Shortages and Vulnerabilities of Hospital Oxygen Systems

Robert L Chatburn and Richard D Branson

The COVID-19 pandemic has inundated hospitals with patients suffering from profound hypoxemia and placed a strain on health care systems around the world. Shortages of personnel, drugs, ventilators, and beds were predicted and, in many cases, came to fruition. As the pandemic wore on, there have been reports of impacts on hospital medical gas supply systems. Oxygen in particular has been a concern for hospitals in terms of supply and distribution. This article outlines procedures for estimating medical gas flow limitations within health care organizations and also methods for estimating gas consumption. *Key words: oxygen therapy; disaster medicine; oxygen use calculator; F_{IO_2} prediction equations.* [Respir Care 2022;67(8):1002–1010. © 2022 Daedalus Enterprises]

Introduction

The last 2 years of the COVID-19 pandemic have revealed many operational weaknesses of our highly complex medical system. Some of these problems were anticipated by Ritz and Previtera in an article in this Journal as early as 2008, including a particularly good description of bulk liquid oxygen systems.[1] These concerns were reiterated in this Journal by Blakeman and Branson in 2013, noting that "The Strategic National Stockpile supplies medications, medical supplies, and equipment to disaster areas, but it does not supply oxygen."[2]

In early 2020, the leadership of Cleveland Clinic formulated predictions of a greatly increased need for mechanical ventilation. Of course, increased demand for ventilators creates an increased demand for health care providers to operate them and increased strain on medical gas supply systems. Like other hospitals, Cleveland Clinic scrambled to inventory every available ventilator and to purchase more. Anticipating the increase in use of both mechanical ventilation and high-flow oxygen therapy, we initiated 3 research projects.

To address the concern about a possible shortage of ventilators, we began 2 different but related research tracts. First, in response to the general difficulty of obtaining more conventional ventilators, we assembled a team of doctors and medical students (who happened to be electrical engineers) to design and build our own emergency-use ventilator with open-source instructions for others to duplicate it.[3] Second, we conducted a simulation-based study of the (then popular) claim that 2 or more people could be ventilated with a single ventilator (called multiplex ventilation). The study concluded that "Three critical problems must be solved to minimize risk: (1) partitioning of inspiratory flow from the ventilator individually between 2 patients, (2) measurement of V_T delivered to each patient, and (3) provision for individual PEEP."[4] We followed this with another simulation-based study describing new inventions to solve the problems but concluded that despite the successful implementation of these devices in simulations "... the application of multiplex ventilation is still recommended to be a last-resort option in ventilating patients and should only be used if there are absolutely no ventilators available for single-patient ventilation."[5]

Fig. 1. Increased demand for liquid oxygen resulted in progressive icing of the heat exchange coils.

Finally, we turned our attention to the potential problem of running out of medical gas. Our concerns were voiced in a guidance document posted on the AARC Newsroom (see Table 3). In addition, as early as May 2020, a web site of the American Society for Health Care Engineering warned that "increased high flow oxygen demand within the hospital can be the cause of ice accumulation on the vaporizers that will reduce bulk medical oxygen supply system capacity, which can be relieved with methods known by oxygen suppliers ... However, most importantly ... the key is that healthcare facility managers know that their internal hospital systems need to be sized to intake the amount of oxygen being demanded by ventilators."[6]

As it turns out, these warnings were prescient. In January 2021, *The Wall Street Journal* was reporting oxygen scarcity from Brazil to Zambia.[7] Also in that month, *The New York Times* reported that "California has deployed the United States Army Corps of Engineers and the California Emergency Medical Services Authority to deliver and refill oxygen tanks. In Los Angeles County, emergency workers have been told to conserve oxygen and administer the minimum amount of oxygen to keep patients' oxygen saturation level at or just above 90%."[8]

In February of 2021, *The New York Times* reported on the consequences of oxygen shortages in Mexico.[9] In April of 2021, the BBC News reported that hospitals across India were experiencing oxygen shortages.[10] A September 2021 Daily Briefing of the Advisory Board stated that "The Covid-19 pandemic has led to shortages of PPE, ventilators, blood, and healthcare professionals—and now, amid a delta variant-driven surge in hospitalizations, several Southern states are struggling to meet demand for oxygen."[11]

Shortages of oxygen, oxygen demand, and oxygen distribution all require an understanding of hospital liquid oxygen systems, piping within the hospital infrastructure, and the consumption of oxygen by devices used to deliver oxygen to hypoxemic subjects. These issues are considered below.

Limitations of Medical Gas Supplies

As the pandemic progressed, the Cleveland Clinic system did in fact experience a large increase in ventilator usage, and new ventilators were purchased. Perhaps more importantly, the use of high-flow nasal cannula (HFNC) increased dramatically. We started (and continue) to monitor both daily high-flow oxygen usage and ventilators in use for both patients with COVID and non-COVID patients. This markedly increased demand and put a strain on our bulk oxygen supply system. Whereas oxygen supply deliveries were never a problem, we were more concerned with icing of the bulk liquid oxygen system. Figure 1 shows the effects of increased demand evidenced by icing on the liquid oxygen heat exchangers.

When oxygen changes state from liquid to gas, it absorbs heat. This heat transfer is the purpose of the heat exchange coils. Cooling of the coils causes water vapor in the atmosphere to accumulate as ice. Over the course of 2020, icing increased dramatically. This was monitored daily, and the plan was that if ice covered more than 50% of the heat exchange coils de-icing procedures would be activated.

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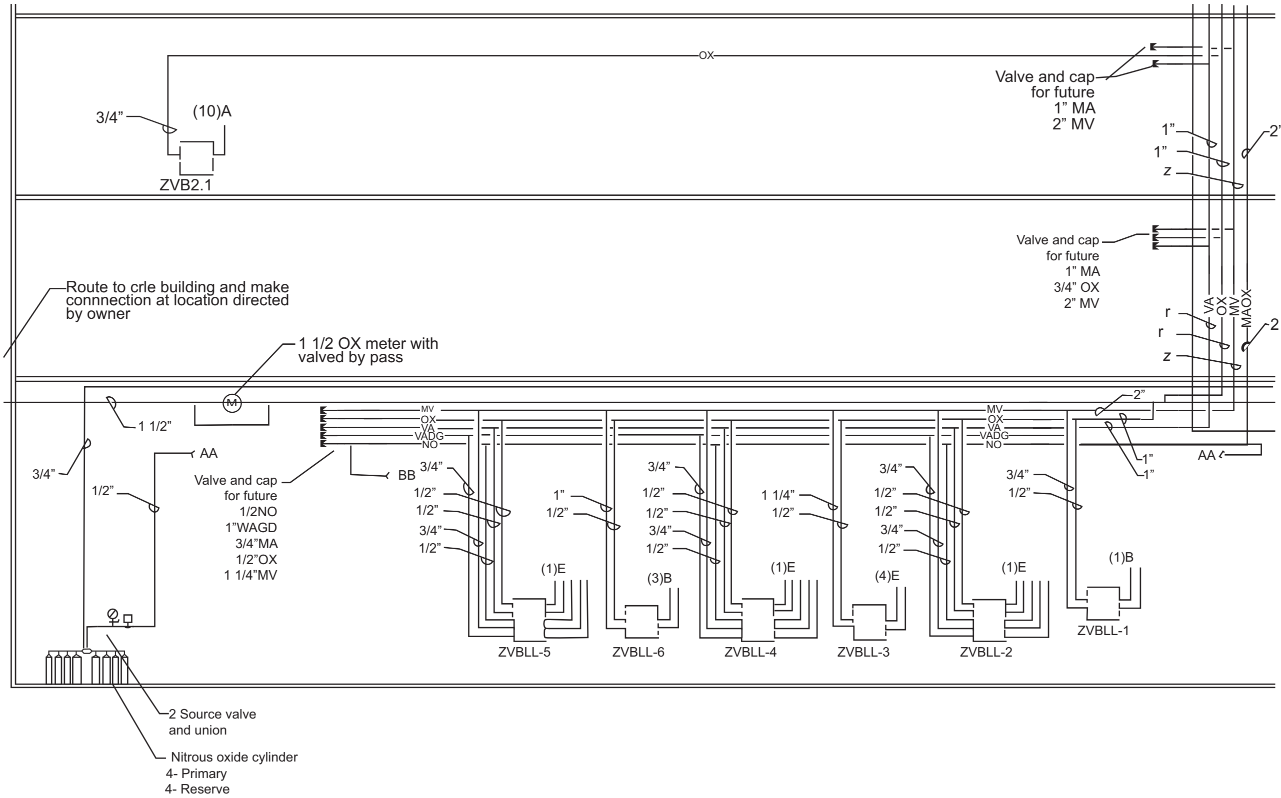


Fig. 2. A portion of a medical gas plumbing schematic.

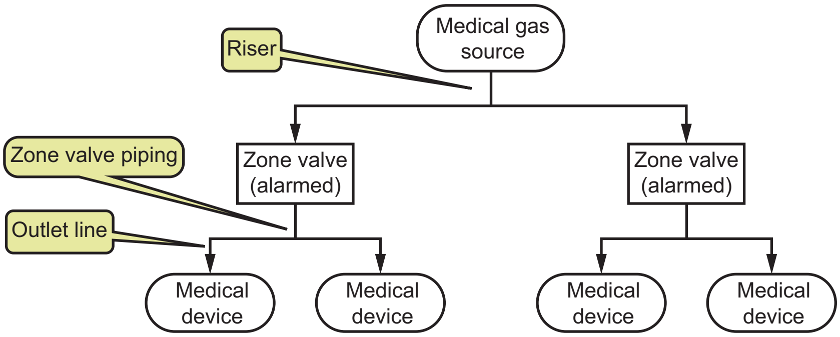


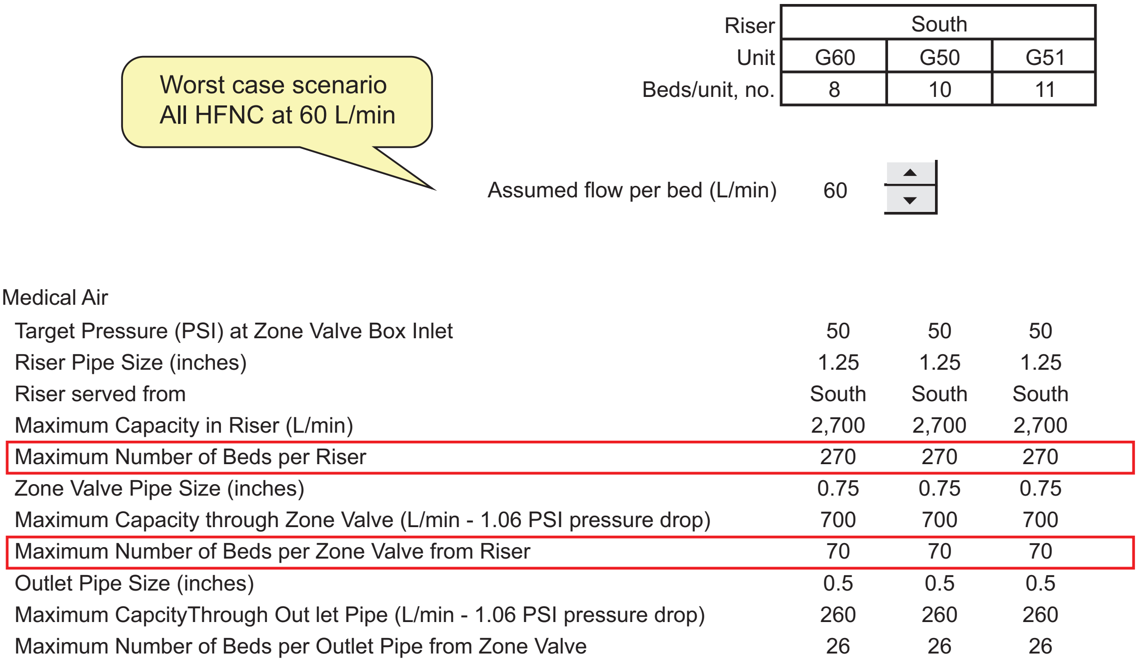
Fig. 3. Simplified medical gas plumbing schematic. Yellow balloons show potential choke points.

Table 1. Example of the Relations Among Pipe Diameter, Pressure Drop, and Flow Capacity

Pipe Size (inch)	Pressure Drop/100 Ft (psig)	Capacity (L/min)
1¼	1.02	2,700
1½	1.02	4,300
2	0.64	7,000
2	0.60	12,000
3	0.53	18,000

This happened in at least one of the Cleveland Clinic Foundation Florida hospitals.

After developing the initial guidance document for the American Association for Respiratory Care, we opened a dialog with engineers from the hospital's Facilities Engineering Department. They helped us broaden the scope of our investigations and the development of 2 calculators we could use to predict limitations of medical gas supply. The engineers reviewed the hospital oxygen plant bulk storage capacity and the maximum flow capacity and identified contingency plans. They shared medical gas plumbing schematics (Fig. 2). A simplified and generalized schematic is shown in Figure 3.

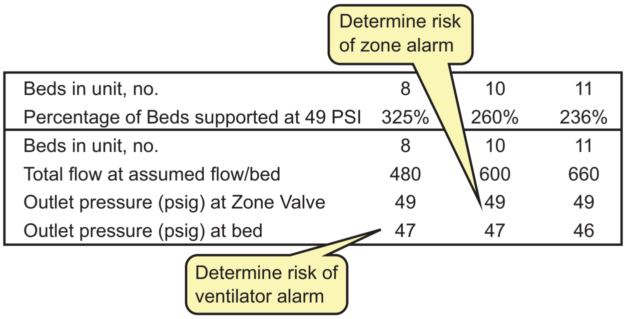


Riser	South		
Unit	G60	G50	G51
Beds/unit, no.	8	10	11

Assumed flow per bed (L/min) 60

Medical Air			
Target Pressure (PSI) at Zone Valve Box Inlet	50	50	50
Riser Pipe Size (inches)	1.25	1.25	1.25
Riser served from	South	South	South
Maximum Capacity in Riser (L/min)	2,700	2,700	2,700
Maximum Number of Beds per Riser	270	270	270
Zone Valve Pipe Size (inches)	0.75	0.75	0.75
Maximum Capacity through Zone Valve (L/min - 1.06 PSI pressure drop)	700	700	700
Maximum Number of Beds per Zone Valve from Riser	70	70	70
Outlet Pipe Size (inches)	0.5	0.5	0.5
Maximum CapcityThrough Out let Pipe (L/min - 1.06 PSI pressure drop)	260	260	260
Maximum Number of Beds per Outlet Pipe from Zone Valve	26	26	26

Fig. 4. Portion of the medical gas flow limitations calculator. HFNC = high-flow nasal cannula; psi = pounds per square inch.



Beds in unit, no.	8	10	11
Percentage of Beds supported at 49 PSI	325%	260%	236%
Beds in unit, no.	8	10	11
Total flow at assumed flow/bed	480	600	660
Outlet pressure (psig) at Zone Valve	49	49	49
Outlet pressure (psig) at bed	47	47	46

Fig. 5. Calculations to assess risk of zone valve overload.

This schematic helps to visualize the main flow limitation areas or choke points. Choke points represent narrowing of the gas delivery system, much like narrowing of airways in the lower respiratory tract. This narrowing and increase in resistance reduce flow distal to the choke point, limiting downstream oxygen delivery to high gas consumption therapies.

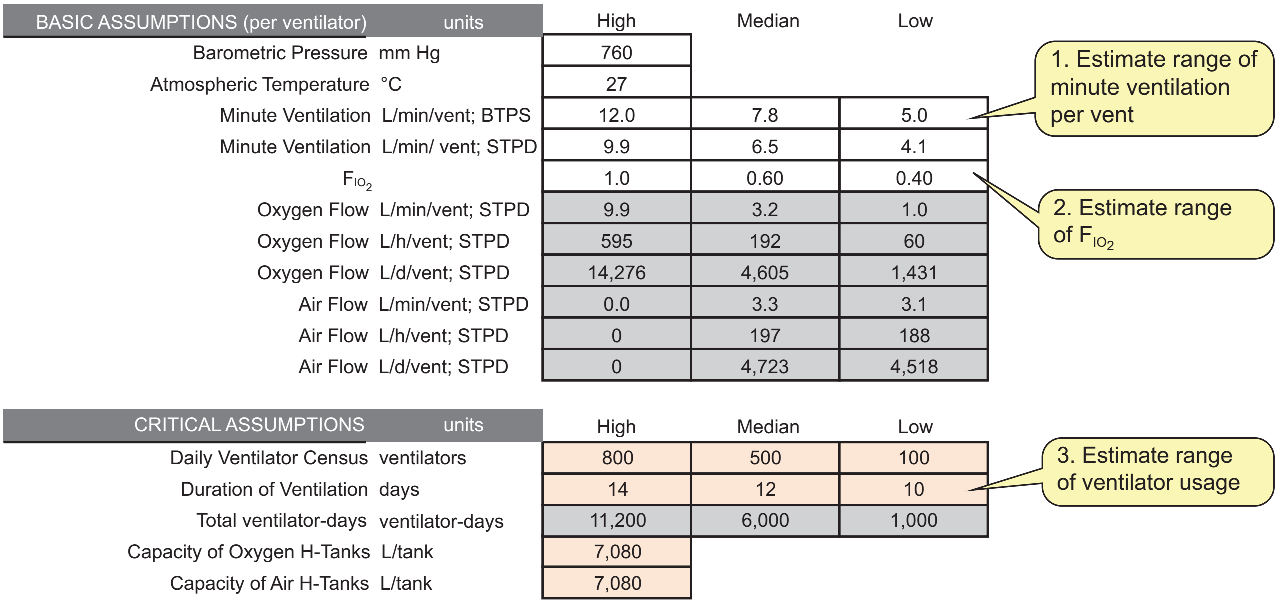
The main choke points are in 3 locations. First there are the riser lines (eg, 1.25 inches in diameter) coming from the medical gas source (either bulk liquid oxygen or compressed gas tanks). Next comes the zone valves and lines connected to them (eg, 0.75-inch diameter). Finally, there are the outlet lines that connect to the medical devices in patient care rooms (eg, 0.5-inch diameter). The principle is that the higher the flow through these lines, and the smaller the diameter, the greater the pressure drop across them. If the pressure drop is large enough, alarms will be sounded in the zone valve boxes (eg, alarm triggered if pressure drops below 45 psig).

The engineers provided tables that show the pressure drop across various diameters of pipe (Table 1). From tables like this, we constructed a calculator (Microsoft Excel spreadsheet) that allowed what-if analyses to determine the maximum number of oxygen consuming devices in patient care areas. We focused on ICUs because that was where we assumed the worst-case scenarios (ie, ventilators and HFNC) would occur during surges.

Determining Medical Gas Flow Limitations

Figure 4 shows a portion of the medical gas flow limitations calculator. In the upper-right corner, there is a small table showing that 3 ICUs (G60, G50, and G51) and their respective bed counts are supplied by a single riser. The calculator allows input of any assumed oxygen consumption rate per bed. In this case we assumed a worst-case scenario of every bed space supplying a patient with HFNC therapy at the maximum oxygen flow of 60 L/min. Below, the calculator shows that a pipe diameter of 1.25 inch is capable of a maximum flow of 2,700 L/min, which could supply 45 HFNC devices at 60 L/min. Given the number of beds in each ICU, the risers were clearly not going to limit oxygen flow. We found the same to be true of the zone valves.

Because the zone valve is evidently the limiting factor, the calculator shows data that allow an assessment of the risk of a zone valve alarm (Fig. 5). In this example, the zone valves were able to supply 2 to 3 times the number of



BASIC ASSUMPTIONS (per ventilator)	units	High	Median	Low
Barometric Pressure	mm Hg	760		
Atmospheric Temperature	°C	27		
Minute Ventilation	L/min/vent; BTPS	12.0	7.8	5.0
Minute Ventilation	L/min/ vent; STPD	9.9	6.5	4.1
F_{IO_2}		1.0	0.60	0.40
Oxygen Flow	L/min/vent; STPD	9.9	3.2	1.0
Oxygen Flow	L/h/vent; STPD	595	192	60
Oxygen Flow	L/d/vent; STPD	14,276	4,605	1,431
Air Flow	L/min/vent; STPD	0.0	3.3	3.1
Air Flow	L/h/vent; STPD	0	197	188
Air Flow	L/d/vent; STPD	0	4,723	4,518

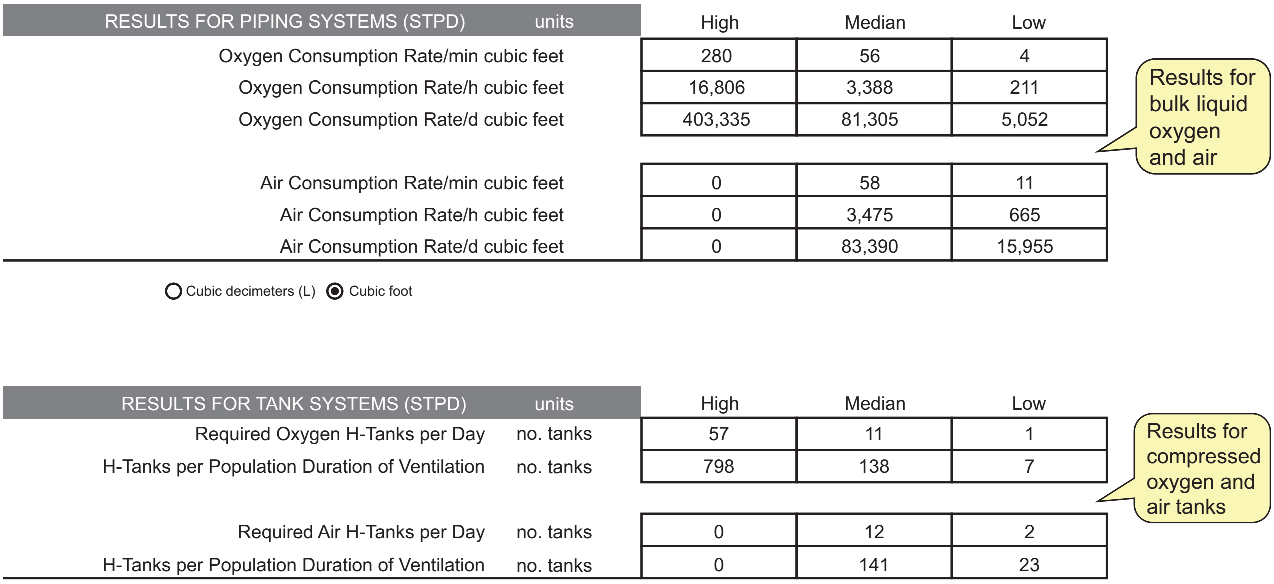
1. Estimate range of minute ventilation per vent

2. Estimate range of F_{IO_2}

CRITICAL ASSUMPTIONS	units	High	Median	Low
Daily Ventilator Census	ventilators	800	500	100
Duration of Ventilation	days	14	12	10
Total ventilator-days	ventilator-days	11,200	6,000	1,000
Capacity of Oxygen H-Tanks	L/tank	7,080		
Capacity of Air H-Tanks	L/tank	7,080		

3. Estimate range of ventilator usage

Fig. 6. Input section of medical gas consumption calculator. BTPS = body temperature and pressure saturated (with water vapor); STPD = standard temperature and pressure dry.



RESULTS FOR PIPING SYSTEMS (STPD)	units	High	Median	Low
Oxygen Consumption Rate/min	cubic feet	280	56	4
Oxygen Consumption Rate/h	cubic feet	16,806	3,388	211
Oxygen Consumption Rate/d	cubic feet	403,335	81,305	5,052
Air Consumption Rate/min	cubic feet	0	58	11
Air Consumption Rate/h	cubic feet	0	3,475	665
Air Consumption Rate/d	cubic feet	0	83,390	15,955

○ Cubic decimeters (L) ● Cubic foot

Results for bulk liquid oxygen and air

RESULTS FOR TANK SYSTEMS (STPD)	units	High	Median	Low
Required Oxygen H-Tanks per Day	no. tanks	57	11	1
H-Tanks per Population Duration of Ventilation	no. tanks	798	138	7
Required Air H-Tanks per Day	no. tanks	0	12	2
H-Tanks per Population Duration of Ventilation	no. tanks	0	141	23

Results for compressed oxygen and air tanks

Fig. 7. Output section of medical gas consumption calculator.

beds in each ICU with a pressure drop of 1 psig. The pressure drop at the outlet was also minimal (3 psig). This is a consideration because ventilators have internal pressure sensors that will alarm if their required inlet gas pressure drops too low (the lower limit of pressure varies among ventilators but is usually about 40–45 psig; check the technical specifications of the operator's manual). The example analysis shows the medical gas plumbing system would not be a limitation.

Estimating Medical Gas Usage

Having determined that gas flow would not be a limitation with the worst-case scenario of 60 L/min of oxygen consumption per bed, further analysis was unnecessary. However, we wanted to provide a tool for situations where plumbing might be a limitation (eg, emergency patient treatment areas built on demand or expanded to areas not designed for such use). For

Table 2. Oxygen Delivery Devices

Device Type	Device	Flow(L/min)	Expected F_{IO_2}	Maximum O_2 Usage (L/min)
Adjustable O_2 Flow	Nasal cannula	1–6	0.22–0.40	6
	Simple mask	5–10	0.35–0.50	10
Adjustable F_{IO_2}	Entrainment mask	2–15	0.24–0.60	15
	High-flow nasal cannula	10–60	0.21–1.00	60
	Invasive or noninvasive mechanical ventilation (no leak)	5–15	0.21–1.00	15
	Noninvasive mechanical ventilation (with leak max 40 L/min)	45–55	0.21–1.00	55
Nonadjustable	Partial rebreather mask	≥ 10	0.40–0.70	15
	Non-rebreather mask	≥ 10	0.60–0.70	15

Table 3. Useful Equations for Estimating Gas Consumption

$$F_{IO_2} \times \textit{total flow} = (F_{O_2} \times \textit{O}_2\textit{flow}) + (F_{O_2} \times \textit{air flow})$$

$$F_{IO_2} \times \textit{total flow} = (1.0 \times \textit{O}_2\textit{flow}) + (0.21 \times \textit{air flow})$$

$$F_{IO_2} = \frac{\textit{O}_2\textit{flow} + (0.21 \times \textit{air flow})}{\textit{total flow}}$$

$$F_{IO_2} = 1.0 - \left(\frac{0.79 \times \textit{air flow}}{\textit{total flow}}\right)$$

$$F_{IO_2} = 0.21 + \left(\frac{0.79 \times \textit{O}_2\textit{flow}}{\textit{total flow}}\right)$$

$$\textit{total flow} = \frac{0.79 \times \textit{O}_2\textit{flow}}{F_{IO_2} - 0.21}$$

$$\textit{total flow} = \frac{0.79 \times \textit{air flow}}{1 - F_{IO_2}}$$

$$\textit{O}_2\textit{flow} = \frac{\textit{total flow} \times \left(F_{IO_2} - 0.21\right)}{0.79}$$

$$\textit{O}_2\textit{flow} = \frac{\textit{air flow} \times \left(F_{IO_2} - 0.21\right)}{1.0 - F_{IO_2}}$$

$$\textit{air flow} = \frac{\textit{total flow} \times \left(1.0 - F_{IO_2}\right)}{0.79}$$

$$\textit{air flow} = \frac{\textit{O}_2\textit{flow} \times \left(1.0 - F_{IO_2}\right)}{F_{IO_2} - 0.21}$$

$$\frac{\textit{air flow}}{\textit{O}_2\textit{flow}} = \frac{1.0 - F_{IO_2}}{F_{IO_2} - 0.21}$$

F_{O_2} = fraction of oxygen in component flows of oxygen or air

Table 4. Example Results for Air/Oxygen Ratio as a Function of F_{IO_2}

F_{IO_2}	Air/O_2
0.21	1.00
0.25	18.75
0.30	7.78
0.35	4.64
0.40	3.16
0.45	2.29
0.50	1.72
0.55	1.32
0.60	1.03
0.65	0.80
0.70	0.61
0.75	0.46
0.80	0.34
0.85	0.23
0.90	0.14
0.95	0.07
1.00	0

example, the first floor of our newly built medical school was converted from administrative space to patient care space including plumbing for medical gas. Fortunately, we never had to use it, but medical gas usage had to be estimated in its design.

As it turns out, estimating gas usage based on equipment type is a more complex problem than calculating flow limitations through plumbing systems. For example, when estimating gas consumption (both oxygen and air) of ventilators, several variables must be considered, including estimates for settings of F_{IO_2} and minute ventilation along with ventilator usage (eg, ventilator days). Another spreadsheet calculator was developed to input these estimates (Fig. 6). Note that the calculator allows inputting estimates as a range of values (eg, low, median, and high) that might be obtained from actual patient care data that are readily available to managers of respiratory care departments. Note that the calculator takes into account the fact that ventilator gas consumption is expressed differently (by clinicians) than gas supply (by engineers), leading to a potential miscommunication. Specifically, the gas conditions for ventilation are assumed to be body temperature and pressure saturated with water vapor, whereas gas supply is assumed to be at standard pressure and temperature dry.

Having input reasonable estimates for gas consumption, the calculator outputs the required medical gas supply for bulk oxygen and compressed gas cylinders or tanks (Fig. 7). If the gas supply is a tank system, then consideration must be given to both transportation and secure storage, which can be serious challenges themselves. All of the underlying equations programmed into the medical gas consumption

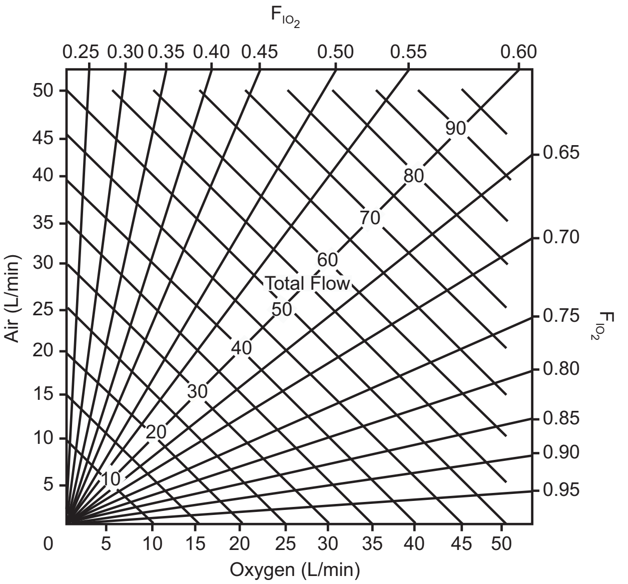


Fig. 8. Example nomogram for estimating medical gas consumption based on F_{IO_2} and total flow (using equations from Table 3).

calculator are clearly visible by clicking on a cell with a calculated value. The calculator is not limited to mechanical ventilators. Instead of minute ventilation, you could enter the oxygen flow supplied to HFNCs or any other oxygen delivery device (Table 2).

There is at least one other calculator available to estimate gas consumption (see Table 6). It is a web-based software program designed by the OpenCriticalCare.org, launched in August 2020 as a repository for reliable, open-access, critical-care learning tools with relevance to resource-variable settings. This calculator allows input of oxygen supply sources and capacities specified as oxygen plant, portable oxygen concentrator, liquid oxygen, and oxygen cylinders. Patient demand can be input for a wide variety of oxygen delivery devices. The output of the calculations is expressed as gas flow consumed per day, H cylinders consumed per day, total fixed supply (cylinders and liquid), total generated supply (plants and portable oxygen concentrators), and fixed supply duration (hours or days). This is a well-designed web site, and it also describes the equations underlying the calculations.

Table 3 shows a list of relevant equations for calculating air and oxygen usage as a function of F_{IO_2}. Table 4 gives some example results for air/oxygen ratios as a function of F_{IO_2}. Figure 8 is an example of a useful graph for medical gas usage prediction based on the equations of Table 3.[12]

Special Considerations for Mechanical Ventilation

For invasive mechanical ventilation, oxygen consumption is usually more than just that determined by the set minute ventilation and F_{IO_2}. Ventilators may have internal leaks during normal operation, and more importantly, any ventilator that provides flow triggering probably has a constant bias low that must be added to the set minute ventilation for accurate calculation of oxygen consumption. You must contact the manufacturer of each ventilator to determine this information, as it is usually not included in the operator's manual.

Table 5. List of Some of the Oxygen-Related Issues Faced by California Hospitals During the COVID-19 Pandemic

1. Icing of liquid oxygen coils
2. Rapid use of oxygen cylinders during transport
3. Rapid comsumption of oxygen from cylinders
4. Power outages
5. Patient discharge to home delays
6. Vendors unable to resupply oxygen
7. Durable medical equipment support challenges
8. Inability to transport on high-flow nasal cannula
9. Shortages of oxygen regulators, tubing, masks
10. Shortages of sterile water

During noninvasive ventilation (NIV), things may be more complicated. The first consideration is whether the patient circuit is active or passive. Active means it has an exhalation manifold and operates like a conventional ventilator (ie, intermittent occlusion of the circuit to achieve inflation during the inspiratory time). However, a passive circuit works by altering a continuous flow through an intentional fixed leak (ie, high flow gives high inspiratory pressure and low flow gives expiratory pressure). Hence, the key variable is the intentional leak flow, which varies with the pressure and is difficult to estimate unless the ventilator is designed to measure it. For example, all Philips devices that have an integral blender measure and display the total leak (V60, V680, EV300, Trilogy 202, Vision). The V60, V680, and Vision are also capable of measuring and displaying the patient leak or unintentional leak (ie, due to poor mask fit). Unfortunately, each of these devices only displays one leak (patient or total) depending on how they are set up on initiation. For example, the total leak can be accessed by changing the mask and port settings on the V60/V680 to other, which results in the total leak being displayed. For the Vision, the total leak will be displayed if the exhalation port test is bypassed on initiation (it will display patient leak following successful completion of the port test by subtracting the intentional leak). Unfortunately, you will not find this information in either the operator's manuals or in any of the training materials. Again, you must check with the ventilator manufacturer for each device.

The intentional leak during NIV will be determined by the orifice of the leak port and the pressure applied. Each leak port has a measurable characteristic (refer to manufacturer's data), and the leak will be determined by multiple factors including inspiratory pressure, expiratory pressure, inspiratory time, expiratory time, breathing frequency, etc. To determine a low-

Table 6. Additional Resources

Sponsor	URL	Content
Americal Association for Respiratory Care	https://www.aarc.org/additional-ventilators-may-pose-risk-to-hospital-gas-systems/	Guidance document: Additional ventilators may pose a risk to hospital gas systems Download link for calculator
Medical Gas Professional Health Organization	https://mgpho.org/	Video: Impact of COVID-19 on medical gas systems
BeaconMedaes	https://www.ashe.org/system/files/media/file/2020/04/MedGasSizing-updated.pdf	White paper: Sizing medical cases for COVID-19
Kaiser Permanente	https://www.dropbox.com/s/nbh6sitchxzbg36/KP White Paper Medical Air and Oxygen Capacity v3.pdf?dl=0	White paper: Medical air and oxygen capacity
The Joint Commission	https://www.jcrinc.com/-/media/jcr/jcr-documents/products/consulting/covid-recovery-services/max-medical-gas-ec-news.pdf	White paper: Maximizing medical gas flow capacity
Hamilton Medical	https://www.hamilton-medical.com/en US/E-Learning-and-Education/Knowledge-Base/Knowledge-Base-Detail2020-07-07Calculating-oxygen-consumption-for-Hamilton-Medical-ventilatorsc1b09f7f-3224-45b9-aa12-4cfd37e6d5ff.html	Download PDF: Calculating oxygen consumption for Hamilton Medical ventilators
Cleveland Clinic	https://1drv.ms/u/s!AuFakBJODC3DgeFlwoQcaOzBu6A jA?e=EcWPhz	Calculators: Medical gas flow limitations; medical gas consumption Slide shows
Open Critical Care	https://opencriticalcare.org/oxygen-supply-demand-calculator/	Calculators: Oxygen supply and demand; S_{pO_2} to P_{aO_2}; cylinder duration and size

end value for leak, you could take the leak at 3 cm H_2O for the smallest orifice available (to mimic the lowest possible leak). Using a specific leak port, you might calculate an intentional leak of around 10 L/min. For the high end, you could use a worst-case scenario of settings (high rate, high inspiratory pressure, high PEEP, high peak airway pressure, I-E ratio = 1:1) coupled with use of a high leak port and get to 40 L/min. Therefore, we could assume that in general the expected range of intentional leak might be 10–40 L/min.

Once you have an estimate of leak flow, then oxygen consumption can be estimated as:

$$\text{Oxygen Consumption (L/min)} =$$

$$\left[(F_{IO_2} - 0.21)/0.79\right] \times \text{total leak}$$

where total leak is in L/min. If oxygen is supplied by tank, then the tank duration is simply the tank oxygen volume divided by the oxygen consumption by the equation above. Tank oxygen volume is calculated as the pressure in the tank (in psi) times the conversion factor (L/psi). Conversion factors are as follows: D cylinder = 0.16 L/psi, E cylinder = 0.28 L/psi, G cylinder = 2.41 L/psi, H and K cylinder = 3.14 L/psi.

Practical Suggestions

In addition to the calculations explained above, there are practical tactics that can help limit oxygen consumption. The most obvious tip is to turn off the oxygen supply to manual resuscitators when not in use. Use air instead of oxygen to power jet nebulizers if possible. Use pressure triggering for ventilators, and if flow triggering is used, reduce the bias flow if the ventilator allows adjustment. Finally, limit the F_{IO_2} for all oxygen therapy to maintain adequate oxygenation and avoid hyperoxemia (a good practice in general[13,14]).

When some of our hospitals had problems with oxygen supply, we drafted a guidance document that emphasized the triage of oxygen delivery devices according to clinical need. In other words, we cautioned that HFNC might not be the first choice until the clinical need was demonstrated because of its high source oxygen flow requirement. To minimize oxygen use, a regular nasal cannula might be the first choice (1–6 L/min oxygen supply) followed perhaps by a simple oxygen mask (5–10 L/min oxygen supply). If higher and more stable oxygen delivery is required, then consider an air entrainment mask (2–15 L/min oxygen supply). Some cannulas are now marked as high flow (up to 15 L/min) and supplied with nonheated bubble humidifiers. However, unpublished data from our lab indicate that using flow > 8 L/min may result in inadequate humidification. Partial and non–rebreather masks can deliver high F_{IO_2} at relatively low oxygen flow (10–15 L/min) while supporting a relatively high patient inspiratory flow demand. Indeed, these devices were invented to conserve oxygen. However, they are typically not used with humidifiers, so short-term use is indicated. Research is needed to see if the high-flow unheated humidifiers mentioned above might extend the duration of treatment using partial and non–rebreather masks. The accepted standard for noninvasive, unassisted oxygenation support is the heated HFNC (20–60 L/min oxygen

supply). Theoretically, the oxygen flow should be set to just exceed the patient's peak inspiratory flow demand. However, flow demand is highly variable, and there is no convenient way to measure or predict it for patients with lung disease. Therefore, as with all oxygen therapy, the required oxygen supply should be assessed by titration with S_{pO_2} or P_{aO_2} monitoring.

A subcommittee from the Task Force for Mass Critical Care offers interim evidence-informed operational strategies to assist hospitals and communities to plan for and respond to surge capacity demands resulting from COVID-19.[15] Ten new suggestions are presented in this interim report emphasizing specific operational strategies intended to prolong the contingency state, thereby avoiding crisis and the need for triage of scarce resources. A recent article describes the disaster response by the state of California to mitigate the emergency demands for oxygen delivery resources.[16] Some of California's many concerns are listed in Table 5.

Even if you conclude that oxygen systems within your facility are unlikely to fail, your planning should include some practical short-term strategies if systems do fail or are near failure. For example, is it possible to use tanks or to reroute gas supplies using zone valves or other systems? If a facility's bulk oxygen ran out, is there a way to get liquid oxygen quickly?

Other Resources

There is an increasing awareness of medical gas consumption issues on the internet. New resources are being added continually. See Table 6 for just a few of these.

Summary

Oxygen supply systems within medical facilities include a liquid supply, heat exchange coils, and a complex piping system that includes risers, zone valves, and outlets. Under normal conditions, these systems operate without much concern. In times of high demand, attention to the replenishment of the liquid oxygen supply, icing of heat exchange coils, and gas consumption requires daily attention. Understanding the capacity of oxygen to supply gas to critically ill patients within a surge capacity unit is important for success and avoiding alarms and failures of the oxygen delivery. Common sense practices can be used to eliminate wasting oxygen. Remember, failing to prepare means preparing to fail.[17]

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