Predicting Surge Requirements for Medical Gas Consumption

Robert L. Chatburn, MHHS, RRT-NPS, FAARC
Research Manager – Respiratory Institute
Cleveland Clinic
Professor – Department of Medicine
Lerner College of Medicine of Case Western Reserve University
Disclosure

• I am a paid consultant for
  – IngMar Medical
  – Hillrom
  – Vyaire Medical

Disclaimer

• I have no experience in the area of facilities engineering
• I do have 40+ years of experience as a medical scientist
• All opinions expressed in this talk are my own and do not represent those of the Cleveland Clinic
Goal of this talk

- To improve the communication between Medical Gas Professionals and Healthcare Professionals to better prepare for emergency surges in oxygen consumption
Overview

• Gas consumption concerns during a surge
• Facilities design issues
  — Limitations on $O_2$ consumption due to facility design
  — Potential problems with design tolerances
• Crash course on medical consumption of oxygen
  — Medical terms
  — Device descriptions
• Crash course on statistics
• How to predict oxygen consumption
  — Misconceptions about data needed
  — Where to get the data
  — How to use the calculator
• Practical suggestions
Predicting medical gas consumption during surge conditions is a complicated topic. This is because hospitals themselves are extremely complex organizations. By definition, the behavior of complex systems is essentially unpredictable.
COVID-19 Epidemic Concerns

• Increased usage of mechanical ventilators
  – Increased usage of current inventory
    • Invasive & non-invasive mechanical ventilators
  – Rapid increase in new ventilator purchases

• Increased usage of other oxygen delivery equipment
  – Conventional and high flow nasal cannulas

• The limiting factor may not be the number of ventilators but the medical gas supply to operate them

The COVID-19 epidemic has placed hospitals in dire risk of having insufficient resources to treat the surge in patients. One critical resource is mechanical ventilation. As hospitals rush to increase ventilator inventory, they may be overlooking an important limiting resource; perhaps as important as ventilator circuits or even clinicians to operate the machines. That resource is the facilities medical gas supply.
Facilities Design Issues
Ventilators used in intensive care units, particularly in the United States, are usually connected to central medical gas supply of oxygen and medicinal compressed air outlets at 50 psig linked by plumbing to huge liquid oxygen storage tanks, filtered air compressors, and dehumidifiers in the building’s mechanical and plumbing systems.

When the demand for oxygen flow exceeds the vaporization of oxygen in the coil system, the pressure drops, starving the ventilators of needed flow. This is often manifested by ice forming on the coils, even in the heat of summer.

This slide shows icing on my hospital’s oxygen system evaporation coils during peak load in April and during a period of reduced usage in September. I recommend that you watch the video provided by the Medical Gas Professional Healthcare Organization.
If the air compressor system and its associated dehumidifying system is overloaded, moisture can enter the hospital air lines and reach the ventilators causing ventilator failure.
There is no single set design procedure for medical system gas sizing. Various companies have their own methods. When designing a hospital, design professionals typically build in a surge capacity factor for medical gas supply lines. This factor may be something like 25%-50% above the expected load, which may be considerably less than the surge expectations of clinicians.

Facilities Design – Tolerance Limits

• No standard design procedure for medical gas sizing
  — Tolerance limits set by engineering experience
  — Clinical experience may be misunderstood or not considered

• System design surge tolerances may not be adequate
  — Tolerances may be based on average normal oxygen usage
  — Surge oxygen use may be based on unexpected use of medical equipment (types and numbers)

• Tolerances must be based on clear communication between clinicians and engineers
  — Data from current COVID-19 surge should be used to improve prediction accuracy
Crash Courses in Medical Terminology
In order to understand the basics of predicting medical gas consumption during surges, we need to review some terminology associated with medical gas use. In particular, ventilator usage is recorded in the electronic medical record using a metric called a “ventilator day”.

**Crash Course in Medical Terminology**

- **Ventilator**
  - Automatic machine use to perform some portion of the work of breathing to assure gas exchange
- **Ventilator-day**
  - Metric for ventilator usage recorded in EMR
  - One ventilator used for 24 hrs = 1 vent day
  - One ventilator used for 2 days = 2 vent days
  - Two ventilators used for 1 day = 2 vent days
Crash Course in Medical Terminology

- Invasive ventilation
  - Intubation with endotracheal tube or tracheostomy tube
Crash Course in Medical Terminology

- Non-Invasive ventilation
  - Use of mask or helmet
Textbooks often classify ventilators by how they are used. For example, there are general purpose ventilators that can be used on any kind of patient from neonates through adults. This is the most common type of intensive care unit (ICU) ventilator. Examples of commonly used general purpose ventilators are the Covidien PB 840, the Dräger Evita XL, the Maquet Servo i.
Another large and growing category is homecare ventilators. These devices are much simpler, smaller, and less costly than general purpose ICU ventilators.

Commonly used homecare ventilators include the Covidien PB 540, the Newport HT 50 and the Carefusion LTV 900.

Transport ventilators are even smaller and simpler, sometimes having only an on-off switch.

They are designed for short term use when moving patients, such as between the ICU and diagnostic areas or between hospitals.
Some ventilators are designed specially for use with neonatal and pediatric patients. The only commonly used specialty ventilator for infants in the US is the Dräger Babylog.
The ventilators we have mentioned so far are referred to as “conventional” ventilators, meaning that they provide ventilatory patterns similar to normal breathing.

Another category is “high frequency ventilators”, so named because they delivery very small breaths at frequencies well above normal breathing frequencies, ranging from about 3 to 15 Hz (cycles per second).

The idea behind high frequency ventilation is to use the smallest possible breaths to avoid stretch injury to the fragile lungs of premature infants or any patient with acute respiratory distress.
Finally, we have the category of noninvasive ventilators, those designed to be used with a mask interface instead of an artificial airway.
Historically, ventilators have been designed with build-in air-oxygen blenders to control FiO2. For this reason, they have traditionally required inputs of air and oxygen at high pressure (e.g., 30 psi). However, ventilators designed for home care and some ICU ventilators now replace the need for high pressure air with an internal turbine (aka blower).
Note that at least one ventilator, the VOCSN, has both a blower and an internal oxygen concentrator to supply its own oxygen needs.

In the era of emergency use ventilators quickly approved by the FDA, expect to see some very strange devices with unusual requirements.

Fortunately these will probably remain an insignificant part of the hospital’s ventilator fleet.
There is a wide range of specifications among ventilators in terms of their required oxygen supply pressure and baseline oxygen consumption. Of particular importance is the constant bias flow many ventilators use to maintain baseline pressure in the patient circuit (positive end expiratory pressure or PEEP). Furthermore, during noninvasive ventilation there are both intentional and unintentional leaks in the system that account for an unmeasured and potentially huge increase in medical gas consumption.

If the oxygen system pressure drops below the required ventilator supply pressure, alarms will sound and the ventilator may malfunction. You have to plan to keep the system pressure always above that required by the ventilators with the highest inlet pressure requirement.
In order to understand the oxygen consumption of a ventilator, you need to understand the components of ventilation itself.

What you need to predict is minute ventilation, which is comprised of tidal volume and respiratory rate.

These components are required in data collection because the electronic medical record (EMR) may not include minute ventilation data directly.

Such data are usually recorded by respiratory therapists (in North America) during routine ventilator checks that occur several times a day.

Note that for most ventilators, minute ventilation is usually an indirect consequence of direct settings for tidal volume and respiratory rate.

Minute ventilation, an average across many breaths, has no correlation with inspiratory flow of individual breaths.
Ventilators account for only a portion of a hospital’s total oxygen consumption
Many other devices are used to deliver oxygen to patients
They each have their own range of oxygen supply flows
Oxygen Delivery Devices

Entrainment (Venturi) Oxygen Mask
(4-15 L/min)

Entrainment Large Volume Nebulizer
(15 L/min)
Current guidance seems to focus on high flow nasal cannula use because it can consume up to 40 L/min for a single patient.

However, do not forget that the combined oxygen flow from all other devices may be just as important.
Of particular concern, and not mentioned in any guidance I have seen, is the use of small volume medication nebulizers. These are often connected to oxygen flowmeters. Because this is perhaps the most common medical treatment given in a hospital, the cumulative oxygen use during peak simultaneous use could be a concern. High simultaneous use is often driven by the common practice of giving aerosol treatments at standard times during the day.

**Oxygen Delivery Devices**

**Small Volume Nebulizer**
(6-8 L/min)

Note: there could be hundreds of treatments per day at perhaps 10 minutes/treatment

**Oxygen Hood**
(10-15 L/min)
All of these simple oxygen delivery devices are usually connected to oxygen flow meters.
Crash Courses in Statistics
To make predictions about hospital medical gas use, we need data.

Data are mined from the hospital electronic medical record databases.

Unfortunately, these databases were designed for billing purposes and are notoriously difficult to mine to answer clinical research questions.

Taking one simple example, data may be obtained for ventilator days for a particular hospital area (e.g., the medical ICU supplied by a particular oxygen zone valve).

This raw data will be provided as a spreadsheet.

Your task is then to turn the date into information answering the question about oxygen use predictions.

One common approach is to graph the frequency distribution and calculate some measures of central tendency or “most common” values from which to make predictions.

Beware that using the mean or average value may be misleading because this point estimate is affected by extreme values in the data set.

It is better to use the median value.

But keep in mind that if you predict oxygen usage based on a median value, you will underestimate actual use 50% of the time.

More accurate predictions require that the data be summarize with a percentile plot.
This allows you to make statements like “95% of the time ventilator usage will be less than 66 vent-days” implying that your prediction is expected to underestimate actual usage only 5% of the time.
Predicting Oxygen Consumption
Let us now unpack the complicated problem of predicting total peak oxygen consumption.

The kind of data we need is that for oxygen use by ventilator and other oxygen delivery devices.

Avoid thinking that average use over an arbitrary time period is sufficient (something I have seen reported in the medical literature).

This may be sufficient for general design specifications for new construction, but it may be misleading for surge protection.

The problem is not only to estimate oxygen use of various devices, but to find some model that predicts the maximum simultaneous use of all oxygen consuming devices.

I don’t think anybody knows how to do this and it should be the subject of serious research.

On the one hand, to assume some average value seems likely to underestimate oxygen consumption and put patients at risk.

On the other hand, to assume maximum usage of all devices would likely overestimate consumption and waste resources.

It seems we have to calculate both limits and simply guess at a target somewhere in between them.

Assuming we can get data from the EMR and summarize it with common statistical methods.
metrics, we need a tool to help make the actual predictions
That is where the oxygen gas consumption calculator comes in
We will review that shortly
First, I want to review that seems to me to be some misconceptions in the video from the MGPHO.

A table in that lecture suggests some data needed to estimate the maximum number of ventilators that can be used simultaneously without overloading the medical gas supply system.

The first misconception is that peak inspiratory flow rate is relevant – it is not.

As mentioned earlier, what you need is the average flow of oxygen through the ventilator per minute, which is not related to the peak inspiratory flow setting.

In theory, if all ventilators were set with the same peak inspiratory flow and they all delivered breaths to all patients in perfect synchrony, then there could be an oxygen overload situation.

But I believe this is obviously not a practical reality for many reasons beyond the scope of this talk.

The second misconception is that average breath rate is important.

It is, but this is only half of the needed data.

Again, the metric of interest is minute ventilation and this is the product of breath rate and tidal volume – tidal volume is not mentioned here.
The third misconception is that FiO2 or % O2 on maximum settings is relevant
Maximum settings are not defined
Rather, what you need to know is the range of FiO2 used most commonly

All of the data you need to collect interact in a complicated way that is not intuitively obvious
That is why you need a calculator designed to do the job

Finally, you will never be able to get the data you need from casual conversations with random respiratory therapists
They do not have direct access to the data
What you need is a task force with relevant content experts, including a respiratory therapist, that can interpret and mine the data from the electronic medical record
Any effort less than this will yield unreliable prediction models
The MGPHO slide show does mention some sources of good advice

The Beacon Medaes report gives tables of point estimates (probably averages) for oxygen consumption of various devices

However, they specifically state that “These numbers are appropriate for source sizing and main line sizing, where demand averaging will occur. However, they should NOT be used for pipe sizing in zones, as it is entirely possible to have whole units with the sickest patients and the heaviest demand concentrated in a zone.”

I was a consultant for the Kaiser Permanente report by Sandy Renshaw P.E. and it has a pretty good summary of the important factors in oxygen consumption and gives tables of pipe sizing

The PB 840 calculator is useful and estimates both air and oxygen use rates and total gas usage if tanks are the source instead of piped gas

However, it is valid only for this ventilator and the ventilator is currently obsolete (although many are still in use)

Perhaps the best way to predict medical gas consumption is not using mathematical models but by means of simulated usage with actual ventilators and expected ventilator settings
I know of at least one hospital that has performed this successfully and got some unexpected results that would have been missed by any mathematical model.
Very
Basic
Prediction
Model
A simple model that I have seen use by facilities engineers involves just two variables.

The first is the estimated average or maximum FiO₂

These equations relating FiO₂ to air and oxygen flow are familiar to respiratory therapists because they are used to deliver oxygen therapy to patients.
You need estimates for oxygen use by ventilators and all other types of oxygen delivery devices for a particular area controlled by an oxygen zone valve.

As you have seen, creating such an estimate is easier said than done.

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Simplified Estimate of Oxygen Flow

- **Estimate oxygen use by ventilators**
  - Estimate ventilators in simultaneous use
  - Estimate total minute ventilation across all ventilators
  - Add estimate of bias flows of all ventilators
- **Estimate oxygen flow to all oxygen delivery devices**
- **Sum to calculate total oxygen flow**
This is the simple prediction model for average oxygen use based on very crude estimates of oxygen delivery device performance.

The larger the area it is applied to, the less accurate the prediction will be due to variations in oxygen use across multiple zone valves.
More Accurate Prediction
It is possible to make a more accurate prediction model

First you need to understand that flow calculations are highly affected by the temperature and pressure conditions under which flow is measured

For example, facilities engineers typically assume gas conditions are standard, meaning zero degrees centigrade or 273 degrees kelvin, one atmosphere of pressure and zero pressure due to water vapor

In contrast, simple oxygen delivery devices are calibrated for atmospheric temperature and pressure dry, as for example, the way gas flows through an oxygen flow meter connected to an oxygen mask or nebulizer

At the other extreme is body temperature and pressure as reported by most (but not all) mechanical ventilators

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**Gas Conditions for Volume Calculations**

- **STPD**
  - Standard temperature (273°K), standard pressure (760 mm Hg), dry (no water vapor)

- **ATPS**
  - Atmospheric temperature (as measured), atmospheric pressure (as measured), dry (no water vapor)
  - This is the assumption used by oxygen flowmeters

- **BTPS**
  - Body temperature (37°C), atmospheric pressure, saturated with water vapor (47 mm Hg)
  - This is the value reported by ventilators
As you can see from this example, proper conversion is essential, especially when estimating gas consumption by ventilators.

Gas volume (or flow) at STPD conditions is about 17% less than gas volume at BTPS due to cooling and removal of water vapor.

Not accounting for this discrepancy can cause important errors in your gas consumption predictions.
To address the specific concerns about increased ventilator usage, we created a calculator that is an Excel file.

- **Calculator built as an Excel file (free download)**

- **Runs on any computer that has Microsoft Excel**
- **Simple numerical inputs from clinical planners**

Medical Gas Calculator – Inputs

To address the specific concerns about increased ventilator usage, we created a calculator that is an Excel file.

It can run on any computer that has Excel installed.

The required inputs are obtained from estimates of ventilator usage that can be obtained from clinical planners.
Specific inputs include atmospheric conditions at the usage location

Estimated ranges for ventilator minute ventilation

Ranges of FiO₂

Predicted ventilator census, meaning the maximum number of ventilators in use simultaneously

The estimated duration of ventilation from actual experience with COVID-19 patients
The outputs are in units that are familiar either clinicians or engineers

The calculator shows the oxygen and air usage rates per minute, hour, or day
The total gas consumption over the duration of ventilation is relevant if tanks of compressed gas are required for locations without central plumbing for medical gases.

Medical Gas Calculator - Outputs

• Total Gas Consumption for Duration of Ventilation
  – Oxygen and air tanks required if no piped oxygen

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<td>Required Air H-Tanks per Population Duration of Ventilation (total tanks)</td>
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<td>141</td>
<td>23</td>
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</table>
In addition to estimating gas usage for mechanical ventilation, consider these other practical activities

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**Practical Suggestions**

1. **Consider simulation testing**
   - Place running ventilators with test lungs in each zone that might be used for critical care during surge

2. **Turn off oxygen to manual resuscitators until used**
   - Automatic shut-off devices are available

3. **Use minimal FiO₂ for adequate oxygenation**

4. **Reduce use of high flow nasal cannula for oxygen delivery**

5. **Find a way to monitor flow through zone valves**
   - Is it possible to use thermal probes across valves to represent flow?
Additional Resources
Additional Ventilators May Pose a Risk to Hospital Gas Systems

Medical Gas Professional Healthcare Organization

Leading through education, we save lives

Impact of COVID-19 on Medical Gas Systems

Inspecting the pressure build vaporizer should be done during the daily system inspection. If the ice on the Pressure Building coil has grown to the point where it is touching the ground, tank shell or any other component it needs to be deiced.

Bulk Oxygen Concerns: Watch for icing in unusual locations

https://mgpho.org/
Sizing Medical Gases for Covid 19

Medical Air and Oxygen Capacity

April 5, 2020

Edward (Sandy) Renshaw, P.E.
Principal Mechanical Engineer
NFS- FSPD

Phone: 714-329-5402
E-mail: Edward.X.Renshaw@kp.org

The Joint Commission

Maximizing Medical Gas Flow Capacity

SURGING VENTILATOR USAGE DURING THE COVID-19 PANDEMIC MEANS HEALTH CARE FACILITIES NEED TO ENSURE THEIR MEDICAL GAS SUPPLY SYSTEMS CAN DELIVER LARGER AMOUNTS OF OXYGEN AND AIR

CGA Industry Toolkit for COVID-19 Response

(Last updated: June 26, 2020)

Calculating oxygen consumption for Hamilton Medical ventilators

Take-Home Messages

• Medical oxygen and air supply systems may not be able to handle the increased usage during emergency surges (eg COVID-19)

• Accurate prediction of medical gas consumption during extreme surges requires a combination of both clinical and engineering information
  – Simple questions to stakeholders will not suffice
  – Create a task force with content experts
    ▫ Facilities engineers
    ▫ Respiratory therapists
    ▫ Statistician
Take-Home Messages

• A calculator is available to make accurate estimates useful to engineers based on relevant ventilator usage data from clinical experience

• Other practical actions should be taken to assure adequate oxygen supplies

• Predicting the behavior of complex systems is extremely difficult
  — Simplified models are tempting but may be misleading
  — This subject requires more study to improve our ability to cope with future surges