Oxygen Supplies During a Mass Casualty Situation

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Mass casualty and pandemic events pose a substantial challenge to the resources available in our current health care system. The ability to provide adequate oxygen therapy is one of the systems that could be out-stripped in certain conditions. Natural disasters can disrupt manufacturing or delivery, and pandemic events can increase consumption beyond the available supply. Patients may require manual resuscitation, basic oxygen therapy, or positive-pressure ventilation during these scenarios. Available sources of oxygen include bulk liquid oxygen systems, compressed gas cylinders, portable liquid oxygen (LOX) systems, and oxygen concentrators. The last two are available in a variety of configurations, which include personal and home systems that are suitable for individual patients, and larger systems that can provide oxygen to multiple patients or entire institutions. Bulk oxygen systems are robust and are probably sustainable during periods of high consumption, but are at risk if manufacturing or delivery is disrupted. Compressed gas cylinders offer support during temporary periods of need but are not a solution for extended periods of therapy. Personal oxygen concentrators and LOX systems are limited in their application during mass casualty scenarios. Large-capacity oxygen concentrators and LOX systems may effectively provide support to alternative care sites or larger institutions. They may also be appropriate selections for governmental emergency-response scenarios. Careful consideration of the strengths and limitations of each of these options can reduce the impact of a mass casualty event. *Key words: oxygen, compressed gas, oxygen concentrators, liquid oxygen, bulk oxygen, mass casualty, emergency preparedness, pandemics*. [Respir Care 2008;53(2):215–224. © 2008 Daedalus Enterprises]

Introduction

Among the many challenges that mass casualty events create is the reliable delivery and maintenance of adequate oxygen supplies when the demand is suddenly increased. Cylinder and bulk oxygen stores can become strained, and delivery and restocking may be interrupted. During these events, large numbers of patients may need a wide variety of interventions, including manual resuscitation, transports to and within care sites, basic oxygen therapy, and mechanical ventilation.

Mass casualty scenarios can be either regional or global. Regional events such as earthquakes, floods, explosions,

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and fires affect a city or region and can disable or overwhelm operations in hospitals and medical response systems. Though hospitals and regions can be supported from outside the affected area in time, disruptions that disable hospital infrastructures, such as bulk oxygen systems or the piping system that connects to the patient-care areas, can have long-term effects. A pandemic event is more frightening since its effect would be global and resource demand could far outstrip any preparations or response plans. Workforce reductions could reduce manufacturing capacity and interfere with delivery. Large numbers of patients who require oxygen could quickly deplete normal oxygen supplies and render life-support equipment useless.

In both local catastrophes and pandemic events, hospitals may be overwhelmed, which would force an expansion of patient care to areas not designed for that purpose, such as auditoriums, dormitories, schools, and other available sites. Government agencies may deploy mobile field hospitals that are equipped with a variety of critical supplies, but not all may include utilities such as bulk oxygen. Careful planning at state and local levels as well as within individual hospitals could help support the oxygen requirements of alternative care sites.

Oxygen is available in compressed gas cylinders, portable liquid oxygen (LOX) systems, produced by oxygen concentrators, and supplied by bulk LOX systems. The purpose of this paper is to narrowly focus on options to best utilize resources and sustain the ability to provide oxygen to patients during mass casualty events.

Compressed Gas Cylinders

Compressed oxygen cylinders come in a variety of sizes (Table 1) and can be classified into 2 general types: smaller portable cylinders (sizes B through M), and larger cylinders (sizes H, K, and larger), which are best suited for stationary placement. The gas capacities of the most commonly available cylinder sizes are also listed in Table 1. With any given cylinder size, the gas capacity may differ slightly, depending on the cylinder manufacturer.

Portable cylinders are commonly used to provide oxygen during ground and air transports, for moving patients within hospitals, and to deliver oxygen in the field. They are convenient because of their light weight and small size, but are limited in the amount of oxygen they contain. Because of this limitation, portable cylinders do not offer a long-term solution for supplying oxygen to the critically ill patient. Smaller portable cylinders (sizes D and E) are commonly used for patient transports, since they are lightweight and compact and under most conditions will supply oxygen for 30 min to one or more hours, depending on the flow rate of gas delivery.

Table 1. Compressed Gas Cylinder Specifications*

Cylinder Type	Size	Service Pressure (psi)	Cubic Feet	Liters
Portable	B	2,015	5.8	164
	C	2,015	8.8	249
	D	2,015	14.7	416
	E	2,015	24	679
	E (HP)	3,000	35	991
	M	2,015	110	3,113
Fixed	H	2,015	220	6,226
	K	2,015	266	7,528

*Commonly found portable and stationary oxygen cylinders. Note that a cylinder's compressed gas volume may differ slightly depending on the manufacturer of the cylinder.

Transport cylinders today are made of steel, aluminum, or composite materials. Steel cylinders are the most economical but are heavier and pose a substantial risk in hospitals of being inadvertently exposed to magnetic resonance imaging areas, where they can become lethal projectiles. They are generally being replaced with their aluminum counterparts. Aluminum cylinders are moderately priced, light-weight, and can be manufactured to be safe in a magnetic resonance imaging environment. Although composite cylinders are extremely light-weight, their expense generally makes it cost prohibitive to be commonly used in a medical environment.

Larger cylinders such as size H or K are most commonly constructed of steel (but are available in aluminum) and provide a greater reservoir of gas. They are commonly used as a stand-alone oxygen source in areas where wall oxygen is not available. They are also used in groups, where a series of large cylinders are connected together by a manifold to either support specific areas or serve as an emergency reserve to a main supply. One possibility when mass casualties cause a sudden increase in patients is to convert areas such as cafeterias or auditoriums into patient-care areas by deploying a pre-constructed manifold to link large cylinders to supply oxygen. Either commercially available or easily fabricated on-site, a system of large cylinders, gas regulators, high-pressure hose, and flow meters could be quickly deployed to supply oxygen to multiple patient sites. An example of a commercially available system is depicted in Figure 1 and Figure 2. These systems can be assembled in a variety of configurations; however, one must consider the flow limitation of the regulator on the manifold. If a regulator is only capable of providing a total output of 150 L/min, the number of flow meters multiplied by their flow rate setting is limited to a combined output of 150 L/min.

Traditionally, cylinders are filled to a service pressure between 2,000 and 2,200 pounds per square inch (psi). Recently introduced higher-pressure cylinders can be pres-

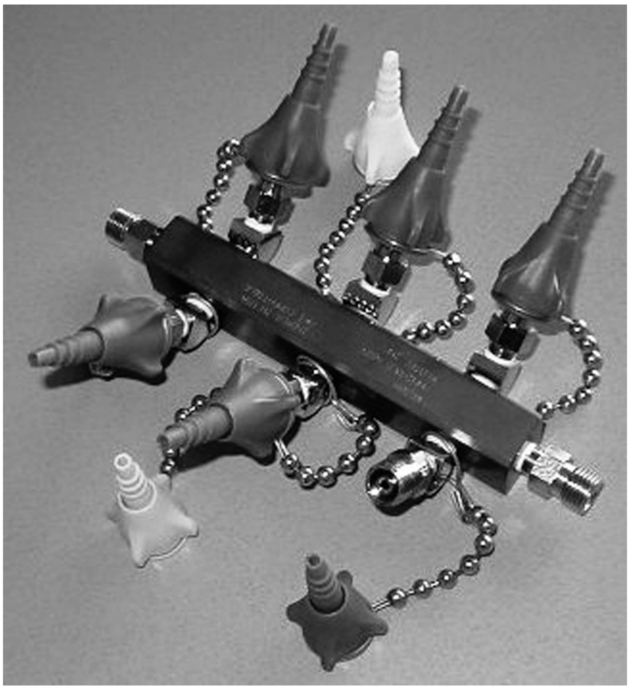

Fig. 1. Portable oxygen delivery manifold 1. A portable manifold to deliver oxygen at an alternative care site includes a master regulator (bottom) that connects to an oxygen cylinder and a series of flow-regulation devices connected in sequence via high-pressure tubing. (Courtesy of Flotec, Indianapolis, Indiana.)

Fig. 2. Portable oxygen delivery manifold 2. An alternative portable oxygen delivery manifold utilizes nipple adapters that are actually restrictors that control the flow rate to the patient. They are available in color-coded versions that make it easy to distinguish various flow rates. (Courtesy of Flotec, Indianapolis, Indiana.)

surized up to 3,000 psi, which increases the available amount of oxygen in a size E cylinder from approximately 650 L to approximately 1,000 L. They require a regulator rated for this higher pressure but otherwise operate the same as the conventional 2,000-psi cylinders.

One option available for portable cylinders is to have them supplied by the vendor with a regulator attached to each cylinder. Though this increases the cost of the cylinder service contract, it has the advantage during mass casualty situations of ensuring a more adequate supply of regulators. Using oxygen cylinders with an integrated valve, regulator, and flow meter also eliminates the possibility of a fire or explosion by civilian medical volunteers who may not be trained in the correct procedure for changing oxygen cylinder regulators. In a joint advisory issued April 2006, the National Institute for Occupational Safety and Health and the U.S. Food and Drug Administration[1] cautioned that “plastic crush gaskets never be reused, as they may require additional torque to obtain the necessary seal with each subsequent use. This can deform the gasket, increasing the likelihood that oxygen will leak around the seal and ignite.” The Department of Homeland Security, as a result of September 11th 2001, Hurricane Katrina, tsunamis, possible flu pandemic, and other incidents, has provided funds for communities to establish citizen Medical Reserve Corps. These volunteer groups may have various degrees of familiarity with the proper handling of oxygen cylinders or specifically changing the oxygen cylinder regulators. This potential for mishap is eliminated by using oxygen cylinders with integrated valves, regulators, and flow meters.

The higher service fee of having cylinders supplied with regulators will be partially offset by a reduction in both the number of replacement regulators purchased each year and a reduction in repair costs. If this option is taken, one should consider stockpiling some of the hospital-owned regulators being taken out of service, because in the case of a mass-casualty scenario you could receive additional portable cylinders from vendor stockpiles that require regulators.

There are several “choke points” associated with relying on compressed gas cylinders to supply oxygen to patients during mass casualty scenarios. Oxygen vendors have a fixed supply of cylinders and rely of hospitals and other users to promptly return empty stock for refilling. Failure to gather and return cylinders will lead to a shortfall in supplies. Refilling cylinders, though efficient, does require a fair amount of manual activity. During a pandemic event this activity could be compromised by a reduction in vendor workforce.

Vendors have stockpiled older but still serviceable cylinders for emergency use. For example, in 2005, in response to the 2004 Hurricane Ivan, LifeGas implemented a Hurricane Inventory Preparedness Plan, which allowed certain hospitals to reserve a limited number of additional E cylinders during the 6-month southeastern United States hurricane season (personal communication, Debbie Capuano, Pandemic Flu Coordinator, BOC Gases, Murray Hill, New Jersey, 2007). Out of necessity, the Hurricane

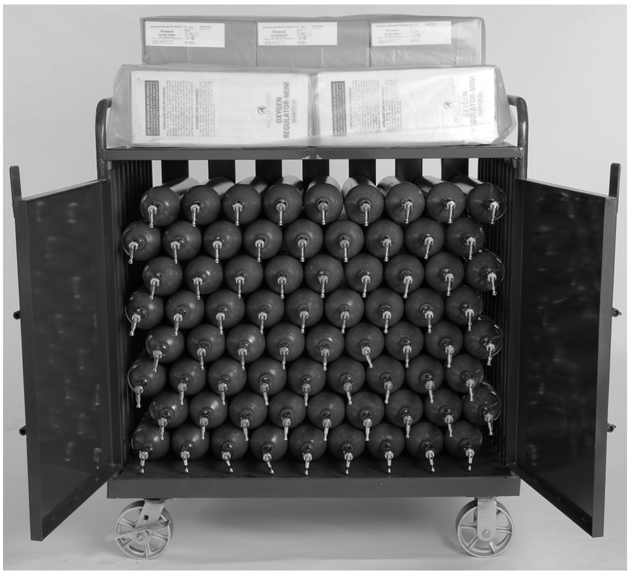

Fig. 3. Oxygen cylinder stockpiling system. Oxygen cylinders can be efficiently stockpiled in a convenient mobile storage system that also contains regulators and basic patient interfaces. It should be noted that once the total volume of gas exceeds 300 cubic feet, additional storage requirements must be followed. (Courtesy of Airgas Puritan Medical, Radnor, Pennsylvania.)

Inventory Preparedness Plan stipulated the timely return of used cylinders to sustain the system. Other vendors have developed similar stockpiling plans to utilize older or surplus cylinders during emergencies. In a pandemic scenario there is also the concern of disinfecting used cylinders prior to returning to the vendor for refill. Who would do that: vendor or hospital staff? Though this seems like a simple task, given the need to contain the spread of contagion and the anticipated reduction in workforce, there may be inadequate staffing to collect and disinfect these cylinders.

Another logistical issue associated with cylinders is the available storage space in hospitals. Commercially available emergency-response cylinder-storage systems are available, and an example is depicted in Figure 3. This system maintains approximately 80 conventional E cylinders and a supply of regulators in a wheeled cabinet, and could support a limited emergency event. Since this system contains over 1,800 cubic feet of compressed gas, certain storage regulations apply. Cylinder storage must conform to certain National Fire Protection Association safety standards[2] and possibly other state and local guidelines. These standards may include fireproofing requirements, ventilation standards, and cylinder handling requirements, based on the volume of gas stored:

- $\geq$ 3,000 cubic feet requires lockable doors, storage racks or chains, indirect heat (if required), and dedicated ventilation systems
- $>$ 300 cubic feet to $<$ 3,000 cubic feet requires lockable doors and passive ventilation
- $<$ 300 cubic feet (12–13 standard E cylinders) may be stored without any restrictions as an operational supply to support clinical operations

Because of space limitations within most institutions and the regulatory requirements associated with cylinder storage that impart an additional expense to hospitals, additional space is often not available for substantial quantities of disaster supplies. With these storage issues in mind, careful planning must be done and, in reality, a reliance on compressed gas cylinders is not a long-term solution for pandemic events.

Oxygen Concentrators

Oxygen concentrators range in size from small portable personal units to large industrial systems that can produce tons of oxygen per day. They all utilize a sieving process to extract oxygen from air and provide $\geq$ 90% oxygen at a variety of flow outputs. Compressed air is applied to a zeolite granule bed that absorbs nitrogen, leaving a residual high concentration of oxygen. By switching to a second, separate bed of zeolite, the extracted oxygen can be diverted to a holding chamber and the nitrogen is dissipated from the saturated first zeolite sieve. The process of switching between 2 sieves is termed pressure swing absorption and is continuously repeated to provide a continuous flow of nearly pure oxygen. Depending on the size and model, oxygen concentrators can deliver oxygen of $\geq$ 90% at various flow rates. Generally, the greater the purity of the oxygen generated, the less liters per hour can be generated.

The traditional medical application of oxygen concentrators has been to support low-flow oxygen therapy for home-care patients. Cabinet-size systems and smaller portable devices have provided flows up to 15 L/min (depending on the model) and serve home application well. They are not commonly available in most hospitals because under normal conditions the institutional bulk liquid system is more economical and convenient. The question is, do they have a role in mass casualty events? Personal oxygen concentrators have an advantage over cylinder gas because they generate their own supply of oxygen and do not need to be refilled. This avoids the logistical issues of monitoring cylinder levels, changing depleted cylinders, and exchanging empty cylinders for full ones. They do require a source of electrical power and are less convenient than an oxygen flow meter connected to a wall outlet. They are expensive and large relative to oxygen flow meters, and stockpiling them for use in a mass casualty event is probably not cost-effective for most hospitals.

There are larger oxygen-generating systems available that range in a variety of sizes from portable trailer-based designs to fixed systems that can provide the oxygen needs of an entire hospital.[3] A search of the Internet yielded the following list of oxygen-generator manufacturers suited for hospital applications:

- AirSep, Buffalo, New York
- Generon Innovative Gas Systems, Houston Texas
- Oxygen Generating Systems Intl, North Tonawanda, New York
- Oxair Ltd, Niagara Falls, New York

Depending on the size, these oxygen generators can produce substantial amounts of nearly pure oxygen. For example, the OG-5000 (Oxygen Generating System Intl, North Tonawanda, New York) can produce 5,000 standard cubic feet per hour (over 1,000 liquid gallons/d) of 93% oxygen and can support wall oxygen delivery systems that provide the standard 50 psi working pressure. In reality, it is likely that the exact size and production capacity can be designed to meet any specific application. Oxygen generators of this size include air compressors and gas dryers to provide a flow of compressed air to a set of extraction sieves that feed a reservoir tank that supplies the patient-care site. They require moderate to large amounts of electricity that can be provided by either a public utility or a portable generator. In addition to being able to supply adequate oxygen flow for wall oxygen systems, they can also refill cylinders. These systems could offer an attractive option for hospitals that may be at risk of oxygen-delivery interruptions that could occur during hurricanes or other natural disasters—as long as electricity is available to power them. Trailer-based systems may be an attractive option for federal, state, and local governments to support alternative care sites that could be deployed during mass-casualty events. They are mobile, and, with an appropriate set of portable manifolds, numerous patients could be quickly supported.

Large oxygen-generating systems do have several drawbacks. They are physically large and require as much or more physical space as a bulk LOX system. They must be protected from environmental extremes. This means they must be installed indoors or fitted with some type of protective structure. They are not "off the shelf" systems, and each one must be designed and built according to individual specifications. The cost for a system that could support an entire hospital would probably match or exceed the cost of a bulk liquid system. The cost for the required electricity could be substantial. And since each system is designed and built for a specific application, the time from ordering a system until its installation could be substantial.

Fig. 4. Liquid oxygen (LOX) refilling trailer. Field LOX systems can be supported by such conveniently sized, trailer-mounted LOX reservoirs. (Courtesy of Essex Cryogenics, St Louis, Missouri.)

Liquid Oxygen Devices

LOX, both portable and satellite filling stations, have been frequently utilized in both home and hospital settings. These devices are essentially large insulated bottles, and for their weight and size, they offer substantially greater oxygen capacity than compressed gas cylinders. Home-use models generally provide only low-flow oxygen (0.25–15 L/min), but larger systems can support 50-psi gas requirements. Single-patient LOX systems do not offer a distinct advantage unless they are already in wide use in a hospital. Most hospitals do not employ portable, single-patient LOX systems in place of compressed gas cylinders, for several reasons. LOX systems, when not in use, slowly dissipate their contents to the atmosphere as the liquid gas evaporates, in order to maintain a stable pressure inside the chamber. Second, portable LOX systems require periodic refilling from a satellite reservoir station, and although not difficult, this process requires a modest amount of training.

There are large-capacity mobile LOX systems that are available in several different configurations (Fig. 4) to support alternative care sites and refill home systems. This type of trailer or truck-based system can provide relatively large amounts of LOX to prefabricated portable distribution systems. These are simply mobile versions of bulk oxygen systems that supply multiple patient-distribution systems. An example of this type of oxygen delivery system is shown in Figure 5 (available from Essex Cryogenics, St Louis, Missouri). This system utilizes a 75-liquid-liter mobile LOX container ($>$ 60,000 gaseous liters of oxygen) that is connected to a series of patient-delivery kits. Each patient-delivery kit is configured with a set of 10 high-pressure hoses and can deliver oxygen to 10 patients, at flow rates of up to 15 L/min. The patient-delivery kits can be connected in sequence to extend the system until the maximum flow delivery of the LOX system is reached. Oxygen flow to each patient can be regulated by a separate flow-control valve located in the patient-deliv-

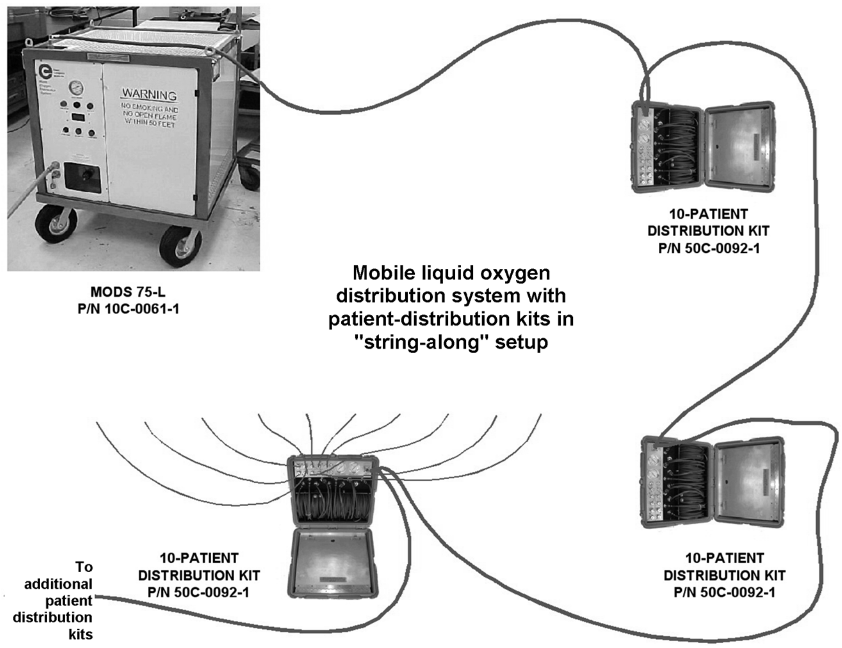

Fig. 5. Mobile oxygen distribution system (MODS) and patient distribution kits in "string-along" setup. Mobile liquid oxygen (LOX) systems can provide oxygen for multiple patients. This model contains 75 L of LOX (64,000 gaseous L) and can be connected to a series of patient-distribution kits, each of which can deliver oxygen to 10 patients. (Courtesy of Essex Cryogenics, St Louis, Missouri.)

ery kit. This type of system provides federal, state, and local agencies, as well as hospitals, with an option for their disaster plans.

The limitation of all LOX systems, besides the evaporative loss when not in use, is the logistical aspect of resupply. Disasters such as floods and earthquakes can interrupt transportation and delivery of LOX. Pandemic events could substantially reduce the workforce at gas-separation plants and impact production and delivery. Operating a mobile LOX system requires regular training of an adequate number of individuals to ensure its functionality.

Bulk Liquid Oxygen Systems

Most hospitals utilize bulk LOX systems to provide wall oxygen at approximately 50 psi to patient-care areas. These systems are robust and reliable under most conditions. The container contents are usually monitored either by the vendor electronically or by the hospital maintenance department (or both). They are often refilled in off hours by large liquid-gas transport trailers to avoid congesting the area around the facility. The vendor delivery staff are trained and certified in the filling technique. As such, respiratory therapists tend to take these systems for granted, much the same as we take most utilities for granted. In planning for mass casualty and pandemic events it is important to understand the operation and potential limitations of the institution's bulk oxygen system

Like portable LOX systems, bulk oxygen systems are composed of an inner vessel and outer vessel. The space between is maintained as a continuously monitored vacuum to insulate the LOX, which helps maintain vessel pressure and reduces the evaporative loss. The inner vessel is maintained at a pressure near 130 psi. LOX is withdrawn from the vessel and routed through a vaporizer that converts it to a gas, and then through a series of regulators that reduce the pressure down to the hospital's working pressure of approximately 50 psi. The vaporizer is the finned structure in the bulk system that can be covered in ice. There are usually 2 vaporizers, and the system automatically switches between the two as the ice reduces its efficiency. An economizer system collects the evaporated gas from the main vessel as the pressure rises and routes this recovered gas through the vaporizer and into the flow into the hospital. Under normal conditions, a hospital's oxygen consumption is sufficient to prevent any gas loss into the atmosphere, as may occur with personal LOX systems. There are also several pressure-relief valves that prevent excess pressure from developing in the system.

Each institution's bulk oxygen system is configured to its specific needs, and it is beyond the scope of this paper to thoroughly detail the process for filling the main system. There is a rigorous and thorough training process that

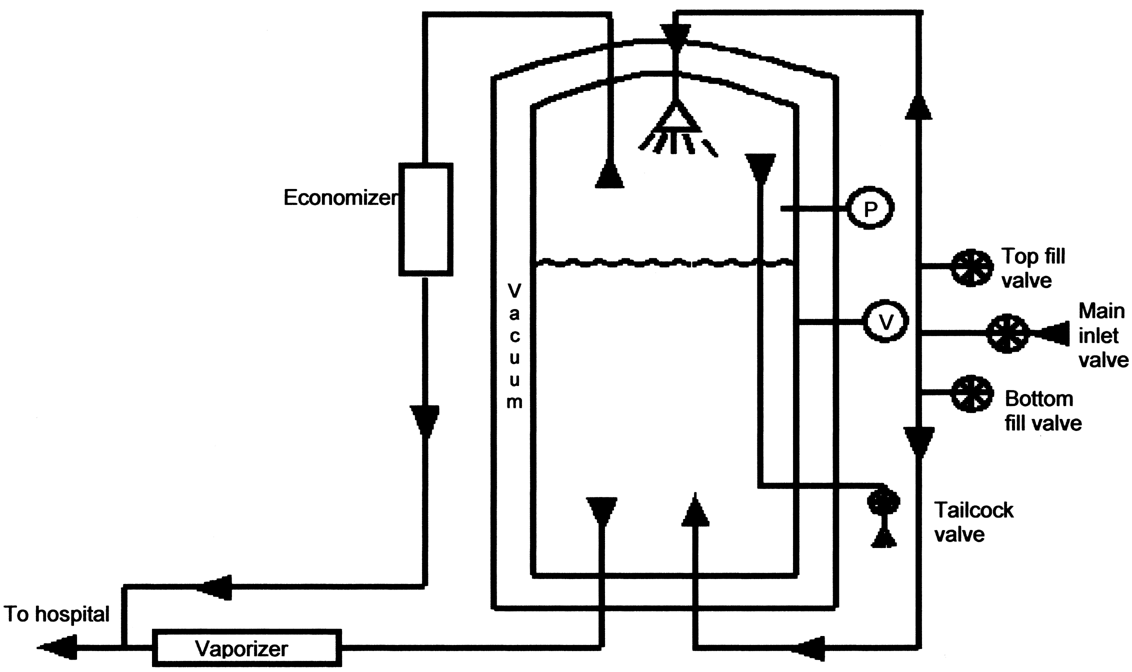

Fig. 6. Bulk oxygen storage vessel. A typical bulk oxygen storage vessel is designed to fill from both the bottom and top, in order to maintain a stable vessel pressure during the filling process. P = vessel pressure monitor. V = vessel liquid oxygen volume monitor.

must be completed to achieve certification to fill and maintain them. This includes appropriate hazardous-material training as well as practical training on filling the vessel without allowing excess pressure to develop. That being said, there is a concern that during a pandemic event such as an outbreak of avian flu (with an attack rate of 35%) the vendor workforce could be disrupted, and trained personnel may not be available to resupply the bulk system. Vendors have substantially more cylinder-filling plants than they have gas-separation plants. Gas-separation plants differ in size, but the number of delivery technicians and delivery tankers is limited. It may be appropriate for institutions to certify some of their engineering staff in the refilling process in case of such an event.

The diagram displayed in Figure 6 is a basic version of a bulk oxygen vessel. The following is a substantially simplified version of the refilling process, adapted from the Taylor-Wharton operation manual for vertical storage tanks.[4] After confirming that the trailer contents match those of the receiving vessel's, the supply tanker is connected to the bulk system's main inlet valve. The bulk system has a bottom fill valve and a top fill valve. The bottom fill valve is opened, and then the top fill valve. As flow through the bottom fill valve increases the liquid volume in the vessel, it compresses the evaporated gas in the top of the vessel. By filling simultaneously from the top of the vessel, using the top fill valve, gaseous oxygen is reliquefied and the vessel pressure is reduced. Thus, by adjusting the bottom fill valve and the top fill valve, the vessel pressure can be maintained as it is filled. Once the vessel is three-quarters full, an overflow valve (the trycock valve) is opened. When LOX spurts from the trycock valve, the vessel is full and the main inlet valve is closed. All valves are now closed, and the filling lines are allowed to depressurize before being disconnected. There are other essential steps not described in this paper, and it is imperative that untrained, uncertified personnel should not attempt this procedure.

Gas-separation plants currently operate at nearly full capacity. There are periodic reductions in their production, due to seasonal industrial consumption or to limit power consumption during peak electrical use. Most production plants store several days or more of product in on-site vessels, so these variances in production do not affect delivery to consumers, but there is a limit on the volume of additional LOX that can be produced at current facilities. Diversion of LOX from industrial applications can be done during extreme conditions. One potential method to increase LOX delivery to hospitals is to convert nitrogen tankers to oxygen. This is easily done by converting the connection fixtures on the tanker to match the gas (if the conversion hardware is readily available), and flushing the nitrogen tanks with oxygen before filling. Under all conditions, special care must be used to confirm that the correct gas is being loaded into the bulk system. Though delivery tankers are equipped with oxygen analyzers to verify that the contents are correct, there have been a number of documented contaminations of bulk systems with incorrect gases.[5]

Table 2. Oxygen Utilization Survey of Beth Israel Deaconess Medical Center*

Type of Use/Location	Number of Beds	Percent of Patients on O_2	Number of Patients on O_2	Average Flow (L/min)	Total Daily Use (L/d)	Total Daily Use (gallons/d)
Floors	320	30	96	4	552,960	170
Intensive care unit	65	70	49	4.5	315,900	97
Operating room	18	100	18	2	51,840	16
Postoperative recovery	23	100	23	4	132,480	41
Cardiac catheter suite	6	100	6	6	25,920	8
Cardiac catheter holding	16	100	16	4	69,120	21
Emergency department	51	35	18	4	102,816	32
Total accounted usage					1,251,036	384
Unaccounted usage					240,969	74

*Data obtained during a 1-day survey.

Bulk oxygen systems provide adequate reserves under most conditions. Unless disabled by accidents or natural catastrophes, they are probably able to provide the needed supply during short-term events. Their primary risk is during long-term high-consumption periods. Since deployment of oxygen delivery systems in alternative care sites presents a marked logistical challenge, most hospitals will plan to move non-oxygen-dependent patients to these locations (if needed) first, reserving bed space with robust oxygen availability for those patients who require supplemental oxygen.

Developing an Oxygen Resource Management Plan

Developing an oxygen resource management plan will depend on the response contingencies an institution plans to implement. Our institution has planned to develop an alternative care site in a nearby university dormitory. We plan to reposition in-patients with less acute illness and no oxygen needs to this location in order to free on-site beds for those patients who need oxygen and other more technically demanding interventions. This would mean that our proposed alternative care site would have modest oxygen resource demands, and we plan to support it with a limited number of emergency oxygen cylinders.

We also plan on utilizing public waiting areas as triage sites to support overflow from our emergency department. These areas would be supported with portable cylinder oxygen, with the intent to move patients to a more stable and supportable location as soon as possible. The patient capacity of a surge area and its anticipated duration of use will dictate the number of additional cylinders that should be stockpiled. We allocated 3 E cylinders per bed space to support this triage area.

It is our philosophy that long-term (more than several hours) oxygen therapy from cylinders is not a feasible option, and patients should be moved to a location where a more robust oxygen supply is present. In these more permanent patient-care areas we attempt to maintain one oxygen flow meter at each potential bed site. Oxygen flow meters are not prohibitively expensive, and maintaining them at potential bed sites avoids the need to distribute them during an emergency. Additional units are stored on-site to replace lost or broken units. Although more expensive than standard flow meters, flow meters with additional high-pressure outlets increase the number and flexibility of wall oxygen outlets. Regulators for both portable and nonportable oxygen cylinders should also be stored in reserve, and the number should be based on the potential surge capacity.

We also assessed the ability of our bulk LOX system to meet the demands potentially placed on it by a mass casualty event. We did a spot survey of oxygen utilization on one campus at Beth Israel Deaconess Medical Center. Our West Campus facility consumes an average of 450 gallons of LOX per day (1.5 million gaseous liters per day) and is supported by a 9,000-gallon bulk vessel and a 1,500-gallon reserve vessel. This system is resupplied every 5–10 days, depending on the vendor's schedule. Our West Campus has 385 beds, with the distribution displayed in Table 2. By gathering data on a random sample of patients, we estimated the amount of oxygen being used in various areas. All ICU patients were assessed for their oxygen use, and the status of their manual resuscitator was noted to determine if it had oxygen flowing to it. The amount of wall oxygen being used was calculated for all mechanically ventilated patients. We could not account for more than 240,000 gaseous liters (74 liquid gallons) per day of oxygen consumption.

There are numerous possible causes for this potentially avoidable gas loss. Wall outlets should be regularly inspected to ensure they do not leak. Unused flow meters should be monitored to ensure they are shut off. Locations for such unused flow meters include clinics, radiology facilities, cardiac catheterization units, postoperative recovery units, and operating rooms. Oxygen flow to manual resuscitators should be turned on only when needed for patient ventilation, and then promptly returned to the off position. Each manual resuscitator, if left running at 15 L/min, will consume 21,600 L or 6.6 liquid gallons per day. Once inappropriate oxygen use is reduced to a minimum, other opportunities for conservation should be considered.

Oxygen Conserving Options

Reservoir cannulas have been available for years, but are not commonly used in hospitals because of their cost. There are 2 types of device currently available: the Oxymizer Reservoir Cannula and the Oxymizer Pendent Cannula (Chad Therapeutics, Chatsworth, California). The reservoir cannula places the reservoir directly below the nose, whereas the pendent model moves the reservoir below the chin. Both models operate without pneumatic or electronic flow controls. When compared to standard oxygen cannulas, these devices have been shown to sustain a given oxygen saturation at rest while using 50–75% less oxygen.[6-10] If we deployed these devices on half of our patients who were receiving oxygen via cannula in our West Campus facility, we estimate we could conserve over 75 liquid gallons of oxygen per day. This would represent over 15% of our daily consumption. Cylinder life would likewise be extended. Though the cost of these disposable devices does not merit their regular hospital use, they could be stored and deployed during mass casualty events when oxygen conservation is critical. We calculated that if we converted half of our nasal cannula patients to oxygen-conserving cannulas we would reduce our bulk system consumption by 20–50 liquid gallons per day. Similarly, they could extend the life of our cylinder oxygen supplies. Electronic or pneumatic flow controllers that deliver oxygen only during inspiration also conserve oxygen but are more expensive. Electronic conservers require batteries and therefore require substantial in-storage maintenance. Reservoir cannulas offer the more economical and simple option.

Another method to extend oxygen resources would be to convert patients with artificial airways from continuous aerosols to heat-and-moisture exchangers and supply low-flow oxygen to sustain a targeted oxygen saturation. A standard continuous aerosol will generally be powered by 12–15 L/min of oxygen. A flow of 15 L/min of gaseous oxygen running for 24 hours will require 6.6 liquid gallons of oxygen. As a last resort it may be prudent to target lower patient oxygenation levels. By reducing oxygen flows and accepting oxygen saturations of 90–92% instead of $> 95\%$, both cylinder and bulk oxygen resources could be extended.

Summary

Whatever emergency contingency an institution decides to adopt, one thing is clear: when a disaster happens, if you don't have what you need, it will not be available quickly, or probably not at all. There is a limit to the amount of cylinder oxygen that can be stockpiled in preparation for a mass casualty event, and those stockpiles will be limited in their duration. Some amount of cylinder gas should be available for surge situations, as long as available storage complies with state and federal regulations. Retrieval, disinfection, and exchange of cylinders must be facilitated in order to ensure resupply. Clear signage must be in place so that staff not familiar with oxygen storage locations are able to quickly locate those supplies.

Personal oxygen concentrators and portable LOX systems have limited value but can be used to support selected areas. Larger-capacity concentrators and LOX systems are attractive options for developing oxygen delivery systems at alternative care sites or to support bulk delivery systems. They must be accompanied by manifold systems that match the total system output and provide a mechanism that regulates the flow to the patient. If mechanical ventilation is anticipated in these locations, they must adapt to the requirements of the ventilators that are available for use.

Routine maintenance should be performed on compressed-gas systems to eliminate system leaks that cause unnoticed but substantial system consumption. Organized efforts must be developed to reduce the volume of oxygen consumed in institutions during mass casualty events. Staff must ensure that unnecessary use of oxygen is curtailed. Elective surgical procedures should be postponed.

Bulk oxygen delivery areas must be accessible and clearly marked. Blockage of access areas can prevent timely resupply of critical commodities. Hospital staff should be trained and certified in the process of refilling bulk oxygen systems in case vendor personnel are not available to perform this duty. Regular monitoring of system levels must be performed.

Dwight D Eisenhower once said, "In preparing for battle I have always found that plans are useless, but planning is indispensable." One cannot anticipate all the needs and complications of a mass casualty event, but some forethought can lessen their impact on how we respond to their challenges.

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Discussion

Hanley: How much oxygen will we need in a mass casualty event? You said you currently use 1.5 million liters per week. I calculated it quickly without a calculator, so I may be wrong, but I think that is 150 liters per minute, which is 15 patients on 10 liters per minute. That's not that much oxygen.

Ritz: In a pandemic environment you would move everybody who is not on oxygen out of the hospital if you can, and convert non-ICU hospital beds into ICU beds. We made some calculations about where the oxygen goes in our hospital. The ORs [operating rooms] don't use that much under normal circumstances. PACUs [post-anesthesia care units] use much more oxygen. Part of the culture in recovery units is that the manual resuscitators run continuously, so the gas consumption is pretty high.

We found that in our ICUs, because we use in-line suction catheters and therefore don't take the patient off the ventilator, we don't have manual resuscitators running continuously. NICUs [neonatal intensive care units] tend to use a lot of gas because they have a lot of their manual resuscitation devices always running. And their ventilators are little less economical because they often use continuous flows, particularly oscillators. We had difficulty estimating the oxygen use per patient.

Out on the floors we estimated that we had about 100 patients out of 350 on low-flow oxygen at any one point in time. Just doing some quick surveys, we usually found that those oxygen flows were 2 to 4 liters per minute. The floors didn't consume a lot of oxygen. The ICUs used a modest amount, the NICUs a lot, ORs a bit, PACUs a lot. But it's difficult to make these kinds of estimates.

We didn't account for all of the leakage in the system and the various labs and clinics and other places, although the clinics tended to use cylinder oxygen instead of wall oxygen. It's difficult to get a clean handle on oxygen consumption.

O'Laughlin: I've looked at setting up oxygen at an alternate care site and I found logistical nightmares associated with that. I'm talking about an area that doesn't have built-in oxygen tubing. Strictly setting up from scratch, this is based on the original oxygen-delivery layout that came out of Denver for alternate care sites and talking about oxygen delivery at those sites.[1] They talked about liquid oxygen setup.

I did some numbers for a 50-patient unit using sets of 2 H-size tanks (per 4–5 patients) combined with a manifold such as the Minilator with a fixed O_2 rate, using Oxymizer nasal cannulas, and I still would have to deal with complete turnover of the tanks twice in 24 hours. The logistics of cylindered oxygen at an alternate care site seem too complex for cylinders to really be useful. What are your thoughts about the logistics and costs of setting something up?

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Ritz: The most common, most available cylinder is an E-size cylinder. There are lots of those. There are not nearly as many larger cylinders for medical use in most hospitals. However, there is a substantial amount of cylinder oxygen in larger-volume cylinders sized for industrial use, and there is industrial oxygen available.

The problem is coming up with the hardware to distribute this oxygen completely, to various patient care sites. With enough preplanning and support from the vendor you could do it, but it's sort of like having to buy insurance from them. You'd have to say, "If I do this, can you guarantee that you can ship this much this fast?"

The manifolds are not hard to make or buy. There's a lot of variations of that kind of equipment. The question is whether you can get the cylinders and do you have somebody around who can change those cylinders out? I'm skeptical that you can get enough cylinders for a long enough period of time in the scenarios we're considering.

O'Laughlin: I talked to a major oxygen manufacturer, and they said they'd be thrilled to store cylinders that we would purchase up front; they would house them for us, for a very nice fee. That's an option, but is it the right balance of resources and the right way to spend the money?

You mentioned the question of using manufacturing (nonmedical) oxygen supplies. I think that the grade of oxygen isn't necessarily considered the same, but is there the potential to use industrial grade oxygen in a medical system? Are there majorequip ment needs to try to hook the system up, or is it relatively the same, or is it not considered appropriate at all?

Ritz: All the oxygen comes from the same plants, whether it is industrial oxygen or medical oxygen. I think the cylinder connections are the same also. There is an indexing system [DISS (diameter-index safety system)] that requires the cylinder threads to be of certain diameter and configuration. So the use of industrial oxygen is not a particular impediment. That seems like a reasonable thing to do. There are labeling regulations and CGA [Compressed Gas Association] regulations that prevent us from doing it currently, but there's no difference between the gases.

Rubinson: With regard to alternate care facilities, the 3 oxygen options are compressed gas, gas production on-site, and liquid oxygen. The portable on-site oxygen-production units I have seen provide approximately 33 liters a minute for $65,000, so that's not a great option for most communities. Individual concentrators can be used, but they require electricity running to each patient site, although at some sites that could work. They would all have large electricity requirements to produce oxygen for hundreds of patients, which is the number being considered for larger alternate care facilities. For liquid oxygen we calculated for 200 to 250 patients on an average of 4 liters a minute, which is a total of 1,000 liters per minute. So we addressed flow in terms of having sufficient vaporizer capability and also having total oxygen capacity.

We worked with one large vendor and looked at Micro-Bulk PermaCyl cylinders. Because the Micro-Bulk distribution truck in our area is different from the bulk trucks, we thought this was appealing because our alternate care facility would not be competing with the hospitals for LOX distribution. We were concerned about how quickly they would have to resupply, and it'd be between 1 and 2 days.

So now we're looking at the option of the truck that they use when a hospital is just about to introduce a LOX system or when they need a temporary alternative external system. Unfortunately, there are actually very few of those in the country. But we are working at being able to adopt this system in Seattle/King County. So there are some potential solutions. I think it's probably going to cost between $100,000 and $200,000 per 200 to 250 patients in alternate care facilities.

With regard to manufacturing oxygen, the key issues are that the electrical grid has to be up and that the workers can make it to work at the oxygen plant. Distribution is also a concern. There are 5 or 6 major oxygen manufacturers, and they have limited distribution redundancy, so if multiple regions are concurrently impacted by an epidemic and the workers are less available to manufacture and distribute it, LOX could be delayed or unavailable. There are thousands of compressed-gas distributors, and about 15% of their business is medical oxygen. There may be the possibility of the FDA [U.S. Food and Drug Administration] relaxing regulations if nonmedical cylinders need to be used, but we can't rely on that. Even if regulations are relaxed, getting enough compressed gas to replace LOX for hospitals will be challenging.

Daugherty: How much oxygen might be saved by canceling elective surgeries? How many days of oxygen would that buy? Lewis said that hospitals need to plan to be independent for the first 10 days of an emergency mass critical care event.

Ritz: With LOX systems the intent is that you never get into your reserve supply. The only loss from your reserve system is the natural evaporation that occurs. LOX cylinders are filled only half full or slightly less than half full, but it seems like there's a fair amount of reserve in a hospital liquid oxygen system. We found that the NICU and PACU had the highest oxygen consumption. In an OR the anesthesia machine consumes oxygen, but there aren't a lot of other sources of gas consumption in an OR; it's just that there's a lot of them and they run a long time. The oxygen flow going through an anesthesia machine can be quite economical. The ORs' consumption might not be so great that if you stopped it, it would extend your oxygen supply by 3 or 4 days.

Branson: Isn't it the practice for all anesthesia machines to have a low flow of oxygen 24 hours a day, to go through the CO_2 absorber to prevent the development of carbon monoxide? Could turning off that flow conserve an important amount?

Talmor: There's a very low flow through the machine; it's less than a liter per minute. Anesthetics are typically delivered with low flows these days, so about a liter of oxygen per minute, except at the end of the anesthetic, when it's turned up to remove the inhaled agents, and then the flow goes up to about 15 liters per minute. The substantial waste in the OR is if the oxygen flow is not turned back down. If you have 35 ORs, like we do, that could add up to substantial waste.

Hanley: Are there legal restraints that prevent oxygen suppliers from gouging hospitals if we suddenly have an increase in demand?

Rubinson: I don't know if there are legal restraints, but I can tell you that the vendors came through after [hurricane] Katrina. The major manufacturers are under strict antitrust rules because there are so few manufacturers. I've been told that if a plant goes down, the other companies will often fill that company's obligations. So I think, typically, the oxygen industry has done the right thing when needed, but I don't know if there is anything specific to oxygen that would get them at gouging any more than any other medical equipment or anything else that's in short supply.