An International Overview and Meta-analysis for Using the Mechanical Ventilation in the Medical Treatment

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Abstract. There are a lot of injuries in lung that makes unique clinical challenges. Mechanical ventilator is considered as an useful solution to treat the respiratory patients. Especially, some of them become so serious that they must stay in Intensive Care Unit during a long time. It causes the overload status in order to take care all patients at the same time. Therefore, the better treatment by using the mechanical ventilator in the initial stage could reduce the rising number of patients and release the burden works for doctors and nurses. The purpose of this investigation is to examine various patterns of the mechanical ventilators and to determine potential opportunities for further development. Many research topics have been revised and synthesized during a long time, from January 2010 to present time, so that our results could provide a systematic overview and brief summary along the historical progress. In addition, a number of different resources which are available in the internet, is mentioned to offer a practical view. Most of these ventilators are classified into several sub-categories according to their technical specifications, usage and working principle. Pressure support and volume assist control are the most common signal for the initial mode in mechanical ventilator that used with or without the inhalation injury. All comments in these articles report in the affirmative that there are certain situations where the early intervention is essential. Target readers consist of doctors, nurses and medical staff who only concentrate on clinical factors and ignore the related technologies.

Keywords: Ventilation system · Respiratory patient · Infectious disease · Artificial inhalation · Home-based treatment

1 Introduction

In the field of medicine, the mechanical ventilation is one of the key methods for breathing aid when the respiratory failure occurs suddenly. The patients who suffer the respiratory diseases, could not breathe in the natural manner. Hence, the artificial ventilation support is a life-saving technique to deal with respiratory failures as soon as

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possible. In general, there are two kinds of the respiratory support system, positive and negative pressure ventilation. However, the positive pressure mechanical ventilation [1] which is applied in various modalities [2], is superior and common. In recent time, to response to the larger requirements of patients [3–6], more investigations on technical ventilators are fully studied. The most important technique is to match the adaptive performance of airflow from artificial machine to human's breath. Obviously, it should be aware that any missing or problem during the respiratory process could cause the severe results for patients. Besides, the over-usage of sedatives or prolongation is able to take place during the medical therapy. To ensure the synchronization in breathing, the lung-like model which is simulated to track human's pattern. It is considered as an component in the control scheme for the type of adaptive support ventilation (ASV) in order to adjust robustly the deep breath and rate of airflow [7–9]. The control design is to maintain the lowest threshold of breathing rate and estimate the frequency of human's breath. In contrary way, the trigger signal from the neural ventilation system is fed to the machine of neutrally adjusted ventilatory assist (NAVA). This signal is activated by electrodes mounted on a naso-gastric tube located at the lower esophagus [10, 11]. Belong to this category, the proportional assist ventilation (PAV) provides the proportionally supplementary pressure to support patient as the additional efforts. In [12–14], the weaning technique could be noticed through the curing process [12–14].

In the last few months ago, there is an increased demand for ventilators during the treatment process of COVID-19 (coronavirus disease 2019) patients [15]. In fact, it is really catastrophic for humankind in those days. Even well-equipped hospitals have many efforts to meet the great increase in the number of sick persons such sharing the same air supply between two patients [16], they could not satisfy all requirements at the same time. To deal with the worldwide trouble of ventilator shortage, developers have innovated to release the low-cost, open-source ventilators [17, 18] for numerous patients. Basically, these developments are able to provide the instantaneous responses in hospital or healthcare service. It is agreed that this approach might be potentially one of the best solutions for poor nations or emergency case [19].

In fact, mechanical ventilator is a device which support human to breath in order to maintain their blood oxygenated. Once, a breathing regularly starts with inspiratory activity when air enters the lung, and ends with exhalation of breath when air is expiratory. The inspiration is prompted by differences of pressure which naturally exerted by diaphragm and the chest motion as well as by machine-driven mechanism, in human's airway that launches a flow of air. Whenever expiration, it is passive and motivated by the elastic force of tissues in lung. Generally, this machine is complicated and expensive in large.

Despite a change to non-invasive respiratory support, mechanical ventilation still becomes an essential tool for the medical care of critically ill patients. A variety of advanced techniques on medical devices with available modes and data fusion presents the potential solutions. Since various manufacturers utilize different nomenclature to depict relative modes of ventilation, communication among users of different machines has turned into challenges. The working modes of mechanical ventilation are often categorized into the act of breathing. Breaths could be started by a timing mechanism in spite of person's inspiratory efforts. Alternatively, breaths might be prompted by the patient's inspiration named as synchronization or patient-triggered ventilation.

2 Materials and Methods

2.1 Purpose

We conducted a survey to determine the development, usage and applications of potential strategies for medical treatment by ventilator-based therapy. Our targets are to synthesize, analysis and release the statistic evaluation in order to provide an overview of present status. The questionnaire consists of items about the purposes of using the ventilation system for clinical applications such:

- Where the ventilator is employed
- What diseases need the ventilator-based solution
- How the ventilator could be solved
- Why this machine is necessary to treat
- When the ventilation system is useful

2.2 Materials

It is important to investigate a large number of articles during the long period, from January 2010 to present time. The other sources such post-graduate dissertations, news, bulletins and so on are also cited in this work. Most of them are available in the cyber space where everyone could access freely and easily. Owing to these evidences, the historical development and the medical procedure to cure which patients are better, are demonstrated clearly. Besides, the advanced functions were added to response the newly adaptive ability of diseases. The progression of serious illness also affects on the health of patients, for instance a respiratory disease patient often suffers the rapid evolution comparing to their responses.

2.3 Target Readers

In our intention, the reader-oriented maxim is obviously integrated into the content of this work. Doctor or nurses could refer to this article to extend their knowledge which is only encapsulated in the medical field. Furthermore, it is similarly useful for the staff who are technical maintenance or operators, to discuss according to their jobs in hospital or healthcare center. Especially, it is considered as the valuable source for both medical students and mechanical learners.

3 Results of Research

In fact, a mechanical ventilator is a machine that helps a patient breathe (ventilate) when they are having surgery or cannot breathe on their own due to a critical illness. The patient is connected to the ventilator with a hollow tube (artificial airway) that goes in their mouth and down into their main airway or trachea. They remain on the ventilator until they improve enough to breathe on their own. Thus, this ventilator is used to decrease the work of breathing until patients improve enough to no longer need

it. The machine makes sure that the body receives adequate oxygen and that carbon dioxide is removed. This is necessary when certain illnesses prevent normal breathing.

It is important to note that mechanical ventilation does not heal the patient. Rather, it allows the patient a chance to be stable while the medications and treatments help them to recover. The main benefits of mechanical ventilation are the following:

- The patient does not have to work as hard to breathe – their respiratory muscles rest
- The patient's as allowed time to recover in hopes that breathing becomes normal again
- Helps the patient get adequate oxygen and clears carbon dioxide
- Preserves a stable airway and preventing injury from aspiration

On the whole, Table 1 describes the summary reviews of previous articles in the interest topics. The first category named as the self-adjusted ventilation system or automated reimbursement ventilation, plays as a typical prototype for synchronization between human and machine. It mainly assists the burden work of patient's lung through the additional airflow. Usually, from the dynamical computation of mathematical model, the control rule is derived to manipulate the system parameters such pressure, airway and inspiratory inflow. The inspiration of patient initially triggers and cycles according to the natural breath. Furthermore, an operator must provide the initial coefficients such size and mode of the appropriate airway. Later, the automated search engine is activated and checks the data table to determine the airway resistance. At this time, the smart control scheme would order the driving commands based on the set-up model. Maybe, this machine must reveal the powerful abilities in computation and interpolation during short period.

Table 1. The review of the state-of-the-art researches.

Classification	Author(s)	Purpose	Advantage(s)	Disadvantage(s)
Adaptive Support Ventilation (ASV)	Claure, N. et al. [20]	Randomized crossover comparative study in a 12-bed ICU (intensive care unit)	In passive patients with acute respiratory failure, the proposed approach is safe and able to ventilate patients with less pressure while producing the same results in terms of oxygenation	Because of the diversity of patients treated, one algorithm might not fit all patients. The most severe and unstable patients or very specific patients require the tuned parameters
	Beijers, A. J. et al. [21]	Observational comparative study with automatically settings selected by ventilator	It is safe to utilize for ventilated patients with various lung conditions	Data is collected once a day and not continuously. Numbers of severe patients are too small to draw definite conclusions on safety

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Table 1. (*continued*)

Classification	Author(s)	Purpose	Advantage(s)	Disadvantage(s)
	Malli, F. et al. [9]	This systematic review provides the principle, algorithm and accuracy of closed-loop controlled oxygen device	The closed-loop controller maintain higher saturation levels, spend less time below the target saturation and save oxygen resources	Fail-safe mechanism, limited reliability of sensors and the need for standardized evaluating method of assessing risk are mentioned
	Hamama, K. M. et al. [22]	For a subgroup of patients, driving pressure and mechanical power are observed to predict the medical risk	In short term, this ventilator could choose the proper driving pressure and mechanical power in safe ranges for lung protection	Only one measurement is made per patient at a given time. Hence, the results do not reflect the average value over a longer period of time
Neutrally Adjusted Ventilatory Assist (NAVA)	De La Oliva, P., et al. [23]	Prospective study in spontaneously breathing patients intubates for acute respiratory failure	This ventilator reduces trigger delay, inspiratory time in excess and the number of patient-ventilator asynchronies in intubated patients	The clinical impact of this improved synchrony should be determined
	Yonis, H. et al. [24]	Comparative study between conventionally lung-protective mechanical ventilation (MV) and lung-protective MV with NAVA	This method decreases the medical risks although it does not improve survival in ventilated patients	The study by its very nature is unblinded, hence it could bias the decisions made by nursing service. Moreover, patient severity of illness is greater than expected
	Gross-Hardt, S. et al. [25]	Respiratory control by extracorporeal CO_2 removal on non-invasive NAVA	This investigation firstly introduces the usefulness of the electrical activity in diaphragm to monitor and guide patients with severe acute exacerbation	Randomized controlled trials in patients with severe acute exacerbations are needed to confirm
Proportional Assist Ventilation (PAV)	Lewis, K. A. et al. [26]	To synthesize the randomized controlled trials of PAV between invasive and non-invasive in critically ill patients	The systematic review and meta-analysis is novel in synthesizing current best evidence for clinical applications of PAV	This study does not support the clinical evidences for the usage of invasive or non-invasive PAV

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Classification	Author(s)	Purpose	Advantage(s)	Disadvantage(s)
	Sindelar, R. et al. [27]	The competitive effect on oxygenation between PAV and NAVA	The results indicate that there is no significant difference in oxygenation indices but NAVA is better in the alveolar arterial oxygen gradient	Whilst arterial samples might have been more precise, the use of capillary blood samples would have substantially influenced these results
	Rebelo, T. et al. [28]	The research of assisted parameters affecting on synchronization and inspiratory workload in PAV	This ventilator could reduce the work of breathing but it brings the asynchrony if the settings are not correct	All tests are performed on lung simulator and, under one typical lung mechanics setting
Noninvasive Open-source Mechanical Ventilator (NOMV)	Arcos Legarda, J. et al. [29]	Low-cost, open-source mechanical ventilator with pulmonary monitoring	The method considers pressure measurements from the inspiratory limb and alerts clinicians in real-time whether the patient is under a healthy situation or not	Alarms using either screen or speaker should be included for further safety cautions
	Zivcak, J. et al. [30]	Mechanical ventilator for baby	The ventilator prototype that produced by continuous positive airway pressure method, is for transferring intensive care between medical institutions	The working ability of long-time process is not ensured
	Borges, E. F. et al. [31]	Pediatric home mechanical ventilator after hospitalization	It allows earlier transition out of the pediatric ICU and with increasing disposition to enhance nursing facilities	The translation of acute-care ventilator management method to those with chronic respiratory failure is unclear
	Nguyen, J., et al. [32]	Mechanical ventilator milano for rapid, large-scale and low-cost production	It is designed to support the long-term invasive ventilation and operate in pressure-regulated ventilation modes	It needs to be verified under the international medical use instead of ISO standards

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Classification	Author(s)	Purpose	Advantage(s)	Disadvantage(s)
	Tharion, J. et al. [33]	A simple, low-cost alternative ventilator using a novel pressure-sensing approach and control algorithm	This technique is potential to provide safe emergency ventilation without any complicated sensors and control software while its construction enables reduction in cost and complexity	The study should be justified in progressing this technology to clinical trials
	Vivas, F. et al. [18]	A low-cost ventilator with readily-available hospital equipment for use in emergency or low-resource settings	This novel ventilator is able to safely and reliably ventilated patients with a range of pulmonary disease in a simulated setting	The current model offers only intermittent mandatory pressure-controlled ventilation
	Tsuzuki, M. S. et al. [34]	The enhanced version of MIT E-Vent in rapidly scalable ventilator prototype	A manual resuscitator, an external compression mechanism and a control system for adjusting tidal volume, inspiration-to-expiration ratio and respiratory rate are included	More advanced sensing modules, adaptive control scheme and stable software are additionally implemented

For the second group, in order to guarantee the high performance of the neutrally adjusted ventilatory assist, the servo control scheme must be taken account into the model of the first one. Nevertheless, this ventilator involves several extra-developments because of its complex platform. For the target of patient-ventilator synchrony, the mechanical ventilator aids either resistive or elastic component for the breathing process due to the respiratory reaction. Customarily, via the inflow, the proposed controller could symmetrically estimate the airway pressure depending on the data possessed from diaphragmatic breathing. Doctor or nurse feeds the fraction between pressure and voltage so as to control the airway pressure. Eventually, the third ventilation system, termed as proportional assist ventilation, often consists of advanced strategy such a servo targeting circuit. In reality, this kind of machine utilizes the more innovative model and difficult computation than the others. Similarly, the third ventilator takes care both resistive and elastic work of breath related to the patient's respiratory effort. This system collects various feedback signals in term of patient-ventilator synchrony. Besides, the operating principle is to regulate pressure based on the equation of air motion. To trigger the operating mode, an operator must insert the desired settings for elastance and resistance to be maintained.

In recent time, the concept of open-source hardware is commonly risen in our community, especially for the mechanical ventilator. To aim at the treatment and prevention of COVID-19, modern microprocessor-based electronic devices have been embedded such that the complexity of control scheme, advanced functions and powerful resources are allowed to implement. In [35], researchers has studied a microcontroller-driven mechanical ventilator using AmbuBag which is pressed by the arm mechanism. The trajectory of mechanical components is planned by camshaft (CAM) generation. The output results presents the time-varying characteristic of tidal volume. In the same method but different mechanism, authors [36] developed a low-cost, open-source ventilator that was initialized by the global shortage of mechanical ventilator for COVID-19 patients. The driving motor which is controlled by Raspberry Pi, provides the maximum pressure up to 70 cm H_2O. Additionally, although the design is simple but efficient, the experimental device for ventilation satisfies the desired volume and pressure in respect to clinical requirements [37]. For future steps, developers discusses about reliability of the mechanisms and software, mass production with appropriate standards and regulatory approval or exemption. With portable purpose, investigators in [38] introduce an ease-to-use and mobile version of AmbuBag-based compression machine. This system is manipulated by Arduino and offers various breathing modes with varying tidal volumes. The rate for breathing is from 5 to 40 breaths/minute and max ratio between inhalation and exhalation is 1:4. The repeatability and precise exceeding personal capabilities in this design are proved in experiments. Although the original design consisting of two paddles is actuated by an electric motor [39], there are still several efforts to represent the pressure-controlled ventilation. It is noted that the usage of electromechanical actuators to press AmbuBag is an excellent solution. Whether the supplies of compressed air is available or not, the tidal volume could increase linearly [40].

4 Conclusion

This work has documented a hugely potential development for mechanical ventilator in clinical therapies. There is wide variation in the diagnosis, inside structure, working principle and management among ventilation systems. The data presented suggest that both doctors and nurses should decide a proper treatment based on the actual condition of the respiratory patients. Many researchers and developers ought to focus on which type is necessary to implement for our community in present-day.

Some results, such as the methodical classifiers, might be beneficial for future work. Although the mechanical ventilators are either the commercial product or not, their motivations still need to encourage owing to public health. Particularly, the open-source design should be promoted to extend for common knowledge so that each patient could build it by themselves. As a result, the solution for home-based treatment is efficient and feasible in the overload of hospital or healthcare center.

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References

1. Pham, T., Brochard, L.J., Slutsky, A.S.: Mechanical ventilation: state of the art. In: Mayo Clinic Proceedings, vol. 92, no. 9, pp. 1382–1400. Elsevier, September 2017
2. Gattinoni, L., et al.: The future of mechanical ventilation: lessons from the present and the past. Crit. Care **21**(1), 1–11 (2017)
3. Yoshida, T., et al.: Volume-controlled ventilation does not prevent injurious inflation during spontaneous effort. Am. J. Respir. Crit. Care Med. **196**(5), 590–601 (2017)
4. Holanda, M.A., Vasconcelos, R.D.S., Ferreira, J.C., Pinheiro, B.V.: Patient-ventilator asynchrony. J. Bras. Pneumol. **44**, 321–333 (2018)
5. Shen, D., Zhou, Y., Shi, Y.: Coupling effects of double lungs on dynamic characteristics of volume-controlled mechanical insufflation-exsufflation secretion clearance system. J. Dyn. Syst. Measur. Control **140**(7), 071008 (2018)
6. Krause, H., Kraemer, J.F., Penzel, T., Kurths, J., Wessel, N.: On the difference of cardiorespiratory synchronisation and coordination. Chaos: Interdisc. J. Nonlinear Sci. **27**(9), 093933 (2017)
7. De Bie, A.J., et al.: Fully automated postoperative ventilation in cardiac surgery patients: a randomised clinical trial. Br. J. Anaesth. **125**(5), 739–749 (2020)
8. Bayram, B., Şancı, E.: Invasive mechanical ventilation in the emergency department. Turkish J. Emerg. Med. **19**(2), 43–52 (2019)
9. Malli, F., Boutlas, S., Lioufas, N., Gourgoulianis, K.I.: Automated oxygen delivery in hospitalized patients with acute respiratory failure: a pilot study. Can. Respir. J. (2019)
10. Chen, C., Wen, T., Liao, W.: Neurally adjusted ventilatory assist versus pressure support ventilation in patient-ventilator interaction and clinical outcomes: a meta-analysis of clinical trials. Ann. Transl. Med. **7**(16) (2019)
11. Vaporidi, K.: NAVA and PAV+ for lung and diaphragm protection. Curr. Opin. Crit. Care **26**(1), 41–46 (2020)
12. Ou-Yang, L.J., Chen, P.H., Jhou, H.J., Su, V.Y.F., Lee, C.H.: Proportional assist ventilation versus pressure support ventilation for weaning from mechanical ventilation in adults: a meta-analysis and trial sequential analysis. Crit. Care **24**(1), 1–10 (2020)
13. Wilcox, M.E., Vaughan, K., Chong, C.A., Neumann, P.J., Bell, C.M.: Cost-effectiveness studies in the ICU: a systematic review. Crit. Care Med. **47**(8), 1011–1017 (2019)
14. Sklar, M.C., et al.: Duration of diaphragmatic inactivity after endotracheal intubation of critically ill patients. Crit. Care **25**(1), 1–15 (2021)
15. Qiu, J., Shen, B., Zhao, M., Wang, Z., Xie, B., Xu, Y.: A nationwide survey of psychological distress among Chinese people in the COVID-19 epidemic: implications and policy recommendations. Gen. Psychiatry **33**(2) (2020)
16. Beitler, J.R., et al.: Ventilator sharing during an acute shortage caused by the COVID-19 pandemic. Am. J. Respir. Crit. Care Med. **202**(4), 600–604 (2020)
17. Pearce, J.M.: Distributed manufacturing of open source medical hardware for pandemics. J. Manuf. Mater. Process. **4**(2), 49 (2020)
18. Vivas Fernández, F.J., et al.: ResUHUrge: a low cost and fully functional ventilator indicated for application in COVID-19 patients. Sensors **20**(23), 6774 (2020)
19. Acho, L., Vargas, A.N., Pujol-Vázquez, G.: Low-cost, open-source mechanical ventilator with pulmonary monitoring for COVID-19 patients. In: Actuators, vol. 9, no. 3, p. 84. Multidisciplinary Digital Publishing Institute, September 2020
20. Claure, N., Bancalari, E.: Automated closed loop control of inspired oxygen concentration. Respir. Care **58**(1), 151–161 (2013)
21. Beijers, A.J.R., Roos, A.N., Bindels, A.J.G.H.: Fully automated closed-loop ventilation is safe and effective in post-cardiac surgery patients. Intensive Care Med. **40**(5), 752–753 (2014). https://doi.org/10.1007/s00134-014-3234-7

22. Hamama, K.M., Fathy, S.M., AbdAlrahman, R.S., Alsherif, S.E.D.I., Ahmed, S.A.: Driving pressure-guided ventilation versus protective lung ventilation in ARDS patients: a prospective randomized controlled study. Egypt. J. Anaesth. **37**(1), 261–267 (2021)
23. de la Oliva, P., Schüffelmann, C., Gómez-Zamora, A., Villar, J., Kacmarek, R.M.: Asynchrony, neural drive, ventilatory variability and COMFORT: NAVA versus pressure support in pediatric patients. a non-randomized cross-over trial. Intensive Care Med. **38**(5), 838–846 (2012). https://doi.org/10.1007/s00134-012-2535-y
24. Yonis, H., et al.: Patient-ventilator synchrony in Neurally Adjusted Ventilatory Assist (NAVA) and Pressure Support Ventilation (PSV): a prospective observational study. BMC Anesthesiol. **15**(1), 1–9 (2015)
25. Gross-Hardt, S., et al.: Low-flow assessment of current ECMO/ECCO 2 R rotary blood pumps and the potential effect on hemocompatibility. Crit. Care **23**(1), 1–9 (2019)
26. Lewis, K.A., et al.: Comparison of ventilatory modes to facilitate liberation from mechanical ventilation: protocol for a systematic review and network meta-analysis. BMJ Open **9**(9), e030407 (2019)
27. Sindelar, R., McKinney, R.L., Wallström, L., Keszler, M.: Proportional assist and neurally adjusted ventilation: clinical knowledge and future trials in newborn infants. Pediatr. Pulmonol. **56**(7), 1841–1849 (2021)
28. Rebelo, T., et al.: ATENA–a novel rapidly manufactured medical invasive ventilator designed as a response to the COVID-19 pandemic: testing protocol, safety, and performance validation. Front. Med. 1312 (2021)
29. Arcos-Legarda, J., Tovar, A.: Mechatronic design and active disturbance rejection control of a bag valve-based mechanical ventilator. J. Med. Dev. **15**(3), 031006 (2021)
30. Živčák, J., et al.: A portable BVM-based emergency mechanical ventilator. In: 2021 IEEE 19th World Symposium on Applied Machine Intelligence and Informatics (SAMI), pp. 000229–000234. IEEE, January 2021
31. Borges, E.F., Borges-Júnior, L.H., Carvalho, A.J.L., Ferreira, H.M., Hattori, W.T., de Oliveira Azevedo, V.M.G.: Invasive home mechanical ventilation: 10-year experience of a pediatric home care service. Respir. Care **65**(12), 1800–1804 (2020)
32. Nguyen, J., et al.: Repurposing CPAP machines as stripped-down ventilators. Sci. Rep. **11** (1), 1–9 (2021)
33. Tharion, J., Kapil, S., Muthu, N., Tharion, J.G., Kanagaraj, S.: Rapid manufacturable ventilator for respiratory emergencies of COVID-19 disease. Trans. Indian Nat. Acad. Eng. **5**, 373–378 (2020)
34. Tsuzuki, M.S.G., et al.: Mechanical ventilator VENT19. Polytechnica **4**(1), 33–46 (2021). https://doi.org/10.1007/s41050-021-00031-z
35. Marzetti, S., et al.: Low cost artificial ventilator embedding unsupervised learning for hardware failure detection [society news]. IEEE Circuits Syst. Mag. **21**(3), 73–79 (2021)
36. Ramos-Paz, S., Belmonte-Izquierdo, R., Inostroza-Moreno, L.A., Velasco-Rivera, L.F., Mendoza-Villa, R., Gaona-Flores, V.: Mechatronic design and robust control of an artificial ventilator in response to the COVID-19 pandemic. In: 2020 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC), vol. 4, pp. 1–6. IEEE, November 2020
37. Domènech-Mestres, C., Blanco-Romero, E., de la Fuente-Morató, A., Ayala-Chauvin, M.: Design for the automation of an AMBU Spur II manual respirator. Machines **9**(2), 45 (2021)
38. Skrzypczak, N.G., Tanikella, N.G., Pearce, J.M.: Open source high-temperature RepRap for 3-D printing heat-sterilizable PPE and other applications. HardwareX **8**, e00130 (2020)
39. MIT E-Vent. MIT emergency ventilator project. https://e-vent.mit.edu/
40. AndalucíaRespira. https://www.andaluciarespira.com/en/andalucia-respira-en