IOP Publishing Measurement Science and Technology
Meas. Sci. Technol. **35** (2024) 085101 (12pp) https://doi.org/10.1088/1361-6501/ad41f6

OxySaver: highly conserving demand oxygen delivery system with increased throughput

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Received 1 November 2023, revised 11 April 2024
Accepted for publication 23 April 2024
Published 2 May 2024

Abstract

Since the beginning of the twentieth century, oxygen has been an essential therapeutic drug. Patients with chronic lung disease and other conditions rely on supplemental oxygen provided by oxygen cylinders for treatment. Because of the sudden increase in oxygen demand caused by the COVID-19 pandemic, combined with a lack of oxygen supply, new methods of oxygen delivery have been investigated as a potential solution. We propose OxySaver, a novel low-cost (∼60$) demand oxygen delivery system that may significantly reduce oxygen consumption. The proposed system consists of a pressure sensor that detects the patient's demand for oxygen, a normally open solenoid valve that switches the supply ON/OFF on demand, and a processing unit that ensures the supply of oxygen only during the patients' inhalation. It is simple to install using existing oxygen cylinders and oxygen pipelines in hospitals. The preliminary prototype tests have been promising, with OxySaver able to save up to 67% more oxygen than conventional methods. OxySaver's pulse setting can reach 18 LPM, as opposed to the 0.2–4 LPM typically found in oxygen concentrators. The system only needs 3.72 W at 50 bpm, which is less than other similar devices. OxySaver in multiplexing mode has the potential to reduce the logistical challenges associated with oxygen refilling and transport. The device is now ready for clinical testing at the bedside.

Supplementary material for this article is available online

Keywords: demand delivery system, solenoid valves, oxygen cylinder, cannula, pressure sensor

1. Introduction

For a patient's survival in hospitals, particularly critical care settings, oxygen is a critical resource [1]. This is supplemental oxygen or oxygen therapy, in which oxygen is delivered to patients with breathing difficulties via a nasal tube, mask, or tent [2]. Multiple diseases impair lung function, resulting in low blood oxygen levels and hypoxia of internal organ tissue. To avoid such situations, patients are given supplemental oxygen, which is frequently used in conjunction with mechanical ventilation, which requires high concentrations of pure oxygen to be delivered to oxygenate a patient [1].

With oxygen being a limited resource, the cost of oxygen supply is a burden on the healthcare system in low-income countries. Supplemental oxygen can be supplied to hospitals via direct pipelines, bedside oxygen concentrators, or high-pressure oxygen cylinders [3]. Bedside concentrators may be a practical solution for the limited oxygen supplies found in remote areas of low and middle-income countries (LMIC),

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but the devices are still power-dependent. Patients frequently receive oxygen from cylinders that require daily refilling due to limited access to direct oxygen pipeline systems and power shortages that are common in these resource-constrained areas [4, 5]. These cylinders can provide a continuous flow of oxygen to patients who need oxygen therapy; however, it is an inefficient method of oxygen delivery that is heavily reliant on regular refilling and a reliable supply chain [6].

Since March 2020, the Sars-Cov-2 pandemic has infected 1.26 million people in Bangladesh, a figure that is growing by the day [7]. The viral coronavirus infection affects patients' respiratory systems, causing severe acute respiratory syndrome (SARS) and other symptoms [8]. Severe cases can result in hypoxia-related complications that necessitate oxygen therapy and mechanical ventilation, with over 500 000 COVID-19 patients requiring oxygen on a daily basis in LMICs [9, 10]. In these COVID-19-infected patients, hypoxia is the leading cause of death [11]. The oxygen required by these COVID patients then significantly increases the oxygen demand already present in other patients suffering from pulmonary diseases, chronic respiratory diseases, cardiovascular disease, and other ailments and infections that cause hypoxia [1, 12].

Due to logistical challenges in refilling cylinders on time and transportation challenges in supplying oxygen from manufacturers to healthcare facilities, the surge caused by this sudden increase in demand for oxygen was not met in resource-limited areas of LMICs. As a result, in our neighboring country of India, a lack of sufficient oxygen supplies for patients has already resulted in thousands of avoidable deaths [13, 14]. During infection surges, demand in our communities has already increased by up to 40%, with industries and oxygen manufacturers diverting supplies to hospitals. The logistical challenges of refilling and distributing cylinders in a timely manner, however, remain [15].

Current settings in these areas only allow for continuous flow of oxygen, which means that oxygen from the source is released at a fixed rate during the patient's inhalation and exhalation. This is inefficient because more than half of the oxygen is wasted while being applied to patients. Because gas exchange and blood oxygenation in the lungs occur during inspiration, the oxygen delivered while patients exhale is almost entirely lost [16]. Because of the wastefulness of this method of oxygen delivery, cylinders must be refilled more frequently, and more cylinders are required to meet patient demands. During times of scarcity, this becomes difficult to achieve, making oxygen conservation one of the few viable options for meeting patient needs.

We present OxySaver, a novel demand oxygen delivery system (DODS) that has been bench-tested and is ready for bedside clinical testing. It is equipped with pressure sensors that detect changes in breathing and allow oxygen to be released from the cylinder only during inhalation, conserving oxygen that would otherwise be lost during exhalation. The proposed solution is aimed at low-resource areas that frequently experience power outages, so it is equipped with an open valve system, as opposed to other oxygen conservation devices, which allows continuous oxygen flow in the event of a power outage. According to preliminary test results, OxySaver is capable of conserving up to 67% more oxygen than conventional methods. The device can be linked to oxygen cylinders as well as hospital oxygen supply lines. OxySaver in multiplexing mode can cut logistical challenges in oxygen refilling and transport in half, reducing the burden of preventable deaths in LMICs due to supplemental oxygen needs. It is thus expected to improve oxygen supply conservation, lower patient costs, and increase hospital capacity for oxygen treatment.

2. Background and comparison

DODS devices, also known as pulse flow oxygen delivery devices, deliver oxygen only during inspiration. There are frequently concerns about their ability to provide adequate and consistent oxygen therapy. A systematic review of commercially available DODS found no significant difference in maintaining oxygen saturation (SpO2) at rest and during exercise compared to continuous oxygen delivery [17]. Other studies on respiratory models and patients have reached similar conclusions [18–21]. During an endurance test, one of these previous studies compared SpO2 values from a liquid oxygen DODS device (CAIRE Spirit 300), a DODS portable concentrator (Inogen G2), and continuous flow (Companion 1000). The results indicated that the oxygenation performance was very similar. SpO2 levels were 90.4%, 89.5%, and 90.5% for continuous flow, liquid oxygen DODS device, and DODS portable oxygen concentrator, respectively [18].

While the previous studies found no difference between the two systems, other research has found an increase in oxygen saturation levels due to the use of DODS devices, as measured by fraction of inspired oxygen (FiO2) in respiratory models and arterial oxygenation for COPD patients [22, 23]. As a result, it has already been demonstrated that the technology used in DODS devices is safe and effective at providing oxygen to patients and maintaining SpO2 levels, even under varying physical conditions with varying respiratory demands.

Most current market-available oxygen delivery devices that can only supply oxygen during inhalation, also known as pulse-dose technology, are used in home-care settings, including portable oxygen concentrators and portable liquid oxygen devices. For oxygen delivery, these devices use either pulse dose or continuous flow technology. Pulse dose oxygen delivery can detect the patient's breathing and deliver an oxygen bolus at inhalation, with some devices able to adjust the oxygen bolus delivered to the patient's breathing rate [24, 25]. The FREO2 low-pressure oxygen storage (LPOS) system [26], which consists of several upgrades to a standard oxygen concentrator, underwent a field trial in Mbarara, Uganda, and the technical results of that trial are reported in this article. Patients had access to 100% oxygen availability for three months. The installation of the LPOS system enables continuous oxygen supply from a concentrator for an extended period of time, even during prolonged power outages, according to this study.

For portable use outside the home, the market-available oxygen devices run on both battery and AC/DC settings, and the power consumption rate varies depending on the functionalities [24]. Our device has a much lower power consumption rate, at 3.72 W for 50 bpm, making it more appropriate for resource-constrained areas. The pulse flow settings of typical portable oxygen concentrator devices range from 0.2 LPM to 4 LPM, and the continuous flow setting ranges from 0.5 to 6 LPM, with high flow oxygen concentrators able to supply at up to 10 LPM [24]. The pulse flow and continuous flow settings of the proposed solution both go up to 15 LPM (using either cannula or mask), which may be required for critical care patients [27].

Unlike oxygen cylinders, oxygen concentrators do not need to be refilled and thus can run indefinitely; however, the disadvantage is that they require a constant power supply. These devices were not designed for low-resource settings and are unable to deliver oxygen continuously in the absence of a power source, posing a major concern in areas prone to power outages [5].

This is in contrast to our device, which was specifically designed for critical care patients in low-resource settings during times of high oxygen demand. The proposed solution is intended to fit both existing oxygen cylinders and hospital oxygen pipelines. These oxygen cylinders are the primary source of oxygen in hospitals in low-income countries, but they are problematic because they must be refilled frequently, with the majority of the oxygen being wasted during administration to patients [6, 15]. Instead of investing in more expensive devices, the proposed solution can be used in conjunction with the current oxygen supply to conserve it. One of OxySaver's distinguishing features is how it handles power outages. When there is a power outage, the normally open (NO) valve remains open, supplying a continuous flow of oxygen. The OxySaver, unlike other oxygen conservation devices with an emergency alert system, has an emergency setting that switches from pulse flow to continuous flow if breathing or pressure changes cannot be detected. This means that patients will continue to receive supplemental oxygen until the problems are resolved, lowering the risk of hypoxia-related complications for patients who require a continuous dose of supplemental oxygen.

One of the proposed solution's other notable strengths is that it is a stand-alone device due to readily available parts, low cost (∼60$), and ease of production. The solution also employs the most recent differential pressure sensor, which has been experimented with to compensate for any changes on its own. Even if a change occurs due to extreme weather, there is a mechanism to recalibrate using a hard reset button. Furthermore, the solution does not control flow because it is designed for hospital patients where the flow rate is manually set by the doctor. Furthermore, because it can be added as an add-on to hospital devices, it is very simple to deploy.

3. Technical design

The system architecture of OxySaver and its setup with conventional oxygen cylinders to deliver demand oxygen flow to a patient is depicted in figure 1. OxySaver can be explained by its embedded system containing sensors and processing unit, NO solenoid valve to control oxygen flow and the power management. The setup additionally includes a conventional oxygen cylinder with an attached flow meter and a patient with a nasal cannula attached. The picture of the complete setup of demand oxygen delivery through OxySaver is provided in S_ figure 4.

The Oxysaver received medical ethical clearance for technical testing of the prototype from BMC (Bangladesh Medical College and Hospital) and technical certificate of approval and recommendation for clinical trials from BME (Biomedical Engineering Dept., KUET).

3.1. Embedded system

3.1.1. Sensor. A pressure sensor (Model: XGZP6897A, CFSensor) was used to detect the constant changes in pressure caused by the lungs' repeated ventilation process. There are several researches in the development of pressure sensors using different technology [28] to achieve ultrahigh sensitivity [29], and high burst pressure [6]. We opted for a commercially available sensor specifically made for medical applications to ensure the quick manufacture and repair of the device in low-resource settings. Selecting the right pressure sensor is very important considering its application in clinical settings where the temperature may vary. The selected pressure sensor is fully calibrated and temperature-compensated between 0 °C to +60 °C (32 °F to +140 °F) for offset, sensitivity, temperature, and non-linearity. The operating temperature of this sensor is −20 °C to +100 °C (−4 °F to +212 °F), whereas the accuracy is ±2.5% (0 °C to +60 °C temperature) and long-term stability is ±1.0% (30 d of operation). Another important consideration in selection of the sensor is the overload capacity. The Max pressure on P2 port is 250 kPa and the Burst pressure is 10X than the Rated pressure (−0.5 kPa to +0.5 kPa). These rating are sufficient as two completely isolated ports are used in our system for oxygen flow and pressure sensing. This nullifies the possibility of causing damage to the pressure sensor by a sudden powerful stream of oxygen flowing into the system with overload pressure. In the scenario where the sensor experiences burst pressure and dies, the proposed device would activate a failsafe which is discussed in detail in later sections. It is also important to note that, the proposed device does not control oxygen pressure rather it is regulated by mechanical oxygen flow meter connected to an conventional oxygen cylinder.

One of the two air vents of the differential pressure sensor, is connected to the nasal cannula. The system's use of differential pressure sensors makes it useful in a variety of climate, altitude, and physical conditions. As the patient breathes into the cannula, a pressure is created at the inlet, resulting in a difference being detected when compared to the second inlet, which is only exposed to atmospheric pressure. The positive and negative pressure differences detected by the differential system indicate whether inspiration or expiration is occurring. The silicon-structured sensor has already been approved

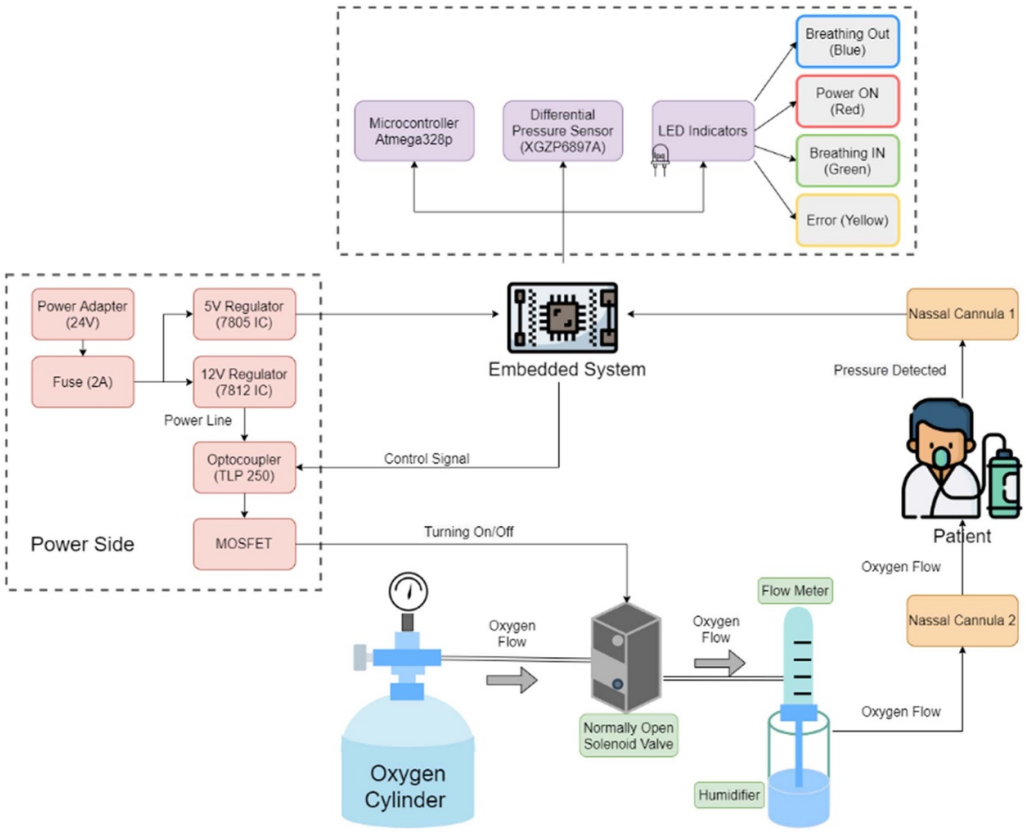

Figure 1. System architecture of OxySaver along with complete setup.

for medical and industrial use in respirators, ventilators, airflow measurement, and gas flow instrumentation, among other devices, and is fully calibrated for pressure changes ranging up to 500 Pa. The sensor fits into the design of the proposed solution with high accuracy and at a low cost [30].

3.1.2. Processing unit. The system's main processing unit is an ATmega328P microcontroller with 32 kilobytes of in-system, self-programmable memory. It is set up to receive data from the differential sensor, compare it, and deduce a trend from which a pressure-time plot can be obtained. A positive slope indicates exhalation and a negative slope indicates inhalation in a normal respiratory pattern that can be represented by a simple sinusoidal graph. When there is no breath or pressure at either of the sensor's air vents, the analog value is used as the middle value. A band/range has been used around the middle value to avoid unwanted triggering or error in triggering the breathing states. The upper and lower bounds of the band are called upper ($P_{\text{u\_th}}$) and lower ($P_{\text{l\_th}}$) thresholds respectively. From the (i) and (ii) equations the values of $P_{\text{u\_th}}$ and $P_{\text{l\_th}}$ are derived. It depends on the value of P_{mid}, which is found from testing the device on subjects not having clinical complications. The constant c was calculated based on the results of testing the device on various subjects of varying ages. A sample of the observation has been included as supplementary material for your convenience.

The sensing algorithm utilizes the values of $P_{\text{u\_th}}$ and $P_{\text{l\_th}}$ to sense the breathing states of subjects. Whenever the value of the sensor data will exceed the $P_{\text{u\_th}}$, the device will traverse to the exhale state. Similarly, data decreasing below the $P_{\text{l\_th}}$ would turn the device's inhale state,

$$P_{\text{u\_th}} = P_{\text{mid}} + (c \times N) \tag{1}$$

$$P_{\text{l\_th}} = P_{\text{mid}} - (c \times N) \tag{2}$$

where,

P_{mid} is the mid-value of the pressure
$P_{\text{u\_th}}$ is the upper threshold of the pressure
$P_{\text{l\_th}}$ is the lower threshold of the pressure
N is the digital representation of the sensor pressure range
c is the constant that has been identified based on test cases.

When the device enters any of the states, the total time spent in that state is accumulated. If any of the states is detected for more than 6 s, the device will interpret the situation as a 'error' and activate its emergency measures to deliver continuous flow oxygen. The error is labeled with the name of the state in which it was discovered. The quiet respiratory rhythm is thought to be between 2 and 3 s for inhalation and exhalation. With a 3 s threshold in each state, a 6 s time period is set as the safer duration after which the device interprets the situation as a 'error'. The reasons for remaining in any of the states for more than 6 s may vary, but for safety reasons, the device will no longer take risks in sensing breathing. Instead, it will activate its emergency measures to maintain a constant flow of oxygen by turning off the solenoid valve. This can be considered one of

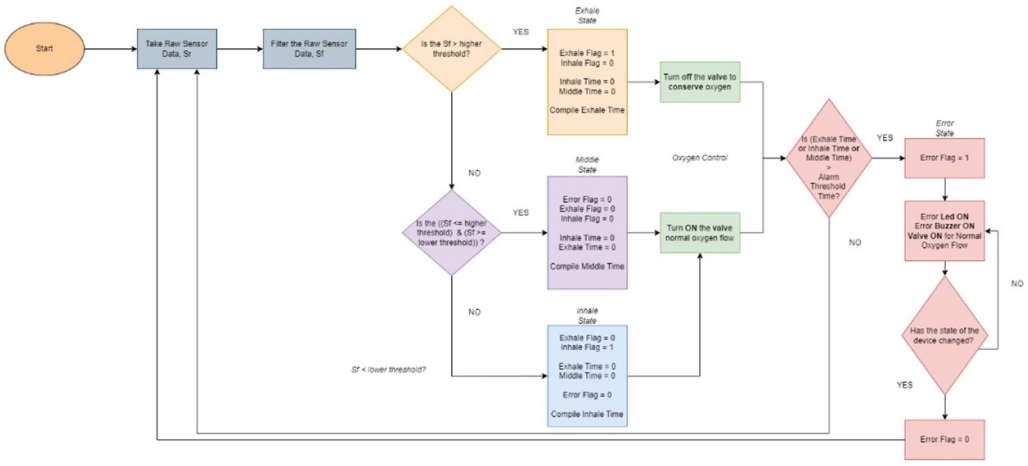

Figure 2. The complete flow of work of the algorithm that details the triggering mechanism, different breathing states and state transitions.

the device's important safety features. When the state changes normally again, the system automatically recovers and returns to the triggered mode.

A workflow in figure 2 explains the entire working mechanism of the sensing system and the transition between different states. Before gauging for errors, the device filters the raw pressure sensor data. A preliminary error check is performed, and if none are found, the device's state is switched to one of three states (exhale, middle or inhale). Following that, it monitored whether the device crossed a predetermined alarm threshold time in order to keep the patient safe. When such a condition occurs, an error is flagged, and error alarms are triggered. The valve is turned on for continuous oxygen flow while the alarms are set to sound.

3.1.3. Indicators and alarm system. The system also includes a set of indicators, as shown in figure 3(a), as well as an alarm system to inform and alert users and healthcare professionals of the device's working status or the patient's emergency condition. The OxySaver has four different colored LEDs (red, blue, green, and yellow) to convey the following device states.

Power on: When the switch is turned on, the red LED illuminates, indicating that the device is receiving enough current. The red light indicator will remain illuminated until the device is turned off or disconnected from the power source.

Calibration: When the power is turned on and a breath is detected, the device enters the calibration stage, during which the blue and red LEDs alternately flash until calibration is complete.

Inhalation: When a patient breathes in, the device detects it. In this case, the blue LED will illuminate and remain lit for the duration of the inhalation.

Exhalation: When the patient exhales or the inhalation stops, the device detects it and the green LED illuminates for the duration of the exhalation.

Error: The yellow LED will illuminate to indicate a system error. This state of the device also activates the buzzer, resulting in an alarm. When no breath is detected for more than 6 s, the device enters an error state and switches to continuous flow oxygen. This alerts medical personnel to check on the patient.

Figure 3(b) shows the design of the LED indicators and buzzer circuit, and figure 3(c) shows the PCB board of the embedded system (c).

3.2. Solenoid valve

As shown in figure 4, a NO solenoid valve with an operating pressure of 0.15–0.8 MPa was used to control the flow of oxygen from the oxygen cylinder to the patient. Until a charge is applied, a NO valve remains open. This ensures that oxygen flow continues in the event of a power outage, making the device ideal for LMIC hospital settings where such incidents are common. The oxygen flow is only interrupted when inhalation stops and exhalation begins, as detected by the embedded system's sensing algorithm. If the exhalation lasts longer than 6 s, the valve returns to its open position, providing continuous flow oxygen.

Barrel Jack and the solenoid: When working with people who connect modules or power externally, reverse polarity protection is a concern. Including this feature in the circuit would necessitate additional circuitry, increasing not only the cost but also the size. This problem has been solved by using a 6.3 mm stereo jack and barrels jack (figure 4(a)), which eliminates the possibility of connecting in reverse. Furthermore, the use of different connectors limits the movement of the connections.

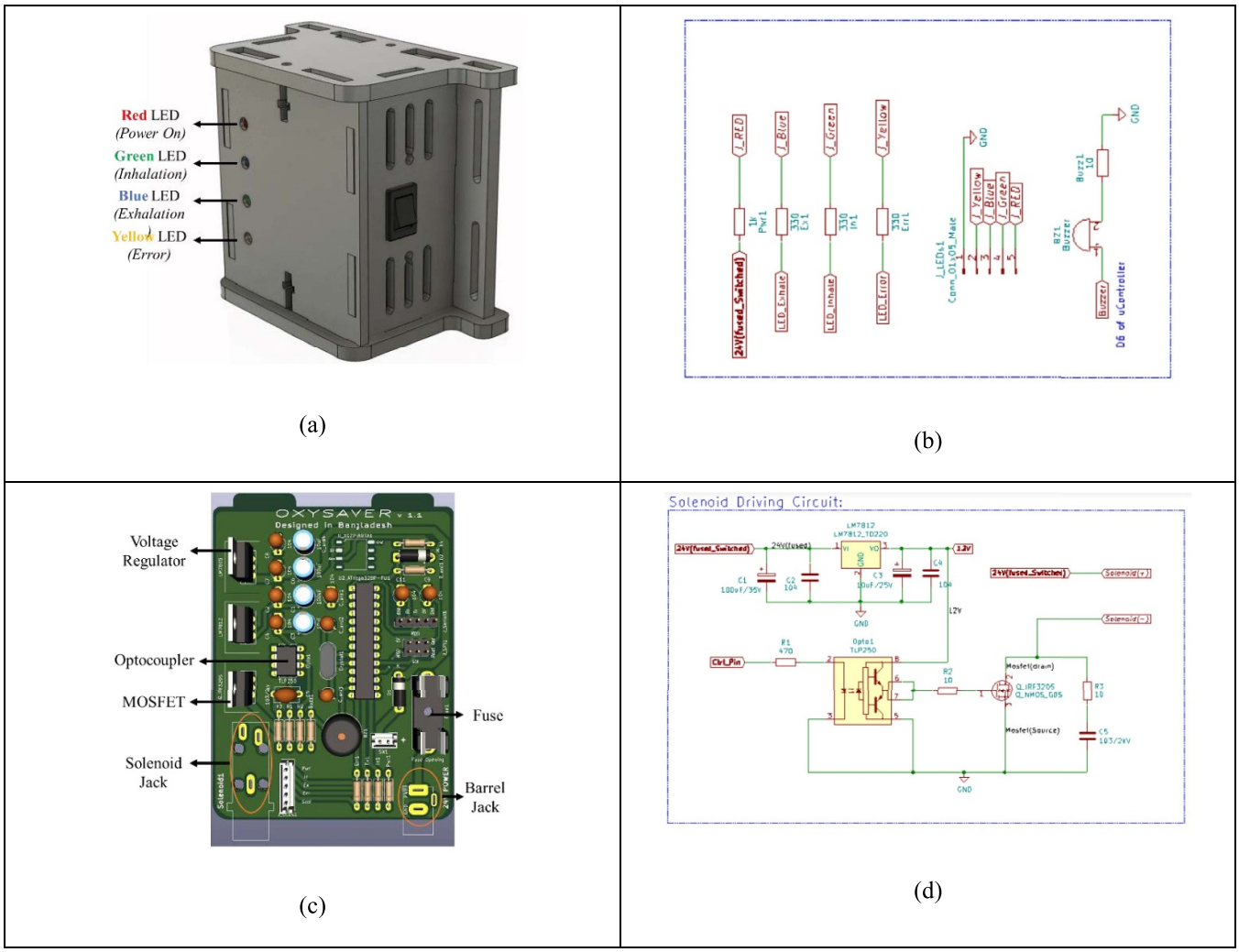

Figure 3. (a) 3D model design of the OxySaver box (b) the LED indicators and buzzer circuit design (c) internal circuitry on PCB (d) Solenoid driving circuit.

Triggering time: The amount of time required to enable continuous oxygen flow after it has been initiated by the microcontroller. Table 1 depicts the components involved in the triggering process. To begin, a high signal from a microcontroller digital pin is used to turn on the optocoupler. The optocoupler then turns on the MOSFET, which activates the solenoid valve. The optocoupler and MOSFET are chosen so that they have little effect on the triggering time. The table shows that their turning-on time is significantly lower than that of the solenoid valve. We could reduce the total time to trigger to as little as 50 ms this way.

Table 1. Triggering time.

Component	Time (s)
Solenoid valve	5.0×10^{-2}
Optocoupler	5.0×10^{-7}
MOSFET	1.2×10^{-7}
Total trigger time	5.0×10^{-2}

3.3. Power system

3.3.1. Power adapter. The external portion of the OxySaver's power system consists of a 24 V power adapter. This was chosen with the goal of making system implementation as simple as possible. The user can easily plug it into sockets, and the voltage requirement is low enough that it can be used at electrical outlets of any common power supply found in hospitals. Using a common power adapter eliminates the need for any external circuits, reducing the complexity and increasing the safety of the external power system. The adapter also employs a barrel jack design with both positive and negative power, as shown in figure 3(c), avoiding a situation in which adapters are connected to the power supply in the opposite direction, resulting in inverse polarity that may damage the device's operation.

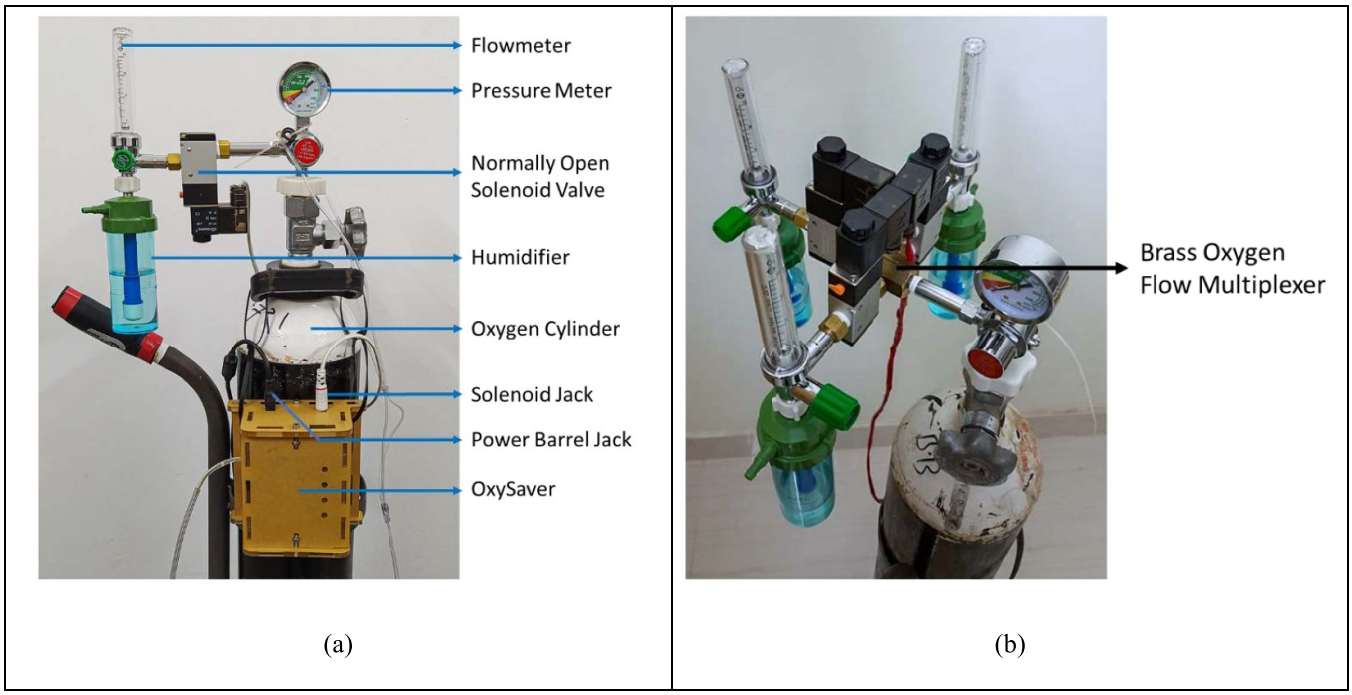

Figure 4. (a) The picture of the OxySaver setup with the conventional cylinder indicating different major components (b) tripartite valve attached to oxygen cylinder to allow multiplexing which can support up to three patients simultaneously.

Table 2. Fabrication cost.

Sl	Component	Cost (USD)
1	Electronic chips	32
2	PCB	2.0
3	Enclosure	5.0
4	Solenoid valve	7.0
5	Lathe machined adaptors	8.5
6	Assembly and testing	5
	TOTAL	∼60 $

3.3.2. Power management system. *Fuse:* Internally, the device is equipped with a fuse for safety, preventing current flows greater than 2 A and thus protecting the wiring and device from any power source malfunctions.

Voltage regulators: The device also employs two separate voltage regulators for 5 V (LM7805 IC) and 12 V (LM7812 IC), as shown in figure 3(d). These are fixed positive voltage integrated circuit (IC) regulators that can accept up to 35 V of input voltage and provide more than 1.5 A of current while maintaining proper heat dissipation. The functionality of the regulators is extensive. They have a thermal shutdown feature that activates when the junction temperature rises to 150 °C, protecting a safe operation area [31]. They can limit current to 2.4 A in the event of a short circuit to protect against damage. The OxySaver connects the power supply to the embedded system via the 5 V regulator and the optocoupler via the 12 V regulator.

Optocoupler: To provide a phase of protection via optical isolation, an optocoupler (Model:0TLP250) was used. The optocoupler receives a signal from the embedded system and provides a gate driving circuit for the MOSFET, which controls the device's solenoid valve. It transmits the power signal from the embedded system via an LED light, avoiding a direct connection with the MOSFET. This safeguards the embedded system against any damage caused by reverse electromotive force [32].

3.4. Multiplexing oxygen delivery

To connect three OxySaver devices to a single oxygen cylinder, a three-way valve (figure 4(b)) can be attached to the cylinder. This is a multiplexing technique that allows three streams of oxygen to be delivered to three patients at the same time. This allows multiple patients to be given oxygen from the same cylinder while also conserving oxygen via the OxySaver device to ensure that hospital oxygen supplies last longer.

3.5. Fabrication cost

Table 2 shows the cost breakdown for producing a single OxySaver unit. If the cost of refilling a cylinder is 12 USD,

the cost of a single OxySaver is comparable to the cost of five cylinder refills.

4. Technical performance testing

OxySaver performance was evaluated using a variety of benchmarking tools, including a flow analyzer (Model: Citrex H4), an oscilloscope (Model: Rigol DS1054Z), and a data logger (Model: National Instruments USB 6001 DAQ mx).

4.1. Performance testing through flow analyzer

An experiment was designed to validate the device's performance using the setup shown in (figure 5). The oxygen supply setup was similar to that shown in (figure 1), with the exception that the oxygen flow output was connected to a flow analyzer (Citrex H4), which was then connected to a nasal cannula, which carried the oxygen to the patient. Another cannula, on the other hand, was connected solely for detecting the patient's nasal pressure in order to operate the OxySaver. The flow analyzer assisted us in graphing the flow of oxygen as the solenoid switched it on and off based on the patient's breath.

Readings were taken under two different conditions: the first using an oxygen delivery system without the OxySaver, and the second with the OxySaver connected to the system. The experiment results, as shown in the graphs (figure 6), show that the OxySaver can smoothly and accurately trigger the solenoid in response to the patient's breathing pattern.

Figure 6(a) depicts the operation of the oxygen supply when the flow meter was set to 5 l min^{-1}. The dotted line represents an arbitrary line that depicts how a conventional oxygen delivery system would behave, whereas the solid line depicts the on/off behavior of the oxygen supply in relation to the patient's breathing ratio. As a result, a significant amount of oxygen is saved per patient per cylinder. Figure 6(b) depicts an oxygen flow cycle in greater detail. Here, we can see that it takes approximately 205 ms to increase the oxygen flow to 90% of its maximum range and 190 ms to return to 10% flow level.

To simulate a situation in which a patient might hyperventilate, the test subject was asked to change breathing rates from slow to fast, hyperventilate, and then return to normal (figure 7). The sharp spikes in the flow change indicate the strength of the OxySaver, which is designed to adapt to any patient's breathing pattern, even hyperventilation. Throughout this portion of the experiment, the oxygen supplied by the cylinder was kept constant.

To validate OxySaver's performance during flow changes during device operation, the flow was varied from 5 l min^{-1} to 10 l min^{-1} to 18 l min^{-1} with a 15 s interval. The flow data logged in the Citrex H4 flow analyzer is shown in (figure 8). There was no discernible difference in the patient's breathing or the device's functionality when the flow level was increased from 5 to 10 and then from 10 to 18 l min^{-1}.

5. Clinical performance testing

5.1. Inhale/exhale ratio detection

OxySaver has UART ports that allow it to be read directly by a computer. This also allows for code uploading by removing the microcontroller from the PCB. The device was connected to a computer for verification of the data generated and how it adapts with different *I:E* ratios, and (figure 9) shows that the system was able to adapt to any breathing ratio that a patient/subject may have. Throughout the experiment, the volunteer Subject's *I:E* ratio had a very slight deviation but remained within an acceptable medical range.

Figure 9(a) depicts the subject's inhale to exhale ratio over time, and 9(b) depicts the solenoid valve's triggering signal in response to analog readings from the pressure sensor responsible for breath detection. As shown in the graphs, the system detects the breathing pattern via pressure changes and generates the solenoid trigger signal accordingly. The signal is activated just before the inhalation and exhalation detection points. Figure 9(c) depicts a single cycle of operation in detail. Here, we can see that the trigger's rising and falling times are both 50 ms, as previously explained in detail in table 1. The trigger is triggered when the sensed pressure rises by 57% and falls by 43% during inhalation and exhalation, respectively. Equations (1) and (2) previously explained how to calculate these threshold values. Table 3 summarizes a detailed picture of the overall latency found in figures 6 and 9. The time it takes from inhalation detection to reaching 90% oxygen flow is approximately 255 ms. The time it takes from exhalation detection to reducing the oxygen flow to 10%, on the other hand, is 240 ms.

A similar test was performed to observe the sensing vs MOSFET switching vs MCU output using an oscilloscope, as shown in S figure 3.

5.2. OxySaver endurance test

The OxySaver has been tested to demonstrate that it can triple the life of an oxygen cylinder. We measured the time it took for the cylinder to run out while connected to a patient, with and without the use of OxySaver, in this test. When the pressure in a typical 10 l oxygen cylinder reaches atmospheric pressure (14.7 psi), the cylinder has completely run out. Both experiments were carried out at an initial pressure of 1800 psi cylinder pressure. The flow rate was kept constant at 10 l min^{-1} in both cases during the experiment (with and without the OxySaver).

The results in table 4 show that the time taken for the cylinder pressure to drop from 1800 psi to 14.7 psi (cylinder empty) was 122.45 min or 2.04 h for the system without OxySaver, but 367.72 min or 6.13 h for the system with OxySaver, indicating that the OxySaver can effectively increase the duration of a cylinder by three times. It is important to note that some observations of this test were completed entirely by hand, including logging of flowrate and pressure data at

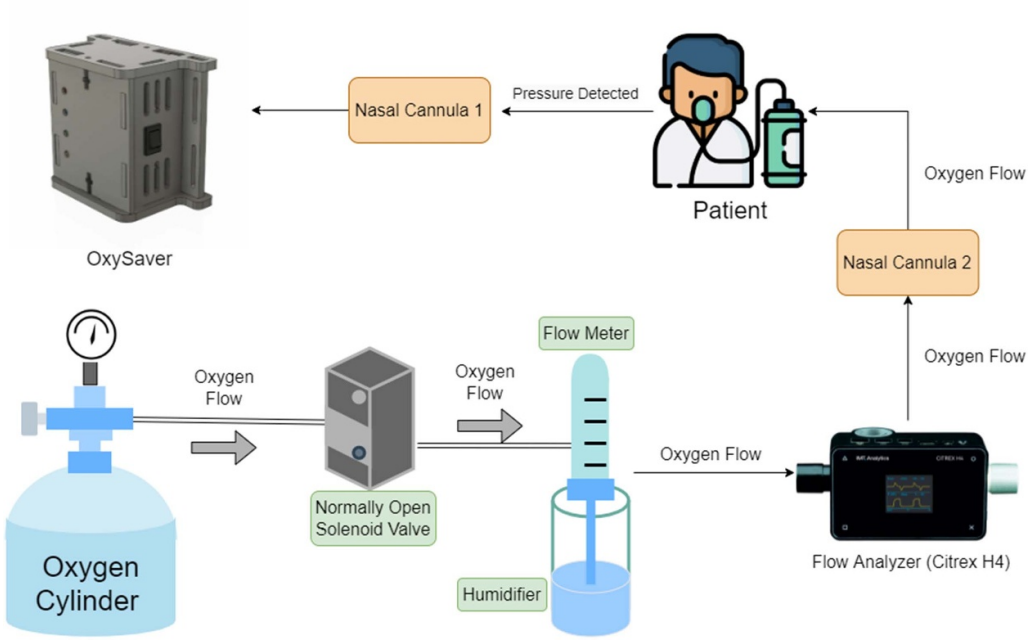

Figure 5. OxySaver experimental setup with flow analyzer for performance testing.

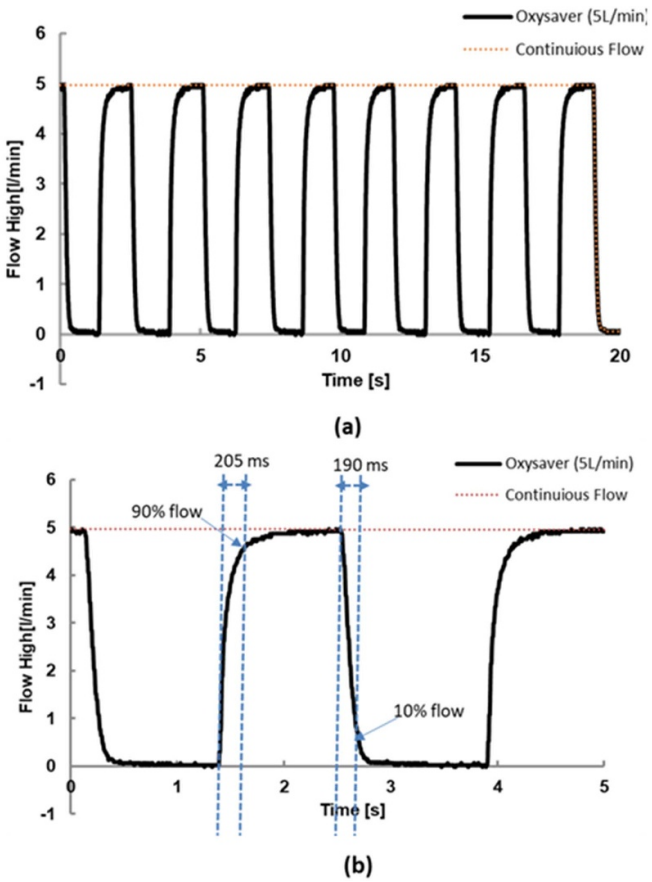

Figure 6. Graph of 5 l min^{-1} oxygen flow with the OxySaver and continuous flow against the time.

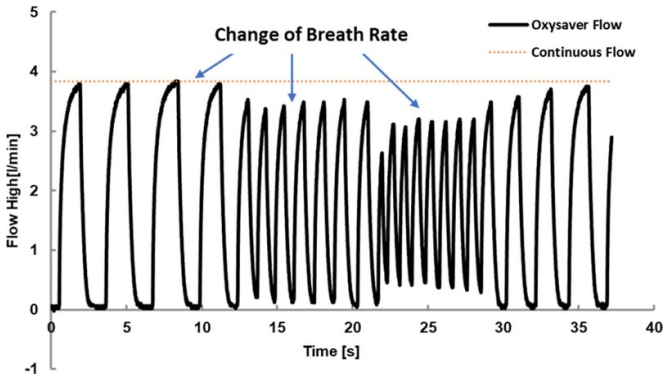

Figure 7. Graph of oxygen flow with the OxySaver and continuous flow against time during the change of breath rate of the patient.

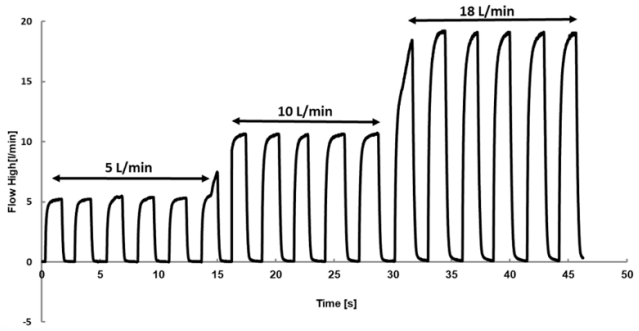

Figure 8. Graph of oxygen flow with the OxySaver with keeping the breathing rate constant but varying flow.

various time intervals. As a result, for comparison purposes, we only considered the total time required to empty the cylinder in each case. Pressure drop vs. time interval data for both continuous and oxysaver would be interesting but doubtful for the reasons stated, so it has not been presented. In the supplementary, we demonstrated another test run in which

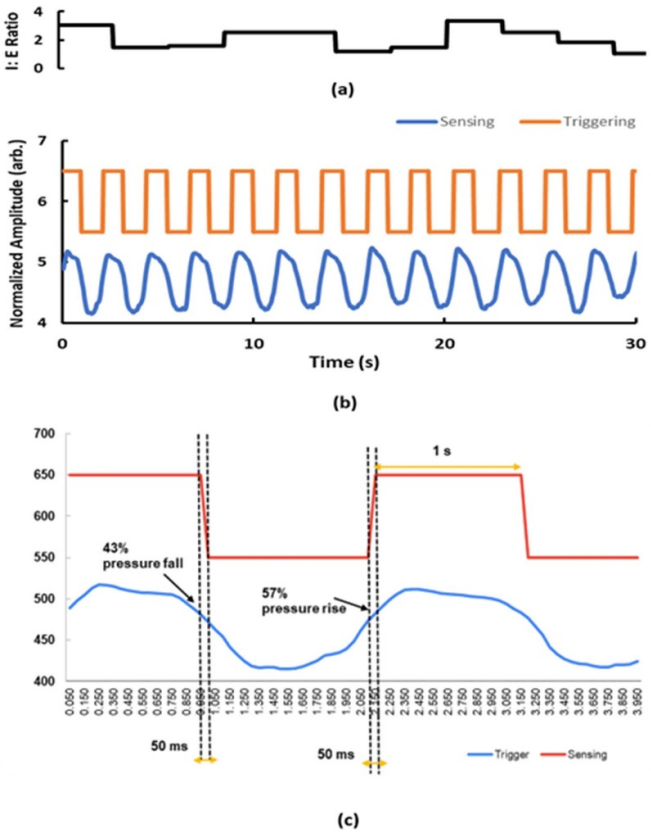

Figure 9. Sensing vs triggering graph indicates the low latency of triggering the solenoid valve.

we attempted to automatically log some data for a shorter segment.

6. Discussion

6.1. Reusability

The OxySaver can be reused without needing to be replaced. To reuse the device, very few changes must be made; all that is required is to attach the valve-mounted flowmeter to the new cylinder and replace or sterilize the nasal cannula connected to the device. Because the OxySaver can extend the life of a cylinder by three times, the device's reusability allows every patient who uses it to save the cost of two cylinder refills.

6.2. Cost vs throughput

In a large-scale scenario, such as a hospital, where several oxygen cylinders are required each day, the OxySaver is expected to significantly reduce the number of cylinders required for a patient within a given duration, resulting in a substantial reduction in the cost of cylinder refills for a patient. We attempted to provide a sample calculation of conservation under normal breathing conditions and a standard/close to normal *I:E* ratio. For example, if 12 cylinders are used in succession without attaching the OxySaver, the cylinders will last approximately 24.48 h, provided that the duration of a single cylinder without the OxySaver is 2.04 h, as shown in the experimental details in table 4. In 24.48 h, approximately 4 cylinders will be used with the OxySaver (about 6.13 h for each cylinder). If each refill costs 12 USD, then using the OxySaver will save you 96 USD, which is the cost of eight cylinder refills. This cost savings is especially significant in LMIC hospitals, where the resource-to-patient ratio is quite high.

6.3. Market comparison

According to market research on commonly used oxygen concentrators made by Airsep, Phillips, O2 Concepts, and Inogen, each of these devices had a built-in alarm system to be used in emergency settings. When the device does not detect a breath, an alarm sounds to notify the user that they are not receiving an oxygen supply. This is possible, however, because these devices are designed for use in a home or personal setting where users have the flexibility and freedom to make adjustments to the device. In clinical settings, emergency provisions must be in place to prevent any prolonged interruption in oxygen flow. Patients in critical care units are also unable to adjust their own oxygen flow, wasting valuable time responding to the alarm and increasing the risk of patient mortality. As a result, unlike these oxygen conservation devices, the proposed solution includes an emergency alarm system with a setting that switches from pulse flow to continuous flow if breathing or pressure changes are not detected for more than 6 s. This means that patients will continue to receive supplemental oxygen until the problems are resolved, lowering the risk of hypoxia-related complications for patients who require a continuous dose of supplemental oxygen.

The comparison of three oxygen conserving devices is shown in table 5. All of these devices use pulse flow settings to conserve oxygen. When compared to the conventional method, OxySaver can save up to 67% of the oxygen, while Oxymizer can save up to a 4:1 savings ratio. OxySaver is the only device among these that has both pulse flow and continuous flow settings, allowing the device to easily switch to continuous flow if an emergency occurs. The pulse flow setting on the OxySaver and Oxymizer can be increased to 15 LPM, while the Inogen One G5 has multiple pulse flow settings. It also shows that OxySaver does not need to be replaced, whereas Oxymizer should be replaced every three weeks or so. The price of these devices is one of the most noticeable differences. The Inogen One G5 is priced between $2495 and $2995. Although the Oxymizer appears to be inexpensive at $ 24.50 per piece, it actually costs more because it must be replaced frequently. OxySaver, on the other hand, is the most affordable, costing $ 191.94 for 11–100 units.

7. Limitations

The Oxysaver device, its technical specifications, and performance are presented here. The current device's performance has been evaluated on a small number of subjects. The device's robustness has not yet been tested, and test performance in clinical settings is lacking. The healthy subjects were

Table 3. Detail information about the time taken to trigger the switch and oxygen supply during inhale and exhale process.

	Trigger time (ms)	Time to reach 90% flow (ms)	Time to reach 10% flow (ms)	Inhalation detection to relay switching	Inhalation detection to oxygen supply	Exhalation detection to relay switching	Exhalation detection to oxygen supply
Inhale	50	205		50	255		
Exhale	50		190			50	240

Table 4. Comparison of Oxysaver and continuous flow endurance.

Device	Starting pressure	Ending pressure	Flow rate	Duration
Oxysaver	1800	14.7	10 l min^{-1}	367.72 min
Continuous flow	1800	14.7	10 l min^{-1}	122.45 min

Table 5. Comparison between Bioforge OxySaver and similar devices.

Company	Bioforge	Inogen	Devilbiss healthcare
Device name	OxySaver	Inogen One® G5	Oxymizer®
Oxygen type	Liquid oxygen —>gas	Concentrated oxygen collected from air	Oxygen cylinders, concentrators and liquid oxygen
Power consumption	3.72 W at 50 bpm	18.7 Watts w/ 8 cell battery, 18.4 Watts w/16 cell battery	—
Device working	Pulse flow and continuous flow	Pulse flow	Pulse dose
Continuous flow setting	Up to 15 LPM	—	—
Pulse flow setting	Up to 15 LPM (both cannula and mask)	Pulse setting 1–5; 210–1260 ml min^{-1}	Up to 15 LPM
Oxygen conservation	Conserve up to 67% compared to the conventional method	Oxygen conserving device using pulse flow technology	Conserve up to 30 ml of oxygen, delivers up to a 4:1 savings ratio
Replacement requirement	There's no replacement requirement	—	Should be replaced after approximately three weeks
Price	11-100 units (16217BDT/$191.94)	$2495–$2995	1/EA- $24.50, 24/Case-$599.95

chosen at random for technical performance testing. As a result, the majority of the experiment was completed in less than 3–5 min because too much oxygen can be toxic to a healthy individual. Despite the fact that the experiments were carried out in the presence of certified physicians, the full clinical settings were missing. The device was only connected to one subject during the endurance test. However, *I:E* ratios can vary and be inconsistent from subject to subject, and it would be interesting to know what the final duration would be if the patient is hyperventilating or has slower breathing patterns than normal.

8. Future work

While the device is demonstrated to work conceptually, the current work does not demonstrate testing the robustness of the device's functionality over an extended period of time in clinical settings. As a result, a protocol titled 'The OxySaver, A Demand-Oxygen Delivery System (DODS); An Effective Device for Oxygen Conservation Compared to Standard Continuous Oxygen Delivery: A Randomized Control Trial (RCT)' was developed and approved by the Bangladesh Medical Research Council. It is now being prepared for rigorous testing in BMC. This will include two distinct study groups that will be assigned to compare two different interventions. Oxysaver will deliver oxygen to patients in the experimental group, while traditional continuous flow oxygen will be delivered to patients in the control group.

9. Conclusion

Patients suffering from chronic lung disease require supplemental oxygen, which is typically delivered in the form of oxygen cylinders. New oxygen delivery methods have been investigated as a potential solution in light of the sudden increase in oxygen demand caused by the COVID-19 pandemic and the lack of oxygen supply. OxySaver, a novel DODS, has been designed to reduce oxygen consumption significantly and cost-effectively. OxySaver might be appropriate for low-resource environments. Multiplexing enables it to serve multiple patients from a single source, maximizing usage efficiency. OxySaver has the potential to increase hospital oxygen treatment capacity. We believe OxySaver's oxygen conservation will assist in meeting COVID-19 or any future oxygen demand.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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