree by changing respiratory mechanics (Fig. 1).⁴⁸ The group also examined the presence of patient-ventilator synchrony in the presence of leaks (which is not uncommon during transport) and found that most of the ventilators exhibited an asynchrony index of >10%. (Fig. 2).⁴⁸ The asynchrony index is defined as the number of asynchronous breaths/total number of breaths, and the threshold of 10% represents whether the patient is considered synchronous with the ventilator. Some of the sophisticated ventilators even outperformed the ICU-like ventilators in this study.⁴⁸ Of note is that patient-ventilator asynchrony has the potential to occur in 3 different phases during inspiration: (1) The initiation of the breath (ineffective triggering or autocycling), (2) flow asynchrony (flow starvation or a flow so rapid that it leads to double triggering), and (3) cycle asynchrony (breath ends either too early or too late for the patient). The consequences of patient-ventilator asynchrony could be an increase in the work of breathing due to the patient fighting the

Fig. 1. Individual tidal volume delivery according to respiratory mechanics changes with ICU-like (A), sophisticated (B), simple (C), and mass casualty/military ventilators (D). R = different values of resistance (5, 10, and 20 cm H₂O/L/s) in combination with different compliance (30, 70, and 120 cm H₂O/L). Dotted lines represent the 10% accuracy range, whereas dashed lines represent the 5% accuracy range. *, $P < .05$; **, $P < .005$. From Reference 48, with permission.

ventilator and excessive sedation. Even in the ICU setting with the most sophisticated ventilators, it has been estimated that patient ventilator asynchrony is around 24%.⁴⁹

Battery function and duration are also extremely important factors for optimal performance of portable ventilators. Intrahospital transports may take patients into environments where electricity is not immediately available. No industry guidelines currently exist for battery duration. The American Association for Respiratory Care guidelines recommend portable ventilator minimum battery duration of 4 h at nominal settings.³ There are several factors that can affect battery duration, however. These include ventilator settings (higher settings will shorten battery duration), battery type and size, and ventilator operating characteristics and drive systems. As was pointed out earlier, there are significant differences in battery duration among

the various transport ventilators.^{40,47} An earlier study by Blakeman et al⁵⁰ found that V_T decreased in some of the portable ventilators studied toward the end of battery duration. Clinically, this could contribute to hypercarbia and respiratory acidosis. Gas consumption is another important consideration with the use of portable ventilators. Operating characteristics of the ventilators and ventilator settings confound the problem of determining oxygen usage and calculating how long a tank will last. For instance, larger tidal volumes and higher breathing frequency will result in more gas consumption, whereas smaller tidal volumes and lower breathing frequency result in less gas consumption. The other operating characteristic affecting gas consumption is bias flow. Manufacturers utilize this continuous gas flow through the ventilator circuit to facilitate triggering and stabilize PEEP, but it results in increasing the gas consumption from the tank.

Fig. 2. Asynchrony management under different levels of leaks with ICU-like (A) and sophisticated ventilators with (B) and without (C) noninvasive ventilation (NIV) mode. Asynchrony index (AI) values are shown as a percentage of respiratory efforts in pressure support and PEEP of 5 cm H₂O. Dotted lines represent the asynchrony index clinical level of significance (10%). Three levels of leaks are shown: L1 = 3.5–4.0 L/min, L2 = 5.0–7.0 L/min, and L3 = 9.0–12.5 L/min. *, $P < .05$; **, $P < .005$. From Reference 48, with permission.

Adverse Events With Portable Ventilators

Although not necessarily a common occurrence, ventilator malfunction can and does happen. A study by Beckmann et al⁵¹ examined the incidence of equipment malfunction from a report of incidents submitted to the Australian Incident Monitoring Study in Intensive Care in a 6-y period. They found a total of 75 equipment-related incidents, of which 4 incidents were transport ventilator malfunction.⁵¹ Other observations made during this study pertaining to potential risk factors include inadequate training, poor maintenance, unavailability of equipment, inexperience, and haste.⁵¹

In another study, Papson et al¹ looked at unexpected events during transport. Of 277 equipment-related unexpected events in 339 transports, 11 were ventilator failures and 18 were ventilator circuit leaks.¹ As with any piece of electronic equipment, clinicians must be aware that malfunction is a possibility. They must also be aware of any malfunction history with the type of transport ventilator that is being used in their institution.

Magnetic Resonance Imaging

In MRI suites, there are a number of issues with conventional ventilators due to their ferromagnetic components. These include an increased risk of projectile events, degra-

dation of image quality, and compromised ventilator performance. To be MRI-compatible, ventilators have to have their ferromagnetic components replaced with non-ferromagnetic ones. Due to this, it is conceivable that the MRI-compatible ventilators may have even more variability in the ventilation parameters. Chikata et al⁴² evaluated 4 MRI-compatible ventilators in volume assist control with 3 different V_T settings. They found statistically significant differences in delivered tidal volumes and PEEP. The V_T range of error was 28.1–25.5%, and the PEEP range of error was –29.2 to 42.5%. Due to the wide variation in ventilator function, the authors concluded that patients undergoing an MRI on mechanical ventilation need to be monitored closely both from respiratory and hemodynamic standpoints.

Adverse Events With Manual Ventilation

It has been reported that manual ventilation during transport has the potential to present some problems, namely the inability control airway pressures and tidal volumes.^{29–31,39} However, if we examine the evidence more closely, some inconsistencies become apparent. For example, there is no definition for being adequately trained in manual ventilation. This leads to the fact that the control groups may not be adequately matched to the intervention group.

In the study by Nakamura et al,³⁹ ABGs were assessed at different points during the transport process. They concluded that a transport ventilator provides more consistent ventilator support than manual ventilation.³⁹ Of note is that the patient-specific ICU physicians were the ones who provided manual ventilation. However, there is no mention of the level of training in manual ventilation, and the fact that it was not the same physician performing manual ventilation in every case opens the possibility that the techniques could have varied significantly. The authors also cited more variation in pH in the manual ventilation group. Although this is true, a closer look at the pH levels reveals that during manual ventilation, the pH values were actually closer to the target of 7.40 at each measurement point than for the group that received ventilation with the transport ventilator (7.44 vs 7.46, 7.41 vs 7.48, and 7.45 vs 7.46).³⁹ The investigators also reported that the P_{aO_2}/F_{IO_2} dropped in 5 subjects in the manual ventilation group.³⁹ However, there was no explanation of what may have caused this. Did the subjects suffer some compromise or was it actually a result of the method of ventilation? The blinded ICU physicians also adjusted the PEEP levels “on the fly,” with the result being higher overall PEEP levels in the manual ventilation group with no airway pressure monitoring available. One possible explanation for deterioration could be that these PEEP adjustments made without the visual display of a manometer could have led to overdistention, resulting in lower P_{aO_2}/F_{IO_2} values.

In the study by Gervais et al,³⁰ ABGs were collected before and after in 30 ventilated subjects. These subjects were separated into 3 groups: manual ventilation alone, manual ventilation with V_T being measured, and a portable transport ventilator. As was the case in the study by Nakamura et al,³⁹ the clinicians performing manual ventilation in the first 2 groups were the accompanying physicians (of unknown expertise level), and they used their own clinical judgment to guide ventilation.³⁰ Again, a variety of physicians were involved, weakening the importance of the manual ventilation group. What is also of interest in this particular study is that the differences in P_{aCO_2} were less in the manual ventilation group that monitored V_T versus the manual ventilation group without V_T monitoring, suggesting that monitoring V_T during manual ventilation helps to minimize hypercarbia or hypocarbia.³⁰

Hurst et al³¹ compared ABGs with clinician-controlled manual ventilation versus the use of a transport ventilator in 28 subjects admitted to the emergency department. The results indicated that P_{aCO_2} and pH varied considerably in the manual ventilation group.³¹ They concluded, based on their results and those of Gervais et al,³⁰ that “our data and those of others suggest that use of a portable ventilator *OR* a system which allows visual assessment of delivered tidal volumes is the preferred method of ventilator support.”³¹ Thus, the important factor may, in fact, be that the clinician can see the

delivered V_T and pressures and react instantaneously. In this particular study, the authors did indicate that the clinician providing manual ventilation was experienced (respiratory therapist or registered nurse).³¹ However, they do not define experienced, so it is unclear whether they meant years of service or experienced specifically with manual ventilation.

Weg and Haas⁵² performed an early single-blind prospective study of 20 subjects requiring transport who received manual ventilation. ABGs were taken at different points: before the transport, during the transport, and after the transport had concluded. They reported that the ABGs did not vary to any clinically important degree except in 2 subjects.⁵² However, in one subject, the oxygen was accidentally disconnected, and in the other, a decrease in P_{aCO_2} was associated with a clamped chest tube. They concluded that manual ventilation during transport is indeed safe provided that the clinician is trained to approximate the settings on the ICU ventilator.⁵²

Bowman et al¹⁴ looked at 27 neonatal professionals who performed manual ventilation on a test lung that simulated a 3-kg infant. The clinicians were provided pressure and volume displays, and they were assessed during periods of altered lung mechanics. They found that having the pressure displayed during ventilation helped slightly in adjusting to changing compliance, but this result increased dramatically when the volume was displayed as well.

Consideration of the evidence leads to the conclusion that it is not merely manual ventilation that contributes to ventilation variations but operator training, expertise, and visual cues. A properly trained clinician should be able to adequately ventilate a patient, provided that he or she has appropriate training and volume/pressure visual access. Variations may still exist with manual ventilation, but they would be minimized. These studies bring to light the importance of appropriate training when it comes to manual ventilation. Unfortunately, there are no rigid standards for this, and the onus should be on each institution for proper manual ventilation training and competency maintenance.

Advantages of Manual Ventilation

There are several advantages to using manual ventilation during transport. The first and most obvious is cost. The cost of portable and manual ventilators varies from institution to institution. However, if we assume for argument's sake that a manual resuscitator costs about \$25 and a portable ventilator with circuitry about \$12,000, then this represents a huge cost savings. This cost does not even include maintenance, staff training, and ongoing competency. Second, there is the logistical issue of space on and around the bed. The more equipment that is involved, the less space that the clinicians have to work in. Some portable ventilators are placed on the bed, whereas others need to be dragged along. This extra congestion on and

around the bed can limit clinicians' access to the patient. Third, equipment failure is another possibility. Although portable ventilator failure is not common, when it does happen it is not a quick, easy fix. Failure of a resuscitation bag, on the other hand, can most likely be fixed quickly at the bedside, especially with experienced staff. Fourth, gas consumption is constant with manual ventilation. However, as mentioned previously, gas consumption with portable ventilators varies, depending on ventilator characteristics and ventilator settings. Fifth, clinicians also need not be concerned about battery duration, since there are no electronics involved with manual ventilation. Finally, other than cost, perhaps the biggest advantage of manual ventilation is setup time. A portable ventilator requires circuit setup, ventilator prechecks, and the setting of parameters. A manual resuscitator can be quickly set up, and the transport can begin within minutes.

Manual Ventilation Still Used Today

Although improvements have been made to portable ventilators, manual ventilation is still used in a variety of clinical situations, including (1) transport of patients to and from the operating theater, (2) transport of patients from the emergency department to the ICU, diagnostics, the operating theater, and the hyperbaric chamber, and (3) during rapid responses/codes and the subsequent transport. In many cases, manual ventilation is used because there may not be time to set up and pretest the portable ventilator appropriately before the patient needs to be moved.

Although situations still exist where manual ventilation is the preferred method during transport (for whatever reason), advanced training and the use of manometers and V_T displays are sorely lacking. When it comes to manual ventilation, most clinicians' training is fairly basic: how to attach the resuscitation bag, how to stabilize the endotracheal tube during transport, and how to watch for the effectiveness of the ventilations. Historically, not much attention has been paid to the delivered V_T levels and/or ventilating pressures.

Summary of the Con Position

Although the use of portable ventilators during transport is gaining more popularity, the argument can be made that there is still wide variability among the different transport ventilators. Many transport ventilators have trouble effectively ventilating in the face of worsening mechanics.^{40,41,46-48} Clinicians must have a keen awareness of the capabilities and limitations of their institution's transport ventilators to optimize patient safety during transport. Although arguments have been made that manual ventilation results in more ventilator variation, it is important to keep in mind that all of the evidence uses surrogate end points, such as ABGs and hemodynamic parameters. There are no

studies that we are aware of that have examined mortality outcomes. We have no idea whether the use of portable ventilators or manual ventilation during transport has any effect on mortality. In summary, there is still a place for manual ventilation during transport. However, to be effective, there needs to be much more emphasis on advanced training focusing on lung protection. Also, manometers and V_T displays are valuable tools that should be utilized to help the clinician ventilate in the safe zone.

Conclusions

The increase in mechanically ventilated patients will undoubtedly result in an escalation in the number of patients requiring ventilatory support during transport. Although there are a wide variety of ventilatory support devices available, careful consideration must be given before transport to ensure that the equipment selected provides adequate ventilation in a safe and effective manner. Although cost may be a consideration, the advanced features and performance of modern sophisticated transport ventilators are clearly superior to manual ventilation. Their use should be considered the standard of care for patients requiring high levels of ventilatory support. Although a manual resuscitator should accompany every patient during transport for use during an emergency, their usage otherwise should be limited to the less critically ill patients and should incorporate or be supplemented with a means to monitor delivered pressures and V_T . Finally, one inarguable fact remains, that more so than any piece of equipment, ensuring the patient is safely ventilated during transport ultimately relies on the skill and knowledge of the accompanying caregiver.

REFERENCES

1. Papson JP, Russell KL, Taylor DM. Unexpected events during the intrahospital transport of critically ill patients. *Acad Emerg Med* 2007;14(6):574-577.
2. Lahner D, Nikolic A, Marhofer P, Koinig H, Germann P, Weinstabl C, Krenn CG. Incidence of complications in intrahospital transport of critically ill patients: experience in an Austrian university hospital. *Wien Klin Wochenschr* 2007;119(13):412-416.
3. Chang DW. AARC Clinical Practice Guideline: in-hospital transport of the mechanically ventilated patient: 2002 revision and update. *Respir Care* 2002;47(6):721-723.
4. Fanara B, Manzon C, Barbot O, Desmettre T, Capellier G. Recommendations for the intra-hospital transport of critically ill patients. *Crit Care* 2010;14(3):R87.
5. Warren J, Fromm RE Jr., Orr RA, Rotello LC, Horst HM. Guidelines for the inter- and intrahospital transport of critically ill patients. *Crit Care Med* 2004;32(1):256-262.
6. Talmor D, Sarge T, O'Donnell CR, Ritz R, Malhotra A, Lisbon A, Loring SH. Esophageal and transpulmonary pressures in acute respiratory failure. *Crit Care Med* 2006;34(5):1389-1394.
7. Loring SH, Malhotra A. Driving pressure and respiratory mechanics in ARDS. *N Engl J Med* 2015;372(8):776-777.
8. Protti A, Andreis DT, Monti M, Santini A, Sparacino CC, Langer T, et al. Lung stress and strain during mechanical ventilation: any difference between statics and dynamics? *Crit Care Med* 2013;41(4):1046-1055.

9. Akoumianaki E, Maggiore SM, Valenza F, Bellani G, Jubran A, Loring SH, et al. The application of esophageal pressure measurement in patients with respiratory failure. *Am J Respir Crit Care Med* 2014;189(5):520-531.
10. Lee HM, Cho KH, Choi YH, Yoon SY. Can you deliver accurate tidal volume by manual resuscitator? *Emerg Med J* 2008;25(10):632-634.
11. Turki M, Young MP, Wagers SS, Bates JH. Peak pressures during manual ventilation. *Respir Care* 2005;50(3):340-344.
12. Godoy AC, Vieira RJ, Vieira Neto RJ. Oxygen outflow delivered by manually operated self-inflating resuscitation bags in patients breathing spontaneously. *J Bras Pneumol* 2008;34(4):212-216.
13. Bassani MA, Filho FM, de Carvalho Coppo MR, Martins Marba ST. An evaluation of peak inspiratory pressure, tidal volume, and ventilatory frequency during ventilation with a neonatal self-inflating bag resuscitator. *Respir Care* 2012;57(4):525-530.
14. Bowman TA, Paget-Brown A, Carroll J, Gurka MJ, Kattwinkel J. Sensing and responding to compliance changes during manual ventilation using a lung model: can we teach healthcare providers to improve? *J Pediatr* 2012;160(3):372-376.e1.
15. Amato MB, Meade MO, Slutsky AS, Brochard L, Costa EL, Schoenfeld DA, et al. Driving pressure and survival in the acute respiratory distress syndrome. *N Engl J Med* 2015;372(8):747-755.
16. Needham DM, Yang T, Dinglas VD, Mendez-Tellez PA, Shanholtz C, Sevransky JE, et al. Timing of low tidal volume ventilation and intensive care unit mortality in acute respiratory distress syndrome. A prospective cohort study. *Am J Respir Crit Care Med* 2015;191(2):177-185.
17. Sutherasan Y, Vargas M, Pelosi P. Protective mechanical ventilation in the non-injured lung: review and meta-analysis. *Crit Care* 2014;18(2):211.
18. Marhong J, Fan E. Carbon dioxide in the critically ill: too much or too little of a good thing? *Respir Care* 2014;59(10):1597-1605.
19. Cullen DJ, Eger EI 2nd. Cardiovascular effects of carbon dioxide in man. *Anesthesiology* 1974;41(4):345-349.
20. Alexander SC, Smith TC, Strobel G, Stephen GW, Wollman H. Cerebral carbohydrate metabolism of man during respiratory and metabolic alkalosis. *J Appl Physiol* 1968;24(1):66-72.
21. Raichle ME, Posner JB, Plum F. Cerebral blood flow during and after hyperventilation. *Arch Neurol* 1970;23(5):394-403.
22. Michiels C. Physiological and pathological responses to hypoxia. *Am J Pathol* 2004;164(6):1875-1882.
23. Wyllie J, Perlman JM, Kattwinkel J, Atkins DL, Chameides L, Goldsmith JP, et al. Part 11: Neonatal resuscitation: 2010 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science with Treatment Recommendations. *Resuscitation* 2010;81(Suppl 1):e260-e287.
24. Martin DS, Grocott MP. Oxygen therapy in critical illness: precise control of arterial oxygenation and permissive hypoxemia. *Crit Care Med* 2013;41(2):423-432.
25. Damiani E, Adrario E, Girardis M, Romano R, Pelaia P, Singer M, Donati A. Arterial hyperoxia and mortality in critically ill patients: a systematic review and meta-analysis. *Crit Care* 2014;18(6):711.
26. Farquhar H, Weatherall M, Wijesinghe M, Perrin K, Ranchord A, Simmonds M, Beasley R. Systematic review of studies of the effect of hyperoxia on coronary blood flow. *Am Heart J* 2009;158(3):371-377.
27. MacIntyre NR. Supporting oxygenation in acute respiratory failure. *Respir Care* 2013;58(1):142-150.
28. Kallet RH, Matthay MA. Hyperoxic acute lung injury. *Respir Care* 2013;58(1):123-141.
29. Braman SS, Dunn SM, Amico CA, Millman RP. Complications of intrahospital transport in critically ill patients. *Ann Intern Med* 1987;107(4):469-473.
30. Gervais HW, Eberle B, Konietzke D, Hennes HJ, Dick W. Comparison of blood gases of ventilated patients during transport. *Crit Care Med* 1987;15(8):761-763.
31. Hurst JM, Davis K Jr., Branson RD, Johannigman JA. Comparison of blood gases during transport using two methods of ventilatory support. *J Trauma* 1989;29(12):1637-1640.
32. Walsh BK, Crotwell DN, Restrepo RD. Capnography/Capnometry during mechanical ventilation: 2011. *Respir Care* 2011;56(4):503-509.
33. Palmon SC, Liu M, Moore LE, Kirsch JR. Capnography facilitates tight control of ventilation during transport. *Crit Care Med* 1996;24(4):608-611.
34. Sassoon C. Triggering of the ventilator in patient-ventilator interactions. *Respir Care* 2011;56(1):39-51.
35. Sassoon CS, Foster GT. Patient-ventilator asynchrony. *Curr Opin Crit Care* 2001;7(1):28-33.
36. Hess D, Hirsch C, Marquis-D'Amico C, Kacmarek RM. Imposed work and oxygen delivery during spontaneous breathing with adult disposable manual ventilators. *Anesthesiology* 1994;81(5):1256-1263.
37. Mazzolini DG Jr., Marshall NA. Evaluation of 16 adult disposable manual resuscitators. *Respir Care* 2004;49(12):1509-1514.
38. Kwei P, Matzelle S, Wallman D, Ong M, Weightman W. Inadequate preoxygenation during spontaneous ventilation with single patient use self-inflating resuscitation bags. *Anaesth Intensive Care* 2006;34(5):685-686.
39. Nakamura T, Fujino Y, Uchiyama A, Mashimo T, Nishimura M. Intrahospital transport of critically ill patients using ventilator with patient-triggering function. *Chest* 2003;123(1):159-164.
40. Blakeman TC, Branson RD. Evaluation of 4 new generation portable ventilators. *Respir Care* 2013;58(2):264-272.
41. Bousset S, Gannier M, Michelet P. Evaluation of ventilators used during transport of critically ill patients: a bench study. *Respir Care* 2013;58(11):1911-1922.
42. Chikata Y, Okuda N, Izawa M, Onodera M, Nishimura M. Performance of ventilators compatible with magnetic resonance imaging: a bench study. *Respir Care* 2015;60(3):341-346.
43. Ahmed AH, Thongprayoon C, Schenck LA, Malinchoc M, Konvalinová A, Keegan MT, et al. Adverse in-hospital events are associated with increased in-hospital mortality and length of stay in patients with or at risk of acute respiratory distress syndrome. *Mayo Clin Proc* 2015;90(3):321-328.
44. Dasta JF, McLaughlin TP, Mody SH, Piech CT. Daily cost of an intensive care unit day: the contribution of mechanical ventilation. *Crit Care Med* 2005;33(6):1266-1271.
45. Zilberberg MD, de Wit M, Shorr AF. Accuracy of previous estimates for adult prolonged acute mechanical ventilation volume in 2020: update using 2000-2008 data. *Crit Care Med* 2012;40(1):18-20.
46. Zanetta G, Robert D, Guérin C. Evaluation of ventilators used during transport of ICU patients: a bench study. *Intensive Care Med* 2002;28(4):443-451.
47. Chipman DW, Caramaz MP, Miyoshi E, Kratochvil JP, Kacmarek RM. Performance comparison of 15 transport ventilators. *Respir Care* 2007;52(6):740-751.
48. L'Her E, Roy A, Marjanovic N. Bench-test comparison of 26 emergency and transport ventilators. *Crit Care* 2014;18(5):506.
49. Thille AW, Rodriguez P, Cabello B, Lellouche F, Brochard L. Patient-ventilator asynchrony during assisted mechanical ventilation. *Intensive Care Med* 2006;32(10):1515-1522.
50. Blakeman TC, Rodriguez D, Dorlac WC, Hanseman DJ, Hattery E, Branson RD. Performance of portable ventilators for mass-casualty care. *Prehosp Disaster Med* 2011;26(5):330-334.
51. Beckmann U, Gillies DM, Berenholtz SM, Wu AW, Pronovost P. Incidents relating to the intra-hospital transfer of critically ill patients. *Intensive Care Med* 2004;30(8):1579-1585.
52. Weg JG, Haas CF. Safe intrahospital transport of critically ill ventilator-dependent patients. *Chest* 1989;96(3):631-635.

Discussion

Holets: I didn't have it in my slides, but we were talking about MRI, and there are a couple of new ventilators out there that are actually built for MRI use. Has anybody here used those or evaluated them?

Kacmarek: No, but I'd like to know what they are.

Holets: Hamilton has one. It's actually yellow. It's supposed to maintain V_T accurately, but I haven't seen any evaluations of it.

Davies: MRI ventilators are also only effective a certain distance out from the scanner. At our institution, we do check our MRI ventilators before they are put into clinical use. For safety reasons, we also tether a certain distance away from the scanner.

Kallet: How many of us have criteria for when to use a transport ventilator? Do we transport everybody who's intubated on one versus hand-ventilating them?

Holets: Our policy now is all intubated patients are supposed to be on a portable ventilator. They're supposed to be; occasionally, however, they aren't. Usually, it is patients coming from the OR [operating room] being manually ventilated by a non-respiratory therapist.

Kacmarek: If a therapist does a transport, we're supposed to use a transport ventilator all the time. Obviously, there are circumstances where that doesn't happen. But for the same reason, anesthesia does not use a transport ventilator; they bag patients. We simply do not have the personnel to take every anesthesia case to the OR and to bring them back. What we've done in cardiac surgical patients is a therapist sets up the ventilator with an agreed upon standard approach to ventilation, has it all ready, and all anes-

thesia has to do is attach it and turn it on. But in the other ICUs, we transport some on portable ventilators, but there are still a number of transports that are being done by anesthesia, and I'm not sure how to fix it, to be quite honest with you.

Kallet: We actually had a policy for years about that. We did a study back in the '80s looking at deterioration and gas exchange intra-operatively, so every patient had to be transported.¹ Our policy grew out of that study, and essentially it was PEEP of ≥ 10 cm H_2O or a high minute ventilation of ≥ 10 L/min. But we've got personnel issues too that made this frustrating from a staffing perspective. For example, we'll have someone on 40% and 5 cm H_2O of PEEP on ARDSNet settings with a minute ventilation of 7 L at a frequency of 22 or 24 breaths/min. The resident or nurse anesthetist would ask for a full ventilator transport. And it's like, "Seriously? We have to transport someone on a ventilator because you can't count to 3 and give a patient maybe a slightly larger breath?" It seems like the problem with manual ventilation for transporting patients is sometimes a self-inflicted one of dumbing down patient care. And I don't like to use that phrase, but it's appropriate. In the old days, a seasoned clinician would kind of figure it out. What's the minute ventilation demand, what's the approximate frequency? Being a drummer I'm used to counting, but it's not that hard to do! So, I'm not sure every patient needs it.

Kacmarek: The patients I worry about most are the ones who are breathing spontaneously, where the interaction with manual ventilation is terrible. You watch people ventilating, and they're talking to other clinicians and their ventilation and the patient are totally out of sync. Dean showed that the work of breathing during spontaneous breathing through a manual ventilator is horrendous.² The skill in

identifying the beginning of the breath and ability to supplement it immediately is not there. I don't care how good you are, it just doesn't happen the right way. So those are the ones I worry about. We had the same policy that if patients were really sick, we would transport them, but it got to be less sick, and less sick, until they wanted everybody transported.

Kallet: We use modified Jackson circuits, which I think are more amenable even with somebody who's breathing spontaneously; you can kind of feel the bag collapse and assist it. Manual resuscitators, I think, are very hard to use with anybody breathing spontaneously.

Berra: I would like to ask a question regarding the reluctance of anesthesiologists to learn the use of these portable ventilators: What did you do with this information? The anesthesiologists should learn the use of ventilators; it is part of their job. If I go to work to a different institution, I will probably need to learn different ventilators. It's a very simple concept. I don't understand where the problem is; why can't the anesthesiologist learn and use the portable ventilators? I have a second question: When do you use paralysis for patient transport? At our institution, it is left to the discretion of each attending/team. What are your thoughts about that?

Davies: The slide I showed was just some feedback that I got from a few of our anesthesiologists. We have quite a few anesthesiologists, and they're busy, so trying to train them on our transport ventilators would be a huge undertaking. Plus there's the fact that we have several different types of transport ventilators. Some of them are fairly sophisticated, which would require more in-depth training. They did say if a respiratory therapist wanted to accompany them on the transport they would be fine with the transport ventilator. But, if not, they feel it would

be safer for them to bag the patient. That's their opinion, and I don't know how to change that unless we have a lot of staff for training purposes. If we need to paralyze the patient for transport, we conduct a 30-min trial on the transport ventilator post-administration to ensure delivery of appropriate ventilatory parameters. If time allows, we may try and do a 10-20-min trial post effect on respiratory mechanics.

Kacmarek: You have to for most MRIs, because they move. You have to paralyze them.

Davies: We try not to paralyze, but heavily sedate. However, there are cases where paralytics are needed.

Kacmarek: Right. So, Lorenzo [Berra] you're from a different world, meaning you were trained in Italy, where you learned how to use a mechanical ventilator from the beginning of your training. That's not the case here, and there's not the appreciation, I believe, from the anesthesia staff unless they have an acute interest in mechanical ventilation to pay attention to the details. I would venture to guess that although anesthesia staff know how to operate the anesthesia ventilator, their understanding of how the ventilator works or if you asked them to set up the vent from scratch they would have difficulty. I'm talking about anesthesia machines because you have anesthesia techs who do all of that.

Berra: Maybe for training purposes for anesthesiologists it is during their residency. At our institution, residents have to set up the ventilators every morning before surgery. It seems to me that if an institution has transport ventilators, anesthesiologists and therapists should learn how to use them. A PEEP valve and bagging does not have the same efficacy (and safety) profile for a patient with 20 cm H₂O PEEP and ARDS.

Kacmarek: Those patients get transported properly all the time. It's the less sick patients who are the ones that may not be transported properly. Although we are actively trying to change that.

Davies: Our biggest obstacle is the sheer number of patients transported to and from the OR on both capital equipment and personnel required for training. I do agree with Bob [Kacmarek]; in my opinion, the residents' interest and focus are not on the ventilator as much as they should be.

Branson: Based on the paper from Masaji's group³ and my own experience, a lot of these ventilators that we use for MRI are downright terrible. They can't provide a consistent rate, they can't provide a consistent F_{IO₂} or V_T, and I don't understand the need for these devices. I'm not the director of respiratory therapy, but if I were in charge, I would buy a good MRI-compatible ventilator and just leave it in the MRI suite. And use my regular transport ventilators to take patients back and forth. I think the money being spent on these ventilators that are just MRI-compatible is, quite frankly, a waste and not efficient for caring for those patients. We just had a sentinel event with a patient during transport. The question is: When you take somebody to any of these remote places, does the therapist stay or does the therapist go? The lack of alarms on MRI ventilators is an issue.

Kallet: Generally, the therapist stays, although we function with a fairly low level of staff, so it depends on acuity and the stability of the patient. If they're very unstable, we don't leave. If it's a computed tomography scan, it's so quick we might as well stay.

Davies: For us, it depends on the stability of the patient. We are fortunate that the scanners are located on the first floor not far from the emergency

department. Because we staff the emergency department 24/7, we have the ability, in some cases, to have the emergency department therapist watch over the patient or be quickly available, if needed. This would depend, of course, on what was going on in the emergency department; effective communication is essential in these scenarios.

Holets: We transport and stay with them. Except for the MRI suite where anesthesia takes over. What's interesting is our therapists are pretty good ventilator managers, so more and more we're asked to come down to the OR and bring the transport ventilator, which works better than some of the anesthesia machines. So we might stay a long time in those cases and then transport them back.

Kacmarek: We're supposed to stay if at all possible, but I would agree that there are times when therapists don't stay because there are other demands and they're being paged out for other circumstances, etc. We had the same issue as Steve [Holets], but we had to stop that. We had to say, "We cannot come to the OR." You have new anesthesia machines that are equivalent to ICU ventilators. I just don't have the staff to put somebody for half a shift or longer into the OR, especially now that we have appropriate anesthesia ventilators. So we've stopped doing that.

Branson: I think the anesthesia issue is another process issue. Because an anesthesiologist or a CRNA (certified registered nurse anesthetist) over the course of a week ventilates, say, 50 or 60 patients. And most of them go to the recovery room from the OR and then pull the tube out. Then the one critically ill patient they have to get that week, it's a different paradigm. They're thinking, "I do this all the time," but it's just a matter of making people aware that the critically ill patient requires more than what you

do normally. Does anybody want to speak to that?

Hurford: You're all just having so much fun anesthesia bashing.

Branson: I don't think I'm bashing. Everything in the hospital is a process, right? If you do something the same way 100 times and then the 101st

time it's completely different, you still will approach it the same way you normally do. It's just a matter of awareness.

REFERENCES

1. Schapera A, Marks JD, Minagi H, Goodman P, Katz JA. Perioperative pulmonary function in acute respiratory failure: effect of ventilator type and gas mixture. *Anesthesiology* 1989;71(3):396-402.
2. Hess D, Hirsch C, Marquis-D'Amico C, Kacmarek RM. Imposed work and oxygen delivery during spontaneous breathing with adult disposable manual ventilators. *Anesthesiology* 1994;81(5):1256-1263.
3. Chikata Y, Okuda N, Izawa M, Onodera M, Nishimura M. Performance of ventilators compatible with magnetic resonance imaging: a bench study. *Respir Care* 2015; 60(3):341-346.