# Low-cost Oxygen Concentrator, Popovic Labs, WPI, April 2020

**(inventors Marko Popovic, Matthew Bowers, Ellen Clarrissimeaux)**

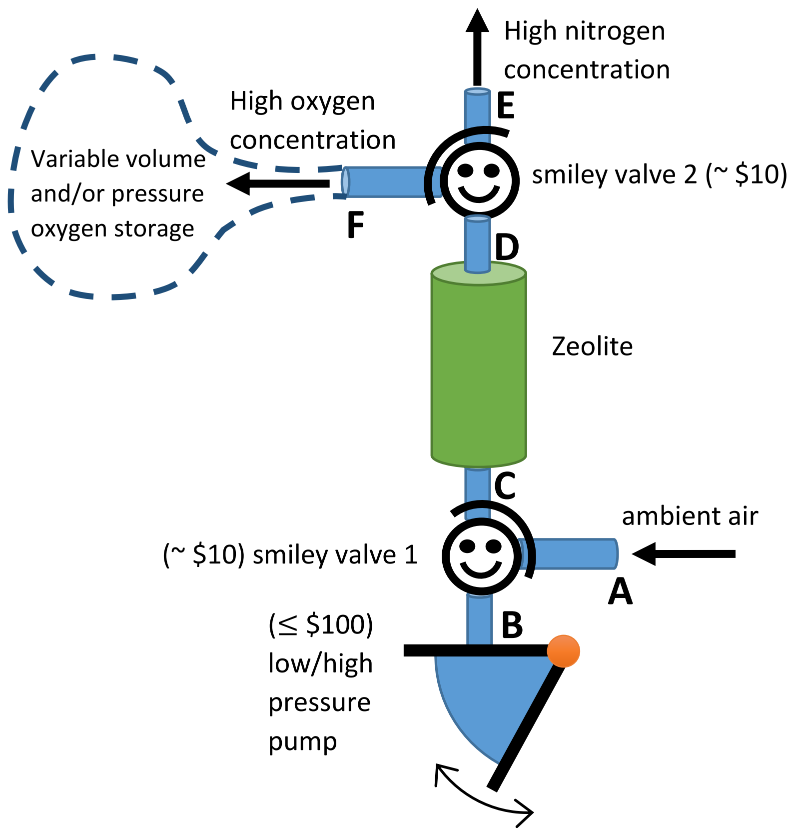



**Figure 1. Simple, easy-to-manufacture, low-cost Oxygen Concentrator anticipated to generate 90-95% medical-grade oxygen in a continuous fashion. The device can be employed as it is or it may be part of a medical-grade ventilator. Its operation is based on a pressure vacuum swing adsorption (PVSA) method. Device consists of: 1 Zeolite molecular sieve, 1 low/high pressure pump, 2 "smiley" 3-way valves, Arduino type controller, tubing and tube connectors. Manufacturing cost is estimated at not more than several hundred USD for system that could provide oxygen supply for in between 4 and 20 patients. (!)**

**<u>Operation principle:</u>**

**Step 1.** Valve 1 BC open, valve 2 closed, pump closing, high pressure

**Step 2.** Valve 1 closed, valve 2 DF open, high-$O_2$-concentration output

**Step 3.** Valve 1 BC open, valve 2 closed, pump opening, low pressure

**Step 4.** Valve 1 AB open, valve 2 closed, atmospheric pressure inside pump

**Step 5.** Valve 1 BC open, valve 2 DE open, pump closing, high-nitrogen-concentration output

**Step 6.** Valve 1 AB open, valve 2 closed, pump opening, atmospheric pressure inside pump

**Executive Summary**

The proposed device inputs ambient air and outputs high-$O_2$-concentrated air by utilizing *pressure vacuum swing adsorption* (PVSA) method. Nitrogen is first adsorbed by Zeolite at high pressure. The leftover high-$O_2$-concentrated air is then passed to output. Nitrogen subsequently detaches from Zeolite by use of very low pressure (below atmospheric pressure) and high-nitrogen-concentrated air is vented out as exhaust.

Another popular approach is *pressure swing adsorption* (PSA) method. The PSA method differs from PVSA method as there is no application of very low pressure. Hence, PSA method requires more time for Zeolite to 'regenerate', that is for nitrogen to detach. Still further, PSA method may leave more nitrogen stuck inside Zeolite micro-cracks after 'regeneration' is completed; this in turn affects the Zeolite's ability to capture more nitrogen during the next cycle. Hence, a device based on PVSA method can have shorter cycle time and may provide better oxygen concentration.

The novelty of the proposed device is that it requires only one Zeolite molecular sieve instead of commonly used pair. This is possible as very little time is required to complete an entire cycle for PVSA method; it may take less than 0.5s (up to 20s) for Zeolite 'regeneration' within the PVSA (PSA) method. This in turn allows for much simpler and more cost-effective device architecture requiring only 2 three-way valves instead of the typical 6 solenoid valves.

Another advantage of this device architecture is that it allows for quick real time control, that is stabilization of volume and/or pressure inside the variable volume and/or pressure oxygen storage, Figure 1, anticipated to be an intermediary between oxygen concentrator and either (1) patient breathing air directly or (2) rest of ventilator for example in the form of motorized Bag-Valve-Mask (BVM) type resuscitator. Additional pressure/volume sensor may be required to monitor pressure/volume inside oxygen storage. For example, if there is accumulation/lack of oxygen the pressure may increase/decrease and motorized low/high pressure pump will automatically slow down/speed up.

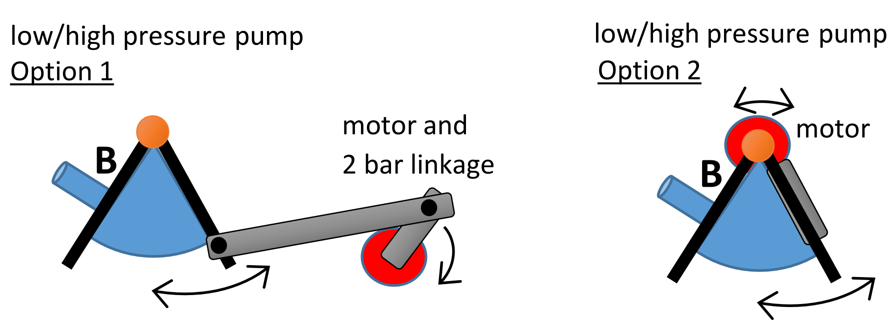



**Figure 2. Option 1: The pump motor may rotate in single direction if added with 2 bar linkage mechanism (similar to slider-crank) with one end attached to the main crankshaft bearing and other end attached to one arm of the bellow pump. Option 2: the pump motor can be directly attached to one arm of the bellow pump requiring alternating direction of rotation; two switch sensors can be used to trigger change of direction and subsequent action of 2 three-way valves.**

While there is a number of potentially good solutions for choice of low/high pressure pump the simple motorized bellows pump is envisioned to be used here. As it will be discussed in more details there is a $100 motor solution that can be used to provide oxygen supplies to number of patients (4 to 20) simultaneously and thus lower the overall manufacturing costs per patient. The pump speed can be finely tuned to provide optimal performance of Oxygen Concentrator.

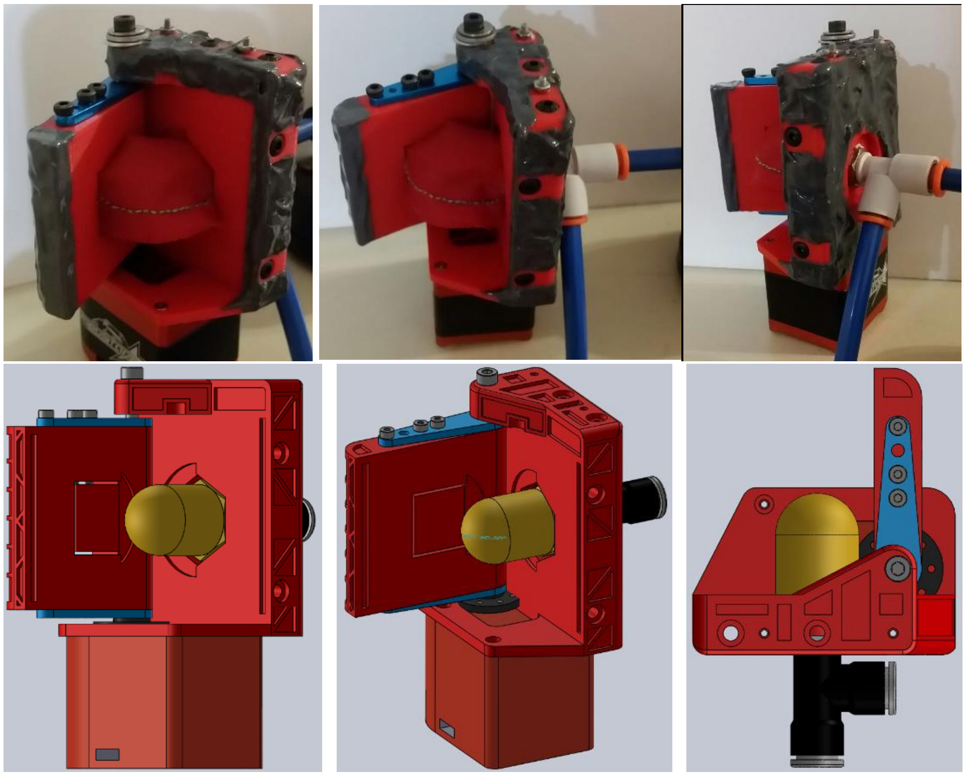
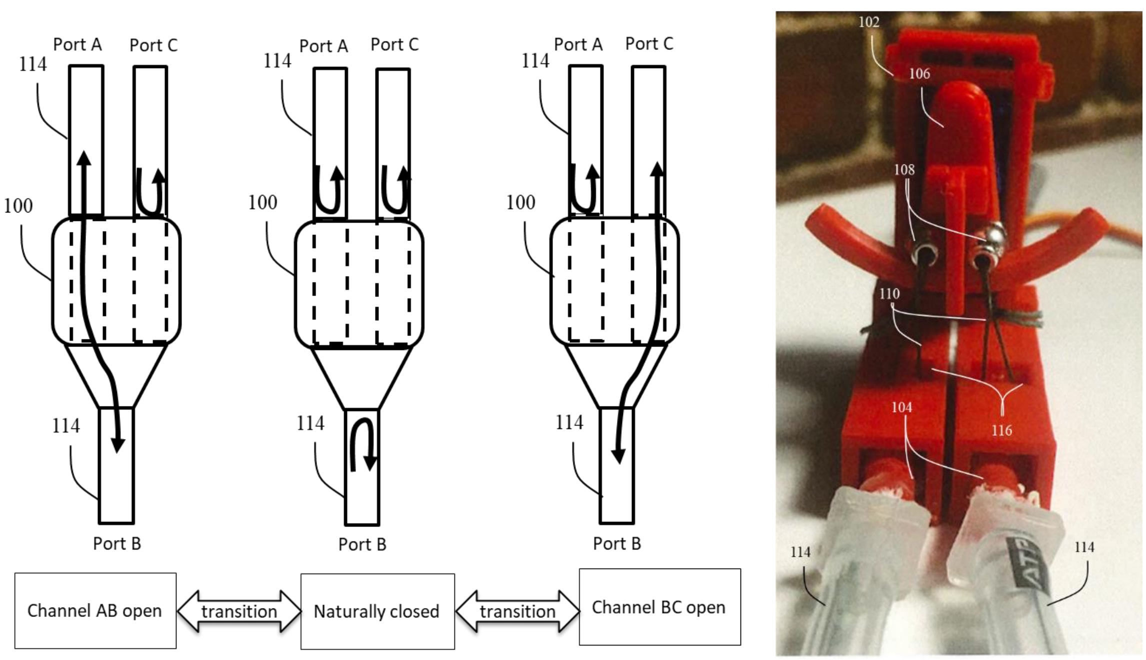


**Figure 3. The miniature prototype and CAD model of *Option 2* low/high pressure pump without valve.**



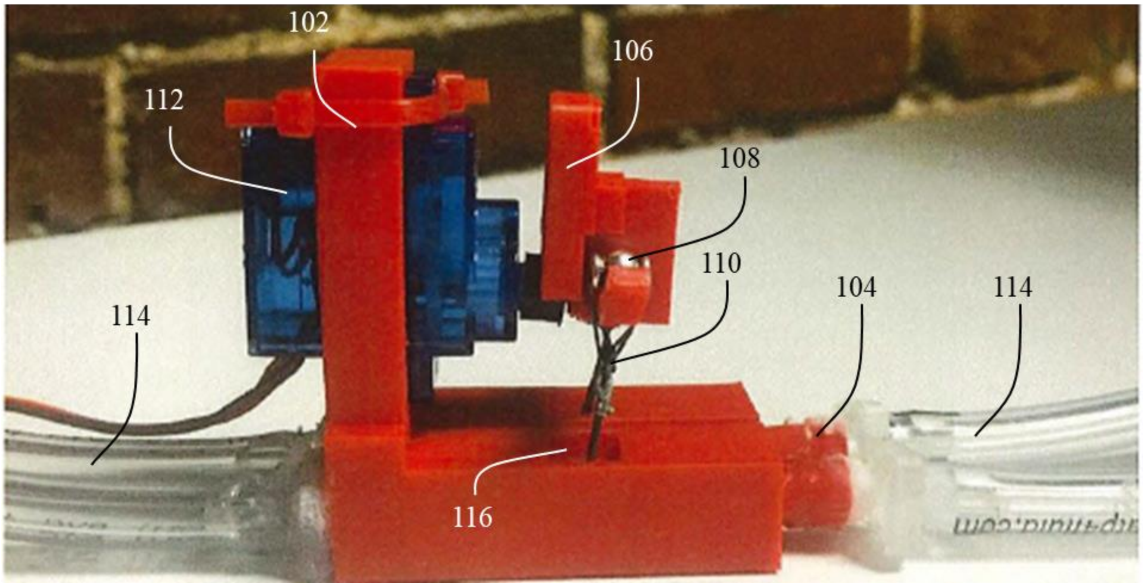



**Figure 4 The Compact Robotic Flow Control (CRFC) Valve** ( https://www.wpi.edu/offices/technology-commercialization/catalog/fluid-flow-control-valve ) **is anticipated to be used as the 3-way "Smiley" valve, see Figure 1. This 3D printed 3-way valve requires only $10 servo to operate for given pressure and flow conditions.**

The Oxygen Concentrator may output high-$O_2$-concentrated air after oxygen storage at desired pressure and in desired volume portions at desired time intervals if additional structure is added. This structure may include some of the following: 1 one-directional check valve, 1 pressure-control check valve, 1 variable volume air compartment, 1 flow meter, 1 pressure sensor, and/or 1 three-way valve.

## Device specifications

| Symbol | Description |
|---|---|
| $V_{PA}$ | volume of pump's air compartment for fully open pump |
| $V_{ZA}$ | volume available to air inside the Zeolite compartment |
| $V_Z$ | volume of the Zeolite compartment |
| $FR$ | flow rate of output high-$O_2$-concentrated air |
| $N_P$ | pump's frequency, i.e. number of pump's opens-and-closes cycles each second |
| $p_{atm}$ | ambient atmospheric pressure |
| $\Delta p_+$ | increase in air pressure relative to ambient atmospheric pressure |
| $\Delta p_-$ | decrease in air pressure relative to ambient atmospheric pressure |
| $R$ | radius of pump's air compartment |
| $l$ | length of pump's air compartment |

$\theta_{max}$ maximal opening angle of pump's air compartment (i.e. angle for fully open pump)

$\tau_{max}$ Pump's motor maximal torque during opens-and-closes cycle

$\omega$ pump's motor angular speed

The pressure range for some of the existing PVSA devices is $\sim 0.2\, p_{atm}\ to\ 2.8\, p_{atm}$ also corresponding to $-0.8\ barg\ to\ 1.8\ barg$, for example see

Pan, M., Omar, H.M. and Rohani, S., 2017. Application of Nanosize Zeolite Molecular Sieves for Medical Oxygen Concentration. *Nanomaterials*, *7*(8), p.195.

( https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5575677/ )

The device proposed here outputs high-$O_2$-concentrated air with flow rate that should be at least in the regular range of 5 to 8 liters per minute, that is 5.0 to 8.0 $\times\, 10^{-3} m^3/min$ or 0.8 to 1.3$\times\, 10^{-4} m^3/s$. This flow rate should be sufficient for patient inhaling high-$O_2$-concentrated air directly from device (with intermediary variable volume and/or pressure oxygen storage). In the case of high-$O_2$-concentrated air even 4 liters per minute should be sufficient according to literature.

In the case of motorized Bag-Valve-Mask (BVM) type resuscitator one may require factor 2 or even 3 larger flow due to leaks and contamination with ambient air. Hence universal device should preferably be capable of outputting up to 20 liters per minute, that is 3.2$\times\, 10^{-4} m^3/s$.

This flow rate can be related to volume of pump's air compartment for fully open pump, $V_{PA}$ , and pump's frequency, $N_P$ , as

$$FR = V_{PA} N_P / 2 \tag{1}$$

according to the device's operational steps. Pump performs two open-and-close cycles per single device's operating cycle for one volume of the pump's air compartment for fully open pump, $V_{PA}$ , to be released by device in the form of high-$O_2$-concentrated air.

The volume of the pump's air compartment for fully open pump, $V_{PA}$ , can be expressed in terms of the pump's air compartment radius, $R$, length, $l$, and maximal opening angle, $\theta_{max}$, as

$$V_{PA} = l R^2 \theta_{max} / 2 \tag{2}$$

The increase in air pressure relative to the ambient atmospheric pressure, $\Delta p_+$, just after the Zeolite chamber air is maximally pressurized can be estimated using isothermal assumption

$$p_{atm}(V_{PA} + V_{ZA}) = (p_{atm} + \Delta p_+) V_{ZA} \tag{3}$$

Hence

$$\Delta p_+ = p_{atm} \frac{V_{PA}}{V_{ZA}} \tag{4}$$

Note that the volume available to air inside the Zeolite compartment is smaller than volume of the Zeolite compartment, that is $V_{ZA} < V_Z$.

The decrease in air pressure relative to the ambient atmospheric pressure, $\Delta p_-$, just after the Zeolite chamber air is maximally depressurized, can again be estimated using isothermal assumption

$$p_{atm}V_{ZA} = (p_{atm} + \Delta p_-)(V_{PA} + V_{ZA}) \tag{5}$$

Hence

$$\Delta p_- = -p_{atm}\frac{V_{PA}}{V_{PA} + V_{ZA}} \tag{6}$$

One could choose desired $\Delta p_+$ and hence $\Delta p_-$ by choosing appropriate $\frac{V_{PA}}{V_{ZA}}$ based on equations [4] and [6]. For example for $\frac{V_{PA}}{V_{ZA}} = 4$ one obtains $\Delta p_+ = 4\ barg$ and $\Delta p_- = -0.8\ barg$.

As shown in Figure 5 more nitrogen than oxygen is adsorbed in Zeolite for larger $\Delta p_+$. However larger $\Delta p_+$ requires a stronger (larger torque) pump motor.

The maximal motor torque, $\tau_{max}$, is related to $\Delta p_+$, if friction is ignored, as

$$\tau_{max} = \int_0^R r\Delta p_+ l dr = \Delta p_+ l R^2/2 \tag{7}$$

Here, as before, $l$ is the length of the pump's air compartment and $R$ is the radius of the pump's air compartment.

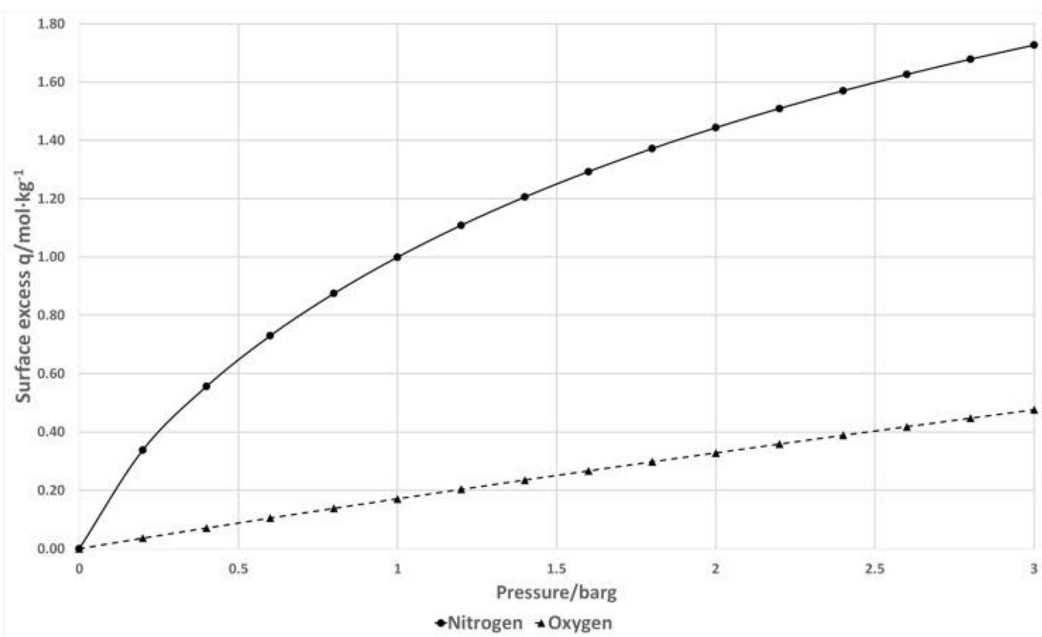



**Figure 5.** Adsorption equilibrium isotherms for nitrogen and oxygen onto zeolite LiX at 20 °C. Reproduced from: Santos J.C., Magalhaes F.D., Mendes A. Contamination of zeolites used in oxygen production by PSA: Effects of water and carbon dioxide. Ind. Eng. Chem. Res. 2008;47:6197–6203. doi: 10.1021/ie800024c.

Finally, the pump's motor speed can be expressed as

$$\omega = 2\theta_{max} N_P \tag{8}$$

By multiplying equations [7] and [8] one obtains the motor's maximal mechanical power output

$$\tau_{max}\omega = \Delta p_+ l R^2 \theta_{max} N_P = 4\, FR\, \Delta p_+ \tag{9}$$

For example if $FR = 3.2 \times 10^{-4} m^3/s$ and $\Delta p_+ = 1.8 \times 10^5 Pa$ then the

output mechanical power is 230W.

Standard concentrators utilize even lower pressure $\Delta p_+ = 1.4 \times 10^5 Pa$ to deliver 90-95% $O_2$ air like standard DeVilbiss Oxygen Concentrator addressed in:

Fenton PM. "The Malawi anaesthetic machine (experience with a new type of anaesthetic apparatus for developing countries)". Anaesthesia 1989;44:498–503.10

Pederson J, Nyrop M. "Anaesthetic equipment for a developing country".British Journal of Anaesthesia 1991;66:264–70.

See also:

R. J. Eltringham and A. Varvinski "The Oxyvent# An anaesthetic machine designed to be used in developing countries and difficult situations". Anaesthesia, 1997,52, pages 668–672.

Available from:

https://www.researchgate.net/publication/13975940_The_OxyventAn_anaesthetic_machine_designed_to_be_used_in_developing_countries_and_difficult_situations [accessed Apr 06 2020].

Thus, one could consider $FR = 3.2 \times 10^{-4} m^3/s$ and $\Delta p_+ = 1.4 \times 10^5 Pa$ corresponding to less demanding output mechanical power of 179W.

**Pump motor considerations – cost effective approach**

For example, low cost motor solution could be:

1.5 HP 50:1 GEAR RATIO 12V SLIM UNIVERSAL DUMP TRUCK TARPING SYSTEM MOTOR (APACHE)

Price: **$113.50** @

https://tarpingusa.com/products/apache-slim-universal-dump-truck-tarping-system-motor-1-5-hp-50-1-gear-ratio-12v

The Apache Slim Universal Dump Truck Tarp Motor 1.5HP 50:1 Gear Ratio 12V specifications:

Type: Direct Drive; Gear ratio: 50:1; Power: 1.5 HP; Output Shaft: 3/4" x 3-3/4", with two 5/16" through-holes; Voltage: 12V; Operating torque: 44 NM; Current Draw @ rated torque: 40 Amps; RPM: 76~80; Wattage: 600W; Gear: Worm to Wheel; Mounting: Three 5/16"-18 bolts; Braking: Inherent; Dimensions: L:12", W:6.5", H:4";

Or similar motor:

900W 90:1 Gear Ratio 1.2HP Electric Tarp Motor (Raptor)

Price: **$124.00** @

https://unitedtarping.com/products/presale-900w-90-1-gear-ratio-1-2hp-electric-tarp-motor-raptor

U-RAPTOR-90-1 specifications:

Case Grounded: No; Chrome Cover: Yes; Diameter: 3.125; Shaft Diameter: 0.750; Shaft Type: Thru-hole; Mounting Pattern: Fits All 3 & 4 Bolt Configurations; Voltage: 12V DC; Rotation: Bi-Directional; Power: 1.2 HP; Wattage: 900 W; Speed: 40 RPM; Gear Ratio: 90:1;

Based on previous specifications either of these motors could actuate one or more bellow pumps simultaneously either through Option 1 (2 bar linkage added, single rotational direction) or Option 2 (motor directly attached to bellow pump, alternating rotational direction).

**In other words, single motor can produce up to 80 liters of high-$O_2$-concentrated air per minute which should be sufficient for in-between 4 to 20 patients (!) depending on how device is exactly used.**