Mechanical-Ventilation Supply and Options for the COVID-19 Pandemic

Leveraging All Available Resources for a Limited Resource in a Crisis

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Abstract

The novel coronavirus disease (COVID-19) has exposed critical supply shortages both in the United States and worldwide, including those in intensive care unit (ICU) and hospital bed supply, hospital staff, and mechanical ventilators. Many of those who are critically ill have required days to weeks of supportive invasive mechanical ventilation (IMV) as part of their treatment. Previous estimates set the U.S. availability of mechanical ventilators at approximately 62,000 full-featured ventilators, with 98,000 non–full-featured devices (including noninvasive devices). Given the limited availability of this resource both in the United States and in low- and middle-income countries, we provide a framework to approach the shortage of IMV resources. Here we discuss evidence and possibilities to reduce overall IMV needs, discuss strategies to maximize the availability of IMV devices designed for invasive ventilation, discuss the underlying methods in the literature to create and fashion new sources of potential ventilation that are available to hospitals and front-line providers, and discuss the staffing needs necessary to support IMV efforts. The pandemic has already pushed cities like New York and Boston well beyond previous ICU capacity in its first wave. As hot spots continue to develop around the country and the globe, it is evident that issues may arise ahead regarding the efficient and equitable use of resources. This unique challenge may continue to stretch resources and require care beyond previously set capacities and boundaries. The approaches presented here provide a review of the known evidence and strategies for those at the front line who are facing this challenge.

Keywords: COVID-19; SARS-CoV-2; mechanical ventilation; high flow nasal cannula; proning

(Received in original form April 9, 2020; accepted in final form November 17, 2020)

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CME will be available for this article at www.atsjournals.org.

Ann Am Thorac Soc Vol 18, No 3, pp 408–416, Mar 2021

DOI: 10.1513/AnnalsATS.202004-317CME
Internet address: www.atsjournals.org

The novel coronavirus disease (COVID-19) has exposed critical supply shortages both in the United States and worldwide, including those in testing capacity, intensive care unit (ICU) and hospital bed supply, hospital staff, personal protective equipment (PPE), and mechanical ventilators for affected regions (1). The illness has been projected without preventative action to be able to affect 40% of the U.S. population, with over 4 million possibly needing ICU-level care over time and up to 300,000 simultaneously requiring ICU beds (2). Even with preventative action, the pandemic has resulted in over 7 million U.S. cases and over 200,000 deaths at the time of publication (3). The Society of Critical Care Medicine maintains a detailed account of hospital beds, mechanical ventilators, and staffing needs in the United States, showing U.S. estimates of 535,000 acute care beds and nearly 97,000 ICU beds (4). However, additional uncertainty remains regarding how extensively a second or extended COVID-19 peak may hit specific regions ahead, especially with the historical reference that the second wave of the 1918 influenza pandemic represented the highest number of U.S. deaths for that pandemic (5, 6). Many of those who are critically ill will require days to weeks of supportive invasive mechanical ventilation (IMV) as part of their treatment (7–9), with estimates during the first peak ranging from 5% to 12% of total cases positive for the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (based on testing capacity at that point) requiring some level of ICU care (10). The burden of patients requiring IMV

or specialized post-IMV care in the post–acute care setting may be dramatically increased as well (11).

Previous estimates set the U.S. availability of mechanical ventilators at approximately 62,000 full-featured ventilators, with 98,000 non–full-featured devices that might be usable depending on indication, including portable and noninvasive devices—devices that in an ideal scenario would not be suitable as full-featured ventilators but could need to be called on (12). An additional 40,000 machines may be available as a combination of anesthesia machines (invasive but not full-featured devices) traditionally used in operating rooms and those stored in the Strategic National Stockpile (4). The U.S. Food and Drug Administration (FDA) has also indicated that they will not object to limited modifications to the indications, functionality, hardware, software, and/or materials for these devices during the COVID-19 public health emergency declaration (13). Various manufacturers worldwide have in addition been seeking to create new supply to meet the demand (14), although others have since attenuated those efforts as the first COVID-19 peak passed their regions (15). Meanwhile, the U.S. government has entered into contracts to produce over 187,000 ventilators by the end of 2020 (16), although a previous contract for the production of 43,000 ventilators over many years was criticized for delayed deadlines, overrun of financial costs, and mismanagement (17).

Even with these efforts, the ramifications of limited supply are likely to affect particular U.S. regions and international settings more powerfully. The Northeastern United States faced borderline regional shortages for mechanical ventilation during the first COVID-19 peak (18–20), and 94% of ICU beds in the country are in hospitals located in metropolitan areas (4). Meanwhile, the Hawaiian islands have about 250 ICU beds and 500 ventilators for a population of about 1.4 million (21), whereas the nation of Haiti, with 11 million people, possesses the capacity to provide IMV to fewer than 100 people (22). The ethical distribution of the limited supply of IMV has been discussed in other settings (23–25).

Given the continued possibility for limited availability of IMV alongside the uncertainty of what future COVID-19 needs may hold across multiple regions, this manuscript expands on prior work to discuss contingency options for hospitals and providers to reduce mechanical-ventilation demand, increase supply, create new supply in crisis situations, and address staffing needs (Figure 1) on the basis of available literature and our experience during the surge in Boston in the Spring of 2020.

Reduce Ventilator Demand

Physicians and scientists are still learning about the various manifestations of COVID-19 respiratory disease, and practice has changed significantly since the onset of the pandemic. We will address the role of high-flow nasal cannulas (HFNCs), noninvasive ventilatory modalities, helmet bilevel ventilation, self-proning, and the importance of meaningful goals-of-care discussions.

Early in the pandemic, concern for rapid decompensation led to early intubation strategies based primarily on escalating oxygen requirements (26, 27). However, with experience, practice largely shifted toward a more nuanced approach to intubation, emphasizing the downstream risks associated with IMV (28). Combined with increasing concerns about ventilator shortages, we suggest a goal of avoiding intubation, if possible, through the use of noninvasive oxygen delivery. Previous literature has suggested that select patients with severe hypoxemic respiratory failure respond well to HFNC treatment (29). Although there are no rigorous studies comparing HFNC use with intubation in the population with COVID-19, there may be a subset of patients who need higher levels of oxygen or positive pressure and merit close monitoring but do not require IMV. At disease outset, some hospitals avoided therapies such as HFNC treatment, bilevel positive airway pressure (BPAP), and continuous positive airway pressure (CPAP), given the potential risk of aerosolizing the virus, as seen in prior *Coronaviridae* viruses (30). However, an abundance of literature has arisen noting the relative safety of standard HFNC use (4, 31–38), and if concerns persist, such use could be further bolstered by steps such as cohorting of such patients and use of negative pressure rooms or well-ventilated rooms with a high-efficiency particulate air filter. For further safety, evidence supports the safe use of a surgical mask on the HFNC apparatus (39).

Noninvasive ventilation (NIV) modalities, such as CPAP and BPAP have the opportunity to add positive pressure to oxygenation but have been limited because of concerns about aerosol dispersion. The World Health Organization and other authorities support the use of CPAP with appropriate PPE, and Italian guidelines promoted the use of helmet bilevel NIV (40), which is unfortunately less available in the United States. We recommend CPAP via a mask covering the mouth and nose or helmet NIV to minimize room-air contamination. Although difficult to obtain, helmet bilevel NIV has been shown to better contain aerosol leakage and provides superior oxygenation, pressure, and outcomes against face-mask routes (41). CPAP can also be delivered with the helmet interface without the use of a ventilator, using only positive end-expiratory pressure (PEEP) valves, filters, and an O_2 source, although clinicians should choose patients judiciously, as there is a potential for rebreathing CO_2. Hospitals should consider working with partners to construct helmet-style masks with three-dimensional printers and interfacing with existing NIV machines (see below under Maximize the Available Supply).

Another area under significant investigation is self-proning for the nonintubated patient. This is a low-cost intervention that partners with the patient to simulate the physiologic benefits of proning intubated patients with acute respiratory distress syndrome (ARDS). Studies support safety and improvement in oxygenation when awake, and nonintubated proning can be used successfully in combination with HFNC use or other NIV oxygenation for moderate ARDS (42). Early studies show similar results with improved oxygenation and, in some cases, a lower rate of intubation in patients with COVID-19–related severe hypoxemic respiratory failure (43). Although more rigorous studies are needed to confirm these benefits, we advocate for policies and education that encourage awake proning, given the low cost and ease of adoption, as a means of potentially reducing ventilator demand and improving patient outcomes.

Unfortunately, with the deluge of literature about clinical management and intense controversy on particular aspects of management, institutions and regions that are not yet exposed to the virus may not have policies and education in place to support the use of these therapies in time for local surges. Given the rapid spread of COVID-19, professional organizations (31) and public health departments would be wise to offer uniform, updated guidelines

Figure 1. A concise view of contingency options for hospitals and providers to reduce mechanical-ventilation demand, increase supply, create new supply in crisis situations, and address staffing and resource needs. BPAP = bilevel positive airway pressure; CPAP = continuous positive airway pressure; EMS = emergency medical services; ex = example; HFNC = high-flow nasal cannula; MV = mechanical ventilator; NIV = noninvasive ventilation; RT = respiratory therapist.

(44) on the safety of HFNC and NIV modalities to ensure the availability and nuanced use of these therapies in developing hot spots, including strategies to match states with unused capacity with those under current strain (45, 46). As demand outstrips limited resourcing and with few alternatives, hospital teams should also develop proactive policies and protocols on delaying invasive ventilation for a subset of patients using noninvasive methods alongside close monitoring to conserve the immediate demand for ventilators and potentially improve outcomes by avoiding invasive ventilation and associated complications in those who do not need it.

In addition, clinicians should only ventilate patients when IMV and possible prolonged support are within the patient's and the system's goals of care (23–25, 47). We strongly recommend that public health outreach and caregiver conversations include meaningful discussions with patients and with loved ones on the patient's individual goals of care (48) and that such conversations are led by partnered and specialized teams so that front-line providers in the ICU are not managing crisis-level medical care concurrently with these delicate conversations. Such conversations both serve the hopes and goals of individual patients and their loved ones and may also decrease ventilator demand and reintroduce ventilators to the supply pool in cases in which outcomes were unlikely to change with prolonged IMV and in which measures were not in line with goals of care.

Maximize the Available Supply: Leave No Stone Unturned

Providers should leverage all sources for IMV within and beyond the walls of their hospitals. Beyond ventilators in the ICU, ventilators in operating rooms should be redistributed for inpatient use (especially as elective surgical cases are deferred). In addition, hospitals should be in touch with their own ambulatory surgical sites as well as any nonaffiliated sites that are currently not functioning and may have unused supply. Hospitals can also connect with other sister sites that may have capacity and may not be expected to be as hard hit by COVID-19, such as affiliated childrens' hospitals. Home medical equipment suppliers, often partnered with health systems in supplying home ventilators, may serve as another potential source of ventilators. Hospitals should remain closely connected and coordinate with their state partners, including state departments of public health, health and human services, and emergency management, to be aware of what additional supply may become available from state and national sources, including the Strategic National Stockpile (49, 50) and other military or disaster supply, or from new production by industry. Hospitals should also coordinate with industry bodies such as the American Hospital Association, which has launched a Dynamic Ventilator Reserve program in coordination with the U.S. Federal Emergency Management Agency to focus ventilator deployment at areas of need (46). In addition, hospitals have engaged in conversation with nearby animal hospitals and manufacturers to discuss whether any large-mammal ventilators may be suitable for human use and whether compatible tubing is available (51). Hospitals should also contact their suppliers for unpurchased, overstocked, or legacy machines. Importantly, hospitals must also assess their disposable supplies that are available to run the machines that they have on hand and must make sure they are able to address supply deficiencies that would otherwise take a working machine offline.

As hot spots shift and develop across the country with an increased need for ventilators, a national strategy to account for and deploy devices and associated staff (or at least state to state communication) will improve the means of moving and allocating resources (45). Sources of potential ventilators that may need to conserve their supplies through a peak, however, are long-term acute care facilities and hospitals. These sites serve as a release valve for hospital capacity for a cohort of patients needing extended ventilation after prolonged ICU care. Public health authorities must be mindful of hospital inflow needs during a COVID-19 peak but should also be mindful of hospital outflow needs as well.

Further discussion is merited on the use of anesthesia machines as dedicated IMV for cases including COVID-19, as anesthesia machines are significantly different from typical ICU ventilators and these differences must not be underestimated. Anesthesia machines are specifically designed for the operating room, not for continuous use but for distinct cases in which an anesthesiologist is present (52). By such design, the anesthesiologist is expected to continually operate the machine, monitor its alarms intended for a dedicated operator rather than for an ICU setting, maintain the machine's unique circuit, and use the machine's specialized medication delivery mechanisms, such as provision of inhaled anesthetics (52–54). Moreover, anesthesia machines use circular airflow circuits involving rebreathing of exhaled air, unlike ICU ventilators, and can also lack circuit water traps like those in ICU systems. These lead to more frequent needs to change the circuit alongside higher risks of airway obstruction, thicker airway secretions, and exposure of those running the machine. The ventilation modes may also differ from IMV used in the ICU. It was our experience that these ventilators are best suited to more stable patients in need of IMV instead of those experiencing the acute hypoxemic respiratory failure brought on by COVID-19. These machines also require the 24-h/d and 7-d/wk presence of an anesthesiologist to help operate, maintain, and troubleshoot them. And, as mentioned above, although such machines can provide unique routes to deliver medications such as inhaled anesthetics, and such medications may serve a role when traditional anesthetics are in short supply, they can also produce notably adverse physiologic effects in those who are critically ill (52). In addition, although the operating-room spaces that anesthesia machines natively reside in may present attractive spaces for COVID-19 isolation during a pandemic peak, hospitals must evaluate the airflow, electric, medical-gas-line, air-filtering, and layout capabilities and needs of such spaces before their use (55). Although anesthesia machines provide a first-line and necessary alternative to ICU ventilators in a shortage, the use of anesthesia machines requires preparation and planning to develop the staffing, protocols, and knowledge base to deploy them effectively.

Not all of the ventilators from these methods will provide the functionality of full-feature mechanical ventilators, nor have they all been studied extensively in the field. However, the devices discussed in this section are intentionally designed for IMV and can be used for supportive care and to

supply additional time for further resourcing when demand outstrips regular supply.

Create New Sources of Potential Ventilation

Beyond optimizing current supply and reducing demand to the extent possible, for further challenged scenarios, we consider additional avenues of extending ventilator supply via modification of non–full-featured devices for invasive ventilation. Given how constrained resources could become in hospitals and regions across the United States as well as in low- and middle-income countries, it is important to consider such admittedly suboptimal but plausible options. In the setting of the pandemic and FDA guidance (13), the measures below may provide options for patients requiring less support or may serve as bridges until a standard full-function ventilator becomes available within the region, creating supply that protects against the outright rationing of ventilators at the hospital level (24, 56).

If needed, BPAP machines can potentially be converted for use with invasive ventilation. With many units, this requires modification, including connecting a second makeshift expiratory limb to blow off CO_2 at the level of the endotracheal tube and using one-way valves to functionally convert a single-limb device into a dual-limb device (57). Although this would improve the efficiency of the ventilator and allow for invasive application of positive pressure, these machines still rely on "bleeding in" or mixing of oxygen with ambient air, limiting the maximum fraction of inspired oxygen to less than 60% (57), far less than needed for the sickest patients. However, the studies examining this were performed with single-limb devices. More advanced machines advertise compatibility with NIV and IMV and offer functionalities such as backup rates (58, 59). If in need of further resources, hospitals may consider an analogous design with CPAP machines.

Alternative devices have been produced that serve as short-term functional mechanical ventilators for emergency scenarios. The Oxylator (CPR Medical) (60, 61) is a portable device that delivers flow-controlled, pressure-cycled ventilation via NIV interfaces or via endotracheal tube. It is untested in the critically ill population but is potentially inexpensive and available for widespread use. The GO2VENT (Vortran) is a similar device (62). These and similar devices may serve as satisfactory temporary or lower-acuity devices for IMV in crisis standards of care. Moreover, such devices may be considered by hospitals for exchange with emergency medical services for the more dedicated mechanical ventilators currently used by emergency medical services in the field.

We recognize the limitations and risks inherent in the above options and only recommend their considered use in resource-limited crisis scenarios that the COVID-19 epidemic may bring about. In the worst scenarios, physicians have also considered a single mechanical ventilator with split limbs being used for simultaneous IMV of multiple patients. Although studies and videos have discussed the feasibility of this (63–68), there is very limited field experience in disaster scenarios (69), and these scenarios were largely focused on populations with trauma rather than those with the physiology inherent in infection-driven acute hypoxemic respiratory failure. Patients affected by COVID-19 facing hypoxemic respiratory failure require longer periods of ventilation and present a much more complicated and riskier substrate for treatment via this method. Although we have seen this concept being authorized in certain U.S. localities (70), this concept brings up a host of infection, ethical, consent, legal, technical, and staffing issues. Even if patients are otherwise young and healthy and well matched, extended ventilation over days entails numerous risks of infection and barotrauma and must be carefully weighed against alternative options. Additional technical issues include proximity of patients, length of tubing, lung compliance, increased staffing challenges, ability to tolerate permissive hypercapnia, inability to manage PEEP and measure pulmonary mechanics, and potential for one patient to directly impact the other, such as through accidental extubation. An attempt to support multiple patients may very well risk doing damage to all of those patients where one might otherwise have survived. For this reason, multiple specialty societies have offered a joint statement recommending against this practice (71). Although we discuss this as a last resort with many notable pitfalls, there is guidance on how to perform this procedure from Columbia University, which is outlined in a recently publicized protocol (72).

Mechanical Ventilation Is More than the Ventilator

It is worth equal consideration that caring for a critically ill patient on IMV life support requires the support of more than the bed and the machine; it requires an entire team focused on detecting minute-to-minute changes in ventilatory needs and recognizing potential harm early. Important components of this team include the respiratory therapist (RT), ICU nurse, and intensivist (73). At the peak of a surge, hospitals may be forced to adopt "crisis standards of care" (74) and assess the available physical space, staff manpower, and supplies they have on hand to care for their patient burden (75). Standard crisis guidelines assist in the management of a high volume of high-acuity patients and can include guidance on management of space and resources (75). However, the guidelines do not always provide detailed instruction on adapting staffing in the ICU to deliver the best care to the maximum number of patients. Several models for staffing published in the recent literature are described below, although we were unable to find any evidence to support one structure compared with another.

Every critically ill patient with COVID-19 should have oversight by an attending intensivist, whether in person or via telemedicine. Physician leads on ICU teams generally follow a pyramid model, with the most experienced critical care physician at the top of the pyramid overseeing a large number of critical care–experienced physicians, such as fellows and residents or nurse practitioners and physician assistants (75–77). These experienced but less-senior providers may oversee another tier of extenders who have less critical care experience, such as physicians from other specialties or other advanced-practice providers. Such models should also account for other necessary staff, such as RTs and those involved in repetitive but critical functions such as procedures and patient proning (discussed further below). Experienced critical care physicians working as telemedicine attending physicians may also serve at the top of these pyramids, especially in community models. Such models have been seen in both multicenter

academic-medical-center collaborations across a large city (76) and multistate hospital systems (77).

With telemedicine attending physicians or critical care teams caring for a high volume of critically ill patients, bedside procedures should be designated to specialized teams to optimize efficiency of the native team (76, 77). That workload should be distributed to the most efficient team members by creating dedicated procedure teams. Depending on the size of the ICU and specialties available, this may include a dedicated anesthesia team for airway management; surgery teams for central line placement, bedside tracheostomy, and other ICU procedures; and nurses and RTs for dedicated proning teams. Dedicated teams with predictable availability allow physicians at the top of the critical care pyramid teams to focus on the medical care of the sickest patients including ventilator management. Proning teams allow nurses to remain at the bedside instead of being pulled away at frequent and sometimes unpredictable intervals to assist in proning and supinating patients (76, 78). An important benefit gained by these teams is expertise in efficient donning and doffing and procedural performance in PPE enhanced for COVID-19. Our anecdotal experience notes that surgeons performing central lines rapidly developed efficiency with the entire line-placement process, including enhanced PPE and ultrasound decontamination.

Perhaps less well described and more difficult to arrange is nursing staffing. It is critical to maintain the close 1:1 or 1:2 nursing ratios for patients with COVID-19 on IMV. To ensure safe staffing, all nurses with critical care training should be leveraged to expand the pool of available nurses as more ICU beds are created during a surge. Critical care–trained nurses traveled from outside the states affected during the first COVID-19 peak to assist during the spring in New York and Boston (79). If staffing is still insufficient, as it was in many hospitals, nurses without ICU training may be recruited to critical care. It is imperative, however, that nurses receive a suitable level of critical care training, including ventilator-alarm interpretation and response, before starting in the ICU, as has been suggested by nursing organizations. Team-based designation of functions such as proning, noted above, also allows front-line nurses to keep their attention foremost on the patients assigned to them. Nurses may also spend disproportionate time donning, doffing, or changing PPE between coming in and out of a room, as staff attempt to maintain their own safety, and protocols to clarify what can be done inside and outside of the room will maintain their efficiency. As an example, some centers put IV machines outside of the room by using longer tubing so that the nurses could interact with the machinery regularly without having to use new PPE. Introducing nurses without training to the ICU may burden an already overwhelmed ICU nursing staff with the onus of training while providing care to more and sicker patients than they have ever encountered previously.

RTs could become similarly strained, although recent projections suggest adequate staffing in the absence of significant attrition (80). As noted by the Society of Critical Care Medicine, "The rate-limiting feature is the absence of the requisite number of RTs to manage the ventilators in concert with skilled intensivists (4)." During surges, RTs are more difficult to extend, as there are few professionals on site that share their skill set. An RT may be called on to perform ventilator maintenance, obtain pulmonary mechanics, assess urgent changes in the machine, and deliver medications through the ventilator. RTs may also be concurrently tasked with non-ICU duties in the hospital, such as managing NIV on the floor, providing nebulizer treatments, and decontaminating ventilators between uses. Clarification around these roles during surges will allow for role clarity and efficiency. Our institution trained and redeployed RTs dedicated to outpatient testing in addition to staff from outside the region to assist with surge needs. Anesthesia technicians may also be able to augment some of these functions as surgical cases are deferred. Others have also suggested training medical students to assist and extend the RT role (81).

Also of note, hospitals around the country have experienced shortages in common ICU medications, which are critical for the care of the patient with COVID-19 on IMV. Government agencies have taken action to allow for increased production of some medications (82), and advocates are requesting extension of expiration dates to maximize supply (83, 84). Pharmacists have also called for safeguards against stockpiling during the crisis (84, 85). There may also be novel means to reduce waste and maximize supply at the local level; as an example, pharmacists at our institution primed the lines for propofol with 20-ml vials, potentially saving 10–20 of the 100-ml vials per day (86).

Conclusions

COVID-19 has presented unique and difficult demands on the domestic and global health system. As need challenges current capabilities, providers and systems will be stretched to provide resources for an incredible burden of illness. Domestic and global interventions to deal with the limited supply may involve many less-than-ideal innovations driven by scarcity. Strategies to reduce mechanical-ventilator demand, increase supply, create new supply, and adequately staff that supply can help mitigate the sizable challenges that may be ahead. ■

Author disclosures are available with the text of this article at www.atsjournals.org.

Acknowledgment: The authors thank the Medicaid Medical Directors Network and their colleagues across the country for their front-line care of critically ill patients.

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