REVIEW ARTICLE

# Enhancing respiratory ventilator availability amid supply shortages during public health crises: distinct experiences during the COVID-19 pandemic and a narrative review

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## ABSTRACT

Mechanical ventilators (MVs) played a critical role during the coronavirus disease 2019 (COVID-19) pandemic, providing respiratory support for critically ill patients and reducing mortality. However, the global scale of the pandemic led to significant ventilator shortages, necessitating various strategies to manage MV supply and optimise resource allocation. Real-time tracking systems in health command and control centers emerged as essential tools for monitoring and distributing ventilators efficiently. This study employed a mixed-method approach, incorporating the experience of the National Health Command Center (NHCC) in Saudi Arabia and a narrative review of strategies used to address MV shortages during the COVID-19 pandemic. Several solutions were implemented to meet the increased demand for ventilators, including optimising high-flow nasal cannulas and using modified single ventilators. Ethical considerations in ventilator allocation highlight the need for a coordinated, multi-sectoral approach to prevent discrimination and maintain public trust. In Saudi Arabia, the NHCC faced substantial logistical challenges in providing respiratory support devices for intensive care units under unprecedented pressure. A successful response was achieved through a live tracking information system, which streamlined medical supply chain logistics and improved resource allocation. These efforts resulted in increased ventilator availability, cost savings, effective redistribution of resources, national self-sufficiency and the ability to export ventilators during critical periods. A comprehensive, country-level strategy is essential for the effective stockpiling and management of MVs. A permanent, centralised ventilator management database would enhance real-time monitoring, optimise resource utilisation and improve preparedness for future public health emergencies.

**Keywords:** Mechanical ventilator, pandemic, emergency health services, delivery of health care, public health.

## Introduction

The initial report from Wuhan, China, marked the global dissemination of coronavirus disease 2019 (COVID-19). Based on phylogenetic analysis, the International Committee on Taxonomy of Viruses classified the causative coronavirus as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Understanding the virus's origin, genetic lineage and transmission pathways remains crucial. Bats are the most likely reservoir hosts, with RaTG13 identified as the closest

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known relative of SARS-CoV-2. However, whether Bat Coronavirus RaTG13 was transmitted directly to humans or through an intermediary host remains unclear [1]. Additionally, despite identifying SARS-CoV-2-related viruses in Chinese rufous horseshoe bats, the definitive animal reservoir has not been established [2–4].

On March 11, 2020, the World Health Organisation (WHO) declared COVID-19 a pandemic. The outbreak led to severe shortages of essential medical supplies and services, including hand sanitisers, N95 masks, intensive care unit (ICU) beds and ventilators [5,6]. Many critically ill patients required supportive invasive mechanical ventilation (IMV) for durations ranging from days to weeks [7]. By the end of 2022, COVID-19 had affected 655 million people worldwide, resulting in 6,683,993 deaths, with a case-fatality ratio of 1.02% [8].

One of the more significant challenges during the pandemic was the shortage of mechanical ventilators (MVs), which highlighted the need for strategic allocation and resource management. Several countries experienced MV shortages and responded with varying strategies, including reliance on foreign aid and implementing stringent rationing protocols based on factors such as age and preexisting medical conditions. These decisions were often controversial. In Saudi Arabia, the experience of managing MV shortages during the COVID-19 pandemic highlighted key strategies for crisis response at the national level [9]. This review examines Saudi Arabia's approach to addressing MV shortages, including implementing a live tracking information system by the National Health Command Center (NHCC) and optimising medical supply chain logistics during a global crisis.

## Methods

This study employed a mixed-method approach, incorporating a descriptive analysis of the NHCC experience in Saudi Arabia and a narrative review of MV shortages during the COVID-19 pandemic. The narrative review aimed to identify articles addressing MV shortages and potential solutions. Articles were retrieved from the Medline, Embase, Cochrane and Google Scholar databases using keyword searches limited to the title and abstract, including 'MV' OR 'ventilator' AND 'COVID' OR 'pandemic.' Cross-referencing was conducted to identify additional relevant publications not included in the database searches. The search covered studies published from 2020 to July 2024. Two public health experts reviewed all articles; the most relevant studies were included.

### *MV shortages during the COVID-19 pandemic*

The COVID-19 pandemic resulted in critical shortages of medical resources, including ICU beds, healthcare personnel and MVs [10]. The high prevalence of respiratory failure among patients with COVID-19 exacerbated MV shortages and highlighted a lack of trained professionals to manage ventilated patients [11].

During the initial peak of COVID-19, regional MV shortages were reported in the Northeastern United States. The Hawaiian Islands, with a population of approximately 1.4 million, had 250 ICU beds and 500 ventilators, while Haiti, with a population of 11 million, could provide IMV to fewer than 100 patients. In Italy, high infection and mortality rates among healthcare workers were partly attributed to inadequate personal protective equipment [12]. In 2019, manufacturers produced 77,000 ventilators to meet global market demands. However, during the first wave of the pandemic, New York alone estimated a need for 33,000 additional ventilators [13].

A study in Brazil found that MV shortages were most severe in the northern region during the first surge (25%) and in both the northern and southern regions during the second surge (17%) [14]. In response to ventilator shortages, Singh et al. [15] implemented a strategy combining surgical tracheostomy with a portable ventilator-tracheostomy weaning approach to increase ICU ventilator capacity. The study included 52 patients with COVID-19-associated acute respiratory distress syndrome (ARDS) who were mechanically ventilated in the ICU for more than seven days and received a tracheostomy between March and May 2020. Of these patients, 47 required long-term respiratory support. The intervention released 32 ICU ventilators and saved 230 ventilator days, with one patient dying due to causes unrelated to the tracheostomy.

### *Strategies for managing MV shortages*

Several innovative approaches helped mitigate MV shortages during the pandemic. Raymond et al. [11] developed a cost-effective ventilator based on the US Food and Drug Administration's emergency use recommendations. This ventilator, designed using a medical gas and flow interruption technique, eliminated several components in conventional ventilators, improving reliability while providing life-saving ventilatory support. Li et al. [16] designed a scalable ventilator for COVID-19 and ARDS patients using a modular approach with non-traditional supply chain components. A test lung evaluation demonstrated a linear actuator-driven pinch valve-based mechanism for controlling pressure and volume with decelerating inspiratory flow assistance.

High-flow nasal cannulas (HFNCs), which deliver warmed, humidified oxygen through nasal prongs, emerged as an alternative to intubation and mechanical ventilation. Physicians at the University of Chicago Medicine reported that some COVID-19 patients responded exceptionally well to HFNC therapy than ventilators [17]. Meta-analyses indicated that HFNC therapy was associated with lower intubation rates [18,19], reduced 28-day ICU mortality [19] and improved outcomes in patients with baseline arterial oxygen partial pressure to fractional inspired oxygen ($PaO_2/FiO_2$) ratios below 200 mm Hg [20].

Alwasel et al. [21] used a three-dimensional printed microscopic size splitter, which increased individual tidal volume by 26% compared with traditional tubing and two-way splitters. This ventilator provided the required pressure and tidal volume for 1 day. When equipped with a four-way splitter, it successfully ventilated four patients with respiratory failure for at least 24 hours [21]. Kumar and Kumar [22] demonstrated that a modified single ventilator could support five or more patients with similar lung physiology. Another study evaluated modifications to breathing circuits for shared ventilation, incorporating a positive end-expiratory pressure valve, an adjustable constriction valve and a pressure-relief valve. These modifications enhanced safety and minimised mechanical interactions between multiple patients, supporting the feasibility of ventilator sharing during public health emergencies [23].

## *Ethical considerations*

The COVID-19 pandemic highlighted ethical challenges in allocating MVs, raising concerns about fairness, justice and the intrinsic value of human life, which significantly impacted healthcare professionals [24]. Decisions regarding ventilator withdrawal and reallocation affected the emotional and psychological well-being of patients and their families, often leading to anger, grief, guilt and confusion, which contributed to diminished trust in local healthcare systems [25].

A systematic review identified key ethical values and principles guiding pandemic responses, including equity, reciprocity, transparency, justice, duty of care, liberty, utility, stewardship, trust and proportionality [26]. Establishing a just, uniform and comprehensive national protocol for resource prioritisation is essential to mitigate the negative effects of resource rationing on public morale [27].

Healthcare professionals faced ethical dilemmas in selecting treatment recipients, raising concerns about potential discrimination and bias in decision-making [28]. The absence of country-specific guidelines during the public health emergency led to inconsistencies in ethical protocol development [29]. For example, significant discrepancies were observed in implementing resource allocation protocols among hospitals in the Chicago metropolitan region [30]. Implementing standardised protocols and ensuring transparency and accountability in the allocation process can help sustain public trust and improve patient outcomes. Ethical resource distribution involves a three-step process: defining essential ethical principles for allocation, applying these principles to establish priority levels and implementing prioritisation measures that align with these fundamental values [23].

Several strategies have been proposed for MV allocation during the COVID-19 pandemic. One approach is a first-come, first-served system, which treats all patients equally, regardless of prognosis [31]. However, this method may disadvantage individuals who live far from healthcare facilities and fail to ensure effective resource allocation based on medical necessity and treatment viability. An alternative approach prioritises the most vulnerable patients at risk of severe disease progression, though this may inadvertently disadvantage individuals who seek care later in the disease course [32].

A lottery system has been suggested to ensure fairness by randomly selecting patients with identical priority scores, eliminating bias and avoiding reliance on subjective outcome predictions [33,34]. However, this method may not account for patient-specific factors influencing survival probabilities and treatment responses. A modified egalitarian approach proposes ventilator distribution based on anticipated per capita excess demand rather than random selection. This method allocates ventilators equitably among regions with varying critical care capacities, ensuring resources are directed to areas with the greatest demand [35]. However, this approach carries risks of overestimation or underestimation and may exacerbate regional disparities.

Additionally, ventilator allocation decisions have been based on six factors: population density, random allocation, patient-to-healthcare personnel ratio, in-hospital mortality rates, population age and general mortality rates [36]. The WHO developed a fair allocation framework emphasising transparency, inclusiveness, consistency and accountability [37]. The New York State Department of Health and the New York State Task Force on Life and the Law also established ethical principles for ventilator allocation (Table 1).

### *Real-time tracking of MVs and health command centers*

During pandemics involving respiratory illnesses, ensuring the availability of oxygen supply and respiratory support equipment is essential [41]. However, logistical challenges often arise, particularly in resource-limited settings and facilities with inadequate medical equipment. To address these challenges, the American Hospital Association, in collaboration with the Federal Emergency Management Agency, initiated the Dynamic Ventilator Reserve program to deploy ventilators to high-demand areas [42].

***Table 1**. Ethical principles for allocation of scarce ventilators [38–40].*

| | |
|---|---|
| Duty to plan | Public health authorities are obligated to plan to allocate stockpiled ventilators during emergencies.<br>It may not be practical to develop a comprehensive plan in specific situations. |
| Transparency | State and local planners should disseminate planning guidelines to hospitals and stakeholders. Additionally, they should actively solicit public input and integrate values into their planning endeavors. |
| Distributive justice | Prioritize facilities that can minimize loss of life during emergencies.<br>Striking a balance between equitable distribution and effectiveness is difficult. |
| Duty to care | The responsibility of healthcare providers to deliver patient care consistent with the standards expected of a reasonable physician<br>If ventilators are inadequate, plans should incorporate alternative curative and palliative care methods. |
| Duty to steward resources | Allocate scarce resources to facilities that can use them most effectively. |
| Equity | Employ a uniform framework to distribute stockpiled ventilators to all facilities in a jurisdiction. |

In a statewide initiative, Oregon, United States, implemented a real-time tracking system known as 'The Oregon Capacity System Tracking Board,' which monitored bed availability across healthcare facilities to manage COVID-19 surges. The system integrated data from manual tracking boards and provided updated information at state, facility and unit levels, improving healthcare preparedness during the pandemic [43].

During the COVID-19 peak in Saudi Arabia, importing medical equipment and supplies was particularly challenging due to export restrictions imposed by several countries [44]. In response, the Saudi NHCC developed strategies to ensure respiratory support for patients with respiratory distress. These strategies focused on securing medical and respiratory devices, optimising supply chain management and increasing local production capacity.

To address global MV shortages and the evolving demands of the pandemic, the NHCC convened urgent meetings with key stakeholders to secure spare ventilator parts from international manufacturers. Discussions focused on contingency planning for hospitals, optimising MV supply, creating alternative distribution pathways and addressing staffing challenges. However, the Ministry of Health lacked a preexisting national strategy to rapidly expand ventilator availability, and there was no centralised database to track the number of ventilators available before procurement decisions were made.

To enhance preparedness, the NHCC conducted on-site evaluations and assessments of respiratory support devices (RSDs) across all healthcare sectors in Saudi Arabia, surveying approximately 450 hospitals (Figure 1). The NHCC established a live tracking system for MVs, integrating real-time monitoring and utilisation data. This database facilitated inventory assessments and identified ventilators requiring maintenance to ensure optimal performance (Figures 2 and 3).

The NHCC identified 20,754 RSDs across all healthcare sectors in Saudi Arabia. Of these, 11,853 (57.1%) were invasive, and 3,451 (16.6%) were portable MVs. However, 1,323 RSDs were identified as nonfunctional but repairable. In March 2020, at the onset of the COVID-19 pandemic, more than 200 ventilators were distributed across various regions to meet anticipated hospital demands. Additionally, over 1,000 helmet-based ventilators, 1,500 HFNCs and high-efficiency particulate air filters were supplied to support respiratory care needs [9].

To ensure adequate ventilator availability, the NHCC implemented daily monitoring plans for maintenance and repair. These plans included procuring necessary spare parts, maintaining an inventory of available consumables and assessing additional needs. By June 2021, 1,094 of the repairable devices had been restored, with 92% repaired within three months (Figure 4). This initiative resulted in an estimated cost savings of approximately US$54 million (SAR 202 million). In addition to increasing the ventilator supply, the NHCC prioritised allocation to the most affected regions. Ventilator distribution was based on worst-case scenario projections, starting with 200 ventilators in March 2020 and increasing to 1,750 ventilators across various regions by the end of 2020.

To address the growing demand for ventilator operation, the NHCC, in coordination with the training department, developed programs to train 22,000 healthcare professionals from multiple specialties on pandemic response. Additionally, 2,710 nurses and anesthesia technicians received specialised ventilator operation and management training. Part-time contracts were activated to ensure 24-hour ventilator operation and a ticketing

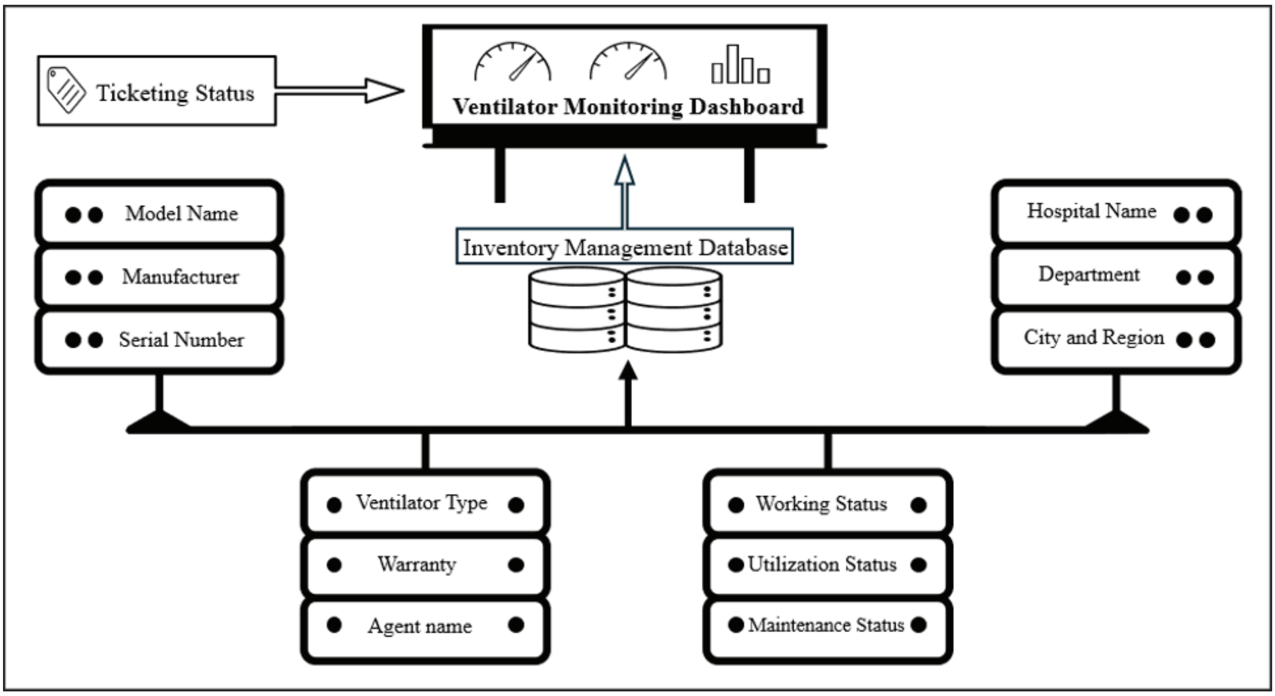


*Figure 1. The key performance indicators included in the inventory management database for the RSDs.*

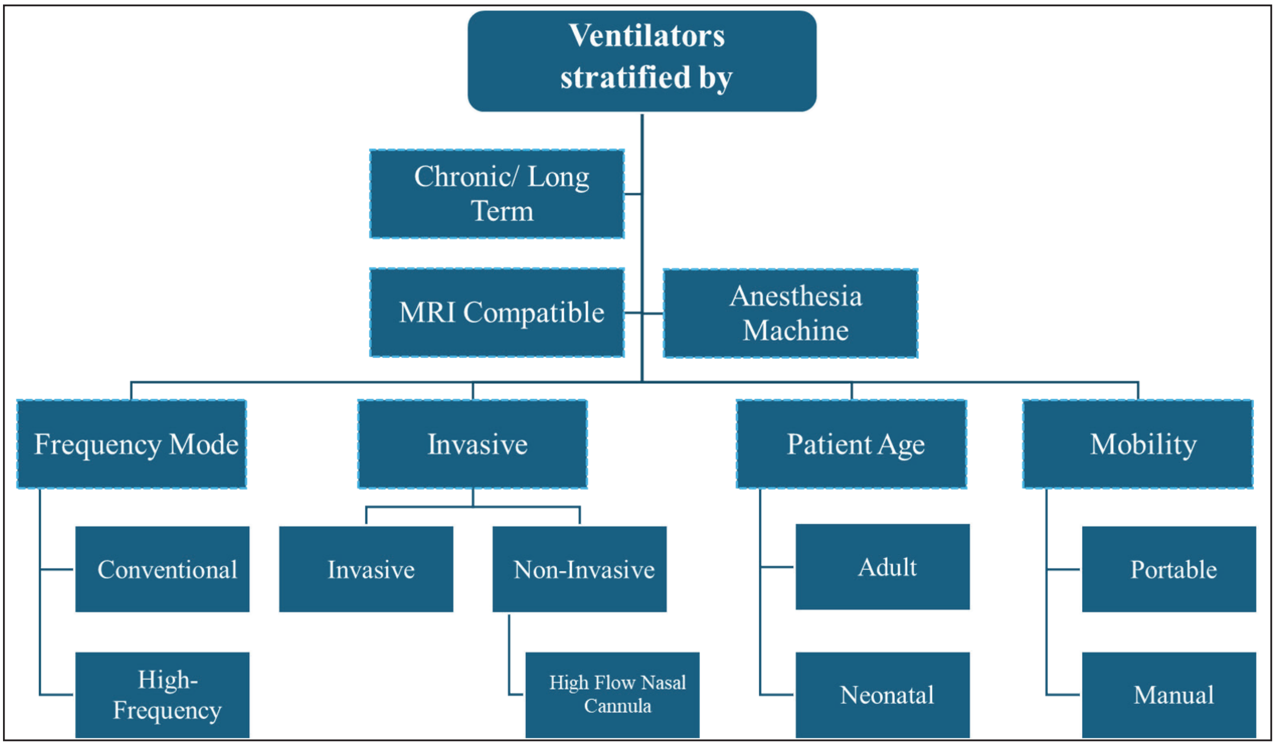


***Figure 2.*** *MV stratifications in the inventory database system. Abbreviations: MRI, magnetic resonance imaging; MV, mechanical ventilator.*

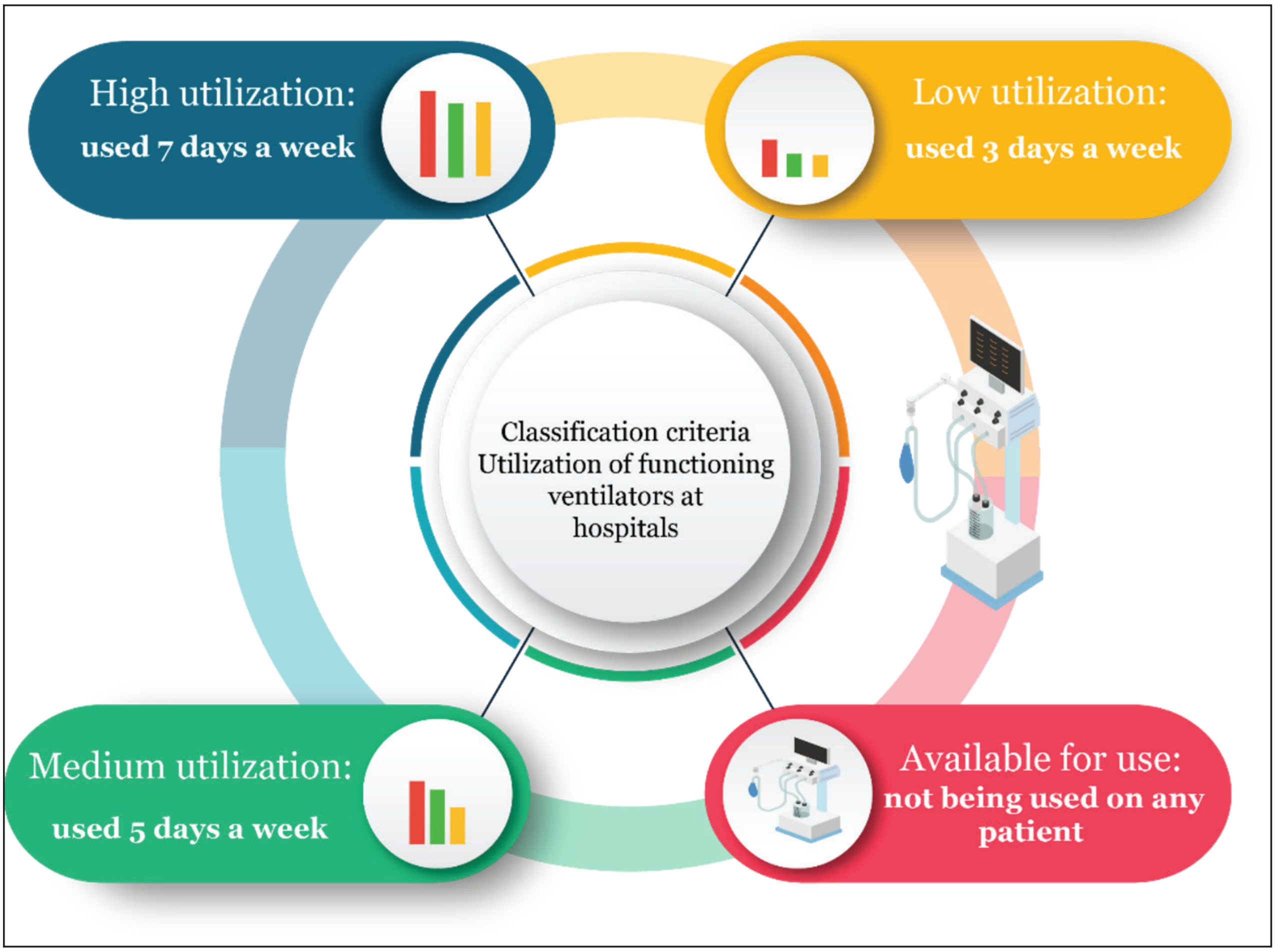


***Figure 3.*** *Use of functioning ventilators in hospitals.*

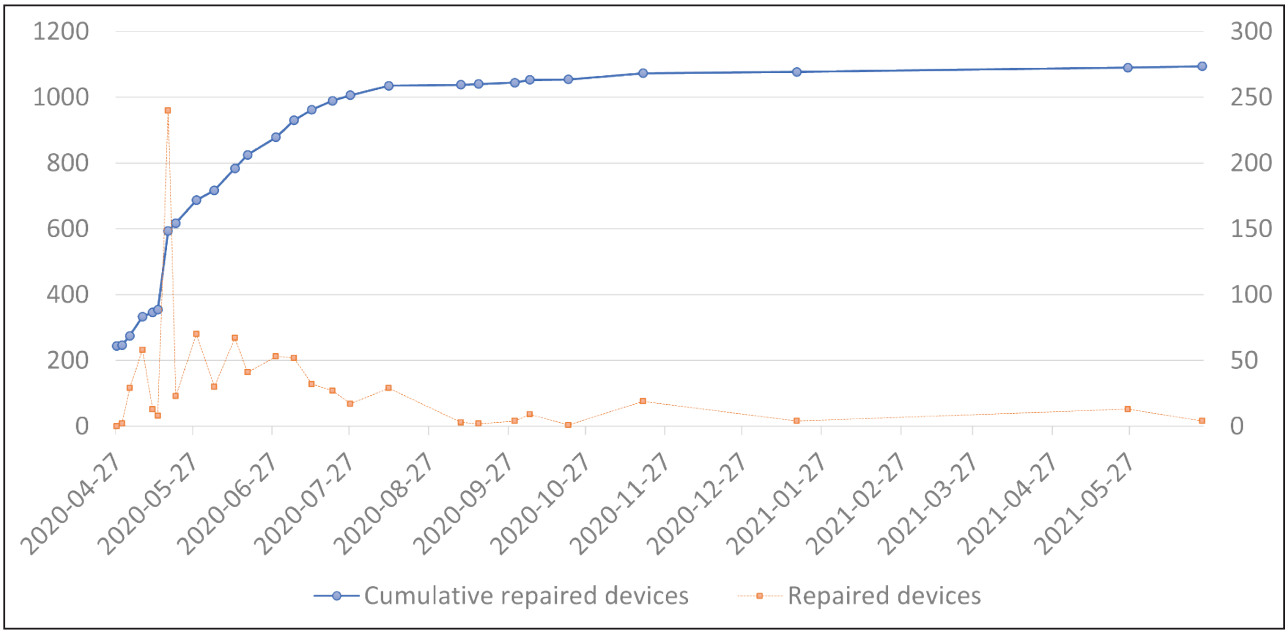


***Figure 4.** Trend of repaired ventilators from the beginning of COVID-19 pandemic. Abbreviation: COVID-19, coronavirus disease 2019.*

system was introduced to promptly resolve operational challenges, request additional devices and facilitate maintenance services. This system enabled coordinated supply management, preventing gaps in equipment availability. Real-time tracking of ventilator availability and predicted demand ensured alignment between supply and need.

The NHCC's multisector interventions provided significant benefits to the healthcare system. In addition to cost savings, increased ventilator availability allowed for redistribution among healthcare facilities based on patient needs and utilisation rates. This approach enabled Saudi Arabia to achieve national self-sufficiency in ventilator supply, making surplus units available for global export. Reflecting on pandemic statistics, Saudi Arabia's case fatality rate was significantly lower than the global average (1.6% *vs.* 2.2%) [45]. Furthermore, the country ranked second globally in its capacity to recover within one year of the COVID-19 pandemic [46].

## Discussion

Access to MVs during the COVID-19 pandemic posed challenges worldwide, including in high-income countries such as the United States [47] and in middle- and low-income countries [48]. These challenges highlighted disparities in healthcare access, particularly for vulnerable populations. As the pandemic tested the resilience of healthcare systems [49], decision-making processes needed to follow an organised, multi-sectoral approach that accounted for various challenges. A comprehensive analysis of these challenges can help develop more effective and adaptable strategies to address future public health crises [50].

The experience of the NHCC in Saudi Arabia demonstrated a practical and effective approach to ventilator management. A unified tracking system for MV monitoring and use was gradually implemented, providing accurate and consistent data on device availability. This system enabled the NHCC to lead a coordinated nationwide response, ensuring the equitable distribution of MVs to both government and private hospitals based on regional needs.

Early planning for worst-case scenarios is essential to enhance preparedness for future respiratory disease outbreaks. Developing a robust national MV allocation and management strategy can optimise this critical but limited resource. A thorough assessment of actual and projected ventilator needs is necessary to ensure efficient and equitable distribution. Additionally, national monitoring of MV stockpiles and utilisation across public and private healthcare facilities is vital for informed decision-making. Increasing the number of qualified personnel for MV maintenance and repair during periods of high demand is also critical to maintaining ventilator functionality.

A permanent, comprehensive ventilator management database within national or regional health command centers is necessary for real-time tracking of ventilator location, status and utilisation. This system would facilitate optimal resource allocation and provide a clear understanding of available capacity, allowing for a more effective crisis response. Lessons from the COVID-19 pandemic emphasise the need to maintain sufficient spare parts for essential medical equipment, considering specific ventilator models and manufacturers.

Portable MVs offer significant advantages by enhancing patient mobility and flexibility within healthcare facilities during a pandemic. Addressing global shortages of critical medical supplies, particularly those essential for managing respiratory diseases, should encourage nations to increase local production capacity. Ethical guidelines for ventilator allocation should be periodically reviewed and updated to provide clear, comprehensive guidance for healthcare professionals facing resource constraints.

A fair and standardised approach to ventilator distribution is necessary to ensure ethical and effective decision-making during public health emergencies.

The WHO should adopt and promote successful ventilator management strategies to support other countries in mitigating the effects of future pandemics. This study successfully demonstrated effective strategies for addressing MV shortages during the COVID-19 pandemic, drawing on successful national responses. However, the study faced limitations due to a lack of scientific literature addressing ventilator management during the pandemic. While MV shortages were a significant challenge globally, published research on this topic remains limited. Further studies are needed to evaluate the long-term impact of MV allocation strategies and their effectiveness in strengthening healthcare systems.

## Conclusion

During large-scale public health emergencies involving respiratory diseases such as COVID-19, countries must develop comprehensive strategies for MV stockpiling and management. These strategies should ensure the effective, efficient and equitable distribution of ventilators. A permanent, centralised ventilator management database is highly recommended to enable real-time tracking of ventilator location, status and utilisation across healthcare systems. Such a database would provide full visibility of resources, allowing for optimal crisis management.

In collaboration with multi-sectoral stakeholders, a NHCC should oversee ventilator deployment and utilisation to ensure a coordinated response. Additionally, revising ethical guidelines for resource allocation can help healthcare systems navigate the complexities of distributing limited resources during future public health emergencies. Disseminating global expertise and best practices in ventilator management is essential for improving pandemic preparedness. By sharing evidence-based strategies, nations can strengthen their healthcare systems and enhance their capacity to address future ventilator shortages.

### List of Abbreviations

| | |
|---|---|
| ARDS | acute respiratory distress syndrome |
| COVID-19 | Coronavirus disease 2019 |
| HFNC | high-flow nasal cannulas |
| ICU | intensive care unit |
| IMV | invasive mechanical ventilation |
| MV | mechanical ventilator |
| NHCC | National Health Command Center |
| $PaO_2/FiO_2$ | arterial oxygen partial pressure to fractional inspired oxygen |
| RSD | respiratory support devices |
| SARS-CoV-2 | severe acute respiratory syndrome coronavirus 2 |
| WHO | World Health Organization |

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