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High potential of technology to face new respiratory viruses: mechanical ventilation devices for effective healthcare to next pandemic emergencies

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ARTICLE INFO

JEL classification:

O30
O32
H12
I10
I18
I19

Keywords:

COVID-19 pandemic
Pandemic preparedness
Public health preparedness/response
Innovation policy
Fatality rate
Breathing devices
Effective healthcare
Medical ventilators
Ventilation machines
Mechanical ventilation
Respiratory therapies
Ventilator technology innovation
Coronavirus Disease 2019
Artificial ventilation

ABSTRACT

Some countries in the presence of unforeseen Coronavirus Disease 2019 (COVID-19) pandemic, caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), have experienced lower total deaths, though higher numbers of COVID-19 related infections. Results here suggest that one of the explanations is the critical role of ventilator technology in clinical health environment to cope with the initial stage of COVID-19 pandemic crisis. Statistical evidence shows that a large number of ventilators or breathing devices in countries (26.76 units per 100,000 inhabitants) is associated with a fatality rate of 1.44% (December 2020), whereas a higher fatality rate given by 2.46% is in nations with lower numbers of ventilator devices (10.38 average units per 100,000 people). These findings suggest that a large number of medical ventilators in clinical setting has a high potential for more efficient healthcare and improves the effective preparedness of crisis management to cope with new respiratory pandemic diseases in society. Hence, a forward-thinking and technology-oriented strategy in healthcare sector, based on investments in high-tech ventilator devices and other new medical technologies, can help clinicians deliver effective care and reduce negative effects of present and future respiratory infectious diseases, in particular when new drugs and appropriate treatments are missing in clinical environment to face unknown respiratory viral agents .

1. Introduction

In the presence of Coronavirus Disease 2019 (COVID-19) pandemic crisis, countries have applied health policies to stop and/or reduce the transmission of the novel infection and consequently high numbers of deaths [1–4]. However, many countries have experienced in the initial stage of the COVID-19 pandemic, although containment and/or mitigation policies, high numbers of deaths, such as Italy, Central and South American countries, etc. [2,3,5–8]. Manifold factors affect the negative impact of COVID-19 pandemic in society, such as high air pollution and density of people in cities [9], intensive commercial trade between countries [10,11], low investments in healthcare sector, etc. [12,13], etc. COVID-19 with initial variants Alfa and Delta generated critically respiratory failure in ill patients, heterogeneous pulmonary parenchymal involvement, profound hypoxemia, pulmonary vascular injury

and other negative health effects [14]. One of the treatments in the initial stage of the COVID-19 pandemic is the application, to patients with respiratory disorders, of mechanical ventilator that is based on an internal compressor and mixer to moderate and control the gas mixture delivered to ill patients. Nevertheless, a major problem was the shortage of these breathing devices [15–17]. Jones [18] argues that in India only 50% of intensive care units (ICUs) has a mechanical ventilator. Innovative projects were launched, during the initial phase of COVID-19 pandemic crisis in 2020, to solve this problem of the shortage of ventilators in order to improve manufacturing and flexibility in supply chain, also with strategic partnership and collaborative networks in this industry to boost R&D performance, production, storage and maintenance of ventilator devices [14,19–25]. A main example is product development of the PocketVent ventilator in less than six months with efficient technical characteristics of pressure and volume controlled to help

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<https://doi.org/10.1016/j.techsoc.2023.102233>

Received 22 March 2022; Received in revised form 14 March 2023; Accepted 15 March 2023

Available online 21 March 2023

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patients in breathing [17]. Other scholars suggested that the use of medical gasses and flow interruption strategy can support high performance and low cost in ventilator technology [14]. This technological approach reduces many physical components present in traditional ventilators, shortens the time from storage to clinical deployment and improves reliability in terms of life-saving ventilatory support, satisfying emergency guidelines of the U.S. FDA. Planners and policymakers also realized that during COVID-19 pandemic crisis, the technical personnel to operate mechanical ventilation was another resource of shortage [15]. Jimenez-Maturano and Licona [26] maintain that the demand increase for the production of ventilation devices can create risks concerning the correct equipment's operation and effective safety to care for COVID-19 patients.

In the presence of Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) and similar viral agents that cause severe respiratory illness responsible of outbreaks, a vital research question is to analyze the relation between numbers of mechanical ventilators (breathing devices) and COVID-19 fatality rates across countries because it can support effective health policy responses of crisis management to face future pandemic threats of deadly infections. In particular, the purpose of the present study is to verify whether the statistical evidence supports the *hypothesis* that, in the initial stage of COVID-19 pandemic crisis, lower rates of fatality in some countries can be explained by large numbers of mechanical ventilators in healthcare. Findings here can clarify the critical role of this medical technology as one of the main resources in effective health strategies of crisis management that improves preparedness and responsiveness of countries to face pandemic threats, reducing negative impact in society.

2. Theoretical framework

Mechanical ventilator is an artificial breathing device used for patients that are not able to breathe naturally because of a critical illness and/or severe acute respiratory disorders, such as respiratory failure generated by Coronavirus Disease 2019 (COVID-19) and similar infectious diseases, Chronic Obstructive Pulmonary Disease (COPD), lung cancer, etc. [27]. In particular, mechanical ventilator is applied to patients with acute or acute-on-chronic respiratory failure that do not respond to standard therapeutic interventions, such as antibiotics, bronchodilators, etc. [28,29].

Mechanical ventilators can be:

- stationary devices for Intensive Care Units (ICUs)
- mobile devices used to transfer patients within and between hospitals, for in-home use, etc.
- Invasive devices based on endotracheal intubation
- Non-Invasive Ventilation (NIV) devices with various types of face masks

Invasive devices for mechanical ventilation are based on endotracheal tube to deliver to patient's lungs the appropriate levels of oxygen and initiate lung healing from respiratory disorders [30]. However, invasive ventilation technology generates some health problems such as, ventilator-associated lung injury, alveolar overdistension that leads to inflammatory processes and fluid accumulation in lungs, ventilator-associated pneumonia (VAP), etc. [31–33]. Garnier et al. [34] confirm that COVID-19 patients treated with invasive mechanical ventilation are at high risk of developing VAP. In fact, VAP affected about 50% of COVID-19 patients with mechanical ventilation and had a negative impact on 90-day mortality.

A different technology is the Non-Invasive Ventilation (NIV) that can reduce ventilator-associated lung injuries, VAP and other health problems [35,36]. The application of NIV devices (with helmet, facemask, etc.) is increasing and now this new technology care better patients having acute and/or chronic respiratory failure, in ICUs or at home [37–39]. Technological advances of NIV are based on respiratory

abdominal sensors and transducers, and other innovations that measure with accuracy patient's airway pressure, monitor and improve breath rate, etc. [40]. In addition, new technology in NIV provides more natural breathing with an adequate humidification to maintain airway clearance and enhance patient comfort (similarly to normal functions of the nose and air passages in the human respiratory tract that are to warm, moisten and filter the inhaled gases before they reach the lungs without damaging the alveoli: tiny air sacs where the lungs and the blood exchange oxygen and carbon dioxide during the process of breathing in and breathing out) [41,42]. Weerakkody et al. [43] argue that the NIV can be superior to high-flow nasal oxygen because reduces the respiratory complications. Zhang et al. [44] find that the early adoption of NIV can improve the health of patients with severe acute respiratory syndrome (e.g., COVID-19), COPD and other respiratory disorders. Chandrasekaran and Monikandan [31] analyze the therapeutic advantages of oxygen helmet with negative pressure ventilator in patients exposed to various ventilator-induced lung injuries, such as barotrauma, VAP, etc. New technology in this industry is also directed to ventilators with flexible application for adults, children and newborns [45]. NIV and other high-tech devices for mobile mechanical ventilation, in ill patients of COVID-19 and other diseases causing respiratory disorders and/or failures, are safe, cost-effective and associated with better technical performance and comfort [43,46,47]. Table 1 and Fig. 1 show that global market of ventilator technology in medicine has leading companies mainly in the USA and Germany. The firms with the highest market share in this high-tech industry, over 2019, are: Hamilton Medical (22%), Getinge (22%), Draeger (16%), Minday (10%), Medtronic (5%), Philips (3%), Vyaire Medical (3%), Becton Dickinson, Fisher & Paykel Healthcare, GE Healthcare, and Smiths Group (cf., [48, 50]; see, Table 1).

Overall, then, mechanical ventilators can play a critical role to treat respiratory illnesses and to cope with negative effects of emerging viral agents that cause severe acute respiratory syndrome responsible of unforeseen pandemics, such as COVID-19, when appropriate drugs are missing. Next section presents the methodology to investigate this

Table 1

Top firms producing mechanical ventilators and their headquarters (city and country).

Company	Headquarters Location	Country
Airon Corporation	Melbourne, Florida	USA
Becton Dickinson and Company	Franklin Lakes, NJ	USA
Bio-Med Devices, Inc.	Guilford, CT	USA
Bunnell Incorporated	Salt Lake City, UT	USA
Cardinal Health	Dublin, OH	USA
GE Healthcare	Chicago, IL	USA
Hartwell Medical Corp.	Carlsbad, CA	USA
Hillrom	Chicago, IL	USA
Vyaire Medical Inc.	Chicago, IL	USA
Oceanic Medical Products, Inc.	Atchison, KS	USA
ResMed Corp.	San Diego, CA	USA
United Hayek Industries, Inc.	San Diego, CA	USA
Ventec Life Systems	Bothell, WA	USA
Hamilton Medical	Bonaduz	USA/Switzerland
ACUTRONIC Medical Systems AG	Hirzel	Switzerland
Smiths Group	London	UK
Medtronic	Dublin	Ireland
Air Liquide Healthcare	Paris	France
Getinge AB	Göteborg	Sweden
aXcent medical	Koblenz	Germany
Drägerwerk AG	Lübeck	Germany
Löwenstein Medical Innovation	Kronberg	Germany
Dima Italia	Bologna	Italy
Philips	Amsterdam	The Netherlands
Avasarala Technologies Limited	Bengaluru	India
Aeonmed co., ltd.	Beijing	China
Mindray Medical International	Shenzhen	China
Triton Electronics Systems, Ltd.	Yekaterinburg	Russia
Fisher & Paykel	Auckland	New Zealand

Source: Müller [48]; Edwards [49].

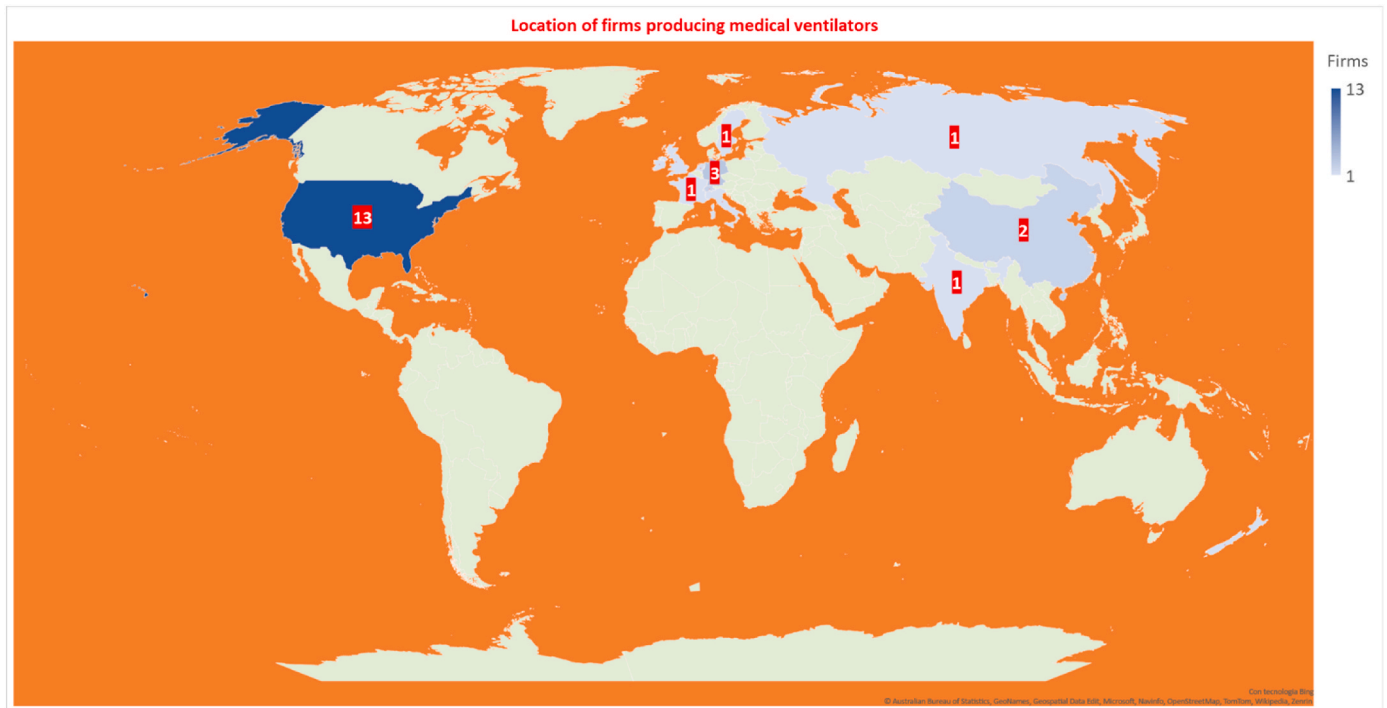


Fig. 1. Geographical distribution in countries of main firms producing mechanical ventilators.

Note: The USA has 13 firms, Germany 3, Switzerland 2, China 2, the UK 1 firm, Ireland 1, France 1, Sweden 1, Italy 1, the Netherlands 1, India 1, Russia 1 and finally New Zealand 1 firm.

critical problem and verify the *hypothesis* stated in introduction that, in the initial stage of COVID-19 pandemic crisis, lower rates of fatality in some countries can be due to large numbers of mechanical ventilators in healthcare, suggesting that these high-tech devices can improve preparedness in crisis management to face unexpected health emergencies (e.g. pandemics of new respiratory viruses),

3. Methods

3.1. Sample

This study analyzes data of mechanical ventilators and of other variables in nine countries: Canada, France, Germany, New Zealand, Norway, South Korea, Switzerland, United Kingdom and United States [51]. This sample has all data of variables under study.

3.2. Measures for statistical analyses

- Mechanical ventilators. Total number of ventilators over 2015–2020. Source: Our World in Data [51].
- Wealth of nations. Gross Domestic Product (GDP) per capita in 2020, constant 2010US\$. Source: The World Bank [52].
- Population total. All resident people in 2020. Source: The World Bank [53].
- Health expenditure as % of GDP. It includes healthcare goods and services consumed during a certain year. Average values over 2008–2018 (2018 is the last year available in dataset). The World Bank [54].
- COVID-19 Mortality. Normalized deaths per country are based on Case Fatality Ratio (CFR) % of COVID-19 [12,55–57]:

$$\text{Case Fatality Ratio (CFR) \%} = \left(\frac{\text{Number of deaths from COVID - 19}}{\text{Number of confirmed cases of COVID - 19}} \right) \times 100$$

CFR of COVID-19 is a critical indicator to support appropriate health policies of governments to cope with pandemic crisis and similar health emergencies [58]. CFR of COVID-19 is measured as of December 31st, 2020, before the plans of vaccination between countries, to assess the effective role of mechanical ventilators to mitigate the number of deaths, when these technological devices were the only therapeutic treatment for COVID-19 patients because effective drugs to face new coronavirus were missing. CFR of COVID-19 is also considered as of February 21st, 2022, after the vaccination campaign, for a comparative analysis of long period. Source of data: Johns Hopkins Center for System Science and Engineering [59].

3.3. Data analysis procedure

- a). Total number of mechanical ventilators is divided by total population of countries and multiplied by 100,000 to have a normalized value between countries. Average value of mechanical ventilators per 100,000 people in sample under study is fifteen units. Hence, countries are categorized simply in:
 - Group 1: Countries with a *large number* of mechanical ventilators: more than 15 ventilators per 100,000 people
 - Group 2: Countries with a *small number* of mechanical ventilators: lower than 15 ventilators per 100,000 people
- b). Arithmetic mean (M) of COVID-19 fatality rates between countries in groups 1 and 2 can suggest the effectiveness of ventilation technology to cope with deadly infections of COVID-19 in society [60].
- c). Parametric independent samples *T*-test assesses whether arithmetic means of variables between groups (1 and 2) are significantly different: i.e., if countries having average large numbers of mechanical ventilators per inhabitants, they have also lower average fatality rates of COVID-19 (cf. *hypothesis* in the introduction here). Finally, the control analysis is performed with the Kruskal-Wallis *H*-test (a rank-based nonparametric test).

4. Results and discussions

Table 2 shows that:

- Countries with *large numbers of mechanical ventilators* have average ventilator devices per 100,000 people over 2015–2020 (last year available) given by M (arithmetic mean) = 26.76 units (Standard Deviation, SD = 14.94 units)
- Countries with a *small number of mechanical ventilators* have average ventilators per 100,000 people over 2015–2020 (last year available) equal to M = 10.38 units (SD = 2.57 units)

Table 2 reveals a main finding: countries having high average numbers of mechanical ventilators per 100,000 people (M = 26.76 units), they have a low average fatality rate of COVID-19 (M = 1.43%) as of December 31st, 2020 compared to countries with low average numbers of mechanical ventilators (M = 10.38 units) that have a higher average fatality rate related to COVID-19 (M = 2.46%) in the same period. These results are in a homogenous socioeconomic framework because GDP per capita and average health expenditure as % of GDP in two groups of countries under study are comparable values.

Table 3 shows a significant difference of the arithmetic means of COVID-19 fatality rate % as of December 31st, 2020 between groups of countries with high and low average number of mechanical ventilators (*p*-value=0.05). Moreover, as of February 21st, 2022, although average COVID-19 fatality rate is lower in countries with large numbers of mechanical ventilators, the difference between groups is not significant. This result can be explained with the widespread and pervasive diffusion of vaccinations to treat COVID-19 in these countries that has generated a substitution effect with mechanical ventilators in therapeutic treatments of COVID-19 [3,61].

Kruskal-Wallis H test in Table 4 confirms a statistically significant difference of COVID-19 fatality rates as of December 31st, 2020 between groups. In particular:

- there was a statistically significant difference in mechanical ventilators between groups $\chi^2(1) = 6.00, p\text{-value} = 0.01$, with a mean rank score of 2.5 for countries having LOW numbers of mechanical ventilators per 100,000 people and a mean rank score of 7 for countries having HIGH numbers of mechanical ventilators per 100,000 people.
- there was a statistically significant difference in COVID-19 fatality rates as of December 31st, 2020 between groups having a high/low level of mechanical ventilators $\chi^2(1) = 3.85, p\text{-value} = 0.05$, with a mean rank score of 7 for countries with LOW numbers of mechanical ventilators per 100,000 people and a mean rank score of 3.4 for

countries having HIGH numbers of mechanical ventilators per 100,000 people.

As explained for Independent sample *T*-test, the differences of COVID-19 fatality rate between groups as of February 21st, 2022 are statistically insignificant because of vaccination plans that have provided with new vaccines an alternative therapeutic treatment to mechanical ventilator devices, because countries with low numbers of mechanical ventilators have, in general, high levels of vaccination in population that reduced fatality rate [3,62–64].

Fig. 2 synthesizes main findings: countries with a high average number of mechanical ventilators of about 27 units per 100,000 people, compared to countries with low numbers of mechanical ventilators of about 10 units per 100,000 people [65], have a lower average fatality rate of COVID-19 given by 1.44% vs. 2.46%.

The ever-looming threat of the emergence of a new viral agent or the evolution of a new variant of SARS-CoV-2 that can evade new vaccines and antivirals is very real [66]. These facts suggest that mutant SARS-CoV-2 and similar respiratory viruses will continue to play a major role in society for the foreseeable future [67].

This uncertain scenario compels countries to face in future more complex social, economic, political, and clinical environments and to absorb the lessons learned from the COVID-19 responses to be prepared for minimizing negative effects of next health emergencies.

Lesson learned of crisis management to face next pandemic threat that this study adds is that statistical evidence here seems in general to support the hypothesis that a lower COVID-19 fatality rate (during the initial phase of pandemic crisis when vaccines and antivirals to treat new viral respiratory disease of COVID-19 are missing) can be explained with a large number of mechanical ventilators that has helped clinicians deliver quality and effective care to mitigate mortality in society [68]. Since the impact of next pandemic will be determined by how well-prepared countries are when health emergency occurs at any time with little warning, and how countries timely respond, these findings here suggest that a technology-oriented strategy based on high levels of R&D investments in health sector and in particular in medical technology of ventilators can support more efficient healthcare and improve the preparedness of countries to cope with pandemic crises and as a consequence to reduce negative effects of high numbers of COVID-19 related deaths in society [2]. Hence, nations have to invest in new mechanical ventilators to prepare healthcare sector to face next health emergencies, probably caused by emerging viral respiratory diseases, as well as in the presence of increasing chronic obstructive pulmonary diseases in society (associated with high air pollution in cities), of many people affected by hypertension and cardiovascular diseases, of growing geriatric population, and finally of increasing tobacco consumption worldwide leading to lung cancer [69–73].¹ The mechanical ventilator market shows that the segment of non-invasive ventilators is growing at a rapid pace because this new technology has fewer side effects in ill patients (e.g., low incidence of ventilator-associated pneumonia, lung injuries, barotrauma, etc.), accelerates recovery of patients and leads to flexible applications to different age group of patients (i.e., pediatric, adult, geriatric people). In this context, Germany is an interesting case study to support empirical results here, because although high numbers of COVID-19 confirmed cases relative to population equal to 45.49% (as of February 28th, 2023), the COVID-19 fatality rate is low (0.44%) compared to other countries, such as Italy having a COVID-19 fatality rate of 0.73% at the same date [59]. One of the reasons is that Germany in 2020, when COVID-19 starts the diffusion in Europe, had about 30,000 mechanical ventilators [51] with a total population of more than 83 million [52], having so the highest number of mechanical ventilators per 100,000 people (Table 1). Leading companies of medical ventilators, headquartered in Germany, have supported a widespread diffusion of

Table 2
Descriptive statistics.

Description of variables	Countries with HIGH numbers of ventilators, N = 5		Countries with LOW numbers of ventilators, N = 4	
	M	SD	M	SD
Mechanical ventilators per 100,000 inhabitants, 2015–2020	26.76	14.94	10.38	2.57
GDP per capita in 2020, US\$	51,196.42	24,067.16	52,093.27	19,156.84
Health expenditure as % of GDP, 2008–2018	10.950	3.680	10.960	0.800
COVID-19 Fatality rates %, December 31 st , 2020 (§)	1.436	0.412	2.460	0.561
COVID-19 Fatality rates %, February 21 st , 2022	0.550	0.470	0.770	0.280

Note: M = arithmetic mean; SD=Standard Deviation; (§) this value assesses the real effect of mechanical ventilators on the health of people because it refers to a previous period the vaccination campaign between countries, when effective drugs to treat the novel coronavirus SARS-CoV-2 are missing.

¹ Cf. also studies by Refs. [102–108].

Table 3
Independent Samples T-Test in countries with high vs. low numbers of mechanical ventilators per 100,000 people.

		Levene's Test for equality of variances		T-test for equality of Means				
		F	Sig.	t	df	Sig. 2-tailed	Mean Difference	Std. Error Difference
Log Mechanical ventilators per 100,000 inhabitants, 2015–2020 (#)	•Equal variances assumed	6.499	0.038	−2.904	7	0.023	−0.852	0.293
	•Equal variances not assumed			−3.144	5.959	0.020	−0.852	0.271
COVID-19 Fatality rates %, December 31 st , 2020 (§)	•Equal variances assumed	0.161	0.701	3.164	7	0.016	1.024	0.324
	•Equal variances not assumed			3.046	5.395	0.026	1.024	0.336
COVID-19 Fatality rates %, February 21 st , 2022	•Equal variances assumed	3.319	0.111	0.822	7	0.438	0.220	0.267
	•Equal variances not assumed			0.874	6.563	0.413	0.220	0.251

Note:# Log transformation is applied to have a normal distribution of this variable within two groups (§). This value assesses the real effect of mechanical ventilator devices on COVID-19 patients with acute respiratory disorders because it refers to a previous period the roll-out of vaccination campaign between countries, when alternative and effective therapeutic treatments are missing.

Table 4
Kruskal-Wallis Test between countries with high vs. low numbers of mechanical ventilators per 100,000 inhabitants.

	Ranks, a)	N	Mean Rank
Mechanical ventilators per 100,000 inhabitants, 2015–2020	LOW number of mechanical ventilators per 100,000 people	4	2.5
	HIGH number of mechanical ventilators per 100,000 people	5	7.0
	Total	9	
COVID-19 Fatality rates %, December 31 st , 2020	LOW number of mechanical ventilators per 100,000 people	4	7.0
	HIGH number of mechanical ventilators per 100,000 people	5	3.4
	Total	9	
COVID-19 Fatality rates %, February 21 st , 2022	LOW number of mechanical ventilators per 100,000 people	4	5.75
	HIGH number of mechanical ventilators per 100,000 people	5	4.4
	Total	9	
	Mechanical ventilators per 100,000 inhabitants, 2015–2020	COVID-19 Fatality rates %, December 31 st , 2020	COVID-19 Fatality rates %, February 21 st , 2022
Kruskal-Wallis Test Statistics, b)			
Chi-Square χ^2	6	3.84	0.54
df	1	1	1
Asymp. Sig.	0.014	0.05	0.462

Note: a) Grouping Variable; b) Kruskal Wallis Test.

high-tech breathing devices in healthcare system that, during the initial phases of COVID-19 pandemic crisis, has minimized the pandemic impact (i.e., mortality) in society [45,74]. In fact, large numbers of mechanical ventilators can support an efficient healthcare that minimizes negative effects of pandemic disease in society, in particular when alternative treatments are missing and drug discovery process to treat unknown viral agents needs years to generate effective innovations. Hence, these findings bring us to suggest that an appropriate strategy of crisis management for respiratory deadly infections should be technology-oriented and focused on high levels of R&D investments in health sector, in skilled human resources and in a pervasive diffusion of high-tech mechanical ventilators that improve the preparedness in countries to cope with unforeseen pandemic crisis [67].

5. Conclusions and technology policy implications for next pandemic crisis

The dynamics and effects of COVID-19 pandemic in society are due to a variety of factors associated with environmental pollution, climate, public governance, institutions, healthcare system, national system of innovation, etc. [9,12,13,75–84]. In the presence of pandemic crises, one of the goals of nations is to mitigate mortality and support the socioeconomic system [13]. Studies analyze different non-pharmaceutical interventions to cope with the spread of COVID-19 but these control measures generate uncertain results to mitigate negative effects given by high numbers of infections and deaths of new viral respiratory disease in society [3,64,85–88]. The findings here suggest a technology-oriented strategy of crisis management for future pandemic threats: high levels of investments in healthcare sector, high levels of R&D investments in drug discovery process and in new technology of mechanical ventilators, etc. that support the preparedness and resilience of countries to face unknown infectious respiratory diseases and also other diseases, such as COPD, asthma, bronchitis, lung cancer, etc. [89–92]. To put it differently, the preparedness of countries for next pandemic crises should be oriented to strengthen new technologies in health system to cope with future health emergencies, especially when effective drugs to treat patients with acute respiratory illness are missing [12,63,78,79,86,89, 93–99]. Koonin et al. [16] observe that according to the extent of the outbreak, there may be insufficient institutional capacity to provide ventilator support to all of those in need. Meltzer and Patel [100] argued that any influenza pandemic can put hospital capacities under organizational stress for insufficient supplies when the burden of ill patients is very high. As a consequence, all capable public health services should develop and carry out plans to stockpile critical resources, such as mechanical ventilators, needed to support patients that are severely ill of severe acute respiratory syndrome when alternative and effective treatments lack. One of the major challenges, based on results here, is to plan the amount of ventilators to stockpile and how to manage them to be effectively and timely used for potential pandemic responses. Appropriate strategies can assist national policymakers and local planners to allocate stockpiled ventilators to healthcare facilities during a pandemic emergence, accounting for facilities' ability to make use of additional ventilators. These strategies include actions for increasing numbers of ventilators both in the pre-pandemic and intra-pandemic stages to minimize fatality rates as the study here reveals. In this context, facilities must have sufficient staff, space, equipment, and supplies to utilize allocated ventilators adequately. Moreover, scarce life-saving resources during a pandemic crisis should also consider ethical principles to allocate with equity ventilator devices across different healthcare structures. In addition to ethical principles,

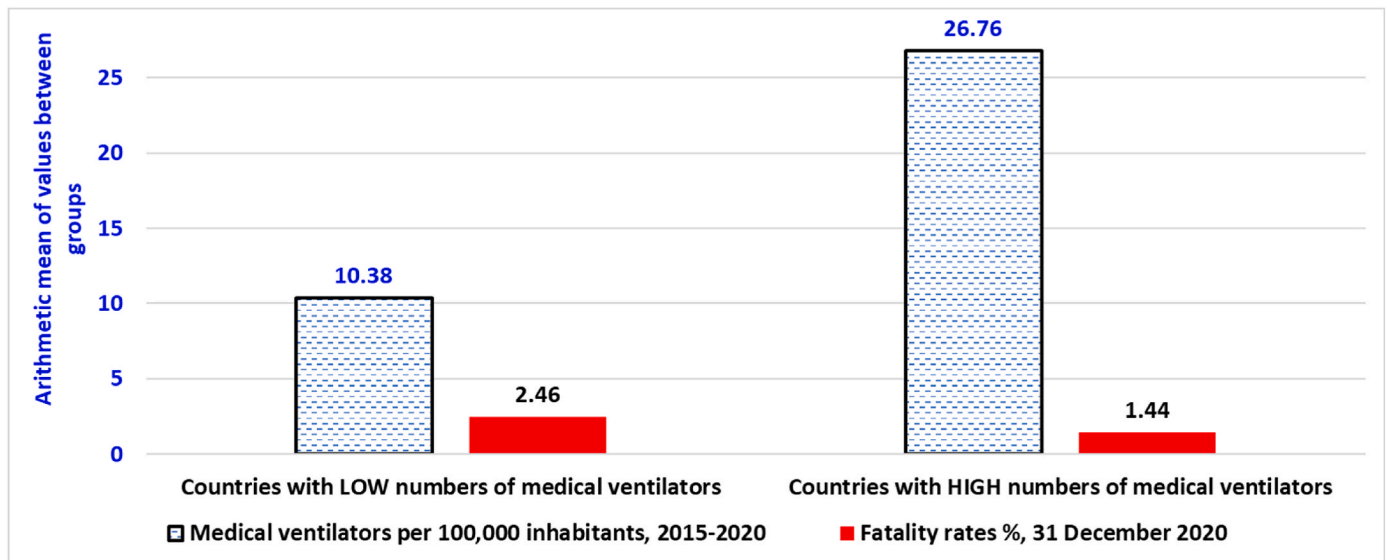


Fig. 2. Comparative analysis of COVID-19 fatality rates between countries with high and low numbers of mechanical ventilators.

decisions of policymakers should assess needs, determinate facilities' ability to use additional ventilators, and also facilities' capacity to ensure access to ventilators for vulnerable populations (e.g., rural, inner city, and uninsured and underinsured individuals) or high-risk populations that may be more susceptible to respiratory illness [16]. Meltzer and Patel [100] also argued that an accurate planning to determine how many ventilators to stockpile and where to stockpile them, it should consider the timing of a pandemic's peak locally (in fact, not all regions will experience simultaneous peak demands for ventilators); wastage (ventilators not sent to where they are needed); and expected unmet demand for mechanical ventilators (i.e., when a hospital has more ill patients that need mechanical ventilation than available breathing devices). Studies suggest that during moderate or severe pandemics, a higher level of unmet demand might need to be expected. Huang et al. [101] argue that hospitals must manage the costs and human resources needed to maintain an excess of ventilators that are likely to be unused in the absence of pandemic-related surges in demand. However, one of the advantages of stockpiling ventilators at hospitals is to facilitate staff training to have skilled human resources prepared when health emergencies occur. Hence, considering results of the study here, a basic strategy to cope with next pandemics is a systematic planning, which should consider the number to be stockpiled of ventilators, how and where stockpiles should be held, maintenance of stockpiles, conditions for release, considerations for use, and what to do when stockpiles are insufficient to adapt meet surges in demand of healthcare structures ([100,101] and [109–129]).

Overall, then, results of this analysis here seem to suggest that in the first pandemic wave of COVID-19, countries with a high number of mechanical ventilators experienced a lower fatality rate of COVID-19. The findings here propose a general strategy of crisis management for future pandemic threats based on high levels of investments in healthcare sector for a widespread implementation of new medical ventilators, a transparent and consistent communication of rules, and also strategic collaborative networks between firms and institutions for improving R&D performance in the presence of health emergencies [24]. These strategic implications can support the overall preparedness of countries to cope with negative effects of next deadly infections on health of people and pandemic impact on socioeconomic system. These conclusions are of course tentative. There is need for much more research in these topics because not all the confounding factors that affect the interaction between COVID-19 fatality rates and diffusion of mechanical ventilators in health systems are discussed. Therefore, results here have

to be reinforced with a follow-up investigation based on a large sample of countries for additional analyses of the relation between diffusion of mechanical ventilators and negative effects of pandemic respiratory diseases in society.

Credit author statement

Mario Coccia, in the role of main author, has totally developed the following intellectual content of the paper: Conceptualization, Data curation, Formal analysis, Scientific investigation, Designed research, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review and editing.

Data availability

Data will be made available on request.

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