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Design and Construction of a Prototype Mechanical Ventilator for Rural Communities in Poor Countries

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Abstract

To mitigate the problem of managing patients with COVID-19 and others having difficulty breathing and needing artificial respiration, a low-cost (Nigeria Naira ₦160,000.00 or British Pound Sterling £320.00 or United States Dollar $415.00) portable mechanical ventilator was designed and constructed for use in rural communities in poor countries. Mass production would half the production cost. The design adopted the cam and follower mechanisms to actuate an Ambu BVM (600ml-size) for the supply of variable pressure tidal volume to the lungs. It delivered 6.2ml and 9.9ml tidal volumes, per Kg of Ideal Body Weight (IBW) for man and woman, respectively. The device was constructed using locally sourced materials for ease of maintenance and repairs. Its power rating and noise levels were 30W (maximum) and 37dB, respectively. Powered by AC/DC, the device would serve healthcare centers in poor rural communities where electricity supply is unavailable. Also, it would serve in emergencies and on the go while transporting patients in an ambulance to the hospital for more intensive care.

Keywords: Prototype Implementation; Mechanical Ventilator; Design Concept; Rural Healthcare; COVID-19; Poor Countries.

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Introduction

The Coronavirus infection (COVID-19) outbreak, the pandemic nature of the spread, and the resultant death recorded world-wide call for urgent attention. The pandemic had caused the lockdown of most economies of the world and job losses across the board. Unfortunately, no known solution to the treatment of the plague has been found. Rather, some researchers have concluded that the contagion has come to stay like the known common ailments and that we would live with it for a long time to come. The researchers are hoping only on the development of herd immunity as a solution, and that would require time to reach after many people would have died of the disease. More so, it was affirmed that achieving herd immunity requires at least between 60% and 70% of the population to be immune – a condition considered difficult to reach ((D'Souza & Dowdy, 2020; O'Grady, 2020).

Experimental drugs and vaccines under trial for treating the infection are expensive and unavailable in the poor economies of the world including Nigeria. Meanwhile, the death toll due to COVID-19 has been on the increase in Nigeria. Nigeria's National Centre for Disease Control (NCDC) statistics on COVID-19 infections as on August 31, 2020, stood at 53,865 (confirmed cases), 11,339 (active cases), 41,513 (discharged cases), and 1,013 (deaths) spreading across all thirty-six states of the federation and the Federal Capital Territory (NCDC, 2020)**.**

Furthermore, it was reported that while the viral infection showed no visible sign or symptom in some affected patients, some others are vulnerable to its life-threatening impacts. Meanwhile, more deaths due to the pandemic were recorded among the minority ethnic groups including the Black, Asian and Minority

Ethnic (BAME) groups in the United Kingdom, the United States of America and other western countries (Public Health England, 2020; Cruickshank, 2020). Several factors including occupational exposure, the health status of the individuals, air pollution, and accessibility to healthcare influenced the severity of the impact. COVID-19 infection disproportionately affected the aged, obese and diabetic people (Cruickshank, 2020). Meanwhile, Nwakideu (2016) reported that about five million people in Nigeria had diabetes, thus making them vulnerable. Besides, air pollution arising from environmental degradation, poor waste management, bush burning, fossil fuel burning, and fumes from petrol and diesel engines and automobile exhausts in Nigeria predisposes people to the risk of COVID-19 infection.

Consequently, the Nigerian government intensifies efforts on strategies for curtailing the spread rather than the management of the infection while providing healthcare for infected patients. However, the inadequate supply of mechanical ventilators in hospitals and healthcare centres due to the prohibitive cost of importation has hampered healthcare management. Meanwhile, patients with COVID-19 at a stage would require a mechanical ventilator for support when they have difficulty in breathing and inability to get sufficient oxygen to the body tissues for respiratory activities, which is believed to be the cause of death. Besides, there is widespread in the country of respiratory diseases and other health ailments characterised by respiratory failure thus needing mechanical ventilation for artificial respiration.

In the quest for managing patients infected with COVID-19 and other ailments needing artificial respiration for resuscitation and in an emergency, a low-cost portable mechanical ventilator is needed in poor countries including Nigeria. However, three categories of low-cost ventilators differing in their operational modes – manual, pneumatic, and electric ventilators are available in the global market. While the use of the cheapest manually operated ventilator would be inadequate to cope with the rate of emergence of COVID-19 cases in Nigeria, the more suitable pneumatic and electric portable ventilators are too prohibitive to acquire with prices ranging from $1,000 to $10,000 per unit (Al Husseini *et al.*, 2016; Blais, Abed, Mnati & El-Hasan, 2023). Using a cam-actuated Bag Valve Mask (BVM) compression strategy for the portable mechanical ventilator, Al Husseini *et al.* (2016) designed a prototype at a cost of less than $500. This paper describes the design and construction of a low-cost portable mechanical ventilator for use in rural healthcare centres where electricity supply is lacking and in the case of emergency, for road accident victims needing the support of artificial respiration. The ventilator, which is powered by AC or DC (battery), can be used in emergency and on the go when transporting the patient to the hospital for more intensive care.

Design and Construction of the Device

Medical requirements and design considerations

The application of a manipulative device to perform artificial respiration or resuscitation when there is the cessation of natural respiration or in the event of irregular breathing formed the basis for the prototyping of a portable mechanical ventilator intended for use with humans of all age groups. Also, the design principles for the prototype ventilation device took cognizance of the ASTM F920-93 (ASTM F920-93, 1999) standard specifications for minimum performance and safety requirements for portable ventilators meant for emergency use both outside and inside hospitals. In addition to the cost elements, size, performance, and medical requirements for normal and artificial respiration, safety and user requirements, and power requirements and source constituted the underlying consideration in defining the technical specifications for which the device was designed. Table 1 summarizes the functional or design characteristics of the prototype mechanical ventilator.

Table 1. Functional / design characteristics of the mechanical ventilator

Medical considerations:	
The fraction of inspired oxygen FiO_2	<0.60
Frequency (f) or Respiratory Ratio (RR)	10–20 breaths/minute.
Tidal Volume (V_t)	6–8ml/Kg of ideal body weight (IBW)
Minute Ventilation (V_e)	5 – 10 L/minute
Inspiratory : Expiratory (I:E) Ratio	1:2
Positive End Expiratory Pressure (PEEP)	3 – 10 cmH_2O
Pressure Support (PS)	8 – 20 cmH_2O
Peak Inspiratory Pressure (PIP)	<35 cmH_2O
Peak Flow Rate (PFR)	60 - 120 L/minute
Mechanical and Electrical considerations:	
Size	Portable, small-size, standalone, and usable on the go (500 mm x 205 mm x 360 mm)
Complexity of operation	simple operation
Durability	Robust mechanical, easy maintenance electrical and software systems
Construction materials	Locally-sourced and readily available repairable parts
Power requirement	Extremely low power i.e., 30 W maximum
Dual power operated	230 V AC with 12 V battery backup or power from the car cigarette lighter port.
Operation mode	One mode i.e., Assist control volume ventilation mode
The purity of air supply to the patient	High-efficiency particulate air filter is incorporated on the main inspiratory line
Noise level	37 dB
Ease of use, Safety and Economic considerations:	
User-friendly interface	LCD; it displays volume, pressure, BPM settings, mode selection, flow rate and status
Alarms for high pressure	Available
Low-cost	≤₦200,000.00 (£400.00 or $500.00)
Performance accuracy	
Accuracy of breath frequency	1 breath/minute

Conceptual Device design

Figures 1 and 2 depict the conceptual flow chart and block diagram for the mechanical mechanism and the control system, respectively for the design of the prototype mechanical ventilator.

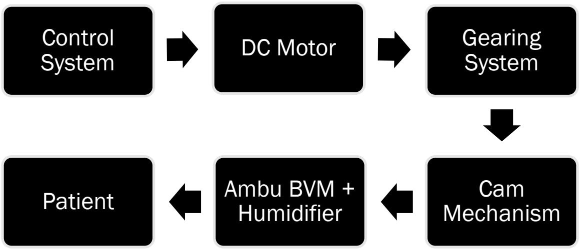


Figure 1. Flowchart of the conceptual mechanical mechanism of Prototype 1

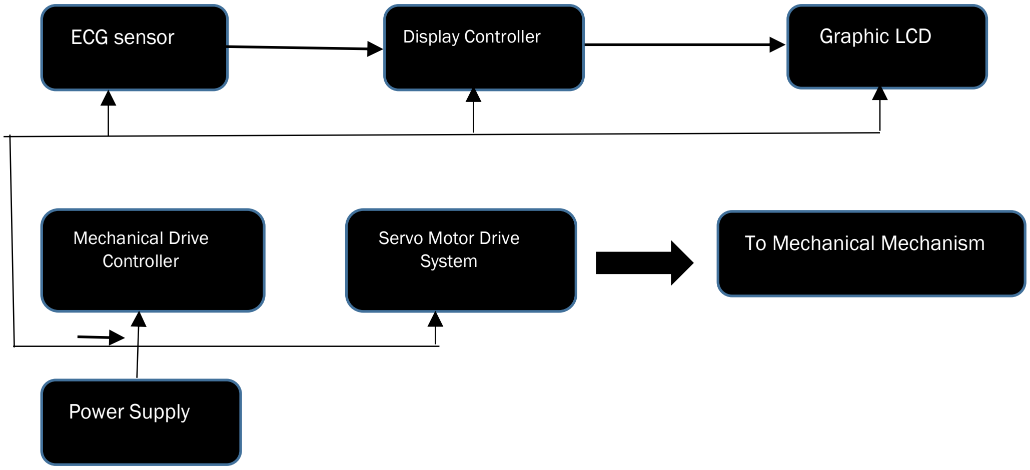
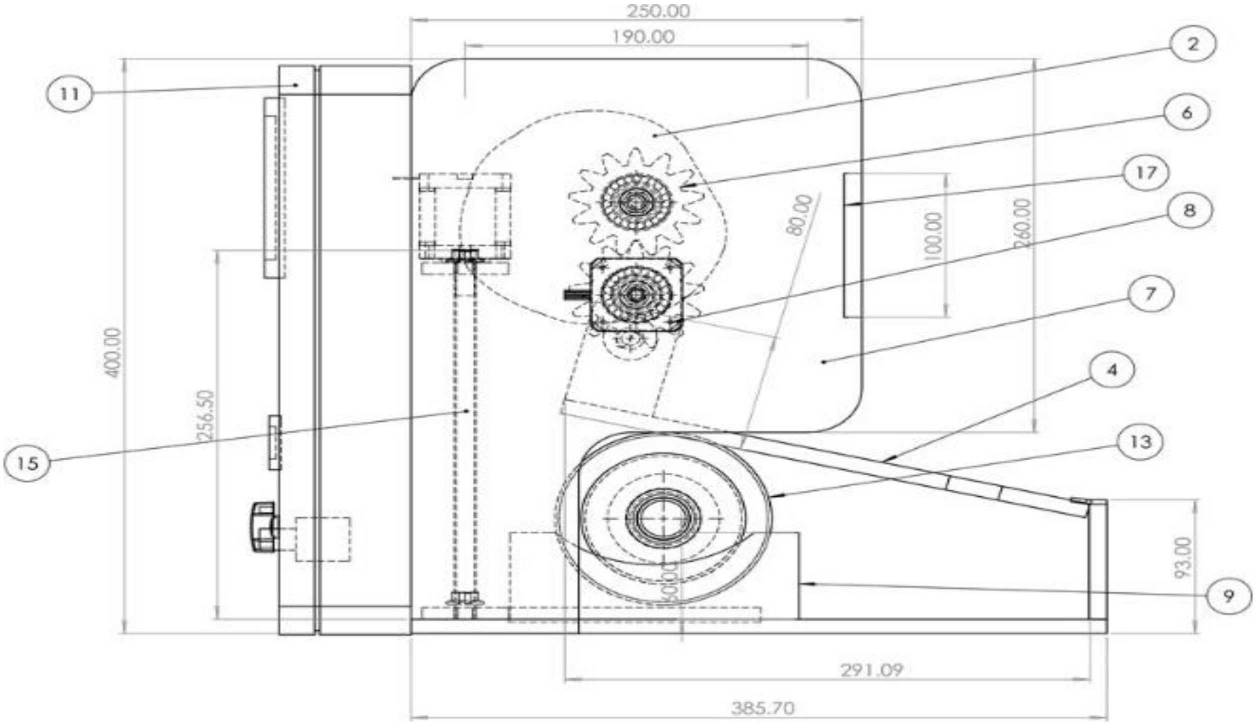


Figure 2. Block diagram of the control system of the mechanical ventilator (Prototype 1)

The cam and follower mechanisms, which were driven by a gearing system were designed to actuate the BVM for the supply of oxygen-rich air into the lungs. Medical variables including Inspiratory/Expiratory Ratio, air pressure, air volume and volumetric flow rate as specified in Table 1 guided the design of the cam profile. A high-torque DC motor powers rotation of the cam through the two 13-toothed spur gears of module 5 each. The number of breaths per minute (BPM) determined the speed of the motor. A second motor (Stepper motor) varies the depth of the compression of the BVM through the linear movement of Plunger 1. A curved member supports the BVM against the depressing force. As the cam and follower mechanism operates, the upward and downward movements of Plunger 2 cause the BVM to push the oxygen-rich air into the endotracheal tube. Figure 3 illustrates the cam and follower mechanisms driven by a gearing system.



2. Cam
6. Spur gears
8. High torque DC motor
11. Control panel
15. Stud rod

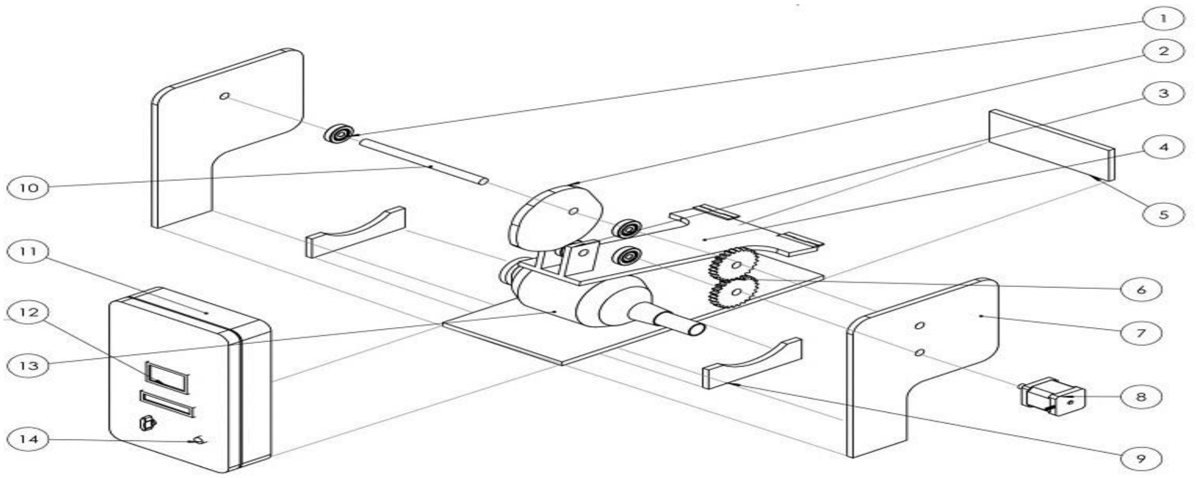
4. Plunger 2
7. Support frame
9. BVM support
13. Ambu bag
17. Braise for support frame

Figure 3 Mechanical operating mechanism

The controller module, display module, electrocardiogram sensor, and power unit made up the control system. The controller module consisted of a mechanical drive controller (Arduino UNO) and a display controller (Arduino MEGA). The MCU controls and monitors voltage supplies to the LCDs and sensors. The design made allowance for further expansion to accommodate additional sensors and the interface for such additions was provided on the controller whenever upgrading was required. The embedded C-programming was used at various operational levels for proper communication among all components.

Design of Prototypes

The initial prototype (Prototype 1) was designed as a trial of the possibility of delivering a constant volume of air/O_2 mixture with constant pressure. Figure 4 depicts the drawing.



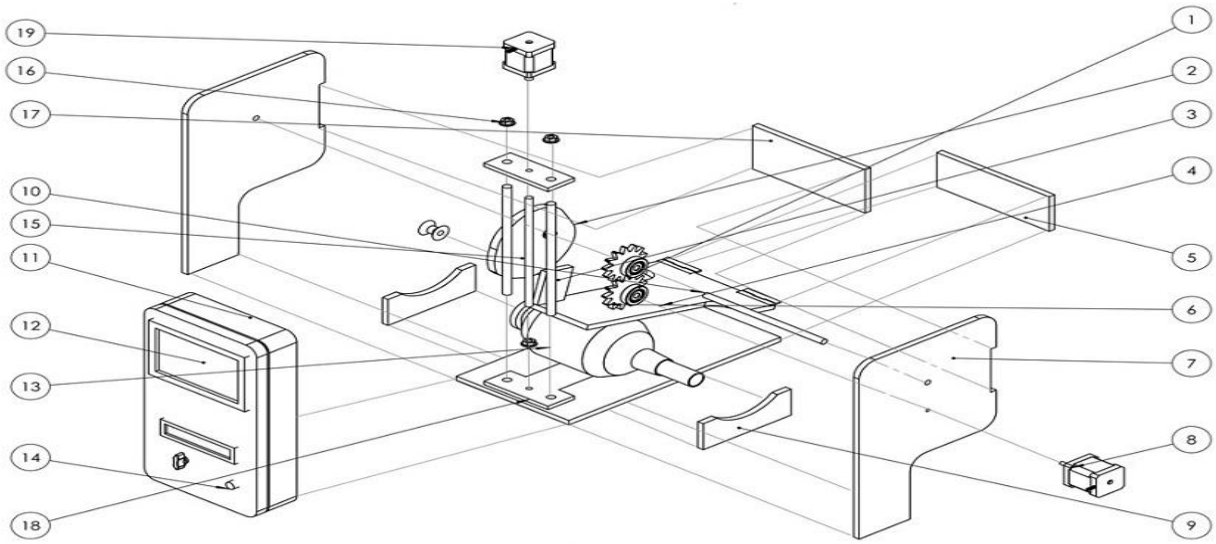
1. Bearing
2. Cam
3. Follower
4. Plunger 2
5. Plunger support
6. Gearing system
7. Support frame
8. High torque DC motor
9. Ambu bag support
10. Transmission shaft
11. Control panel
12. LCD
13. Ambu bag
14. Power button

Figure 4. Exploded drawing of Prototype 1 of the mechanical ventilator

The whole setup was mounted in a casing (500 mm x 205 mm x 360 mm) made of transparent acrylic material of thickness 10-15 mm that ensured visibility of all components. The acrylic material was cut to the desired dimensions with a laser cutting machine. The DC motor-8 was mounted on the mainframe-7, which drives two spur gears-6, which in turn rotates the cam-2 via the camshaft. The cam makes direct contact with the roller follower-3 mounted on the plunger2-4). Plunger 2 actuates the Ambu BVM-13 for air supply. The control panel-11 supplies the controls.

With the design of Prototype 1, constant air volume delivery with a plunger was achieved. The variation of the speed of the stepper motor to achieve the desired range of breaths per minute (BPM) resulted in noise and power loss to drive the mechanical system. Consequently, it was necessary to correct these anomalies in the subsequent design.

The setup of the second prototype (Prototype 2) mechanical ventilator is shown in Figure 5. This trial used devise casing of the same material and size as that tried in Prototype 1. Following the successful compression of BVM and the pumping of constant air/O2 volume into the demo artificial lungs at constant pressure with the cam and follower mechanisms, the same mechanism was used but at varying air/O2 volume to take care of differences in the requirement for artificial respiration exhibited by different patients' health conditions. Consequently, the design consideration took cognizance of tidal volume and pressure support specified in Table 1.



1. Bearing
2. Cam
3. Follower
4. Plunger 2
5. Plunger 2 support
6. Spur gears
7. Support frame
8. High torque DC motor
9. Ambu bag support
10. Transmission shaft
11. Control panel
12. LCD
13. Ambu bag
14. Power button
15. Stud rod
16. Nut
17. Braise for support frame
18. Plunger 1
19. Stepper motor

Figure 5. Design of Prototype 2 of the mechanical ventilator

Modifications to the mechanical and control systems shown in Figures 6 and 7 are the introduction of the second DC motor (stepper motor), a plunger, air volume control and air pressure sensor for regulating the volume and pressure of oxygen-rich air released from the BVM to the lungs.

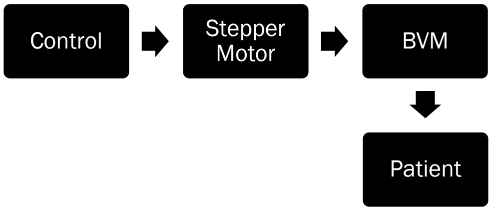


Figure 6. Flow chart showing the modification to the flow chart of the mechanical system of Prototype 1

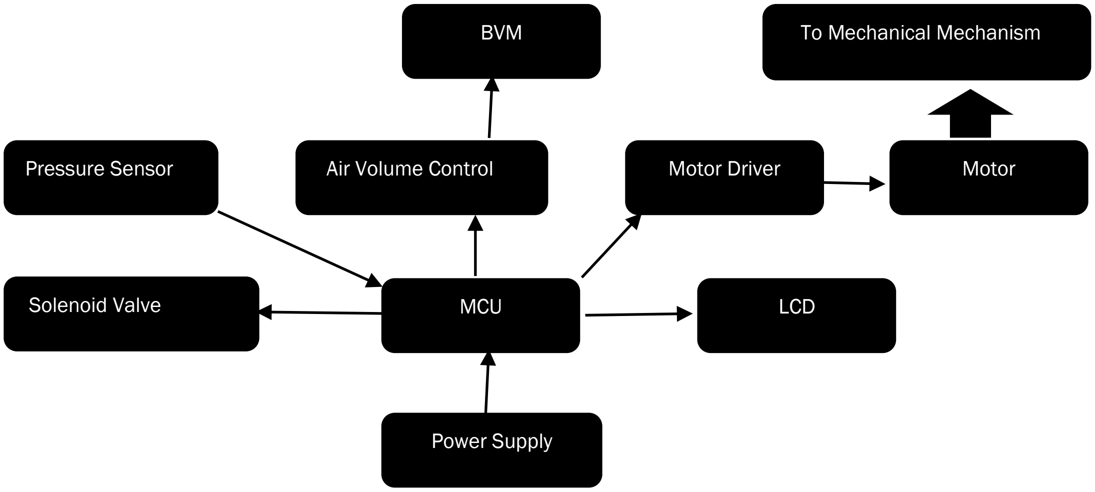
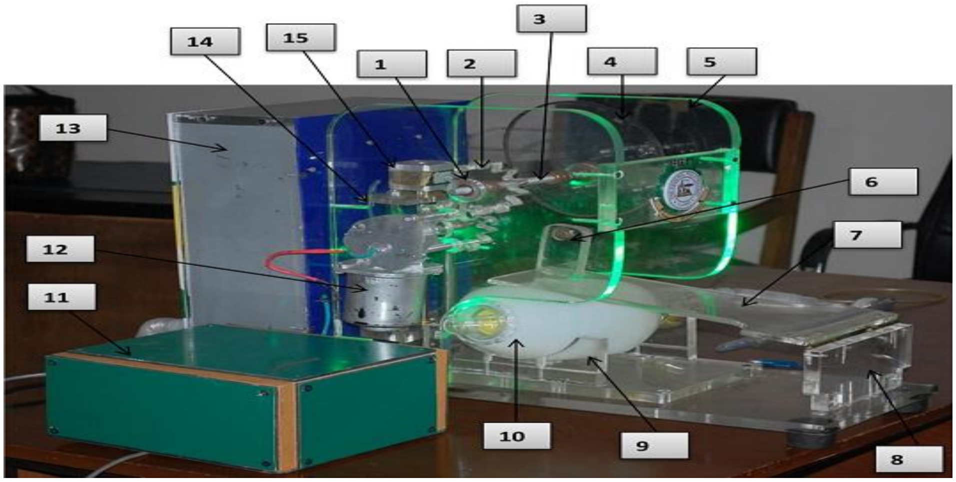


Figure 7. Block diagram showing the modification to the control system of Prototype 1

Also, the audiovisual alarm system was incorporated in the setup to indicate the performance status of the device. The alarm signifies normal working and faulty conditions. Consequently, the additions/modifications to the design consideration in the first prototype necessitated the observed differences in the setup of the second prototype.

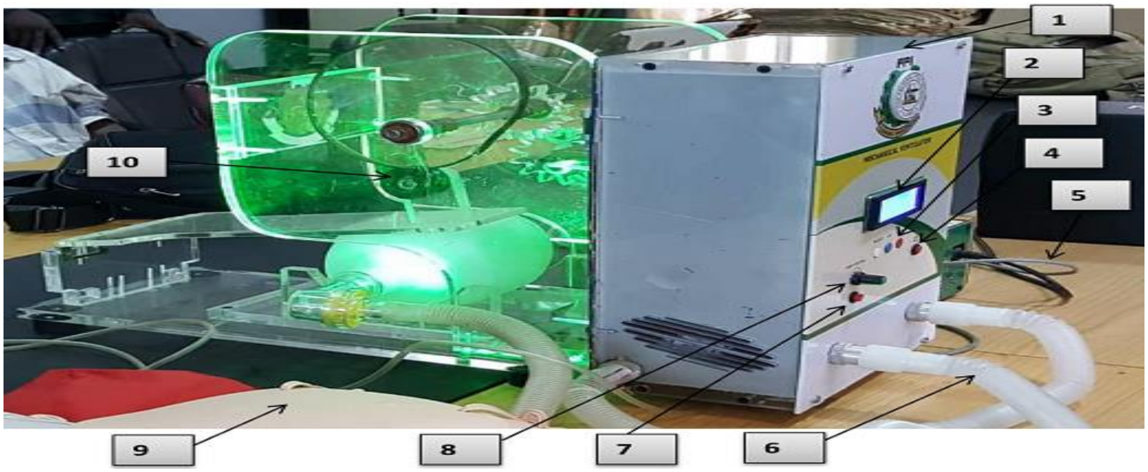
The arrangement of the components in the prototype 2 was similar to prototype 1 expecting that Prototype 2 provides the initial depression of the Ambu BVM for volume variation through plunger1-18, which is controlled by a stepper motor-19. The introduction of the second plunger and air/volume control made possible the delivery of variable air volume and the desired range of BPM through variation of the DC motor’s speed. The noise level generated was low (i.e., 37 dB) and there was no power loss.

Figure 8 shows the picture of the constructed prototype 2 of the portable mechanical ventilator, while Figure 9 illustrates the setup of the device in use for artificial respiration of human patient mannequin.



1. Bearing
2. Spur gears
3. Transmission shaft
4. Cam
5. Support frame
6. Follower
7. Plunger 2
8. Plunger 2 support
9. Ambu bag support
10. Ambu bag
11. Power supply
12. High torque DC motor
13. Control panel
14. Stepper motor support frame
15. Stepper motor

Figure 8. Side view of prototype 2 portable mechanical ventilator



1. Control panel
2. Screen
3. Mode setup buttons
4. Power button
5. Endotracheal tube
6. Airway tube
7. Cam on/off button
8. Potentiometer
9. Mannequin
10. Follower

Figure 9. Setup of the constructed prototype portable mechanical ventilator in use with a mannequin

Power delivery

The power unit supplies and distributes DC-voltage to all the sub-modules involved in the system. An ATX power pack/unit, which delivers a pure DC-voltage output was the power source. Three output voltage levels (12 V, 5 V, and 3.3 V) were used for the different sub-modules involved in the system. The 12 V was used to power the solenoid valve and the electric motors, while 5 V was used to power the micro-controller, and 3.3 V was used for power indicators and system illumination.

Motor and driver

A permanent magnet DC motor and a stepper motor were used in the system. The driver system consists of a MOSFET-based variable drive which was used to control the speed of the DC motor and a stepper driver for the volume control system.

User interface

The 20 x 4 LCDs show the motor's speed, air pressure and volume, and flow rate readings. The design incorporated a control knob for the variation of BPM, and three setup buttons for menu control, adjustment and mode selection.

Safety precaution

An audiovisual alarm system was introduced to indicate normal working conditions and fault. The green LED indicates normal operation, and the red LED indicates an excess pressure fault.

Analysis, Testing and Costing

The air pressure tidal volume (V_t) delivered by the device was measured using a spirometer Model SY-8888 high precision digital display electronic Tester (Range [Scope]: 0 - 10000ml; Graduation value [Resolution]: 1ml) manufactured by Hangzhou Pangong Sporting Goods Co., Ltd., China. The device delivered 6.2ml and 9.9ml tidal volumes, per Kg of Ideal Body Weight (IBW) for man and woman, respectively.

The noise level of the device when in operation was determined in a soundproof room using a digital sound level meter and it was 37dB. The results indicated that the device is suitable for use in the internal hospital environment. For instance, the permissible noise level for such an environment range from 30 – 40 dB and 35 – 45 dB as specified by WHO and USEPA, respectively (United State Environmental Protection Agency (1974).

All materials used for constructing the prototype mechanical ventilator were sourced locally. The cost of constructing a unit was ₦160,000 (£320.00 or $415.00). An additional variable cost of a 12 V battery depending on the power rating is required if the device is intended for use in a rural healthcare centre lacking electricity infrastructure. The battery would not be necessary if the device is used in the hospital ambulance where it would be powered through a cigarette lighter port.

Conclusion

A prototype low-cost portable mechanical ventilator using cam and follower mechanisms to actuate an Ambu BVM to supply the lungs with varying air tidal volumes has been designed and constructed using locally sourced materials. Powered by AC/DC, the device would serve healthcare centres in poor rural communities where electricity supply is unavailable. Also, it would serve in emergencies and on the go while transporting patients to the hospital for more intensive care.

Acknowledgement

The design and construction of this device is an intervention project of the Federal Polytechnic, Ilaro in the wake of COVID-19 outbreak in Nigeria. Indeed, it represented the Polytechnic's contribution to the national quest for healthcare solution to the pandemic. Special thanks are due to Dr O. O. Aluko, the Rector of the Polytechnic for initiating and facilitating the project implementation; and Messrs. S. G. Ojetunde and A. R. Oseni of the Department of Mechanical Engineering for technical support.

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