Surge Capacity Mechanical Ventilation

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Mechanical ventilation in a situation of mass casualty respiratory failure will require a substantial increase in the capacity for mechanical ventilation, to prevent unnecessary mortality. Concern over the difficulties of treating large numbers of patients with respiratory failure is exceeded only by our lack of experience on which to base decisions. This review evaluates the likely scenarios that could lead to mass casualty respiratory failure and the types of respiratory failure anticipated. A literature review was conducted, using the National Library of Medicine Medical Subject Headings terms "mass casualty respiratory failure," "pandemic flu," "disaster preparedness," and "mass casualty care." Papers were reviewed for relevance to the topic. There is little historical or empirical evidence upon which to base decisions regarding mass casualty respiratory failure and augmenting positive-pressure ventilation capacity. Matching the degree of respiratory impairment anticipated from the most likely mass casualty scenarios allows conclusions to be drawn regarding the performance characteristics of ventilators required for these situations. Little is known about the success of mechanical-ventilator stockpiling for mass casualty respiratory failure. Careful planning with an emphasis on matching ventilator performance to patient need and caregiver skill is critical to appropriate stockpile choices. *Key words: mechanical ventilation, mass casualty, pandemic.* [Respir Care 2008;53(1):78–88. © 2008 Daedalus Enterprises]

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Introduction

Recent natural disasters, the threat of terrorism, and concerns regarding severe febrile respiratory illness (severe acute respiratory syndrome [SARS] and avian flu) have focused health care planners on the requirements for mass casualty mechanical ventilation.[1–4] Though the potential for a mass casualty event that would result in a large number of patients requiring mechanical ventilation seems evident, health care systems do not have the experience to allow an evidence-based approach to preparedness.

Globalization and information sharing allow us to be aware of disasters around the world in a matter of minutes. These disasters occur frequently worldwide, in the form of earthquakes, floods, and other natural events.[5] To date, none of these events has resulted in overwhelming numbers of patients requiring mechanical ventilation. Most injuries are traumatic in nature, and the majority of patients who survive the incident are not critically injured.[6–8] Patients who require mechanical ventilation have been handled by local and regional resources, without the need for triage or rationing of care because of an insufficient number of ventilators.[9–11]

Smaller, local incidents such as structure fires or building explosions might be expected to create large number of patients with respiratory failure resulting from heat, smoke, and debris in a closed space. To date these events have rarely produced more that 100 victims, only a small percentage of whom require mechanical ventilation.[12–17] In each of these cases, local resources allowed all patients to receive mechanical ventilation with existing resources.[18–20]

The purpose of this review is to evaluate the potential scenarios that might result in large-scale, survivable respiratory failure. These include natural disasters, intentional catastrophes, biologic and chemical exposures, and febrile respiratory illness. Currently the looming threat of an influenza pandemic has fueled the urgency of public health agencies to plan for mass casualty respiratory failure. In an event such as a deadly strain of influenza, local intensive care beds and mechanical ventilators are likely to be in-

sufficient to care for the number of critically ill patients. The second purpose of this paper is to describe the performance characteristics of mechanical ventilators that might be stockpiled to meet the needs of patients with respiratory failure from the most likely mass casualty scenarios.

Historical Precedent

History is often said to be the best teacher. However, despite considerable concern and earnest preparation, modern-day experience with situations that require ventilation of a large number of patients is lacking. The most recent SARS epidemic resulted in severe respiratory failure and mortality in a number of countries.[21,22] The Toronto experience suggests that about 20% of patients with SARS develop acute respiratory distress syndrome (ARDS) and require mechanical ventilation. In retrospect, the Canadian group did not include ventilator shortage in their list of insufficient components required to respond to the SARS outbreak.[23,24] The relatively limited size of the Toronto outbreak suggests that the possibility of a ventilator shortage should, however, be anticipated in future, larger outbreaks

Widespread exposure to nerve agents, with the accompanying respiratory paralysis and bronchorrhea, could result in numerous victims who require mechanical ventilation. On 2 separate occasions the nerve gas sarin was released in Japan by terrorist groups. In both cases, the number of victims who required mechanical ventilation was quite small.[25,26] In both instances, less than 6 patients required mechanical ventilation, and in most of those, ventilation was short-term, limited by antidote administration.

Perhaps the most important event in modern history was the polio epidemic in Copenhagen in the early 1950s.[27] During the months of July to December 1952, 2,830 patients presented with poliomyelitis, 1,235 patients with paralysis. Respiratory paralysis was diagnosed in 345 of these cases. With a mechanical ventilation complement of one iron lung and 3 cuirass devices, the staff was quickly overwhelmed. The maximum number of patients who required mechanical ventilation at one time was 70. During the initial phase of the epidemic, mortality was 87% (27/31). Anesthesiologists improvised by performing tracheostomy and using medical students in 4-hour shifts to provide manual ventilation with a to-and-fro, non-self-inflating bag that incorporated a soda lime carbon dioxide absorber. This ingenious design conserved oxygen and provided heat and humidity. Figure 1 depicts the system for manual ventilation and Figure 2 depicts a patient receiving manual ventilation with the non-self-inflating bag and carbon dioxide absorber. The key lessons from this outbreak include the importance of definitive airway control and the evidence that manual ventilation can be successful, not only

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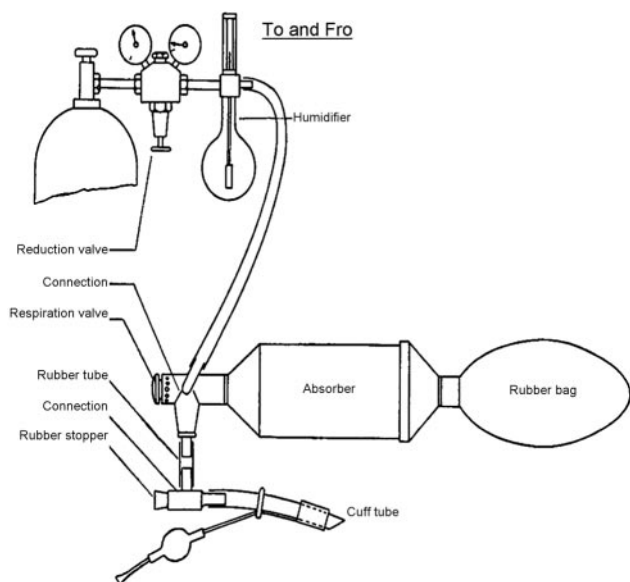
Fig. 1. Manual ventilation system used during the polio epidemic of 1952. (From Reference 27, with permission.)

Fig. 2. Patient receiving mechanical ventilation during the Polio epidemic of 1952. (From Reference 27, with permission.)

Fig. 3. Manual ventilation following hurricane Katrina. (From Reference 28, with permission.)

in the short term, but for prolonged periods. Interestingly, manual ventilation also proved to be successful following hurricane Katrina.[28] Figure 3 depicts a patient receiving manual ventilation following hurricane Katrina.

These events provide an interesting historical vignette, but they fail to provide the experience required to plan for pandemic flu and other events that would result in large numbers of patients who require mechanical ventilation. In order to determine the requirements for mechanical ventilators for mass casualty care we must know the nature and severity of lung injury associated with each anticipated event. The following is a list of scenarios and injuries that may lead to mass casualty respiratory failure.

Scenarios

When would the number of patients who require positive-pressure ventilation far exceed the available mechanical ventilators? The medical impact of a mass casualty event will depend on the disaster characteristics (eg, lethality of exposure, numbers of persons exposed) and interaction with the exposed population's and medical response systems' capabilities and vulnerabilities. Only in disasters likely to result in exposed victims developing acute respiratory failure (ARF) or ARDS will mechanical ventilation potentially be a limiting factor for survival. Disaster characteristics that may influence the demand for ventilators include the number of victims with ARF, the time from exposure to development of ARF, and the duration of ARF. It is plausible that the victims who require mechanical ventilation may far outnumber normal mechanical ventilator capacity. If this were to occur, large numbers of patients with potentially reversible ARF will assuredly die. Each scenario will consider the expected

number of victims who require mechanical ventilation, time from injury until need for mechanical ventilation, the pathophysiology that necessitates the mechanical ventilation, and the geographic area affected.

Traumatic Injury

Traumatic injury may result on a local level from fires, explosions, or terrorist attacks. These events typically result in < 100 casualties. The Israeli experience with homicide bombers suggests that most incidents result in 20–30 casualties, and about half of those patients are hospitalized. Of those, half require intensive care, primarily for mechanical ventilation. In these cases, blast injury of the lung is the predominate mechanism of injury.[29–32]

Traumatic injury may also result from a natural disaster such as an earthquake or tsunami. These events occur over a wider area and include damage to infrastructure as well. In most instances the injuries of survivors are orthopedic in nature. However, respiratory failure may result from near drowning, crush injuries, and chest trauma.[8]

Expected Number of Victims. In a local explosion or fire, typically less than 100 victims require hospitalization, and fewer require mechanical ventilation. Israel's experience suggests substantially fewer than 100 victims. In the case of a closed-space fire and smoke inhalation the number may be greater. Following a natural disaster the number of victims may be greater, but they will be spread across a larger geographic area, which should allow local resources (if undamaged) to absorb additional patients.

Time From Injury to Need for Mechanical Ventilation. Traumatic injuries are a common event in the civilian and military experience. The severity of trauma may require immediate mechanical ventilation for survival (eg, head injury). In a number of cases, however, mechanical ventilation is not initiated until surgical repair.[33,34] In a larger natural disaster that causes multiple casualties and infrastructure damage, patients with near-lethal injuries will probably be triaged to palliative care. In these cases, the injury severity of casualties will be reduced.

Pathophysiology. Traumatic injuries that result in a need for mechanical ventilation include closed head injury, hemothorax, pneumothorax, pulmonary contusion, flail chest, traumatic amputation, blood loss, and blast injury.[29–34] As in traditional trauma care, patients with the most severe injuries require mechanical ventilation for treatment of acute lung injury and ARDS.

Geographic Area Affected. In an explosion or fire, the affected area is usually finite. This includes a building, a bus, or an outdoor gathering (eg, sports event, concert).

The result is a defined local area where casualties are limited. Additionally, local events allow undamaged areas of the city or town to absorb the increased demand for critical care and to provide support. A larger natural event may affect greater numbers of patients and result in damage to hospitals and transportation systems. In these instances, the walking wounded are the most likely victims, and critically ill victims at the scene are likely to expire.

Chemical Weapons

Injuries following chemical weapons exposure vary with the agent. Globally, chemical agents are classified as lung-damaging agents, blood agents, blister agents, and nerve agents.[35–37] Chemical agents likely to be used include chlorine, phosgene, and ammonia. These chemicals are commonly used in industrial processes and are readily available. Nerve agents that cause paralysis have been used recently and are likely to be used in the future as well.[25,26,38] Mustard gas is perhaps the best known blister agent, and cyanide the most likely blood agent. These topics are covered in detail by Muskat.[39]

Expected Number of Victims. Under the appropriate environmental conditions, population density, and dispersion, chemical agents may result in thousands of victims. Despite this prediction, however, to date the number of victims has been in the hundreds, and the number of victims who have required mechanical ventilation has been less than a dozen.[40] The exception here is the Bhopal incident, which resulted in 75,000 deaths and many casualties (150,000).[39]

Time From Injury to Need for Mechanical Ventilation. The time until respiratory failure requires mechanical ventilation varies with the agent and exposure. Pulmonary agents can cause sudden death as a result of laryngeal obstruction or result in severe respiratory failure days after exposure. Nerve agents that cause paralysis may require ventilation at the scene. Historically, those patients who survive exposure to nerve agents require only short-term mechanical ventilation (< 8 h).[25,26,40]

Pathophysiology. Chemical weapons enter the body through the respiratory system and skin.[40] Blistering agents and choking agents result in bronchospasm and, over time, parenchymal lung injury and ARDS. Cyanide poisons mitochondria and prevents cellular respiration, resulting in death from cellular hypoxia. Nerve agents result in flaccid paralysis and apnea, but also produce substantial bronchorrhea and bronchospasm. So, though patients exposed to nerve agents may have normal lung compliance, airway resistance may be substantial.

Geographic Area Affected. Optimum effectiveness of these agents as weapons includes exposure of a large number of victims in a closed space. Outdoor exposure may also occur, but is limited by winds and weather. As such, these exposures are thought to be limited to a single geographic area.

Epidemics and Febrile Respiratory Illnesses

Epidemics and febrile illnesses may result from both natural and man-made causes. The SARS epidemic of 2000 and looming pandemic flu epidemic are classic examples of natural febrile illnesses that may result in large numbers of patients with respiratory failure. To date, avian flu has occurred in clusters, with 2–8 cases per cluster. Nearly all of the cluster cases have occurred among blood-related family living in the same household. Most people in these clusters have been infected with the H5N1 virus through direct contact with sick or dead birds. However, human-to-human transmission of H5N1 virus, though rare, cannot be excluded. The current mortality rate from H5N1 flu is greater than 50%.[41,42]

In this category we have included anthrax and botulism exposure. Both are likely to be the result of bioterrorism, although botulism poisoning can occur from improperly preserved foods.[43] Anthrax, caused by *Bacillus anthracis*, has been used in the United States as a weapon, which infected 22 people and killed 5. Anthrax is not transmitted from one person to another.[44–46]

Expected Number of Victims. Epidemics have the possibility of involving people from all over the world. If the avian flu virus were to mutate into a more easily transmissible virus, tens of thousands could be affected. Botulinum toxin and anthrax have the ability to infect similar numbers of people.

Time From Injury to Need for Mechanical Ventilation. Though epidemics are likely to result in the greatest number of casualties, the time from exposure until development of respiratory failure may be hours to weeks.[40,43,46] In these cases, patients will probably arrive at the hospital with early signs of respiratory infection and respiratory distress.

Pathophysiology. H5N1 flu, plague, and SARS all result in ARDS from damage to the alveolar capillary membrane. Botulism results in neuromuscular ventilatory failure from paralysis, and may require mechanical ventilation for prolonged periods, with an increased risk of ventilator-associated pneumonia.[47] Anthrax results in hemorrhagic mediastinitis, hemoptysis, sepsis, profound hypoxemia, and ARF.[48]

Geographic Area Affected. Natural epidemics and bioterrorism agents in this class have the ability to infect entire regions, depending on the duration of the incubation period and the continued presence of the contagion. These events may be limited to a municipality or may include an entire city. In the case of pandemic flu, entire portions of a country may be affected.

Planning for Mass Casualty Respiratory Failure

The previous discussion of anticipated scenarios is critical for disaster planning. These issues are discussed in more detail in this issue by Muskat and Sandrock.[39,49] However, in order to determine what performance characteristics of ventilators are required, we must understand the mechanical characteristics of the respiratory systems of the patients who require mechanical ventilation. The combination of all of the scenarios includes patients with low lung compliance, hypoxemia, and acute lung injury or ARDS. The one exception would be the agents that cause paralysis, which result in patients with near-normal lung compliance but high airway resistance.

Ventilators may be needed for mass casualty care in 3 different environments. The first is movement of patients from the scene of an accident (eg, explosion, natural disaster), the movement of patients between facilities (decompressing a localized event), and for the in-patient care of critically ill and injured patients. The movement of patients from the scene may be accomplished with oxygen therapy, manual ventilation, or use of a portable ventilator. This is under the purview of the emergency medical services director. Remember, in scenarios such as pandemic flu, patients are likely to seek medical attention for relief of flu symptoms long before they require mechanical ventilation. In these cases large numbers of emergency-medical-services ventilators will be unnecessary.

The last 2 scenario categories generally involve the care of critically ill patients with acute lung injury and ARDS, who require mechanical ventilation. Ventilators used for inter-facility transport and intensive care are under the purview of the critical care team, including an intensivist and a respiratory therapist (RT). The following discussion reviews the requirements of mechanical ventilators used for surge capacity in hospitals for definitive care.

Time Out: How to Ventilate the Patient With ARDS

Time outs prior to procedures have become popular in the hospital as a method to prevent errors. In the case of a surgical procedure this involves identifying the patient, the site, and the procedure. The nature of mass casualty care has caused many states, cities, and hospitals to purchase ventilators while swept up in the emotion of the moment. A time out is sorely needed.

Evidence-based management of the patient with ARDS is founded in the success of the ARDS Network trial published in 2000.[50] The principles of ARDS management are straightforward:

- Low tidal volume (V_T) (4–8 mL/kg of predicted body weight)

- Body-weight prediction based on height

- Constant volume delivery

- Plateau pressure $\leq$ 30 cm H_2O

- Stable fraction of inspired oxygen (F_{IO_2}) from 0.21 to 1.0

- Continuous mandatory ventilation: maintain minute ventilation

- Positive end-expiratory pressure (PEEP) to prevent alveolar collapse and lung injury

The ARDS Network data demonstrated that patients in the low-V_T group received a PEEP of 9.4 ± 3.6 cm H_2O, an F_{IO_2} of 0.56 ± 0.19, and a minute ventilation of 12.9 ± 3.6 L/min on day 1 of the study. By day 7, PEEP was reduced to 8.1 ± 3.4 cm H_2O, F_{IO_2} to 0.50 ± 0.17, and minute ventilation increased to 13.7 ± 3.8 L/min. These data provide us with some standard requirements for the functional performance of ventilators to be stockpiled for use in mass casualty respiratory failure (MCRF). Within a single standard deviation of the means of these ventilator settings, we could suggest that ventilators for MCRF should be capable of setting PEEP of 6–13 cm H_2O, F_{IO_2} of 0.35–0.75, and minute ventilation of 10–18 L/min. Assuming predicted body weights of 62–90 kg (males 165–196 cm tall), V_T of 250–720 mL (4–8 mL/kg) must be capable of being set. It is important to note that the desired V_T is based on patient weight, not lung compliance.

In previous publications we and others have listed ventilator functionality in an attempt to describe performance characteristics of ventilators.[3,4,51] Unfortunately, these are open to interpretation and subject to "spin" in the marketing literature of manufacturers. As the very simplest of tests, a ventilator stockpiled for MCRF *must* be capable of delivering a respiratory frequency of 6–35 breaths/min, a V_T of 350–600 mL (the adjustment of respiratory rate and V_T must be separate), an F_{IO_2} of 0.35–0.75, and a PEEP of 5–15 cm H_2O. Ventilators that are unable to produce those settings at a minimum *are not suitable* for MCRF.

Ventilator Performance Characteristics

Other operational characteristics of ventilators for MCRF have been suggested by the American Association for Respiratory Care.[4] Some explanation and clarification of these characteristics are in order. Table 1 lists the desirable characteristics of ventilators for MCRF. The optimal ranges for operation remain to be determined, but here we try to represent the minimum required characteristics and characteristics that might provide added benefit. These recommendations are always in flux, and guidance such as the American Association for Respiratory Care ventilator guidelines[4] are living documents subject to change in the face of new evidence.

Characteristics of ventilators for MCRF that are more difficult to quantify are clearly just as important. A ventilator for MCRF should be rugged, portable, withstand shock and vibration, and continue operation if dropped. There is a military specification for these characteristics, but it is unclear if ventilators for MCRF must meet this standard. Clearly, meeting the military standard would be desirable. Portability is important, and ideally the devices would be, well, "portable." A weight of < 10 kg is often a goal.[4] In our minds, a portable device is one that an RT or nurse can pick up with one hand (with or without a carrying case) and move without difficulty.

Ideally a ventilator for MCRF should have minimal gas consumption. That is, oxygen from a limited source should not be wasted. Gas consumption by a ventilator can be affected by pneumatic or fluidic control, continuous flow for triggering, pressure relief from mechanical blenders, and other internal leaks.[52] Although this has not been well studied, we believe that, ideally, 90% of the gas entering the ventilator should go the patient as part of the minute ventilation. Equally important is battery life. Battery life is affected by the age of the battery, temperature, and charging history, regardless of the ventilator. Ventilator characteristics that decrease battery life include the mode of ventilation, the F_{IO_2}, and the PEEP.[53] Patient characteristics can also affect battery life: the greater the load (lower compliance, higher airway resistance), the shorter the duration of operation. This is just one of the factors that create a conundrum in choosing ventilators for MCRF. A ventilator may be considered desirable by some clinicians by virtue of delivering pressure-control ventilation, but the use of pressure control ventilation can reduce battery life by nearly 50%, compared to volume control with the same delivered V_T.[53]

The ventilator should be easy to trigger and have an acceptable work of breathing. Most current-generation portable ventilators meet this requirement.[54,55] Cost should be less than $10,000. In large purchases, such as those made by the states for mass casualty care, substantial price reductions can be realized.

The ventilator should be intuitive and easy to use. This is a soft criteria that is difficult to measure. In addition, the manufacturer should provide training in person and via multimedia (digital video disc [DVD] or Web-based). Mainte-

Table 1.   Performance Characteristics of Ventilators for Mass Casualty Respiratory Failure

Characteristic	Rationale	Capabilities	
		Mandatory	Desirable
FDA-approved for adults and pediatric patients	Natural disasters, pandemics, and chemical/bioterrorism will also affect children	Ventilate 10-kg patient	Ventilate 5-kg patient
Ability to operate without 50-psig compressed gas	The redundancy for electrical power in hospitals far exceeds oxygen stores and redundancy. In the absence of high-pressure oxygen, low-flow oxygen from a flow meter can be used to increase F_{IO_2}.	Operate without 50-psig input F_{IO_2} from 0.21 to 1.0	Operate from a 50-psig gas source or alternating-current power, whichever is available
Battery life $\geq$ 4 h	Allow for transport from facility to facility. Provide continuous support during intermittent power failure	4 hours of operation at nominal settings	$>$ 4 h operation at nominal settings
Constant volume delivery	Meet guidelines for V_T delivery, as dictated by the ARDS Network protocol. Reduce potential for ventilator-induced lung injury. Provide age-appropriate settings	Volume control ventilation (250–750 mL)	Pressure control and volume control ventilation
Mode: CMV	Meet ARDS Network guidelines. Assure minimum ventilation in a situation of multiple patients and a shortage of caregivers	CMV	CMV, IMV, and pressure support
PEEP	Meet ARDS Network guidelines. Prevent ventilator-induced lung injury. Reverse hypoxemia	Adjustable: 5–15 cm H_2O	Adjustable: 5–20 cm H_2O
Separate controls for respiratory rate and V_T	Meet ARDS Network guidelines. Assure minute ventilation in apneic patients	Respiratory rate 6–35 breaths/min	Respiratory rate 6–75 breaths/min (for pediatric patients)
Monitor airway pressure and V_T	Meet ARDS Network guidelines. Provide assessment of patient's lung compliance. Patient safety: prevent overdistention	Monitor peak inspiratory pressure and delivered V_T	Monitor plateau pressure and patient V_T
Appropriate alarms	Patient safety. Improve ability to monitor large numbers of patients with reduced staff	Alarms for: Circuit disconnect High airway pressure Low airway pressure (leak) Loss of electrical power Loss of high-pressure source gas	Alarms for: High V_T in pressure modes Low minute ventilation Remote alarms

FDA = Food and Drug Administration
F_{IO_2} = fraction of inspired oxygen
CMV = continuous mandatory ventilation
ARDS = acute respiratory distress syndrome
IMV = intermittent mandatory ventilation
PEEP = positive end expiratory pressure

nance, including battery charging and replacement, is also an important issue. Ventilator maintenance should be able to be accomplished by trained technicians on site, and requirements for battery charging should be explicitly detailed.

Finally, vendor support and longevity is critical. The manufacturer should commit to support of the product for a minimum of 6 years, preferably 10 years. The manufacturer should have a 24-hour-a-day, 365-day-a-year technical support line. There is some advantage in purchasing ventilators made in the United States, as in a pandemic situation, both shipping time and loyalty of foreign manufacturers may create a problem. There is no way to judge if a manufacturer is a long-time player in the market or a fly-by-night operation, aside from history. Determining a manufacturer's intentions and quality is critical, but elusive.

Ventilators

Classification of mechanical ventilators is a complex task, which has been handled admirably by Chatburn and Branson.[56] For the purposes of describing ventilators for MCRF, we have categorized types of ventilators that might be used, based on characteristics.[3,51] This description includes automatic resuscitators, emergency-medical-services ventilators, pneumatically powered portable ventilators, electrically powered portable ventilators, and full-feature intensive-care ventilators.

Automatic Resuscitators

An automatic resuscitator is designed to replace the need for hand-bagging. These devices are predominantly pneumatically powered and pressure-cycled. Automatic resuscitators have few to no alarms, cannot provide a constant V_T, cannot set rate and V_T separately, and commonly provide 100% source gas or a lower concentration with the use of an air-entrainment mechanism.[52] Most manuals of automatic resuscitators lead with a warning, "WARNING: Do not leave the patient unattended," which is problematic in a scenario where there are too many patients and not enough caregivers. Operational characteristics of these devices suggest that use in ARDS will be unsuccessful. The inexpensive nature of these devices is attractive. However, until manufacturers prove success in ventilating patients with ARDS, these devices are not suitable for MCRF. Stockpiling an inexpensive device that will not meet patient need is still a waste of money.

Emergency Medical Services Portable Ventilators

An emergency medical services portable ventilator is used in patient transport, typically in emergency care via ambulance. These devices are more reliable, rugged, and have greater functionality than automatic resuscitators. The functionality and cost in this group are quite varied. Some devices set V_T and respiratory rate via a single control. Others have separate controls for both settings. PEEP is usually supplied via an external valve. Emergency medical services portable ventilators often provide continuous mandatory ventilation and/or intermittent mandatory ventilation. F_{IO_2} is commonly 100% source gas or a single lower concentration, with use of an air-entrainment mechanism. Most of these devices are pneumatically powered, with or without electronic control. Monitoring and alarms are limited. These devices require 50-psig input, and this, along with the limited alarms and monitoring, preclude stockpiling for MCRF.

Sophisticated Portable Ventilators

Pneumatically Powered. Sophisticated pneumatically powered portable ventilators have the ability to provide continuous mandatory ventilation and intermittent mandatory ventilation, set PEEP, have a low work of breathing, and allow separate control of V_T and respiratory rate. These devices meet most of the performance characteristics for MCRF. The limitations of these devices surround the pneumatic power source. In the absence of a 50-psig gas source these devices cannot operate. F_{IO_2} is typically limited to 100% source gas, which wastes oxygen. Some ventilators use an entrainment device to allow an F_{IO_2} of 0.60. Blenders can be used but require compressed air as well. Finally, the absence of electronics precludes the necessary alarms required to be recommended for MCRF stockpiling. These ventilators cost $3,000 to $4,000.

Electronically Powered. These devices are often used in home care and in-hospital transport. Several electronically powered, sophisticated portable ventilators meet the performance characteristics required of a ventilator for MCRF. There is some substantial difference in weight among these devices (5–15 kg). Battery life and gas consumption vary, depending on the driving system (turbine, piston, compressor) of the ventilator.[52] There are a number of commercially available ventilators in this category, which have been stockpiled by the Centers for Disease Control,[57] by hospitals, and by local, regional, and state organizations for MCRF. The cost of these ventilators ranges from $5,000 to nearly $15,000.

Critical Care Ventilators

Critical care ventilators are capable of managing all types of respiratory failure. These devices have not been recommended for MCRF, due to the large size, cost ($> $30,000), and complexity. The plethora of modes and

Table 2. Possible Sources of Additional Ventilators in a Mass Casualty Respiratory Failure Scenario

Source	Strategy	Possible Problems
Affected hospital	Cancel elective surgeries Repurpose anesthesia workstations as mechanical ventilators and intensive care unit monitoring (during nontrauma disasters)	Number of anesthesia machines is limited. If the duration of mechanical ventilation is prolonged, anesthesia machines will be needed when surgeries and other procedures are re-initiated.
Unaffected hospital	Redistribute available equipment from unaffected hospitals to those in need	There are few extra available ventilators at most hospitals, even during usual conditions. Delayed situation awareness may reduce willingness of unaffected hospitals to share equipment.
Mechanical ventilator rental services	Obtain additional ventilators from a rental company	The same company may have contracts with a number of affected hospitals, so the total number of additional ventilators may be limited. Logistical delays may be encountered when sending ventilators from distant geographic areas.
Strategic National Stockpile	Deploy mechanical ventilators to states or cities in need	Delay in distribution because most states still have limited capacity to distribute equipment from the Strategic National Stockpile Unclear how distribution will be prioritized when multiple hospitals request ventilators at the same time

options provided by a critical care ventilator is an advantage in routine use by critical care RTs and intensivists, but becomes a liability in a mass casualty situation.

Noninvasive Ventilators

Noninvasive positive-pressure ventilation (NPPV) is a standard of care for respiratory failure in patients with acute exacerbations of chronic obstructive pulmonary disease, under normal circumstances.[58-61] The use of NPPV in MCRF, however, has important limitations. In many circumstances the final stage of MCRF is ARDS. The use of NPPV for ARDS has been reported,[62,63] but recent evidence cautions against this practice because of lack of efficacy and potential for complications.[64,65] A recent survey of United States hospitals suggested that NPPV is not commonly used for ARDS.[66]

The literature that details the success of NPPV in chronic obstructive pulmonary disease clearly demonstrates a substantial time commitment (1–2 h) spent by the RT at the bedside at initiation, which is an impracticality in MCRF.[67] Additionally, recognition of NPPV failure and the requirement for emergency intubation are more difficult in a scenario of too many patients and too few caregivers.

Some concern over NPPV qualifying as an "aerosol-producing procedure" that possibly increases the risk of caregiver exposure has been raised,[68,69] although the evidence is weak and the experience from southeast Asia does not support this theory.[70,71]

Noninvasive ventilators tend to be less expensive and smaller than many invasive devices, but have limitations that preclude recommendation for stockpiling, which include no battery back-up, limited monitoring, limited alarms, and inability to provide volume control (most devices provide pressure-targeted ventilation).

Despite the limitations of noninvasive ventilators, many hospitals have these devices available. In an MCRF situation we suggest the re-purposing of noninvasive ventilators for use as invasive ventilators, especially in situations related to ventilator shortages, which could result in patients receiving no mechanical ventilatory support.

This re-purposed use will address concerns regarding potential environmental/caregiver contamination by "aerosol production" associated with use of NPPV, yet still provide adequate ventilatory support for many patients. Some of the newer NPPV devices have built-in alarms and are more suitable than those without alarms. When simpler devices are used, the addition of pressure monitoring and low-pressure/disconnect alarms is recommended. These devices should also be used only under the supervision of an RT. There is a concern over re-breathing if a single-limb circuit with a leak is used during invasive ventilation. A circuit with an exhalation valve would be preferred.

Other Sources of Ventilators

This paper has predominantly discussed stockpiling as an answer to ventilator shortages. However, local resources should be used as well. Table 2 lists the possible sources of additional ventilators during MCRF.

Summary

MCRF represents an important concern for health care systems and governments around the world. The best so-

lution is thoughtful planning and cooperation between all the shareholders. Despite our inability to predict when an event may occur and how many patients will require mechanical ventilation, we must plan using best evidence. Ventilators purchased for MCRF must meet the demands of the patient and the skills of the operator. This is a serious matter that requires serious effort by clinical experts. We must plan unemotionally and effectively.

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Discussion

Sandrock: I have a question. Our hospital is a big academic center and we have 10 high-frequency oscillatory ventilators. I want to hear your opinion about using these in a mass casualty situation, particularly in ARDS. We have talked about this in our hospital, and of course some of our RTs get excited and think "yeah, we will take out the oscillator." But the time commitment to run that machine is different than a conventional ventilator, along with many other issues, such as a pneumothorax, frequent use of radiographs, et cetera. The RT time is very time consuming. I would like to hear your opinion—if you had a mass casualty incident and there were many cases of acute lung injury and ARDS, would this be something that you would employ, given limited staff potentially? What are your thoughts on that and other modalities of nonconventional ventilation in a mass casualty setting?

Branson: It's kind of an unfair question, because I wouldn't employ it under normal circumstances. HFOV [high-frequency oscillatory ventilation] obviously has its spot in neonatal ICU. We have not used HFOV in our adult ICUs. I don't think you need to deploy high-frequency oscillators in a mass casualty care situation. Now, having said that, if you have 10 and if your staff has the time and you have sick patients and that's what you normally do, then that's what you should do. But I don't think the idea that somehow we're going to have to stockpile oscillators, and inhaled nitric oxide, and prone-positioning beds is a good one. The standard of care is still volume-control or pressure-control ventilation, at the appropriate tidal volume and plateau pressure with the appropriate PEEP providing a lung-protective strategy.

Daugherty: There are significant infection-control concerns related to using HFOV in epidemics of respiratory illness. The most commonly used HFOV ventilator has both an exhalation port and 2 high-pressure dump valves. The valves are really not amenable to filtering, and scavenging all of them would be very difficult. So, although there is not confirmed evidence that use of HFOV increases risk of secondary infection, its use could potentially pose substantial challenges in terms of infection control.

Rubinson: I totally agree with you, theoretically. It's just like the NPPV issue, though. The Canadian report did not show increased risk with use of HFOV,[1] although there was a very small number of cases, so we don't know if it really is that it doesn't harm people or in fact if it was just that they were way underpowered to find any effect, but they didn't find any additional exposure to their staff with that. But, again, it's hard to interpret. The NPPV in Canada had suggestions of secondary transmission, but not in Asia, as Rich mentioned.

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Ritz: Rich, you didn't go through the array of portable ventilators that you had on the screen, but I know some use specialized breathing circuits that are unique to those machines. That really seems to be a bit of a complication, because it really ties you to a product that you may have limited access to. Any thoughts on that? Is that a good idea to choose ventilators with specialized circuits?

Branson: I think ideally—we've discussed this—it would be great if all ventilators would be able to make the circuits for us just by cutting aerosol tubing and putting Y-pieces on. The simple fact is, the greater functionality of the ventilator, the more likely it is to have a specialized circuit. Most adult ICU ventilators can use a simple circuit, and while we would love to stockpile these devices, the cost is prohibitive. Many of the portable ventilators require a proprietary circuit, which includes a flow sensor and an exhalation valve. Others use a standard IPPB [intermittent positive-pressure breathing] circuit. Circuit availability is an issue, as most hospitals seem to stock just the circuits needed for the short term.

I guess the question is, would you buy a ventilator that weighs 30 pounds so that you could use a universal circuit, or would you buy one that weighs 15 pounds that uses a proprietary circuit? I think each individual group will have to balance weight, storage space, and performance with circuit availability. There is no perfect ventilator for this purpose, and people have purchased many different kinds. I think the right thing, Ray, is that it would be great if we could use a single circuit for all of these ventilators, but I don't think it's practical.

Rubinson: We just completed a survey of respiratory equipment in Seattle/King County, and our highest risk item, in terms of not having enough, is circuits. We think it's because they're so cheap and storage is so expensive that the cost to store them makes it easier to get them just in time. So most of our hospitals are getting their circuits on an almost daily basis. There are endotracheal tubes till the cows come home in the market place and in manufacturing, but ventilator circuits are actually in substantially short supply if all of us in all of our different geographical areas clamored for many additional circuits at the same time.

Branson: One of the other things about that, Ray, is we've recommended that every ventilator that's stockpiled be stockpiled with a minimum of adult and pediatric ventilator circuits, HMEs [heat-and-moisture exchangers], devices to add oxygen. If you're doing it right and you get 6 ventilators from your state's stockpile, you'll not only get those individual circuits within the case, but automatically a big box comes that has enough to keep those individual ventilators running for 7 to 10 days.

Ritz: The other issue that comes up—and I haven't played around with every one of those ventilators that you showed on the screen, but some of them. There is a fair amount of complexity with all of those machines, and a lot of very subtle background controls that can have some very dramatic effect on how the ventilator actually works. And it's not really very feasible to expect the caregivers to flip through a 150-page operator's manual to operate a ventilator that they may or may not have seen before. I'm not sure that you can come up with a 3×5 file card that is going to show you how to operate some of these complex features. It's not to knock the special features, but I've found them to be pretty challenging to learn how to

run some of those things. Any thoughts on training?

Branson: When we did the training with the stockpile ventilators, one of the issues about being considered for the stockpile is that you have a quick setup card. So you have to be able to have a single card—I forget what size it is—that you can pull out and it can tell you in very simple steps how to set up that ventilator appropriately. I know that is done by virtually every manufacturer, to my knowledge. You're right; each of these ventilators has its nuances underneath the surfaces, but for the most part the number of controls that they have for setting respiratory rate, tidal volume, PEEP, and F_{IO_2} are pretty simple. Is the question that we should be simpler? Where are you going?

Ritz: It wasn't so much should they be simpler. I did develop a healthy respect for how important it was to not get too complicated with your expectations. Having a quick-start button on the ventilator so that it comes up in some basic settings and doesn't expect you to do anything fancy in the background is probably critical. Having evaluated some transport ventilators recently for programs within our institution, I was impressed how many times one of my staff said, "I think the machine is broken," because they had just told it to do something that they didn't realize that they had told it to do.

Branson: Clearly, we've encouraged all of the manufacturers that we have talked to that there ought to be a way to input the patient's body weight and it would automatically come up with reasonably appropriate settings for the therapist to move from, from there. Most of them, to my knowledge, have done that.

Wilgis: I would like to add to the discussion here. It's been one of the ongoing problems we've had in Florida. We first worked with Impact [Impact Instrumentation, West Caldwell, New Jersey, manufacturer of the Uni-

Vent 754], who was a primary source for the state, and now we've branched out to allow awareness of all of the other transport ventilators in the market. The one thing that we have asked our industry partners was to *please* work with us on the education for the end user. And how can you do that?

Florida has approximately 11,000 licensed RTs. What is the best way to educate all of them on how to use these machines? It is a real challenge for us. You have to go beyond pulling the card out of the box. That is simple operation, but if you have someone in ARDS, then you need to get to the nitty-gritty of those machines, and it's a challenge. So we continue to work proactively with industry to come up with simpler systems and intelligent ventilation. Just a point of reference.

Muskat: Many inexperienced and inadequately trained individuals in the military are used for the critical care support. Inadequately trained means we take some critical care nurses who normally don't treat ventilator-dependent patients and teach them how to use the Uni-Vent 754 ventilator. We think they should be required to know the "knob-ology" just as well as the physician and the RT. I have been impressed by the RTs, as they are well-trained and understand the transport ventilators—at least the ones that we teach, the LTV 1000 and the Uni-Vent 754. Each is relatively easy to learn.

I agree there is some degree of mastery that comes with experience. That experience came the hard way. We've learned from experience that when the fuse breaks, how does the RT who has never worked with that ventilator recognize the problem? But it is the non-traditional critical care provider, such as the ones we're beginning to use with mass casualty, that we're really talking about. It's the individual who has relatively little experience with *any* kind of ventilator, much less a transport ventilator.

I think the education piece must be as simple as a one-page cheat sheet,

but accompanied by a relatively simple manual. It also should include the simplification of the options that they can manipulate. We want to get away from the multi-level choices of different modes of ventilation and simply just pick one or two and say that's all you've got to worry about.

Ritz: I'm not sure how many of the vendors provide this level of support, but having virtual ventilators on the Internet that let you play with the machine at your convenience. This provides more time to become familiar with a device after a vendor drops one machine off for 2 weeks, and maybe some of your staff use it and maybe they don't. Particularly folks who are younger than me and are used to computer simulations. They get very proficient very quickly when they use those kinds of training systems. I would almost like to see that be one of the requirements— that there has to be some kind of online training system, virtual ventilator, to play with.

Branson: I think that's a great idea, and, again, it does go toward John [Wilgis]'s talk tomorrow, which is, if you're going to buy a bunch of ventilators in your state, are you just going to put them all in a room and break them out when you need them? It makes more sense to me to offer at least half of your stockpile to your hospitals to actively use them on a regular basis and then they take over the maintenance of that device, and the staff doesn't need to be trained because they eventually start using it on a daily basis, either for transport, or in their emergency room, or in their recovery room. Clearly some of the ventilators are sophisticated enough to easily be used in cardiac intensive care, where patients are ventilated for 3 or 4 hours. You don't need a $30,000 ventilator to do that. I agree, Ray; one of the issues that we have to get to is training; it's not just the ventilator, but the caregiver and the training they get.