An Improvised Oxygen Supply System for Pandemic and Disaster Use

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Abstract

Background: Current disaster planning for pandemic influenza anticipates overwhelming numbers of patients in need of hospitalization. The anticipated use of extra, or "surge," beds is common in both hospital and community disaster response planning. In a pandemic of respiratory illness, supplemental oxygen will be a life-saving intervention. There are currently few options to provide these proposed surge beds with the necessary oxygen.

Objectives: A method of providing an improvised oxygen delivery system for use in a disaster was developed and tested. This system was designed to use readily available commercial materials to assemble an oxygen delivery system.

Methods: The study consisted of a laboratory design, assembly, and testing of an improvised oxygen system.

Results: A liquid oxygen (LOX) Dewar container was used to supply oxygen systems built from inexpensive commercially available plastic tubing and fittings. The system will drive ventilators without significant pressure drop or ventilator malfunction. The final developed system will supply 30 patients with up to 6 L/min (l pm) oxygen each by nasal cannula from a single oxygen Dewar.

Conclusions: An improvised system to deliver oxygen for patient beds or ventilator use can be easily assembled in the event of a disaster. This could be life-saving in the event of a pandemic of respiratory illness.

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An outbreak of pandemic influenza is expected to greatly tax health care systems worldwide. Health care systems, communities, and governments have instituted programs to provide increased patient care in the event of a disaster. Many regions stock supplies and plan for personnel to expand clinical care areas. Improvised alternate care facilities capable of providing low levels of hospital care are common in community disaster plans.[1] Most hospitals in the United States are required to have plans for alternate care sites in their disaster response plans.

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The ability of improvised health care facilities to provide oxygen to patients is a major weakness of the health care response. This is particularly critical in the event of pandemic influenza. Influenza is primarily a respiratory illness. The primary lethal complication of pandemic influenza is community-acquired pneumonia.[2] It seems likely that in the absence of supplemental oxygen, mortality rates will be much higher than if respiratory support can be provided to seriously ill influenza patients.

Consideration has previously been given to the need to provide oxygen in out-of-hospital mass care situations, but to date there are no good solutions.[3,4] The issue of mechanical ventilator support in mass care situations is even less explored.[5] The volume of oxygen used in typical health care settings is staggering. Hospitals use large liquid oxygen (LOX) storage tanks delivering oxygen through copper piping at 50 pounds per square inch (psi). A ward of 50 patients each receiving 4 L per minute (l pm) nasal cannula oxygen will consume 288,000 L of oxygen daily. A large hospital "H" oxygen cylinder contains 7000 L of oxygen. A bank of eight "H" cylinders will last 50 patients at 4 lpm for 4.7 hours.[1] The logistics of keeping these cylinders full

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in emergency use is daunting. The United States military has developed sophisticated portable oxygen generation capability. For example the Expeditionary Deployable Oxygen Concentration System (EDOCS) will supply 120 lpm oxygen.[1] This system costs more than $480,000. This cost for even a single unit is unlikely to be borne by the civilian disaster-preparedness system. Thousands of such units would be needed in a severe pandemic. An alternative method to supply oxygen is clearly needed.

There currently exists a large infrastructure of LOX supplied by Dewar containers used in multiple commercial and medical applications. These are commonly used by medical facilities such as ambulatory surgery centers to supply their limited oxygen needs. These portable units are rotated for resupply on a regular basis and are connected to fixed piping delivery systems at the site of use.

A typical Dewar is a double-walled tank using an internal vacuum to insulate the LOX. A system of internal piping warms the vaporizing oxygen to near room temperature at the oxygen outlet.

The surface area of the Dewar container limits the rate of oxygen vaporization, providing a theoretical maximal oxygen delivery rate based on the size of the Dewar. In practice, the limits of the ability of the Dewar to warm the oxygen are less than the maximal vaporization rate.

We developed and tested a means to rapidly improvise an oxygen delivery system using a LOX Dewar and commonly commercially available low-cost supplies. This system is suitable for emergency use in disasters where supplemental oxygen is needed.

METHODS

Study Design and Setting

Data were obtained on a typical oxygen Dewar and on typical oxygen design requirements for clinical use.[6] Two different applications were tested. The first was the ability of the improvised system to deliver adequate volumes of oxygen at a constant 50 psi required to drive ventilators. Fifty pounds per square inch is the standard pressure used in hospital circuits, and ventilators could be sensitive to significant fluctuations in operating pressure.

The second application was the ability of an improvised system to supply patient care ‘‘beds’’ with oxygen at 5 lpm, simulating an improvised ward in an alternate care facility. We calculated that we could supply approximately 38 ‘‘patient beds’’ at 5 lpm. We sequentially increased the number of ‘‘take off’’ points until we reached the maximum the system would support.

The improvised oxygen delivery systems were designed using large-diameter tubing to safely deliver large volumes of oxygen. The systems were built from commercially available materials in common use. The materials used and approximate costs are summarized in Table 1.

Study Protocol

The sizes and vaporization rates of different sizes of commercial oxygen Dewars were obtained from the manufacturer.[6] A review of commercially available tubing capable of meeting the pressure and size requirements for oxygen distribution was performed. Tygon high-pressure tubing (Saint-Gobain, Akron, OH) was selected as it meets the pressure needs of the system and has widespread availability. We selected ¾-inch tubing as the standard main supply tubing based on the National Fire Protection Association (NFPA) requirements for main hospital distribution systems for 50 beds.

The LOX Dewar (Dura-Cyl 230, Chart Industries, New Prague, MN) was connected to a standard low-pressure single-stage oxygen regulator (Victor LC350DR-540, Thermadyne, St. Louis, MO). The regulator was connected to a standard brass reduction/expansion fitting of ½ to ¾ inch (Watts Industries, North Andover, MA). A ¾-inch internal diameter (ID) Tygon food-grade high-pressure tubing was attached (Cole-Parmer, Vernon Hills, IL) and secured with a hose clamp. Fifteen feet of tubing was routed to allow the Dewar to be out of the immediate patient care area. At intervals simulating the spacing of patient beds a series of polyethylene barbed reducing fittings ¾ × ¾ × ½ inch were inserted as the oxygen takeoff points (Fittings4Less.com). If cots are spaced 3 feet apart (for respiratory droplet isolation), approximately 5 feet are needed between each takeoff. Each reducing ‘‘T’’ serves as an individual bed takeoff. Tygon food-grade high-pressure tubing ½-inch ID was connected to each T in short segments. Each ventilator connection or reduction fittings for oxygen tubing is then connected to the takeoff (Figure 1).

The capability of the improvised system to deliver various oxygen flow rates and pressures was measured with a Fluke Gas Flow Plus gas analyzer (Fluke Industries, Everett, WA). The ability of standard oxygen flow meters to measure flow with a nonstandard driving pressure of oxygen was also measured. As standard flow meters are calibrated to be used at a 50 psi driving pressure (at sea level at 20°C), a conversion chart was generated (Figure 2). Four standard commercial flow meters (two Timeter [Allied Healthcare Products, St. Louis, MO] and two Ohmeda [Datex-ohmeda, Madison, WI] flow meters) were tested.

Data Analysis

Descriptive analysis only is reported.

RESULTS

The vaporization rate available from a typical large commercial LOX Dewar container was calculated and is sufficient to provide approximately 188 lpm oxygen.[6] This Dewar generates a total of 176,810 L of vaporized oxygen.

Ventilator Testing

The ¾-inch line had takeoffs inserted to allow for a ventilator every few feet. Five feet of Tygon ½-inch ID tubing were used to route oxygen from the supply line to each ventilator. Each ½-inch tubing terminated in a brass fitting ½-inch HB × ¼-inch barb (Watts Industries, North Andover, MA). This connected directly to the

Table 1
Required Items for a 30-bed Improvised Oxygen Setup

Category	Item	Role	Number needed	Unit cost $US
Tubing	Tygon pressure tubing, ½-inch ID × ¾-inch OD, 50-feet/roll	Patient bed supply line	1	240
	Tygon pressure tubing, ¾-inch ID × 1-inch OD, 50 feet/roll	Main oxygen line	3	320
	Standard oxygen connector tubing	Patient supply	30	1.20
	Standard nasal cannula	Patient supply	30	1.00
Polypropylene connectors	½-inch × ¾-inch × ¾-inch reducing T barbed	Takeoff for patient bed	30	1.80
	½–¼-inch reducing fitting barbed	Reduction to standard oxygen tubing	30	0.80
	¾–¾-inch barbed	Repair	5	1.23
	½–½-inch barbed	Repair	5	0.68
	¼–¼-inch barbed	Connects oxygen tubing to cannula	30	0.20
	¾-inch barbed to threaded	Caps end of oxygen supply line	1	1.60
	Threaded cap	Caps end of oxygen supply line	1	1.10
Clamps	1¼-inch hose clamp	Secure ¾-inch fittings	65	1.4
	½-inch hose clamp	Secure ½-inch fittings	61	1.32
	Keck ramp tubing clamp	Adjust oxygen tubing flow	30	5
Brass fittings	Brass ¾-inch MIP–¼-inch FIP	Connects ¾-inch tubing to low-pressure oxygen regulator (Dewar)	1	2.50
	¼-inch male–male extension	Connects ½-inch tubing to high-pressure regulator (backup tank)	1	1.25
	½ inch HB × ¼ inch MPT	Connects ½-inch tubing to ventilator oxygen inlet	Variable	1.25
Oxygen regulators	Low-pressure regulator	Connects LOX Dewar to oxygen line	1	275
	High-pressure regulator	Backup oxygen source	1	150
Oxygen flow meter	Inline flow meter (Taga Liter, Salter Lab Liter meter, etc.)	Measure oxygen flow	1	20

FIP = female iron pipe; HB = hose barb; ID = internal diameter; MIP = male iron pipe; MPT = male pipe thread; OD = outside diameter.

standard hose oxygen fitting on the ventilators. Hose clamps were used on all fittings. Testing with cable ties showed them to be adequate to secure the ½-inch lines, but not the ¾-inch lines. As the larger lines were moved about, the connections with the system with 50 psi would flex and separate. In sustained use, the ½-inch fittings would also be likely to separate with time as they are moved about. For safety, all fittings at 50 psi should be secured with hose clamps.

Ventilators were added in series until a total of three ventilators (Drager Evita XL [Draeger Medical, Inc., Telford, PA], Marquet Servo I [Maquet Inc., Bridgewater, NJ], and Siemens Servo I [Siemens Medical Solutions USA, Inc., Malvern, PA]) were simultaneously tested. These models were selected as they utilize oxygen at a higher rate than transport or other models of ventilators. The ventilators were all set at fraction of inspired oxygen (FIO_2) 1.0, tidal volume 500 mL, and rate of 20 breaths/min. This requires an oxygen-minute volume of 10 L for each ventilator. The ventilators functioned smoothly without malfunctions or alarms. Supply line pressure was constant at 50 psi with fluctuations of less than 3 psi as the ventilators cycled. The ventilator internal diagnostics revealed normal pressures and volumes delivered. Ventilator visual display waveform was smooth with normal traces.

Patient Bed Delivery Testing

The Tygon ¾-inch tubing was again used as a main supply line to supply a simulated ward of patient cots (Figure 1). The line was pressurized at 20 psi instead of the standard 50 psi, to reduce stress on the fittings preventing leaks and as a safety measure. This also facilitates using a roller clamp to adjust individual patient oxygen flow.

The oxygen supply line was suspended by cable ties from a section of rope tied overhead to suspend the tubing 6 feet off the ground. The low-pressure regulator from the LOX Dewar was again connected to the ¾-inch supply line. The tubing was strung in a straight fashion using ¾ × ¾ × ½-inch reducing T-pieces to ½-inch ID Tygon tubing for individual distribution lines to the patient beds. Initially, several feet of ½-inch tubing was used to route the individual patient line from the main supply line. Subsequent testing with the oxygen flow analyzer revealed the use of a standard oxygen connector tubing delivered the identical flow as the larger tubing for these short segments. Therefore, for ease of use, weight, and cost considerations, standard oxygen connecting tubing was used to connect to a short segment of ½-inch tubing. A segment of the ½-inch tubing is necessary, because ¾-inch to ¼-inch reduction T-fittings are not widely commercially available. A 6- to

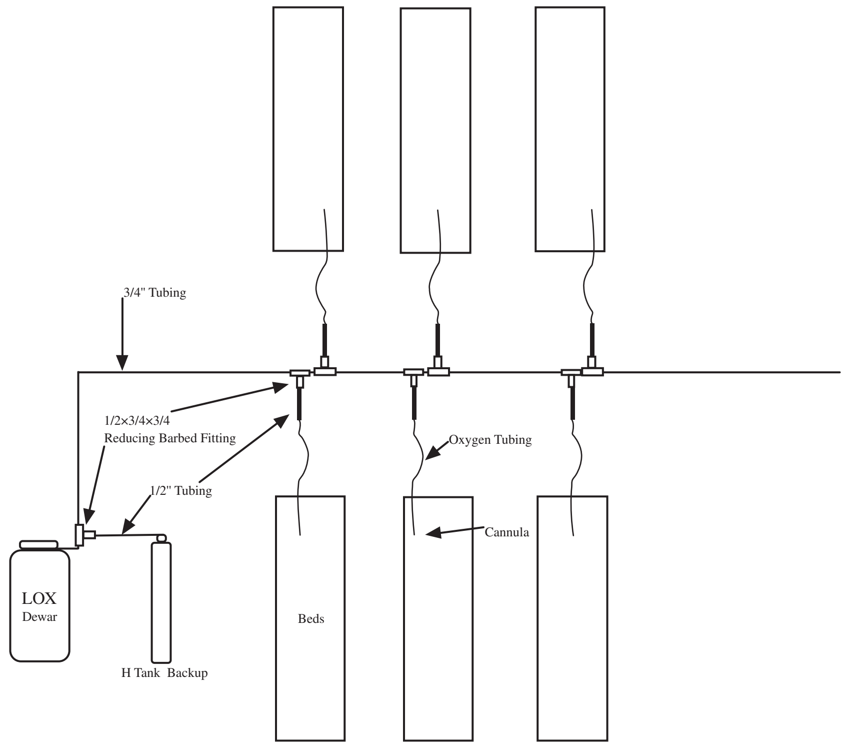

Figure 1. Improvised oxygen system layout. LOX = liquid oxygen.

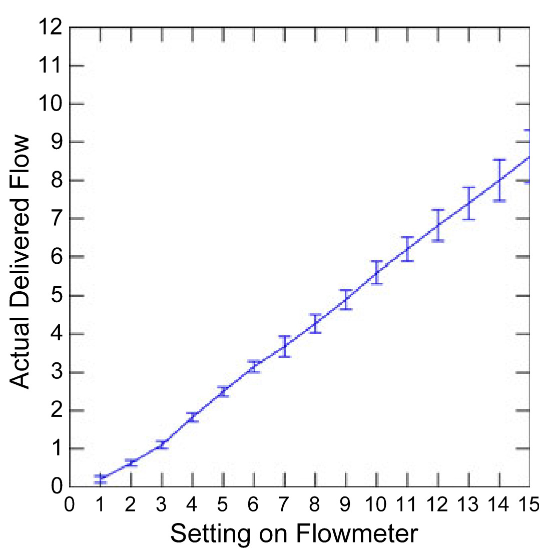

Figure 2. Standard flow meter measurements of oxygen delivered at 20 psi. Mean ± standard error.

12-inch segment of tubing was used as a safety feature, because this length allows the tubing to be folded over to ''clamp'' oxygen flow if needed. Each short segment of ½-inch tubing terminates in a polypropylene ½-inch–¼-inch barbed reducing fitting. A standard oxygen connector tubing was then attached to the ¼-inch fitting. The oxygen connector tubing is fitted with a Keck ramp clamp (Cole-Parmer, Vernon Hills, IL) to control oxygen flow. This roller clamp is one of the keys to the system, because the clamp must be capable of variably adjusting the oxygen flow, while being large enough to fit on standard oxygen tubing. Multiposition ratcheting clamps were tested, but could not adjust the flow adequately. Hoffman screw compressor type hose clamps would also work.

Each patient terminal was adjusted with the Keck clamp to deliver 5 lpm of flow using the Fluke oxygen analyzer. Standard oxygen flow meters could be used in the event of a disaster. The ability of standard oxygen flow meters to measure oxygen flow when driven at 20 psi is significantly skewed and requires an adjustment. The conversion chart is reported in Figure 2. The oxygen flow in the circuit can be tested at the end of the oxygen connector tubing. There is no reduction in measured flow by adding a nasal cannula, oxygen connector tubing, or oxygen masks to the circuit. We were experimentally able to add up to 50 takeoff points at 5 lpm each until we reached the maximal flow the Dewar would support without icing up, for a total flow of 250 lpm. The manufacturer's suggested maximal rate of vaporization for our Dewar of 188 lpm would support about 38 beds. While we were able to support 50 oxygen takeoff points, the maximal number of beds supported by this size of Dewar should be 30 or less to support a margin of safety and prevent system freeze-up (see Limitations).

DISCUSSION

This method of an improvised oxygen system can be quickly built from common commercially available materials at modest cost. This could be a significant benefit in a pandemic respiratory illness.

The tubing dimensions were based on national standards for distribution systems. We lowered the driving pressure for the patient bed system to increase safety and ease of use. It would be possible to use smaller diameter tubing to build the system, but the risk of pressure drop off and the need for higher system pressures would increase. With smaller tubing, the friction from oxygen flow in the system would also increase. It is difficult to estimate the minimal tubing diameter needed because it will vary with the desired flow (number of patient take off sites). The coefficient of friction for plastic tubing with multiple polypropylene fittings is unknown, and calculations of delivered flow are thus unreliable. Because the cost and weight differential between ¾-inch and ½-inch tubing is relatively small, a system is best built with ¾-inch main tubing. If a smaller tubing system were built, careful testing of flow delivery and monitoring for heat generation would be necessary.

This system will power multiple ventilators. The total number of ventilators would be dependent on the ventilator types and oxygen settings. Ventilator types with internal compressors or supplied from a separate air compressor would need significantly less oxygen. Some ventilators may require very high oxygen flow rates for peak inspiration, but this is cyclic for a few seconds and the total flow over time is not generally greater than the 10 lpm tested. The Dewar tested in this project in theory would support up to 18 ventilators at 10 lpm for 16 hours. It would be preferable to support fewer ventilators per Dewar with less frequent resupply. There is some risk that multiple ventilators all cycling at the same time would cause a significant pressure drop in the line. If this were to happen, the ventilators would reset, and again cycle and should continue to work. Because the oxygen system driving line pressure and supply line diameter are equal to that currently used in hospital oxygen systems for multiple ventilators, a synchronous malfunction of ventilators appears unlikely.

The system will support multiple patient beds. The optimal configuration is about 25 to 30 beds supplied by a Dewar. This is based on safety and resupply considerations.

Resupply

In our current configuration the inclusion of a side port to a standard hospital H tank will supply the several minutes of oxygen needed to allow the Dewar to be replaced with a full one (Figure 1). Note that one H tank will empty in 46 minutes with 30 outlets at 5 lpm. If the improvised oxygen system supports 30 beds each averaging 5 lpm, the Dewar used in this experiment would need to be replaced every 20 hours. As the average hospital patient averages less than 5 lpm (unless multiple masks are in use) it should be possible to resupply once daily.

Cost and Storage

The total cost of the improvised oxygen system is approximately US$2,100. This is well within the cost parameters that community and hospital planners can spend on disaster preparedness. The components require only 2–3 cubic feet for storage and have a lengthy shelf life. They do not require assembly except at time of use. The oxygen Dewar can be ordered from a local supplier at the time of use. Preexisting memoranda of understanding or contracts would be important in this process.

LIMITATIONS AND SAFETY ISSUES

This was a laboratory study of the building of the system and testing of flow rates. Prolonged use in an actual emergency may uncover other design issues.

System Freezing Issues

The ability of the Dewar to warm the oxygen is less than the maximal rate at which vaporization occurs. The side of the Dewar will reveal frost accumulating in an upward fashion, and as the frost reaches near the top of the Dewar, the valve fittings will rapidly freeze. If this occurs, the plastic delivery line will freeze solid. Oxygen continues to flow but the risk of tubing fracture is high, and very cold oxygen will flow to the nearest take off points. The low-pressure regulator will freeze and the oxygen flow must be shut off using the main Dewar valve.

The rate of maximal practical oxygen flow will vary with size and manufacturer of the Dewar. We found an oxygen flow of 260 lpm was the maximum we could achieve before we exceeded the ability of the Dewar to warm the oxygen and freezing of the regulator occurred. This rate is slightly above the 50 oxygen ports functioning at 5 lpm that we successfully tested as a delivery circuit. In clinical use, if several nonrebreathing oxygen masks were inserted into the circuit at 15 lpm with the remainder of 50 ports running at 3–5 lpm, the risk of freezing would be very high.

Icing may also occur if there is separation of the fittings and the supply line pressure drops to near zero. If this is not corrected rapidly the LOX in the Dewar will vaporize at a near maximal rate, and icing of the regulator and tubing is likely. The use of hose clamps on all fittings improves the safety of the system. Because hose clamps are ubiquitous and inexpensive, this should be easily achievable.

The ability to rapidly respond to a system separation requires the ability to clamp the tubing to control the oxygen flow. Standard cardiac bypass tubing clamps will not work on the thick high-pressure tubing. A suitable clamp is a needle nosed vise grip pliers with segments of ½-inch tubing on the jaws.

Other Risks

There is a significant fire risk with using this system with plastic tubing conveying 100% oxygen. Control of any flame source is imperative.

Large tubing diameters are used to ensure adequate flow, but also to minimize friction in the tubing. This allows lower pressures to be used and reduces the risk of separation on the system. This system should only be used in a true emergency setting. Normal oxygen systems are built of copper. If used for a prolonged time course, or if ample warning occurs before need, it would be safer to make the main piping system out of copper. This could be done with the plastic fittings used for short segments only.

The presence of contaminates in the tubing and fittings is a possibility. Given the high flow of oxygen, any contaminates would be quite diluted but potentially deleterious to already sick individuals. The use of food-grade tubing probably ensures a cleaner manufacturing process. The fittings appear clean of contaminates to gross inspection. It is unlikely that funding will be obtained to test the oxygen purity delivered with this type of system, so the risk versus benefit of this type of improvised system must be assessed at the time of considered use. In a pandemic where individuals will die without oxygen, this will be an easier decision than other potential circumstances.

The icing potential, as well as the other risks, mandates that the system be continuously monitored during use by individuals capable of intervening as needed if untoward events happen. This may involve the decision to shut off oxygen flow for a period of time with the clinical risks to patients that would entail.

The actual delivery of oxygen through the system must be calculated and monitored. It would generally be better to build 25- to 30-bed systems each with its own supply Dewar. These smaller systems will allow some of the individual oxygen outlets to support higher flows (e.g., nonrebreather masks) with less risk. This will lessen the risk of freezing, mitigate the risks if a disconnection occurs, and make resupplying the LOX Dewar easier.

CONCLUSIONS

This method of rapidly providing an improvised oxygen system to alternate care sites is feasible, quickly assembled, and inexpensive. This could be a life-saving methodology in the event of an outbreak of pandemic respiratory illness such as influenza.

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