

Positive-Pressure Ventilation Equipment for Mass Casualty Respiratory Failure

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In the event of an influenza pandemic, patients with severe acute respiratory failure (ARF) due to influenza will require positive-pressure ventilation (PPV) in order to survive. In countries with widely available critical care services, PPV is delivered almost exclusively through use of full-feature mechanical ventilators in intensive care units (ICUs) or specialized hospital wards. But the supply of these ventilators is limited even during the normal course of hospital functioning. Purchasing and maintaining additional full-feature mechanical ventilators to be held in reserve and used only during mass casualty events is too expensive to allow the stockpiling of such equipment. Consequently, planning and preparedness efforts to respond to a severe influenza pandemic have stimulated consideration of limited-feature, less-expensive ventilation devices to augment traditional PPV capacity. This article offers guidance to authorities charged with preparing for mass casualty PPV in deciding which PPV equipment would be adequate for ventilating patients for days, weeks, or even months during a medical catastrophe.

EXTENSIVE EFFORTS are being undertaken to prepare the medical community for a moderate to severe influenza pandemic. If the currently circulating H5N1 virus causes the next human pandemic, and if the clinical conditions of the approximately 180 people infected as of mid-March 2006 are representative of the pandemic strain's virulence, then many people will develop severe acute respiratory failure (ARF).¹

In countries where advanced medical care is widely available, patients with severe ARF who cannot maintain adequate blood levels of oxygen despite noninvasively delivered supplemental oxygen, or who have elevated blood levels of carbon dioxide and a low pH, are treated with positive-pressure ventilation (PPV). Most patients with severe ARF who receive PPV survive, in spite of their severe illness, when treatment includes full-feature mechanical ventilators used within intensive care units (ICUs) or specialized hospital wards. Even 35%–65%

of patients with acute respiratory distress syndrome (ARDS) survive.^{2–8} By comparison, without PPV, almost all patients with severe ARF, except when it is caused by conditions immediately correctable by pharmacologic antidotes (e.g., naloxone for opiate overdose), are likely to die.

Hospitals typically have sufficient numbers of ventilators to meet everyday demand but not enough for demand peaks, when they are forced to rent additional equipment. During a large mass casualty event when a region's ventilator supply is already allocated and rental inventories are depleted, a state can request distribution of additional mechanical ventilators from the Centers for Disease Control and Prevention's Strategic National Stockpile (SNS). The SNS maintains thousands of Impact Uni-Vent Eagle 754 and Puritan Bennett LP-10 ventilators and is considering accumulating thousands of additional ventilators. These portable ventilators have limited functions when

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TABLE 1. CHARACTERISTICS OF ALTERNATIVE POSITIVE-PRESSURE VENTILATION EQUIPMENT FOR MASS CASUALTY CARE

<i>Device</i>	<i>Power</i>	<i>Constant V_T</i>	<i>Effect of Leak</i>	<i>Alarms</i>	<i>PEEP</i>	<i>Cost</i>
Bag-valve manual ventilator	Operator	No (may use volume limiter)	Reduced V _T	None	External valve	\$10
Automatic resuscitator	Compressed gas	No	Reduced V _T failure to cycle	None	No, low levels based on operation	\$45–\$300
Portable ventilators						
EMS transport ventilator	Compressed gas	Yes	Reduced V _T	High pressure, disconnect	External valve	\$1,500–\$3,500
Portable (pneumatically powered)	Compressed gas	Yes	Reduced V _T alarm	Low/high pressure, disconnect, apnea	Yes	\$4,000–\$8,000
Portable (internal gas source)	Compressed gas or electricity	Yes	Reduced V _T alarm	Full range	Yes	\$5,000–\$12,000
Full-feature mechanical ventilator	Compressed gas or electricity	Yes	Reduced V _T alarm, some have leak compensation	Full range	Yes	\$25,000–\$36,000
Anesthesia machine ^a	Compressed gas	Yes	Reduced V _T alarm	Full range	Yes	\$30,000–\$40,000

V_T = Tidal Volume; EMS = Emergency Medical Services; PEEP = positive end-expiratory pressure.

^aVentilator component of anesthesia machine is purchased together with monitoring and gas delivery systems.

compared to full-feature mechanical ventilators, but, despite their limitations, the SNS ventilators are likely to be adequate for a number of mass casualty events and are important federal resources. However, during a moderate or serious influenza pandemic, the SNS ventilator reserve is likely to be overwhelmed by a surge of patients with ARF, even if the number of ventilators is doubled or tripled.

For most hospitals, purchasing and maintaining sophisticated, full-feature mechanical ventilators to hold in reserve and use solely during very high demand situations such as mass casualty events is financially and logistically infeasible. The implication of a limited supply of mechanical ventilators is apparent: In a hospital without the ability to accommodate a surge of patients with ARF, such as may occur during an influenza pandemic, many patients with survivable conditions may die. Consequently, local, regional, and state ventilator caches are being contemplated and developed. A wide range of alternative PPV equipment, which has been designed and used for short-term PPV in non-ICU locations (Table 1),

is being considered for such additional caches, in anticipation that this equipment will be repurposed for definitive PPV* during mass casualty events. To date, there is no published guidance to assist in the selection of alternative PPV equipment.

There are a number of plausible scenarios in addition to an influenza pandemic in which a community may require alternative PPV equipment. We offer an evaluation of alternative PPV equipment based on anticipated scenarios where traditional PPV capacity is exceeded. This article is intended as a guide for authorities charged with preparing for such situations. It is our hope that it will prove a valuable tool in deciding which equipment is most appropriate for planning to augment PPV during civilian medical response to a mass casualty event.

**Definitive PPV* here refers to providing PPV (usually for days to weeks) until the patient no longer requires PPV. *Short-term PPV* is a temporizing PPV strategy (usually for minutes to a few hours) until definitive PPV can be provided.

PATIENT NEED FOR PPV WILL EXCEED NUMBER AVAILABLE

The medical impact of a mass casualty event will depend on specific characteristics of the disaster (e.g., lethality of exposure, numbers of people exposed, types of injuries) and the interplay between the exposed population's and the response systems' capabilities and vulnerabilities.⁹⁻¹² Recent experiences in which ventilation of a large number of patients was required are extremely limited. Lack of substantial PPV reserves has had little, if any, negative impact on disasters with traumatic injuries. However, the nature of mass casualty events in the era of globalization and catastrophic terrorism is changing. Outbreaks of emerging infectious disease such as SARS or pandemic influenza, deliberate civilian exposure to a serious pathogen, or widespread chemical or radiological exposure, either deliberate or accidental, may result in multiple exposed victims developing severe ARF. Additionally, disasters such as earthquakes or floods may render traditional PPV capacity in ICUs nonfunctional; thus, alternative PPV equipment will be urgently required.¹³⁻¹⁵

Perhaps the most significant modern mass casualty event yielding large numbers of people with respiratory failure was the polio epidemic in Copenhagen in the early 1950s.¹⁶ From July through December 1952, 2,830 patients were diagnosed with poliomyelitis, and 1,235 patients had some component of paralysis. Respiratory paralysis was identified in 345 victims. As many as 70 patients required assisted ventilation concurrently, but only 1 iron lung and 3 cuirass devices (which are also negative pressure ventilators) were available. Anesthesiologists performed tracheostomies, and medical students provided manual ventilation in 4-hour shifts. The manual ventilation device was a to-and-fro, non-self-inflating bag incorporating a soda lime carbon dioxide absorber—an ingenious design that conserves oxygen and provides heat and humidity. This event demonstrates that manual ventilation can be used for definitive assisted ventilation for patients with uncomplicated neuromuscular ventilatory failure.

Disaster characteristics that directly influence the demand for PPV include the number of victims with ARF, the time from exposure to development of ARF, and the duration of ARF. Table 2 lists some of the initial strategies available to temporarily increase PPV capacity. Patients' conditions underlying the respiratory failure will dictate which PPV equipment will be adequate. Clearly, patients with ARDS will require PPV equipment features that patients with uncomplicated, neuromuscular ventilatory failure may not need. Thus, for disasters resulting in mass casualty ARF, increased survival may depend on adequacy of features as well as quantity of PPV equipment available.

Table 3 summarizes plausible PPV needs and potential barriers to increasing capacity in response to epidemics, conventional explosions, and inhalational exposures to chemicals. These scenarios are not all-encompassing but represent the possible range of numbers of victims with ARF and the categories of respiratory failure that must be considered when selecting alternative PPV equipment. We include conventional explosions, not because they usually overwhelm PPV capacity, but because they occur in numerous locations and are the modality most frequently used by terrorists.¹⁷⁻²⁰ The likelihood of an epidemic or widespread chemical exposure is unknown and thought to be less than that of conventional explosions. However, such events are more likely to overwhelm local PPV capacity.

EVALUATION CRITERIA FOR ALTERNATIVE PPV EQUIPMENT

Even under normal ICU operations, many critical care healthcare professionals are in short supply.^{21,22} Almost certainly, when the need for PPVs overwhelms capacity, a number of non-critical care specialized health professionals will be required to participate in the care of the additional patients with ARF. Therefore, PPV equipment for such situations must be simple to use. Courses imparting fundamental critical care knowledge and skills for use during disasters, such as the Society of Critical Care Medicine's Hospital Mass-Casualty Disaster Management course, are likely to improve PPV sophistication among non-critical care specialized health professionals. Even with such cross-training, simple, user-friendly equipment will optimize skills and outcomes.

In the U.S., vacant ICU beds are in short supply.²³⁻²⁵ After the usual means to increase critical care capacity are exhausted (e.g., boarding ventilated patients in emergency departments and post-anesthesia care units), nontraditional sites for PPV must be used.^{26,27} Recently, the Working Group on Emergency Mass Critical Care recommended that this care continue within hospitals or similarly equipped, sophisticated temporary hospitals, by expanding the utility of the non-ICU wards.⁹ Existing patient rooms are highly adaptable in that they provide a means to control exposure to contagious patients, are constructed for safe delivery of medical gas, and have an established infrastructure for patient monitoring. Hence, we anticipate that alternative PPV equipment will be used outside of traditional ICU settings. Ruggedness, patient interface alarms, and battery operability, as well as ease of accommodating high and low pressure oxygen sources, must be considered when evaluating alternative PPV equipment.

Oxygen supply may be a limiting resource during a prolonged event in which the commerce infrastructure is

TABLE 2. OPERATIONAL ACTIVITIES THAT MAY AUGMENT POSITIVE-PRESSURE RESOURCES AND POTENTIAL SITUATIONAL LIMITATIONS

<i>Category of Response</i>	<i>Action</i>	<i>Potential Limitations</i>
Equipment		
Affected hospital	Canceling of elective surgeries Repurposing anesthesia machines as mechanical ventilators (during nontrauma disasters)	Number of anesthesia machines is still limited. If duration of mechanical ventilation is prolonged, anesthesia machines will be needed when surgeries and other procedures are re-initiated.
Unaffected hospital	Redistribution of available equipment from unaffected hospitals to those in need	Few extra ventilators are available at most hospitals even during usual conditions. Delayed situational awareness ^a may reduce willingness of “unaffected” hospitals to offer their equipment. During an influenza pandemic, many hospitals may be concurrently affected.
Mechanical ventilator rental services	Provision of additional ventilators by a rental company	Same company may have contracts with a number of affected hospitals, so total number of additional ventilators may be limited.
Federal mechanical ventilator reserve (Strategic National Stockpile)	Deployment of mechanical ventilators to states in need	Distribution may be delayed, since most states still have limited capacity to distribute equipment from the Strategic National Stockpile. It is unclear how distribution will be prioritized when multiple hospitals are requesting ventilators at the same time.
Evacuation		
National Disaster Medical System (NDMS)	Stabilization of critically ill patients, transport to unaffected regions, and admission to unaffected hospitals	Delayed situational awareness or presence of contagion may limit willingness of NDMS participating hospitals to accept evacuated patients. Also, contagion may increase logistical barriers to transporting patients or may be recommended against to facilitate control of secondary transmission. During an influenza pandemic, many hospitals may be concurrently affected.

^aSituational awareness refers to an accurate ascertainment of the temporal and geographic limits of the disaster and the number of people exposed.

TABLE 3. DISASTER SCENARIOS AND IMPACT ON MECHANICAL VENTILATION NEEDS

<i>Scenario</i>	<i>Expected Numbers of Victims Requiring Mechanical Ventilation</i>	<i>Time to Required Mechanical Ventilation</i>	<i>Length of Time for Mechanical Ventilation</i>	<i>Specific Need for Mechanical Ventilation</i>	<i>Geographic Area Affected</i>
1. Conventional explosions	Usually fewer than 100	Immediate	Days to weeks	ARDS, air embolism, severe traumatic brain injury, postoperative hemodynamic instability	Limited, unless there are concurrent explosions in multiple locations
2. Inhalational chemical exposures	Up to thousands	Immediate to hours	Hours to weeks	ARDS, proximal airway injury, bronchospasm, bronchorrhea, flaccid paralysis	Limited, unless there are concurrent explosions in multiple locations
3. Epidemics	Up to tens of thousands	Hours to days (after incubation period)	Days to weeks	ARDS (plague, SARS, avian influenza), altered mental status, hypoxemic respiratory failure not due to ARDS (anthrax), neuromuscular ventilatory failure (botulism)	May be an entire region, depending on length of incubation period and presence of contagion

impaired (e.g., Hurricane Katrina or influenza pandemic) or when hospital infrastructures are rendered nonfunctional (e.g., floods or earthquakes). Consequently, device consumption of oxygen must be evaluated.

In disaster scenarios, children may be victims, and, ideally, alternative PPV equipment will be appropriate for children (excluding neonates who require specialized equipment) as well as adults. Planning specifically for neonatal victims should be done in consultation with neonatal clinical experts and is beyond the scope of this article.

Several of the disaster scenarios most likely to overwhelm traditional PPV capacity pose additional logistical challenges. Events involving respiratory contagious diseases such as an influenza pandemic are particularly worrisome. The potential for healthcare workers to be harmed while caring for patients with ARF must be considered. For diseases spread by droplet, contact, or airborne transmission, the time spent by healthcare workers in the patient's room increases risk of transmission to them.²⁸ Especially in instances where healthcare workers may become very sick or even die from exposure, all efforts to maximize their safety must be undertaken, or the hospitals may cease to function.²⁹⁻³² In planning to augment PPV, the need to reduce the time staff are exposed to patients undergoing PPV must be considered. Some alternative PPV equipment has no alarms to alert caregivers that a potentially life-threatening situation is occurring for the patient. Consequently, alternative PPV with limited or no alarms will require nearly constant time at the bedside for caregivers to directly monitor the patient-PPV interactions.

STOCKPILING PPV EQUIPMENT AND THE IDEAL DEVICE FOR MASS CASUALTY VENTILATION

Stockpiling of material and equipment is an expensive disaster preparedness undertaking. The costs associated with the stockpiling of mechanical ventilators include the initial purchase cost, technical support to maintain quality assurance and control, and the purchase, maintenance, and storage costs of ancillary supplies, such as ventilator circuits. The logistical considerations of maintaining stockpiles of mechanical ventilators include maintenance of purchased equipment, replacement of equipment as technology is improved and updated, end-user training, and transportation and distribution of equipment.

Stockpiled mechanical ventilation and ancillary equipment should have broad utility. It should be appropriate to meet the anticipated clinical requirements of adult and pediatric victims in a variety of mass casualty situations. Ancillary supplies allowing the end user to make the me-

chanical ventilator immediately operational when it is distributed to local hospitals are clearly beneficial and preferable. Consideration should be given to purchasing more than one model of mechanical ventilator, or ventilators made by more than one manufacturer, to provide a safety net in the event of equipment failure or manufacturer recall. Finally, the acquisition of mechanical ventilators for federal stockpiles should be done in a manner such that national shortages of equipment are not created.

The ideal alternative PPV equipment is capable of ventilating patients across a wide range of clinical conditions, is appropriate for most of the population (e.g., children and adults), is safe to operate, and is relatively inexpensive to purchase and maintain (Figure 1). In addition, conditions during disasters warrant medical gas conservation, ability to operate for periods of time without reliable electricity, and simplicity of use. The selected alternative equipment should be flexible enough to be used during everyday hospital functions, so that staff will become familiar with operation of the equipment. We recommend that several locally, regionally, or state-cached PPV devices be distributed to each of the jurisdiction's hospitals to be used every day for transport of ventilated patients to and from the ICU (from the emergency department to the ICU or during transport to operating rooms or radiology). The remaining reserve equipment should be stored for efficient distribution to the sites in most need during a mass casualty event.

AIRWAY MANAGEMENT FOR MASS CASUALTY RESPIRATORY FAILURE

When assessing PPV equipment for disasters, one must consider the interface between PPV devices and patients. Endotracheal intubation has long been the gold standard of airway management. In recent years, alternative devices such as the laryngeal mask airway (LMA) and various types of ventilating airways have been advocated for short-term airway management in both the preoperative setting and on hospital wards for patients who require emergent airway management.^{26,33,34} In the ICU and other specialized hospital wards, noninvasive ventilation with a tight-fitting facemask is used to provide PPV for a number of conditions causing acute respiratory failure.³⁵⁻³⁷ These useful airway options are available in everyday hospital practice; however, during a mass casualty event, we anticipate suboptimal patient monitoring and the use of personnel inexperienced with ventilating through masks and laryngeal mask airways. Therefore, for patient safety concerns, the use of endotracheal tubes in all patients receiving definitive PPV in such an event is warranted.

<p>Population</p> <ul style="list-style-type: none"> • FDA approved for use in adult and pediatric populations • Capable of providing adequate oxygenation and ventilation for most adult and pediatric victims with respiratory failure <p>Patient and Healthcare Worker Safety</p> <ul style="list-style-type: none"> • Provides audible alarms, recognizing, at a minimum, patient apnea, high pressure, low source gas pressure, and disconnection • Operator control of minimum respiratory rate, tidal volume, PEEP, and FIO₂ • Promotes healthcare worker safety through the ability for remote alarm monitoring, thus minimizing harmful exposures • Intuitive to use and requires minimal training for safe operation <p>Performance</p> <ul style="list-style-type: none"> • Uses medical gases efficiently and should not require pressurized medical gases as the sole power source • Able to operate on a battery or non-AC power source • Operates consistently for days to weeks • Standardized connections • Inexpensive to purchase and maintain
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FIGURE 1. CHARACTERISTICS OF THE IDEAL ALTERNATIVE POSITIVE-PRESSURE VENTILATION EQUIPMENT

Infection control concerns further support the use of endotracheal intubation for airway management. The laryngeal mask airway provides an effective seal only up to peak inspiratory pressures of 20 cm H₂O. This pressure is often inadequate to ventilate patients with ARF. Air leaks around the laryngeal mask airway may be a source of contagion and thus pose a danger to healthcare workers. Non-invasive ventilation with a face mask may pose similar problems, although this was not confirmed by the experience in one Hong Kong hospital during the SARS outbreak.^{38,39} We, therefore, have not included equipment that is intended for noninvasive ventilation in the evaluation of alternative PPV equipment, since we do not advocate stockpiling such equipment. Nevertheless, some of this equipment can be repurposed during a mass casualty event to ventilate patients with endotracheal tubes.

EVALUATION OF ALTERNATIVE PPV EQUIPMENT FOR MASS CASUALTY EVENTS

While both negative-pressure and positive-pressure devices can assist patient ventilation during mass casualty incidents, we concentrated our evaluation on positive-pressure equipment, because negative-pressure ventilation is unfamiliar to almost all practicing healthcare professionals. Positive-pressure devices are numerous, with differences in power requirements (compressed gas, electricity, or both), control of different inspiratory and expiratory parameters, ability to provide and compensate for PEEP (positive end-expiratory pressure), monitoring, and alarms. To facilitate

equipment evaluation, we adopted a previously described schema to categorize positive-pressure devices.⁴⁰

Devices were evaluated within the context of definitive mechanical ventilation for mass casualty events. Our assumption was that this device must be used from initiation of ventilation until the patient no longer required mechanical ventilation (Table 4).

Manual Ventilation

Manual resuscitators are inexpensive, simple to use, and require only human power. These devices are commonly used in many healthcare settings, so most healthcare professionals are familiar with the majority of manual ventilation devices. However, staff familiarity has not been consistently translated into maintenance of appropriate gas exchange for patients undergoing manual ventilation. Several investigators have noted hyperventilation, overexpansion of the lungs, and acute respiratory alkalosis during manual ventilation, resulting in cardiovascular complications. Such outcomes can be expected due to limitations in certainty about tidal volume, frequency, and pressure delivered to patients.

Still, manual ventilation can be successful in the hands of a skilled clinician, but it may require additional volume- and pressure-monitoring capabilities. Monitoring end-tidal CO₂ may also prove helpful in preventing hyperventilation but may not be possible during a mass casualty event. For patients with hypoxemic respiratory failure secondary to ARDS, prolonged manual ventilation may cause volutrauma (PPV-induced lung injury due to overexpansion of lung units) and atelectrauma

TABLE 4. EVALUATION OF POSITIVE-PRESSURE VENTILATION EQUIPMENT FOR MASS CASUALTY CARE

<i>Adequacy for Population</i>		<i>Safety</i>			<i>Performance</i>		
<i>Device</i>	<i>Adequate Gas Exchange for Range of Patients</i>	<i>FDA Approved for Pediatric</i>	<i>Requires Constant Caregiver Presence</i>	<i>Detects Apnea and Disconnect</i>	<i>Ability for Remote Alarming</i>	<i>Ease of Use</i>	<i>Oxygen Consumption</i>
Bag-valve manual ventilator	Generally, yes except for most severely ill patients	Yes	Yes	No	No	Easy (but to master requires training)	10–15 L/min
Automatic resuscitator	No, except for patients with normal lungs and no airway secretions	No	Yes	No	No	Operational principles require significant training	15–40 L/min
Portable Ventilators							
EMS transport ventilator	Yes, except for most severely ill patients	No	Yes	No	No	Simple setting of rate and tidal volume	Depends on particular ventilator
Portable (pneumatically powered)	Yes, except for most severely ill patients	No	No	Some devices capable	Some devices capable	Simple setting of rate and tidal volume	Equivalent to minute ventilation
Portable (internal gas source)	Yes, except for most severely ill patients	Yes (>5 kg body weight)	No	Yes	Yes	Simple setting of rate and tidal volume up to more sophisticated devices requiring additional training	Depends on particular ventilator
Full-feature mechanical ventilator	Yes, except for most severely ill patients	Yes	No	Yes	Yes	Operational principles require significant training	Able to minimize O ₂ consumption
Anesthesia machine	Yes, except for most severely ill patients	Yes	No	Yes	Yes	Operational principles require significant training	Able to minimize O ₂ consumption

(PPV-induced lung injury due to cyclical opening and closing of lung units), unless an external PEEP valve is used.⁴¹ Ventilator-associated lung injury may worsen patients' outcomes,⁴² although suboptimal ventilation is likely better than no PPV.

Manual ventilators require the operator to be with the patient at all times, since operation depends on human power and the ventilators lack audible alarms. During events where staff are not in short supply or when close proximity to the patient does not pose significant risks (e.g., in the absence of contagion or continuing source of chemical exposure), manual ventilation is an acceptable, albeit suboptimal, means of providing PPV. Use of a non-self-inflating manual ventilator that alerts the operator to failure of oxygen supply (disconnection or empty oxygen source) may further improve patient safety.

Manual ventilation cannot replicate the tidal volume, frequency, fraction of oxygen in inspired air (FIO₂), PEEP, and mode of ventilation with the consistency and precision of a ventilator, especially when ventilation is anticipated to be necessary for days to weeks. Manual ventilation generally has limited oxygen provision options, thereby limiting the ability to titrate and conserve oxygen.

Automatic Resuscitator

Automatic resuscitators are inexpensive, pneumatically powered devices that have been considered for mass casualty mechanical ventilation. The most commonly marketed devices are pressure-cycled—that is, when the selected inspiratory pressure is reached, inspiration ends. For patients with significant air leaks, such as pediatric patients with uncuffed endotracheal tubes that do not fill the entire diameter of the proximal trachea, the set peak inspiratory pressure may not be achieved and the ventilator may remain stuck in inspiration. (Vortran's Surevent device is not FDA approved for pediatric patients.) Also, for patients with alterations in airway resistance (e.g., bronchoconstriction, secretions) or alterations in lung/chest wall compliance (e.g., pulmonary edema, chest wall edema), these devices will be unable to maintain a constant respiratory rate, tidal volume, or PEEP. Hence, in virtually all mass casualty conditions requiring augmented mechanical ventilation capacity, the operator has little control over delivered rate and tidal volume. This limitation can be particularly problematic when ventilating patients with severe airflow obstruction. For example, patients with significant nerve agent exposure will have copious airway secretions and bronchoconstriction until sufficient and repeated doses of atropine are administered. For these patients, the automatic resuscitators may cycle through inspiration so rapidly that no alveolar ventilation is accomplished, and

hemodynamically significant dynamic hyperinflation also may occur.

Automatic resuscitators have no disconnect or apnea alarms. Since the respiratory rate and tidal volume may change rapidly, a staff member must be monitoring the ventilated patient at all times, posing an additional risk to staff in the instance of infectious agents. In addition, use of automatic resuscitators would likely require significant training, since most healthcare professionals have minimal experience with pressure cycled ventilators. There are several reports of successful use of the Vortran;^{43,44} however, during Hurricane Katrina these ventilators could be used only for patients who had nonpulmonary reasons for mechanical ventilation (e.g., head injury). An experienced intensivist at Charity Hospital commented, "We found them to be absolutely useless in our ARDS patients. We found that hand bagging with a PEEP valve was best for these patients" (B. Deboisblanc, personal communication, January 28, 2006). There also has been concern about the instability of operating the Vortran when its position is changed.⁴⁵⁻⁴⁷

The automatic resuscitators require compressed gas to operate, and a single E-cylinder of oxygen will last only 30–45 minutes. Thus, despite the low cost, we believe these devices will not prove useful in any situation without a limitless supply of compressed gas and attendants who can monitor patients closely. The devices offer little additional utility over manual ventilation. In scenarios where adequate highly trained supervision is unavailable, such devices may even prove dangerous to the patient.

Portable Ventilators

Portable ventilators are compact and capable of operating on battery or pneumatic power, such that the equipment can easily travel with patients (e.g., field, intra- and inter-hospital transport). For this evaluation, EMS transport ventilators, pneumatically driven portable ventilators (which have more advanced alarm and monitoring functions than EMS transport ventilators), portable ventilators with internal compressors, and home ventilators are all considered to be portable ventilators.

Devices within each subgroup of portable ventilators are capable of ventilating and oxygenating all but the sickest of patients with acute respiratory failure. The EMS transport ventilator allows respiratory rate and tidal volume to be set but generally has limited versatility. Devices that have patient triggering capabilities and triggering mechanisms that compensate for device-provided PEEP are preferable. FDA-approved portable ventilators for pediatric use are available. Some of the home ventilators are not designed to deliver high fractions of inspired oxygen and may have limited utility for ARF.

Portable ventilators have a broad range of alarm and monitoring capabilities, from minimal to extensive. Devices without disconnect or apnea alarm capability will require constant staff presence. Some devices have an output that signals an alarm monitor (purchased separately) located outside the patient's room. Remote alarm capability makes it possible to close patients' doors, allowing for optimal staff and patient safety during an outbreak with a respiratory contagious disease.

The devices with internal compressors and oxygen blenders will be the most oxygen sparing. Additional features typically cost more. There are a number of portable ventilators available for purchase, and several meet most of the criteria for the ideal mass casualty PPV devices (see Table 4).

Full-Feature Ventilators and Anesthesia Machines

Most mechanical ventilators employed for definitive ventilation within modern hospitals are full-feature mechanical ventilators. Many of these devices can be used for children as well as adults. Full-feature ventilators afford greater control of ventilator variables, which may translate into an improved ability to ventilate unstable patients with severe ARF and improve patient-ventilator synchrony as compared to the alternative ventilation devices. However, the exact percentage of patients with ARF after a mass casualty event who may be insufficiently ventilated by an alternative device and who would do well with a full-feature ventilator and still have a significant chance of survival is unknown. From our everyday practices, our best guess is that this will be less than 20% of patients with ARF. Existing full-feature ventilators in hospitals can be reassigned to this group of patients when the alternative PPV equipment arrives.

Depending on the full-feature ventilator, many different modes of mechanical ventilation can be provided. Although there is much dogma about which modes are best for certain categories of patients, no proprietary modes have been shown to yield improved, meaningful outcomes for adults with ARF.

The most recent generation of full-feature ventilators have sophisticated alarm and monitoring capabilities. Again, the ability to monitor alarms outside of a closed patient room is optimal. The sophistication of these devices is both a strength and a potential point of concern. Under normal hospital operations, well-trained respiratory care professionals undergo targeted training to learn how to operate, maintain, and troubleshoot the particular ventilator they are using. During mass casualty events, some staff (especially from outside hospitals) may be asked to operate mechanical ventilators with which they

are not familiar. Thus, easier to use devices may be more appropriate for disaster situations.

Many full-featured ventilators can optimize oxygen use. The purchase price, which exceeds \$20,000–\$30,000 apiece, will likely prohibit the stockpiling of substantial quantities of these ventilators. Anesthesia machines can likely ventilate the majority of patients with ARF, and the existing hospital equipment can be repurposed to provide definitive ventilation. These devices, which are part of a sophisticated anesthesia delivery and monitoring array, are much more expensive than full-featured ventilators and thus not realistic candidates for large-scale stockpiling.

CONCLUSIONS

Plausible disaster scenarios may lead to numbers of patients with severe acute respiratory failure, necessitating response beyond individual hospitals' existing capacity of traditional full-feature mechanical ventilators for PPV. Planning and preparing for a disaster requires thoughtful provision for advanced airway management and delivery of adequate mechanical ventilation. Stockpiling of equipment to allow such support, while expensive, is an important component of disaster planning, with the potential to save thousands of lives in a scenario such as an influenza pandemic.

Portable ventilators are reasonable alternative PPV devices for use during mass casualty events. Healthcare organizations and agencies considering the acquisition of mechanical ventilators for emergency use in a disaster should understand the advantages and disadvantages of each ventilator type in order to make informed purchases and provide the greatest chance to save the most lives and optimize safe conditions for providers and patients.

Full-featured ventilators used in the ICU in times of routine operations are prohibitively expensive to stockpile in numbers sufficient to affect patient outcomes in a mass casualty situation, and their added capabilities will likely benefit only a small number of patients with ARF. We believe automatic resuscitators offer no advantage and, in fact, may be harmful when compared to manual ventilation. Emergency medical services transport ventilators may be helpful in moving victims from the scene to definitive care. Once in the hospital, portable ventilators capable of managing patients with respiratory failure are required. Fortunately, the costs of such ventilators continue to decrease while capabilities improve.

Even with significant state and regional investments in PPV caches, there will likely be a shortage of available PPV equipment during a severe influenza pandemic. Standardized approaches to prioritize allocation of scarce resources such as ventilators must be considered for such

events.^{9,29,48} In addition, the PPV equipment alone will not allow for augmented PPV capability. Non-critical-care-trained staff will likely be needed to assist with caring for the surge of critically ill and injured patients. The Working Group on Emergency Mass Critical Care, the Society of Critical Care Medicine's Hospital Mass Casualty Disaster course, and the Agency for Healthcare Quality and Research's Project Xtreme have begun important introductory work on cross-training health professionals for such catastrophes.

Even though not enough PPVs could be stockpiled to ensure that each patient with ARF has a ventilator during a severe influenza pandemic, the additional capacity afforded by reasonably sized caches can help a significant number of patients survive. This additional PPV equipment must be purchased within the context of a rigorously developed strategy to provide a coordinated medical response to catastrophes. Without such equipment, many patients may die despite having survivable clinical conditions.

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