ICMIEE18-318

Design Construction and Performance Test of a Low-Cost Portable Mechanical Ventilator for Respiratory Disorder

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ABSTRACT
Mechanical ventilator is a medical device which is usually utilized to ventilate patients who cannot breathe adequately on their own. Among many types of ventilators Bag Valve Mask (BVM) is a manual ventilator in which a bag is pressed to deliver air into the lungs of the patient. In present work, a mechanical system along with microcontroller has been developed to automate the operation of BVM. The constructed prototype contains two arms of 0.30 m long, powered by two servo motors through pulling wires and pulleys, supported by wooden frame. These arms compress the BVM in prescribed manner at the rate set by the operator through a control knob. With principal dimensions of 0.55m*0.15m*0.3m, weight 2.5 kg and three 9 V battery for supplying power for at least one hour continuous operation, the prototype can be moved easily. The dimensions of the frame are selected as such to be compatible with the physical dimension of Ambu bag. The performance of the device was tested using BIOPAC Airflow Transducer which illustrates that the Tidal Volume vs. Time graph of the automated system is similar to the graph produced by manual operation of the BVM and to the graph produced by a human subject, but with a mean deviation of 0.332 Litres with manual operation and 0.542 Litres with human subject. Although the developed device cannot compress the bag completely due to low powered servo motors, it proves the concept of automating the operation of BVM using mechanical system for developing a portable ventilator.

Keywords: Mechanical Ventilator, BVM, BPM, Airflow Transducer.

1. Introduction

Mechanical ventilation is an important treatment which is usually utilized to ventilate patients who cannot breathe adequately on their own [1]. Patients with underlying lung disease may develop respiratory failure under a variety of challenges and can be supported by mechanical ventilators. These are machines which mechanically assist patients inspire and exhale, allowing the exchange of oxygen and carbon-dioxide to occur in the lungs, a process referred to as artificial respiration [2].There are many techniques and methods of artificial ventilation, both manual and mechanical. While modern ventilators are computerized machines, patients can be ventilated with a simple, hand-operated bag valve mask (BVM) also. [3]

Although there are many elegant positive-pressure ventilators with sophisticated safety controls, they are rarely available in the field, thereby forcing arescuer to resort to manual methods of ventilation [4].

In present work, designing principle of a low-cost portable mechanical ventilator based on the BVM, along with the methodology for its construction and performance test has been described. The prime objectives of the project are described below.

(1) To design and construct a portable mechanical ventilator by automating the operation of bag-valve-mask or ‘Ambu bag’.

(2) To test the performance of the constructed mechanical ventilator using BIOPAC airflow transducer.

(3) To assess the cost of production of the designed ventilator to justify its use instead of manual resuscitators and existing portable ventilators.

1.1 History of Mechanical Ventilation

Numerous works and literatures on the historical development of mechanical ventilation and the design of portable ventilators are available.

Robert M Kacmarek et al. [5] presented a historical review of various techniques of mechanical ventilation is. It is interesting to note that artificial ventilation is not a new or modern concept; rather it can be traced back to Biblical times. But modern and automatic devices didn’t appear until the early 1800s. Fig. 1 illustrates a 19th century mechanical ventilator which is negative-pressure type. [3]

In the work by Abdo Khoury et al. [6], evolution of Mouth-to-Mouth to Bag-Valve-Mask Ventilation is illustrated. Various developments in the components of Ambu bag and its valves are noticeable.

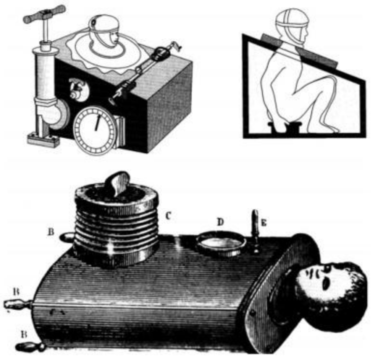

Fig. 1: A 19th century mechanical ventilator **[4]**

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The article by L. A. Geddes [4] summarizes the history of the development of artificial ventilation methods, both manual and mechanical. In this article two methods of manual artificial resuscitation methods, namely Sylvester's and Schafer's method and five mechanical devices for artificial ventilation, namely Bellows, the Pulmotor, the Iron Lung, Cuirass and Rocking Bed are described in chronological order. Fig. 2 illustrates the two manual methods four of the mechanical devices.

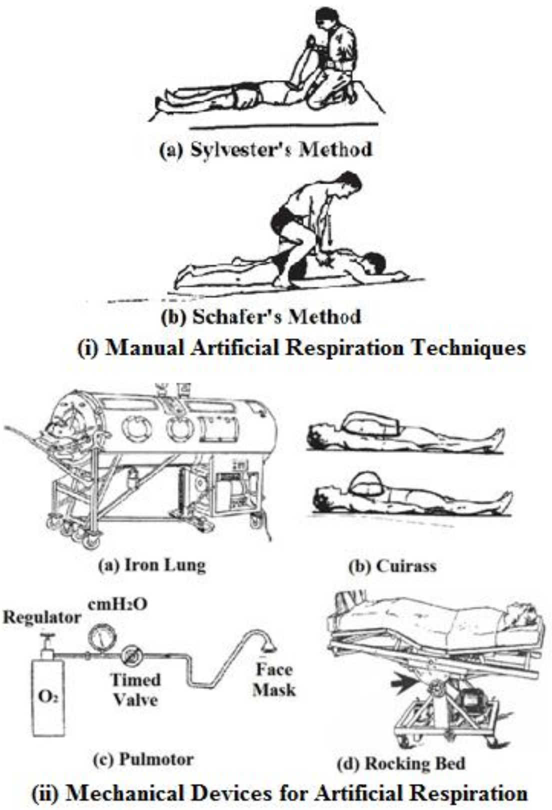

Fig. 2 : Artificial Respiration Methods **[4]**

1.2 Previous Works on the Design of Portable Ventilators

Stuart Fludger et al. [7] described various types of portable ventilators and their historical development. The concept of portable ventilators is rather new compared to ICU ventilators

Portable ventilators are evolved from the necessity of ventilating a patient during shifting or moving from one place to another. Ambu bag is often not reliable or it cannot be used for the unavailability of trained personnel. For these reasons, portable ventilators came into existence.

Portable ventilators vary by different parameters. In Table 1 comparison among three common portable ventilators is presented. [7]

Harrison et al. [8] of Rochester Institute of Technology, New York, developed a traditional portable ventilator 'Mediresp II' further. A US patent by Reno L. Vicenzi et al. [9] describe a detailed construction of a portable emergency mechanical ventilator.

Table 1: Comparison among common portable ventilators [7]

Model	Power for cycling	Power for inspiratory flow	Internal battery supply	External electricity supply
VentiPAC 200D	Pneumatic	Pneumatic	>1 yr (alarm only)	N/A
LTV-1000	Electric	Electric	1 h	Battery 12V DC
Oxylog 3000	Electric	Pneumatic	3 h (NiMH) 0r 4 h (Li)	10-32V DC, 240V AC

The work that is most similar to the present work is by Husseini et al. [2] in which a BVM is automated mechanically to construct a portable mechanical ventilator. Cam mechanism was used in that work to produce the desired motion of the BVM.

The main difference of the present work with the work by Husseini et al. [2] is the use of mechanical arms and servo motors instead of cam mechanism to actuate the compression of BVM. In section 4.4 the uniqueness of present work is illustrated further.

2. Theory and Principles

The theoretical background and principle of the operation of mechanical ventilators and Ambu bag are presented below.

2.1 Principle of operation of Mechanical Ventilators

The ventilator is connected to the patient through a tube (endotracheal or ET tube) that is placed into the mouth or nose and down into the windpipe. When the doctor places the ET tube into the patient's windpipe, it is called intubation. Some patients have a surgical hole placed in their neck and a tube (tracheostomy or "trach" tube) is connected through that hole. The trach tube is able to stay in as long as needed and is more secure than an ET tube. At times a person can talk with a trach tube in place by using a special adapter called a speaking valve.

The ventilator blows gas (air plus oxygen as needed) into a person's lungs. It can help a person by doing all of the breathing or just assisting the patient's breathing. The ventilator can deliver higher levels of oxygen than delivered by a mask or other devices. The ventilator can provide a pressure (PEEP pressure) which helps hold the lungs open so the air sacs don't collapse. The tube in the windpipe makes it easier to remove mucus if someone has a weak cough. [10]

The ventilator should stop delivering air into the lungs with external force as soon as the patient starts to breathe himself. If it operates while the respiratory system of the patient is active it may cause damage to the lungs and vomiting of the patient may occur. So, there is a system to monitor when the patient starts to breathe himself and stop the operation of the ventilator.

2.2 Operation of Ambu bag

In Fig. 3 the various parts of an Ambu bag is identified. Manual resuscitators cause the gas inside the inflatable bag portion to be force-fed to the patient via a one-way valve when compressed by the rescuer; the gas is then ideally delivered through a mask and into the patient's trachea, bronchus and into the lungs. The tidal volume and respiratory rate has to be maintained as per the conditions of the patients by the rescuer.

Typical tidal volume is 500 to 800 mL of air and typical respiratory rate is 10 to 12 respiration per minute for adults and 20 respirations per minute for infants. Professional rescuers are taught to ensure that the mask portion of the BVM is properly sealed around the patient's face. [11]

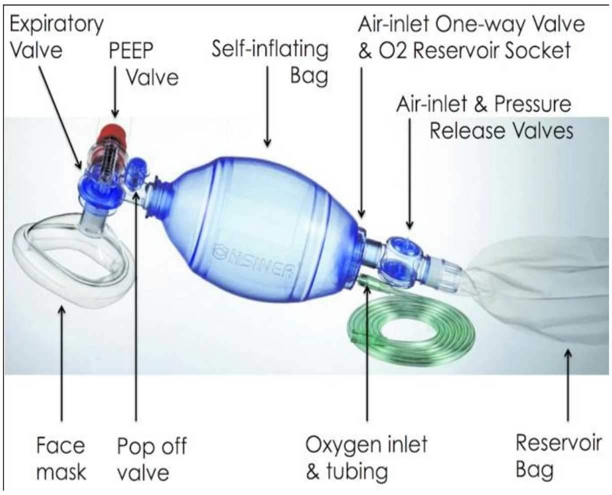

Fig. 3: Various parts of Ambu Spur II resuscitator **[12]**

3. Design and Construction

3.1 Design Assumptions

The design of the proposed portable mechanical ventilator for adult patients was done on the basis of following assumptions—

i. Tidal volume to be delivered = 200 to 750 mL
ii. Breath rate to be maintained = 10 to 20 BPM
iii. Maximum power required by the motor = 30 W
iv. Maximum torque to be delivered by the motor = 1.5 N.m

The design assumptions are based on the work by Husseini et al. [2], as they determined the assumptions after necessary experiments taking the mechanical properties and dimensions of the Ambu bag into considerations. So, there assumptions can be taken without further experimentations.

3.2 Principle of Proposed Design

Where most emergency and portable ventilators are designed with all custom mechanical components, it was chosen to take an orthogonal approach by building on the inexpensive BVM, an existing technology which is the simplest embodiment of a volume-displacement ventilator. Due to the simplicity of their design and their production in large volumes, BVMs are very inexpensive and are frequently used in hospitals and ambulances. They are also readily available in developing countries. Equipped with an air reservoir and a complete valve system, they inherently provide the basic needs required for a ventilator.

The main drawback with BVMs is their manual operation requiring continuous operator engagement to hold the mask on the patient and squeeze the bag. This operating procedure induces fatigue during long operations, and effectively limits the usefulness of these bags to temporary relief. Moreover, an untrained operator can easily damage a patient's lungs by over compression of the bag.

The methodology taken has been, therefore, to design a mechanical device to actuate the BVM. This approach will result in an inexpensive machine providing the basic functionality required by mechanical ventilator standards [2]. In Fig.4, the schematic diagram of the proposed system is illustrated. To automate the operation of Ambu bag, the mechanical system developed to compress the bag must be synchronized with the ideal motion that is maintained by a professional rescuer.

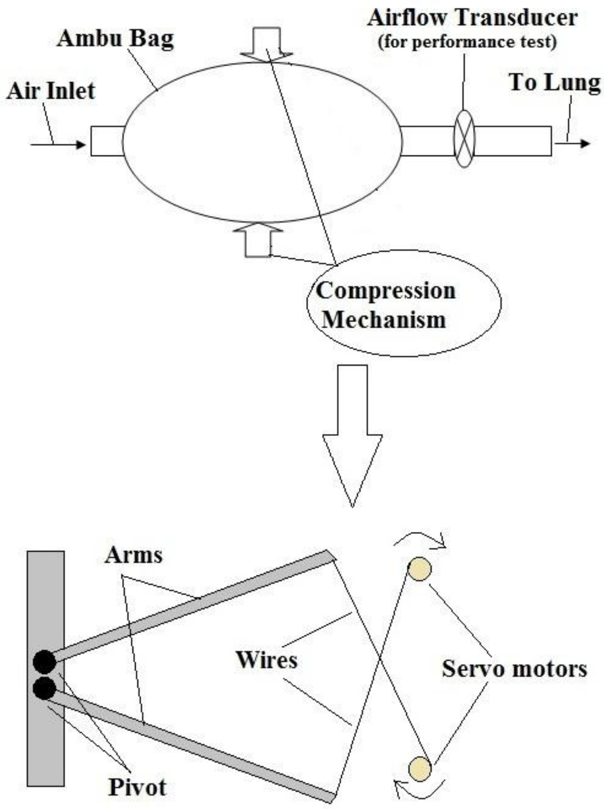

Fig. 4: Schematic diagram of the proposed design

3.3 Components Used

The materials and equipment were selected on the basis of the design assumptions discussed previously.

Materials and components needed to construct the prototype are presented in Table 2.

Table 2: Materials and Components used

Component	Rating or Specifications	Quantity
1. Ambu Bag	Ambu SPUR II PVC Disposable Manual Resuscitator	1
2. Servo Motor	MG 996R	2
3. Frame and Arm	Wooden, As designed	1
4. Microcontroller	Arduino MEGA 2560	1
5. Project Board		1
6. LCD Display	LCD 1602	1
7. Battery	9V DC	3
8. Potentiometer	10 K ohm	1
9. Wires and Jumpers		As needed

3.4 The CAD Model
A CAD model of the frame designed is illustrated in Fig.5. The model is developed using SolidWorks 2013. The Ambu bag and other components to deliver power and control the motion is installed on the frame.

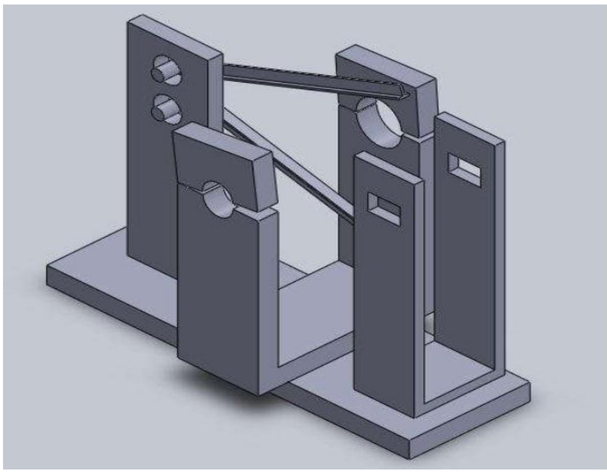

Fig. 5: The CAD Model of the frame

3.5 Dimensions and Calculation of Mechanical Advantage
The dimensions of the frame and the arms are selected as such to be compatible with the physical dimension of the Ambu bag. The length of the arms is 0.13 meters and in uncompressed state the arms start to touch the bag at 0.13 meters from pivot.
The frame and the arms deliver some mechanical advantage to compress the bag.
The length of the total arm = 0.3 meters
The length of the portion from pivot to the bag = .13 meters
Mechanical Advantage, M.A. = $\frac{.3}{.13} = 2.3$
So, the arm will provide a M.A. of 2.3 to compress the bag.

3.6 Control Implementations
The servo motors were coded to be controlled for compressing the BVM in required breath per minute (BPM) value. The Arduino MEGA 2560 microcontroller was used to control the servo motors. A potentiometer was used to control the BPM. The user can use the knob of the potentiometer to adjust the BPM. A LCD screen was used to display the BPM of the device operating with.

4. Results and Discussion

4.1 The constructed model
The constructed model is illustrated in Fig. 6.

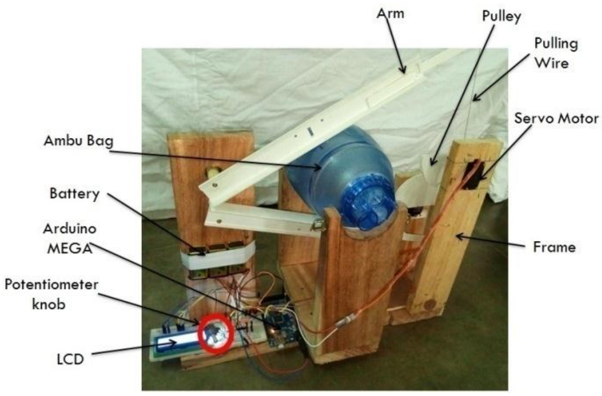

Fig. 6: The constructed model

The model automates the operation of BVM. The principle dimensions are 0.55m*0.15m*0.3m and weight is 2.5 kilograms. Only three 9V DC battery is used to operate the device which runs the device continuously for one hour. So it can easily be carried to emergency spots. The control knob can be used to adjust the BPM required for different patients and for different ventilation settings.

4.2 Performance Test
The developed prototype was tested using Biopac Airflow transducer. The experimental setup is illustrated in Fig. 7. The transducer along with the Biopac Students LabV4.1 software records the lung tidal volume and airflow for every millisecond. In Table 3 data of tidal volume for each second is presented. The lung tidal volume, V_t vs. Time, T graph was obtained for a human subject, for the device and for manual operation. In Fig.8 the graphs are presented.

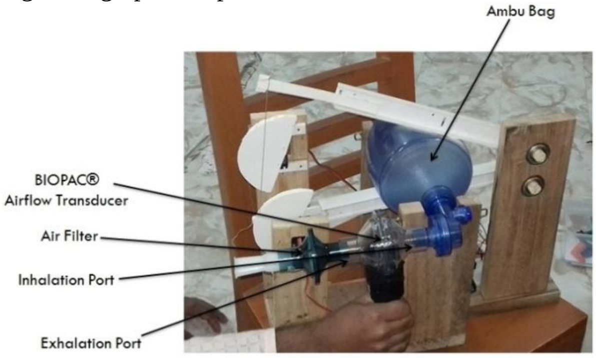

Fig. 7: Experimental setup

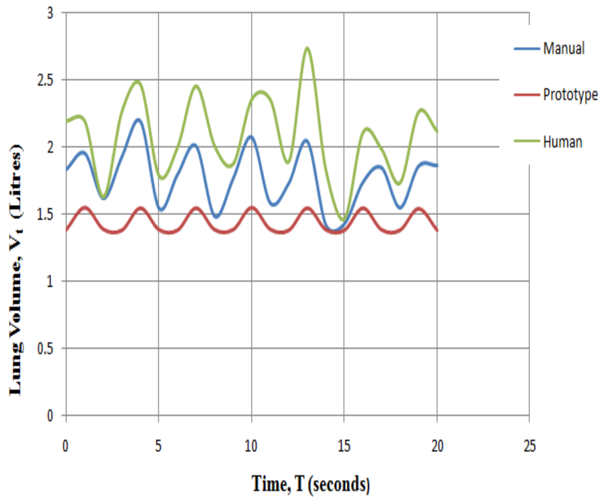

Fig. 8: Tidal volume vs. Time graph

Table 3: Tidal volume for manual operation of the BVM, for constructed prototype and for a human subject

Time (Seconds)	Tidal Volume (Liters)		
	Manual	Prototype	Human
0	1.83384	1.3898316	2.195069
1	1.952133	1.5526239	2.191187
2	1.620012	1.3920472	1.629568
3	1.927859	1.384977	2.264765
4	2.188488	1.5493066	2.466729
5	1.546177	1.3887128	1.787522
6	1.796241	1.384977	1.998717
7	2.005329	1.5493066	2.453686
8	1.486377	1.3887128	2.007818
9	1.765406	1.3898316	1.874575
10	2.071216	1.5526239	2.354588
11	1.584592	1.3920472	2.353157
12	1.730899	1.3843648	1.892085
13	2.040938	1.5489166	2.734889
14	1.421615	1.3886887	1.82856
15	1.429697	1.384977	1.46641
16	1.738724	1.5493066	2.109159
17	1.845986	1.3887128	1.984328
18	1.550398	1.3855922	1.733285
19	1.856896	1.5450019	2.261398
20	1.862131	1.3855323	2.118213

The mean deviation of the tidal volume obtained by the prototype from manual operation was 0.332 Liters or 332 mL and from human subject was 0.542 Liters or 542 mL.

4.3 Cost analysis

The total construction cost of the prototype was approximately 4500 Taka. The details of the cost are presented in Table 4. It should be noted that, if more powerful motors are used the construction cost will increase.

Table 4: Construction cost of the prototype

Sector	Description	Cost (BDT)
1. Raw materials for frame	Wood, PVC arm, PVC Sheet for pulley etc.	1800
2. Electronic components	Arduino MEGA, Servo motors, LCD, Potentiometer, Wires etc.	1700
3. Labor cost	-	600
4. Transportation and testing	-	400
	Total =	4500

It is assumed that, the cost of commercial production will be much lesser than prototype construction. The price range of available portable mechanical ventilators in the market at present varies from $1000 to $9600 (Equivalent to 83,124 BDT to 797,990 BDT) [13].

4.4 Uniqueness of the present work

The present work is based on the automation of BVM to construct an emergency portable mechanical ventilator, similar to the work by Husseini et al. [2]. But in present work, mechanical arms and servo motors have been used to actuate the BVM, whereas, Husseini et al. used cam mechanism for the purpose.

The technique used in present work proves to be more effective as it permits programming the required compression pattern, while in cam mechanism the compression pattern is fixed and unchangeable. So, more controllability is achieved by implementing mechanical arms and servomotors to actuate the BVM.

4.5 Discussions

The prototype could not compress the Ambu Bag completely. It compresses the bag partially. The reason behind this might be—

i. The motors were not powerful enough to compress the bag.
ii. The frictions among the mechanical linkages absorbed reasonable power.
iii. The prototype could not be built precisely due to lack of precise construction tools.

Though, the prototype works as a proof-of-concept in automating the operation of Ambu Bag. In future developments of the prototype these problems may be resolved.

5. Conclusions

The project work proves the concept of automating the Ambu bag or BVM for developing a low cost portable mechanical ventilator. Improvements of the model will lead to a successful and useable portable mechanical ventilator for actual emergency cases where existing sophisticated devices are not present. Although the device cannot perform like existing devices, its low cost justifies its use in emergency cases.

With three 9 volts battery as power supply the prototype can operate continuously for one hour. With principle dimensions of 0.55m*0.15m*0.3m, and weight 2.5 kilograms, the prototype may easily be transported. It also have a feature to control the breath rate and a LCD display shows the BPM the device is operating with.

6. Future development scopes

Following developments might be implemented for a usable portable mechanical ventilator—

i. More powerful servo motors can be used.
ii. DC motors can be used along with DC motor controller to reduce the cost and increase the driving torque.
iii. More features can be implemented to control various ventilation parameters like tidal volume, inspiration to exhalation time ratio etc.

NOMENCLATURE

BVM	Bag-Valve Mask
ICU	Intensive Care Unit
ET tube	Endotracheal tube
BPM	Breath Per Minute
M.A.	Mechanical Advantage
LCD	Liquid Crystal Display
V_t	Tidal Volume

REFERENCES

[1] Y. Shi, S. Ren, M. Cai and W. Xu, "Modelling and Simulation of Volume Controlled Mechanical Ventilation System," *Mathematical Problems in Engineering,* vol. 2014, 2014.

[2] A. M. A. Husseini, H. J. Lee, J. Negrete, S. Powelson1, A. Servi, A. Slocum and J. Saukkonen, "Design and Prototyping of a Low-cost Portable Mechanical Ventilator," in *Design of Medical Devices Conference,* Minneapolis, 2010.

[3] "Medical Ventilator," [Online]. Available: https://en.wikipedia.org/wiki/Medical_ventilator. [Accessed 12 February 2018].

[4] L. A. Geddes, "The history of artificial respiration," *EEE ENGINEERING IN MEDICINE AND BIOLOGY MAGAZINE,* 2007.

[5] R. M. Kacmarek, "The Mechanical Ventilator: Past, Present, and Future," *RESPIRATORY CARE,* vol. 56, no. 8, August 2011.

[6] A. Khoury, S. Hugonnot, J. Cossus, A. D. Luca, T. Desmettre, F. S. Sall and G. Capellier, "From Mouth-to-Mouth to Bag-Valve-Mask Ventilation: Evolution and Characteristics of Actual Devices—A Review of the Literature," *BioMed Research International,* vol. 2014, 27 May 2014.

[7] S. Fludger and A. Klein, "Portable Ventilators," *Continuing Education in Anaesthesia, Critical Care & Pain,* vol. 8, no. 6, pp. 199-203, 2008.

[8] M. Harrison, R. Muckel, C. Freeman, M. Revekant, D. Fenton, D. Zielinski, K. Kong, D. Engell and E. Welch, "PORTABLE EMERGENCY VENTILATOR," in *Multidisciplinary Senior Design Conference, Rochester Institute of Technology,* Rochester, New York, 2013.

[9] R. L. Vicenzi and T. R. Findlay, "PORTABLE LIGHT WEIGHT COMPLETELY SELF-CONTAINED EMERGENCY SINGLE PATIENT VENTILATOR/RESUSCITATOR". USA Patent 4,905,688, 6 March 1990.

[10] "Mechanical Ventilation," [Online]. Available: www.thoracic.org. [Accessed 11 April 2017].

[11] "Bag valve mask," [Online]. Available: https://en.wikipedia.org/wiki/Bag_valve_mask. [Accessed 19 April 2017].

[12] C. Nickson, "Bag-Valve-Mask (BVM) Ventilation," 6 May 2018. [Online]. Available: https://lifeinthefastlane.com/ccc/bag-mask. [Accessed 29 October 2018].

[13] "AliBaba.com," [Online]. Available: https://www.alibaba.com/showroom/mechanical-ventilation-price.html. [Accessed 20 February 2018].