REVIEW ARTICLE

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Challenges of Ventilator Procurement and Distribution in the ICU During the COVID-19 Pandemic: A Scoping Review

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OBJECTIVES: The goal of this scoping review was to review some of the challenges hospitals faced in dealing with the shortage of ventilators during the COVID-19 pandemic and the solutions they were able to implement or suggested. By highlighting these problems and solutions, we hope this review can catalyze further discussions about how to better prepare for future pandemics and medical supply shortages.

DATA SOURCES: A comprehensive search strategy using identifying key words was applied to several different databases to procure relevant literature.

STUDY SELECTION: Four thousand two hundred fifty-nine studies were found in the initial search. Inclusion and exclusion criteria were created and applied to screen studies. Included studies focused on the supply and distribution of ventilators during the COVID-19 pandemic. In the case where reviewers disagreed about whether a study should be included, a third reviewer acted as a tie-breaker.

DATA EXTRACTION: Thirty-three studies were included for final data extraction. Two independent reviewers collected various data points from these studies, including the main challenges discussed by the authors, the level of ventilator shortage being addressed, whether ventilator sharing was discussed, and the limitations of the study.

DATA SYNTHESIS: A third reviewer compared the collected data and decided on the results.

CONCLUSIONS: Some of the common solutions for the ventilator shortage discussed included augmenting overall ventilator supply through increased production, transporting ventilators between hospitals, ventilator sharing, designing new ventilators, and repurposing other resources to help address shortages of supplies.

KEYWORDS: COVID-19; disaster management; scoping review; supply and distribution; supply chain; ventilator

The emergence of COVID-19 brought an unprecedented health crisis (1). Emergency departments and ICUs faced significant strain in having adequate supplies and personnel (2). The combination of the COVID-19's high severity and infectivity overwhelmed ICUs (3, 4). Ventilators became a critically scarce resource and its shortage was one of the main obstacles to providing optimal patient care during the pandemic (5). In April 2020, the world economic forum published an article stating how ventilator manufacturers boosting their production by 50–100% was insufficient to meet the 500–1000% growth in production required. In April 2020, New York City alone forecasted a need for 30,000 additional machines (6). In response to the acute need, the U.S. government mobilized thousands of ventilators from the Strategic National Stockpile and allocated them to hospitals nationwide. However, the stockpile

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KEY POINTS

Question: We hoped to highlight the challenges hospitals faced in providing an adequate supply of ventilators during the COVID-19 pandemic and some of the solutions that were discussed.

Findings: Augmenting ventilator production, decreasing ventilator demand, and repurposing ventilators for ICU level care were some of the common solutions.

Meaning: Creative solutions were implemented to overcome the ventilator shortage. Further preparation in optimizing the supply chain, increasing production of ventilators, and enhancing ventilator-sharing strategies can help prevent future shortages.

had approximately 20,000 ventilators and quickly proved insufficient in the face of rapidly escalating demand (7). To combat these shortages, some hospitals explored alternative strategies, such as repurposing anesthesia machines as ventilators and, in more extreme cases, sharing ventilators between patients (8, 9). While oxygen was in short supply for less developed countries with less robust medical oxygen infrastructures, developed regions such as Western Europe and the United States had a sufficient supply of oxygen to meet pre-pandemic demand and did not experience significant shortages. To provide continuous oxygen supplies, medical oxygen was redistributed from nonessential or underutilized healthcare facilities and repurposed from existing nonmedical supplies (10).

This scoping review aims to assess the literature on ventilator supply and distribution during the COVID-19 pandemic. By understanding some of the challenges faced and solutions employed by hospitals globally, this review seeks to contribute to better preparedness for future pandemics and ensure more effective allocation of critical resources.

METHODS

Study Design

This scoping review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews checklist to examine the challenges and strategies related to ventilator shortages during the COVID-19 pandemic.

Literature Search and Screening Strategy

We included publications in peer-reviewed journals that were focused on critical care and the ventilator supply during the COVID-19 pandemic. We excluded articles that focused on animal modeling, personal protective equipment (PPE), and ethics about ventilator distribution or anesthesia machines. While some of these topics were briefly discussed in the articles we included, we wanted the focus of this review to be on the preexisting ventilator supply used during the COVID-19 pandemic and felt that including these other topics would create a scoping review that would be overly broad. Additionally, conference abstracts, letters to the editor, and non-English articles were excluded. A medical librarian conducted the literature search using a combination of keywords and standardized index terms. After limiting to publications from 2019 onward, 4259 citations were retrieved and imported into Covidence (Melbourne, Australia) for review (**Fig. 1**). Duplicates were removed.

Data Extraction and Synthesis

Independent reviewers decided whether they believed each article should be included for a full-text review or excluded based on screening criteria. In the case of disagreement, a third reviewer acted as the tiebreaker. During data extraction, two reviewers independently reviewed each article and filled out data according to a pre-made template. A third reviewer then compared the two completed forms to help reach a consensus. For the abstract and title screening stage, there were four pairs of reviewers. The random agreement probabilities for these four pairs were 0.876, 0.866, 0.926, and 0.9444. The Cohen's Kappa for these four pairs were 0.064, 0.171, 0.169, and 0.166. For full-text screening, there were two main pairs of reviewers. The random agreement probability for these two pairs was 0.734 and 0.549. Cohen's Kappa was 0.304 and 0.287, respectively. Data points extracted included title, author, location, study date, article type, study purpose, population

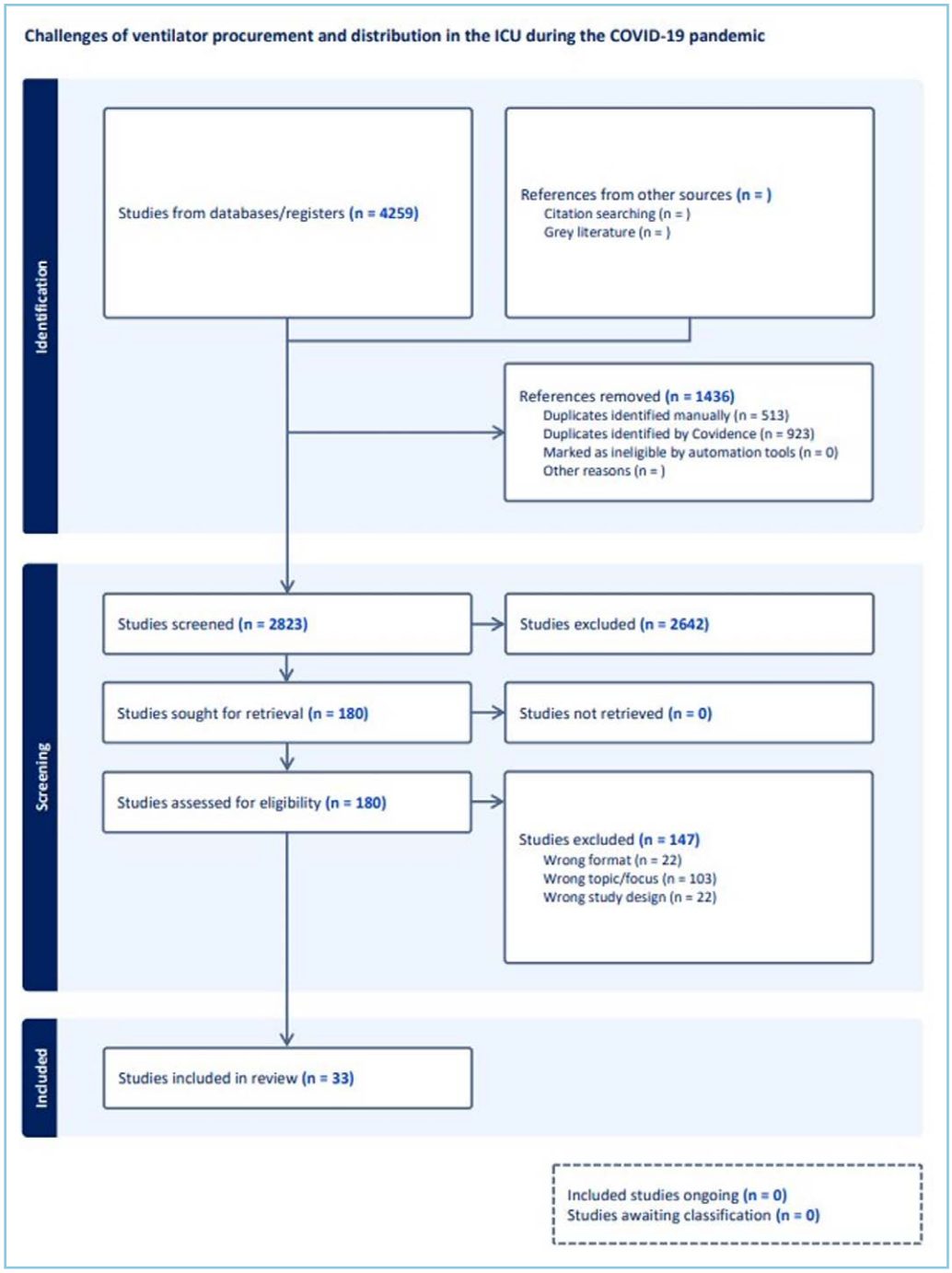

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flowchart for scoping reviews. Four thousand two hundred fifty-nine studies were imported into Covidence after the initial search. One thousand four hundred thirty-six duplicates were removed leaving 2823 studies for abstract and title screening. One hundred eighty studies were included for full-text review. Thirty-three studies were included for data extraction.

studied, main challenges, interventions, level of ventilator shortage being addressed (individual ICU vs. hospital vs. national), transport of supplies between hospitals, if a shortage of work personnel was discussed, ventilator sharing practices, barriers to sharing, study outcomes or recommendations, and the limitations of each study.

RESULTS

The combination of search terms with selection criteria and limits yielded 4259 studies (**Table 1**). One thousand four hundred thirty-six duplicates were removed. Two thousand eight hundred twenty-three studies were moved to the title and abstract screening phase. One hundred eighty-one studies were included for full text review. Of these studies, 22 studies were excluded due to having the wrong format, 22 studies were excluded due to wrong study design, and 103 studies were excluded due to focusing on the wrong topic. This left 33 studies for the data extraction phase (Fig. 1). Twenty-one of 33 studies were conducted in the United States. The rest were conducted in different countries in Europe, Asia, Africa, and Australia (12/33) (**Table 2**). Fifteen studies were identified as review articles and 18 as original articles. Of the 18 original articles, four were opinion articles, four were cross-sectional surveys, and one was a retrospective cohort study. Ten of 33 studies highlighted a shortage of work personnel. An equal number discussed the sharing of medical supplies between hospitals (**Table 3**). The scope of ventilator shortage discussions varied: 26 studies

TABLE 1.
Databases Used During Initial Literature Search

Databases and Registers	No. of Hits
Central (clinical trial register)	98
Cinahl	335
Elton B. Stephens Company	379
Embase	1765
Medline	487
Scopus	768
Web of Science	427
Totals	4259

TABLE 2.
Number of Studies Classified by Location of Study

Country	No. of Studies
Australia	1
France	1
Italy	2
Botswana	1
India	2
Japan	2
Kingdom of Saudi Arabia	1
United Kingdom	1
United Kingdom and Spain	1
United States	20
United States and India	1
Total	33

addressed the issue at a national level, whereas four studies and three studies focused on individual hospitals and single ICUs respectively (**Table 4**).

Key themes found during the data extraction phase, including strategies for ventilator sharing, the augmentation of ventilator production through alternative methods, approaches to decrease ICU surge capacity by reallocating resources, and the revision of ventilator allocation policies in response to shortages, which are detailed in **Supplemental Digital Content—Table 5** (http://links.lww.com/CCX/B497).

Major Themes

Issues With the Supply Chain. The unprecedented demand for medical supplies during the COVID-19 pandemic highlighted some of the issues with the supply chain at that time. The supply chain during the pandemic was designed for minimal redundancy and high efficiency. It worked best when demand was predictable. This lean management principle helps reduce costs, minimize waste, and enhance efficiency. Along similar lines, the "just in time" principle of supply chains, previously employed by those in the automotive and computer industry, strives to keep inventory low and only move only material right before it's needed. While this can reduce costs, it also makes the supply chain more vulnerable to supply and demand shocks such as those seen during the COVID-19 pandemic (11). Some of the recommendations proposed to address issues with the supply chain included the appointment of a single emergency supply chain (ESC) leader, developing a transparent chain of command, improving technology to better predict

TABLE 3.
Number of Studies Classified by the Type of Study, if Shortage of Work Personnel Was Discussed, and if Transportation of Supplies Between Hospitals Was Discussed

Type of Study	No. of Studies	If Shortage of Work Personnel Was Discussed	No. of Studies	If Transportation Supplies Between Hospitals Was Discussed	No. of Studies
Original research article	18	Shortage of work personnel was discussed	10	Transportation of supplies between hospitals was discussed	10
Review article including systematic/literature review	15	Shortage of work personnel was not discussed	23	Transportation of supplies between hospitals was not discussed	23
Total	33		33		33

TABLE 4.
Number of Studies Classified by the Level of Ventilator Shortage Discussed

Level of Setting Addressed	No. of Studies
Nationwide	26
Single hospital	4
Single ICU	3
Total	33

shortages, and identifying a source of financing for the supplies (12). It is also beneficial if the ESC leader has relationships with public health agencies, distributors, and other community organizations to facilitate coordination. Diversifying distribution materials and stockpiling supplies can mitigate disruptions during crises. Continually monitoring stock rotations to avoid product expiry and waste management training are also important. In addition, development of strong information network systems so that information is shared along the supply chain promptly can help anticipate shortages, prevent overstocking, and reduce the time needed to procure essential medical supplies (12). Conducting regular readiness exercises and personnel training can keep staff aware of emergency protocol and identify areas for improvement (12).

Augmenting Ventilator Supply. Various countries looked for ways to augment their ventilator capacity (5, 13). In the United States, the federal government enacted the Defense Production Act (DPA), encouraging automobile manufacturers to partner with ventilator manufacturers to resolve supply chain issues and increase manufacturing (14). National organizations, such as the Centers for Disease Control and Prevention, can help coordinate efforts to distribute ventilators to areas that have the highest demand (15). Some studies suggested enlisting the help of technology companies that could track the projected needs and availability of equipment in real time, ensuring a close match between supply and demand (15). In Australia, collaboration between the government and medical technology industry helped augment the ventilator supply during the pandemic (16). In India, the Defense Research and Production Organization took a lead in ramping up manufacturing of medical equipment. Ventilators were added to a list of urgent purchases and submitted to the authorities (17).

Several studies also discussed designing new ventilators and using 3D printing as a way to address the shortage (18–21). Such ventilators can be developed with Leitat-1 technology, which helps reduce the components needed to produce a ventilator (18). The study by Savary et al (19) discussed how the robustness and simplicity of pneumatic transport ventilators can provide an additional source of ventilators. The article by Srinivasan et al (20) in 2020 mentioned how 3D printing could be used to help produce or replace parts for ventilators. A relatively new ventilator produced from 3D printing, called CRISIS, is manufactured with an adjustable pressure valve that allows clinicians to set tidal volume, peak inspiratory pressure, and positive end-expiratory pressure (PEEP) (21). Three-dimensional printing can also be used to address some of the challenges associated with ventilator sharing. In the study by Sorg et al (22) in 2021, the authors used 3D printing to design a new type of flow-proportioning device that would allow for the division of inspiratory flow from the ventilator to two separate patients, which would allow for individual control of tidal volume.

Guidelines for Ventilator Allocation. Another common theme that emerged was developing guidelines for ventilator allocation. The Sequential Organ Failure Assessment (SOFA) score was widely employed by multiple hospitals as an objective way to decide which patients qualified for ventilators. In one study that examined ventilator allocation policies across 68 organizations from 34 U.S. states, all but one policy used the SOFA score as part of their triage criteria (23). However, SOFA scores can be fluid, potentially changing significantly from before to after intubation. In addition, SOFA scores have been primarily used in patients with sepsis or for general intensive care not isolated respiratory disease (24). The same study found that all policies emphasized the importance of palliative care. One major difference between policies was whether life-limiting conditions were treated as exclusion criteria or factored into a triage point system (23). Despite some similarities in policies, other studies have found that ventilator allocation guidelines vary significantly between states. In one study that examined ventilator allocation policies in the metropolitan Chicago area, only half used assessment of medical comorbidities in their scoring system (25). Certain groups such as pregnant patients and healthcare providers were given priority. Few protocols were created

with community input, and no protocol was available for public review. There was also significant variation in the implementation of resource allocation (25). A study in Japan found that distribution of resources to maximize survival and save the greatest number of lives was the most popular principle. In Delhi, India, it was considered that patients whose condition was deemed salvageable should receive a better ventilator compared with those whose condition was considered difficult to salvage (17). One article also talked about the development of a dashboard in the ICU that helped monitor patients and distribute equipment (26).

Ventilator Sharing. Nine of 33 studies extracted discussed ventilator sharing. While there have been reports of ventilator sharing during mass casualty situations and ventilator sharing being tested on mechanical test lungs and animals, there have not been many studies that examined the feasibility of ventilator sharing in actual clinical situations (27). One article described ventilator sharing for three pairs of patients. All patients tolerated the 2-day sharing period and survived to hospital discharge (9). There have also been several studies that have described ventilator sharing in simulations or with animal models. In the study by Herrmann et al (28) in 2020, computational modeling was used to illustrate some of the dangers of connecting patients in parallel to a ventilator without individualization of ventilatory parameters. Some of the commonly encountered issues authors brought up for ventilator sharing include uneven distribution of volume, requirements for constant monitoring, cross contamination between patients (13), and inability to distinctly vary PEEP, F_{IO_2}, and other ventilatory parameters between patients (27). One can also consider that ventilator sharing reduces the benefit that single ventilation could have provided to a patient (27) while an alternative means of oxygenation, such as continuous positive airway pressure, would be used for the other patient. Despite these concerns, several studies have also discussed ways to circumvent these challenges including design of devices that allow for individualization of ventilatory parameters (20, 22).

Alternative Options. In addition to augmenting ventilator supply through increased manufacturing, other studies have suggested alternative means to combat the ventilator shortage (17, 29). The article by Santini et al (29) discussed how reallocating and centralizing patients, repurposing operating rooms/using anesthesia ventilators, decreasing ventilator demand through noninvasive ventilation, and expanding the pool of available ventilators, including stocks and back-ups, can help address the ventilator shortage. Tempe et al (17) suggested using back-up ventilators, such as transport ventilators, in cases where standard ventilators could not be used. Although the exact number of mechanical ventilators in the United States is unknown, a survey of U.S. hospitals from 2010 estimated around 62,000 full-feature ventilators. The same report also identified approximately 100,000 positive pressure devices, some of which had sufficient capability to be used in case of a mechanical ventilator shortage (7, 30). Some studies in our review suggested using noninvasive ventilation as a way to decrease the demand for mechanical ventilators.

The study by Dar et al (5) further explores how we could decrease ventilator demand through different methods such as self-proning for nonintubated patients, maximizing high-flow nasal cannula use, and incorporating helmet bilevel noninvasive ventilation. The article also emphasizes having effective goals of care discussions so that clinicians are only ventilating patients where mechanical ventilation and other possible extended support are in alignment with the patient and their families' wishes (5).

DISCUSSION

This scoping review aimed to examine some of the challenges of maintaining an adequate supply of ventilators during the COVID-19 pandemic and some of the ways hospitals and organizations circumvented such shortages. The review focuses on step A of the Prosci Awareness, Desire, Knowledge, Ability, Reinforcement model of change (31), and we hope that highlighting these challenges and solutions catalyzes discussions about how to better prepare for future pandemics. There were also shortages of PPE, clinical staff, and high levels of burnout during the COVID-19 pandemic but we chose to focus mainly on ventilators as we felt the scope of the review would have been too broad to encompass the other issues comprehensively (32, 33).

While there were also shortages of other types of invasive support such as extracorporeal membrane oxygenation and hemodialysis machines in patients who developed severe COVID-19 complications, the shortage of ventilators was more broad and prevalent given its widespread use for respiratory support (34, 35).

Some of the main solutions suggested by various studies included increasing production of ventilators, improving distribution, redesigning our supply chain, and looking for alternative solutions to mechanical ventilation and ventilator sharing (**Fig. 2**). Our results were similar to what had been previously described but also highlighted some unique challenges faced by hospitals and organizations in the implementation of these solutions. For instance, while the DPA allowed for the manufacturing of approximately 200,000 ventilator devices, the new ventilators had several limitations including limited PEEP, increased dead space, and missing pieces of equipment (7).

Another important consideration for ventilator use is having enough staff to operate them safely. While not the primary focus of our review, we found that multiple studies commented on the shortage of work personnel and the need to have adequate PPE. Having an adequate number of qualified hospital staff to operate new ventilators or ventilators not typically used in the ICU may help maximize their efficacy and aid in preparing for future pandemics or strains on the healthcare system.

Although our review sought to exclude articles that focused on the ethics of ventilator distribution, multiple articles discussed how hospitals had to make difficult decisions regarding ventilator allocation due to the shortage of ventilators during the initial waves of the pandemic (25). Discussions about resource allocation during pandemics and other times of scarcity highlighted the need for frameworks emphasizing equality, maximization of benefits, prioritization of disadvantaged populations, and recognition of instrumental value (35). Many studies used objective criteria, such as the SOFA score, as part of their triage policy indicating that many organizations were relying on objective criteria to make clinical decisions. Despite this, there seemed to be a lot of variability in determining what other criteria were used and how these policies were implemented. Many organizations did not have allocation guidelines in place.

We found that multiple studies mentioned sharing of supplies between hospitals. Hospitals that can reach out to neighboring hospitals, such as ambulatory surgical centers or affiliated children's hospitals, would be better available to maximize the available supply of ventilators (5).

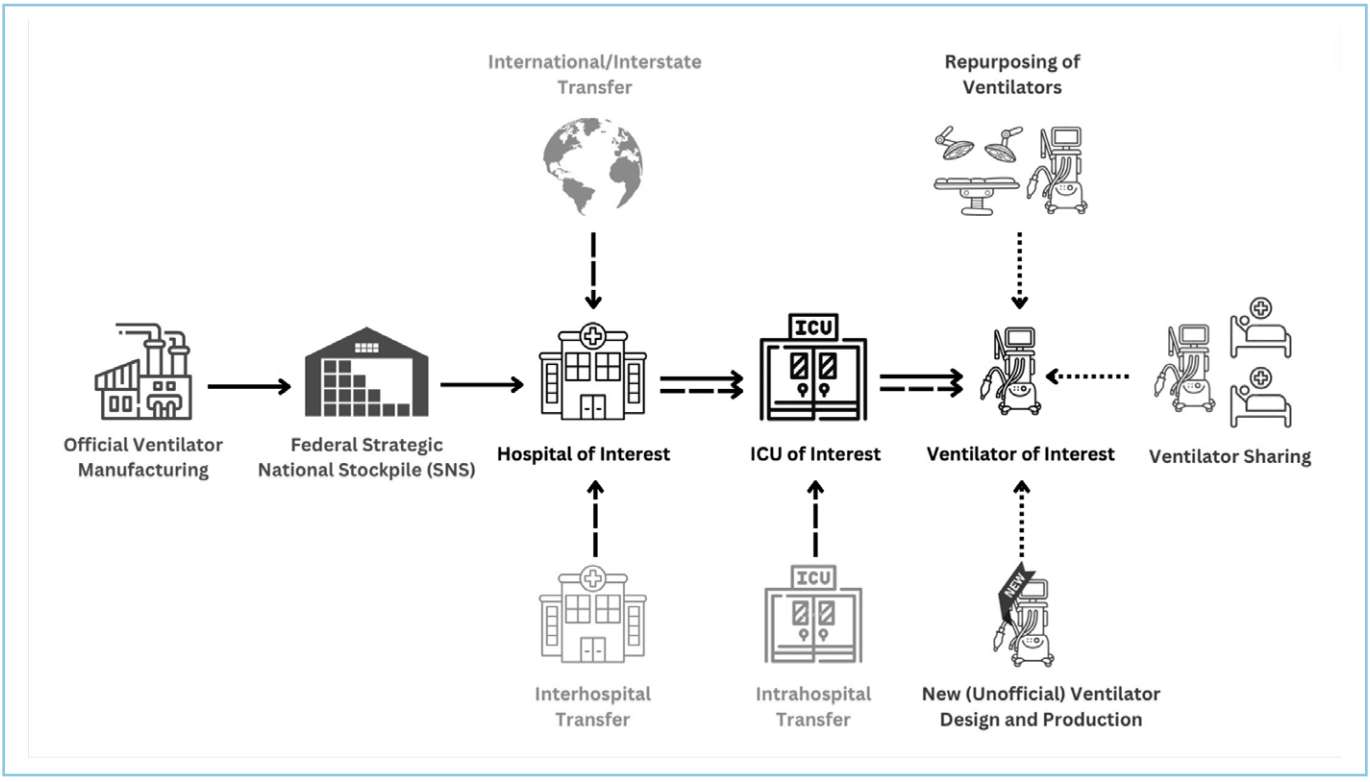

Figure 2. Strategies for ventilator supply chain and management during healthcare crises. First line defense: official factories and national stockpile. Second line defense: ventilator transfer—intrahospital, interhospital, international, interstate. Last line defense: ventilator repurposing, new ventilator designs, ventilator sharing.

In the literature, it has been described that supply chains at the global or regional level were not adequately prepared to handle such a pandemic. The global supply chain for essential medical equipment evolved after World War 2 and reflected various goals including affordability, improved quality, and broad access. However, large expenditures and limited resources of patients led to the introduction of the lean supply chain. "Lean" management led to reduced costs but also decreased the medical supplies available to help buffer increased demand during crises such as COVID-19 (36, 37). A nonmedical example of the dangers of "lean management" was seen during the Texas winter storm of 2021 where more than 10 million individuals lacked access to electricity (38).

Supply disruptions in gas, the main source of electricity in Texas, as well as in wind, coal, and nuclear, resulted in a gap between demand and production. This forced the nonprofit grid manager, the Electric Reliability Council of Texas, to cut off supply to millions of customers (38, 39).

Some of our articles discussed the importance of having an ESC leader during times of crises. During the Suez canal blockage, supply chain leaders had to make difficult decisions about how to handle the blockage (40). Other articles also highlighted the importance of "supply chain resilience" and the different ways organizations can increase resilience capabilities. Some of the key ones include flexibility, redundancy, agility, visibility, and collaboration. Flexibility is the ability of the supply chain to adapt by redeploying various resources in response to disruptions. Redundancy is the ability to reserve some resources for use if disruptions occur and agility is the ability of the supply chain to respond quickly to sudden and unexpected changes in demand and/or supply (41). Some of the solutions suggested by the studies in our review seem to support these traits. Diversification of the supply and distribution can significantly help in flexibility while improved communication systems would increase agility.

Ventilator sharing was another common solution brought up. Ventilator sharing is not a new concept but only one study in our scoping review discussed ventilator sharing with actual patients. Other studies have investigated the feasibility of ventilator sharing with simulation or animal models. Several studies commented on ways to overcome some of the barriers of ventilator sharing such as using 3D printing to develop devices that allow for more individualization of ventilatory parameters.

One of the limitations of this study was that we only focused on the adult population and excluded certain topics. As children have fewer comorbidities and are generally healthier than adults, it would be interesting to see if the same solutions employed in adults would be feasible in children. By choosing to mainly focus on the supply and distribution of ventilators during the COVID-19 pandemic and excluding other topics, our review may miss important factors that could influence ventilator supply and distribution. We hope to more comprehensively explore these topics in future studies. The review only included peer-reviewed journals and articles written in English. Although we had independent reviewers and a third reviewer to resolve disagreements, the screening of studies, and data extraction processes are inherently subjective, leading to biases about which studies are included and how data are interpreted. In addition, differences in the reviewers' expertise and background can lead to greater variability, potentially affecting the reliability and consistency of our outcomes. There are also significant differences in the design, size, and type of studies we extracted. This heterogeneity may make it challenging to draw conclusions and compare results. Our study only focused on literature up to a specific point in time and may not reflect the evolving nature of ventilator supply and distribution practices. In addition, our study did not focus on the supply of noninvasive ventilation and further studies in this area may shed light on how to best optimize the respiratory support needed for COVID-19 patients.

CONCLUSIONS

Invasive mechanical ventilators were in short supply during the initial stages of the COVID-19 pandemic. Hospitals used and suggested multiple strategies to circumvent this shortage such as increasing production, redesigning our supply chain, developing guidelines for allocation, and decreasing demand. Such strategies may help us prepare for future pandemics.

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Dr. Wang was involved in conceptualization–equal, investigation–equal, methodology–lead, project administration–lead, writing original draft presentation–lead, and writing/reviewing/editing–lead. Drs. Nemet and dos Anjos were involved in investigation–equal, methodology–equal, project administration–equal, and writing/reviewing/editing–equal. Drs. Zec and Zambrano were involved in conceptualization–equal, investigation–equal, methodology–equal, project administration–equal, and writing/reviewing/editing–equal. Drs. Rovati and Truong were involved in conceptualization–equal, investigation–equal, and methodology–equal. Dr. Dong was involved in conceptualization–lead, investigation–equal, methodology–equal, project administration–equal, and writing/reviewing/editing–equal.

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