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THE COREVENT 2020: AN OPEN-SOURCE, RAPID DESIGN-BUILD-TEST EMERGENCY VENTILATOR DEVELOPED FOR COVID-19

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In the first quarter of 2020, SARs-CoV-2 (COVID-19) infections began to grow at an alarming rate despite drastic measures to reduce infection rates. Severe COVID-19 cases required mechanical ventilation, resulting in ventilator shortages worldwide. To address the ventilator shortages, the authors developed the CoreVent 2020, an emergency-use ventilator for adult patients that was designed, built, and tested in ten days. The CoreVent 2020 is a pressure-cycled, time-limited ventilator with a breath-assist mode that operates on standard pressurized oxygen and medical air. It provides adjustable peak inspiratory pressure (PIP) and positive end-expiratory pressure (PEEP). A medical-grade commercially available breathing circuit is used to minimize non-medical component requirements. The CoreVent 2020 was fabricated in-house at Stony Brook University Hospital and tested on three mechanical lung simulators in which the operating modes and alarm features were demonstrated. Animal studies were also performed in both normal breathing mode and breath-assisted modes. Arterial blood gas measurements confirmed that the ventilator provided satisfactory ventilation for the test subjects. The COVID-19 pandemic presented unique constraints on the design and innovation process not normally encountered in typical practice. Design decisions such as component choice, delivery time, and ease of high-volume, rapid manufacturing influenced all aspects of the design process. This aspect of the design/innovation process is also discussed, as well as an introductory discussion on how training and simulations can be developed so that innovation can occur efficiently in future crises situations.

Key words: Ventilator; COVID-19; Innovating under duress; Pandemic; Off-normal design

INTRODUCTION

The early stages of the COVID-19 pandemic resulted in widespread mechanical ventilator shortages worldwide (1). When the pandemic first hit, estimates for the number of ventilators that would be needed in the United States alone ranged from several hundred thousand to nearly a million. This far exceeded the supply that was currently available. The greater New York area was hit particularly hard early in the crisis. Referring to Figure 1, data from the New

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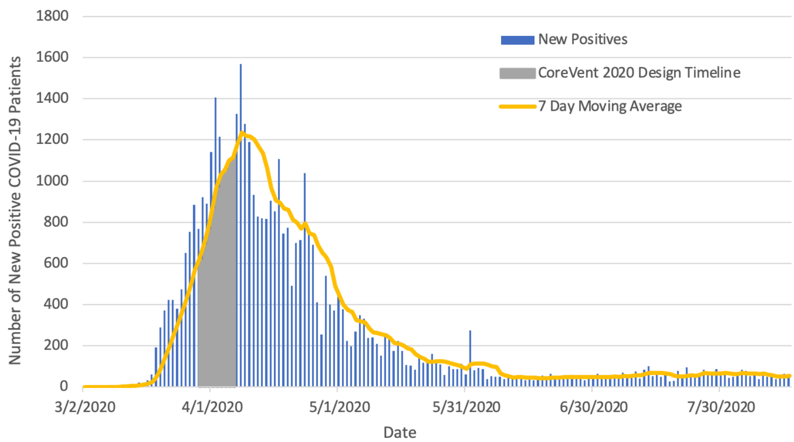

Figure 1. Number of COVID-19 cases by date for Suffolk County New York (Long Island)

York State Department of Health via the Electronic Clinical Laboratory Reporting System (2) shows that infection rates grew dramatically from mid-March to mid-April. The period during which the ventilator discussed herein was developed is shown in gray in Figure 1. At the time the project was undertaken, the cases were climbing at a large and alarming rate.

A number of strategies (3) had been proposed to address the ventilator shortage, including placing two or more patients on one ventilator (4-8) and using anesthesia machines (9-10); however, both approaches suffer drawbacks and limitations. In response to dwindling university hospital ventilator reserves early in the pandemic, the authors, consisting of a team of engineers, respiratory therapists, and medical doctors, were charged with developing a viable ventilator as quickly as possible. The result was the CoreVent 2020 (CV20), a computer-controlled, pressure-cycled, time-limited ventilator that includes an assisted-breathing mode. The CV20 was designed, prototyped, tested, and outfitted for patient use in ten days (Saturday, March 28th, 2020 to Monday, April 6th, 2020).

The pandemic presented unique constraints on the design and innovation process itself. The CV20 design philosophy was to keep the system simple, reliable, and to utilize readily available parts from multiple vendors wherever possible. Specifications for components were intentionally kept as broad as possible so that different components could be substituted without affecting the overall operation, while also providing a multi-source supply stream, should the device need to be produced in volume.

While a number of ventilator designs have been publicized since the COVID-19 crisis, nearly all fall into one of two groups: 1) Commercially manufactured ventilators (11) and 2) DIY designs (12-22), each with shortcomings. Commercially manufactured ventilators include both new and legacy designs. While fully featured, these devices require custom components, specialized manufacturing techniques, long delivery times, and can be produced at only a handful of facilities. DIY designs can be fabricated from readily available components, but many of these designs were overly simplistic, lacked features, reliability, and posed safety issues, or required proprietary components to build.

Pearce provides a comprehensive summary of low-cost (14), emergency-use ventilators. The author provides ten criteria for a ventilator design to be considered open source, all of which are met with the CV20 design. In particular, Pearce found that most published designs suffer from one (14) or more deficiencies and recommended designs that use readily available materials and components where possible, non-proprietary processes, and standard fabrication techniques to maximize the ability to fabricate devices in a flexible manner.

MAJOR DESIGN FEATURES

The CoreVent 2020 is a computer-controlled, pressure-cycled, time-limited ventilator that includes an assisted-breathing mode. Low- and high-pressure alarm functions are incorporated, and the user is provided both visual system status indicators and a simple menu-based computer interface to control the ventilator. Design features of the ventilator include:

- Ventilation modes that are applicable to patients with advanced respiratory compromise from COVID-19-type physiology based on clinical input from experts that possessed firsthand knowledge from directly caring for these patients.
- Adjustable peak inspiratory pressure (PIP), positive end expiratory pressure (PEEP), inspiration/expiration ratio, and oxygen concentration (FiO_2) from 21–100%.
- Alarms and safety mechanisms that meet the clinician's minimum acceptance standards consistent with commercially available ventilators.
- Use of general-purpose components available from multiple vendors, in anticipation of disrupted supply chains.
- Use of readily available, medically approved components wherever possible.
- A user interface that is intuitively understandable by personnel trained in the use of ventilators (ICU physicians, anesthesiologists, respiratory therapists).
- Design for rapid manufacture and quickly scalable to high volume production, if needed.

CV20 Design

The schematic of the CV20 is shown in Figure 2. Although specific part numbers are provided, these are representative only, and any suitable substitute would be satisfactory. A complete Bill of Materials (BOM) is provided in Appendix I. Ranges for each component are provided where possible.

Starting on the left of the figure, compressed oxygen and medical air at 50 psig (345 kPa) are connected to a medical-grade, commercial gas blender, which provides a continuously adjustable oxygen concentration from 21 to 100%. Two oxygen-compatible Wilkerson R03-01-000 regulators provide a two-step pressure drop to approximately 1.5 psi (100 cm H_2O) for delivery to the patient. The first regulator is set at a fixed value of 15–20 psig (100–133 kPa). The second regulator is accessible on the front panel of the device to the healthcare professional and is used to adjust the inspiration flow rate to achieve the desired inspiration time. A single regulator is acceptable, but it was found that two regulators provide more precise control over the inspiration time adjustment. The pneumatic components are selected with commonly

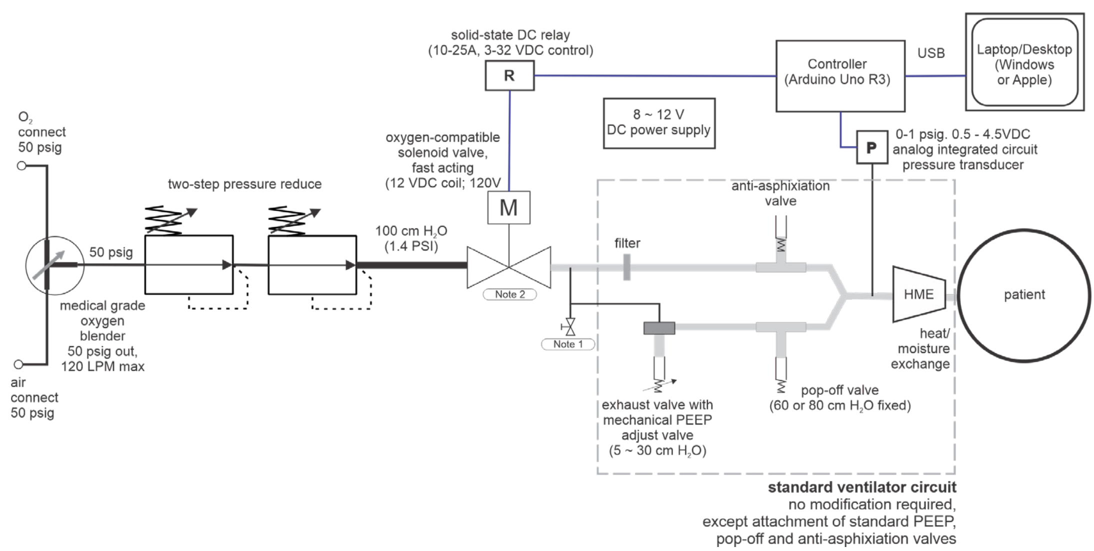

Figure 2. Ventilator schematic. Components inside the dashed box are medical-grade, commercially available breathing circuit components.

available National Pipe Taper (NPT) and diameter index safety system (DISS) process connections. These fittings and adapters can commonly be found in hardware stores and medical settings, respectively. Components made of stainless steel are desired when available, however, high-grade brass components that meet or exceed the 2014 Federal Safe Drinking Water Act can also be used in emergency situations.

Inspiration is controlled with a single solenoid-driven oxygen-compatible Omega SV171 valve. The valve is driven by 12 VDC with a current draw of less than 3 A. The valve current is controlled by a solid-state DC relay that is optically isolated and controlled by a 5 VDC logic pin from the Arduino controller. The solenoid valve is connected to a Westmed 9147 Adult Single Limb Vent Circuit commercial breathing circuit with a manual, pressure-driven exhaust valve. The integrated exhaust valve eliminates the need for a second solenoid valve, simplifying the design and increasing reliability. The additional components within the dashed box on the right of the figure are industry-standard, FDA-approved medical breathing circuit components. They are readily available, and alternates of each are available from other manufacturers. These components include:

1. One-way valve (Teleflex 1664)
2. Manual PEEP valve with 30mm female fitting and adjustable range of 0–20 cm H_2O (Mercury Medical 1055330)
3. Anti-asphyxiation valve (Teleflex 1664)
4. Bacterial filter (22mm I.D. X 22mm O.D. / 15mm I.D.) (Mercury Medical 105376)
5. PEEP Valve adapter to circuity (Mercury Medical 1055330)
6. Pressure line adapter (Teleflex 1642)
7. Aerosol Tee (Westmed 0219)
8. Kink-resistant tubing (Westmed 0008)
9. Pop-off safety release valve (Str-Val RVi20-01T, <100cm H_2O, 1/8" NPT)
10. Heat/moisture exchange (HME) (Ballard Technology 150)

Expiration occurs automatically through the expiration valve in the breathing circuit. The expiration valve has a pneumatically actuated diaphragm incorporated within it. The front of the diaphragm is presented to the breathing circuit and thus the patient's current airway pressure. The backside of the diaphragm is connected to a sealed chamber with a plastic tube, which is connected upstream to the breathing circuit just after the inspiration valve. When the inspiration valve opens, the slight pressurization in the breathing circuit causes the expiration valve to close. When the inspiration valve closes, the pressure equalizes in the circuit and the exhaust valve — which is slightly pre-tensioned to return to the open position in the absence of a pressure difference — opens to allow the patient to exhale. Thus, once the inspiration valve closes, expiration will start immediately without any other control or hardware required by the system. This form of expiration control has been standard on commercial ventilators for many years. It was chosen for its simplicity and reliability.

An integrated-circuit analog pressure sensor (GA100-001PD, Measurement Specialties, Inc.) is connected to the breathing circuit at the patient through the provided port just upstream of the patient intubation connector. The sensor provides an analog voltage between 0.5 and 4.5 VDC, corresponding to 0 – 70 cm H_2O (0 to 1 psig), although any sensor with a maximum pressure of 50 – 350 cm H_2O (0.75 – 5 psig) would be acceptable. The pressure sensor is read by the native 10-bit ADC on the Arduino controller at a rate of approximately 2,000 samples/sec, although any sampling rate greater than 100 Hz would suffice. A 12 VDC power is supplied to the system by a high isolation, medical-grade, RECOM RACM100-12S AC/DC regulated power converter.

An Arduino Uno is used to control all operations of the ventilator. These are readily available, low-cost, and reliable microcontrollers used in hobby applications. There are extensive open-source libraries available that make attaching sensors and related peripherals fast, easy, and reliable. The Arduino source code is freely available for download and modification at https://github.com/jlongtin/CoreVent.
The CV20 does not have the ability to measure tidal volumes or control the volume of air delivered to the patient. Expiratory tidal volumes can be manually measured by placing a suitable measuring device (either volume- or flow-based) inline or at

the end of the expiratory circuit when a measurement of volume is desired. A flow-sensor attached to the discharge side of the PEEP valve could also be incorporated into the system to estimate volume flow on a breath-by-breath basis. The working ventilator can be assembled in two to three hours, provided all parts are on hand.

Ventilator Operating Modes

Referring to Figure 3, the CV20 operates in one of three possible breathing modes, as follows:

1. Case 1—Normal pressure-cycled mode: Case 1 is normal pressure-cycled operation (Figure 3, top). The inspiration solenoid valve is opened by the microcontroller to begin inspiration and the pressure at the patient, P_s, is monitored. Inspiration is stopped once the target pressure, P_c, is reached, at which time the inspiration time, T_i, is recorded. The solenoid valve closes and the passive expiration valve on the breathing circuit opens automatically to allow the patient to

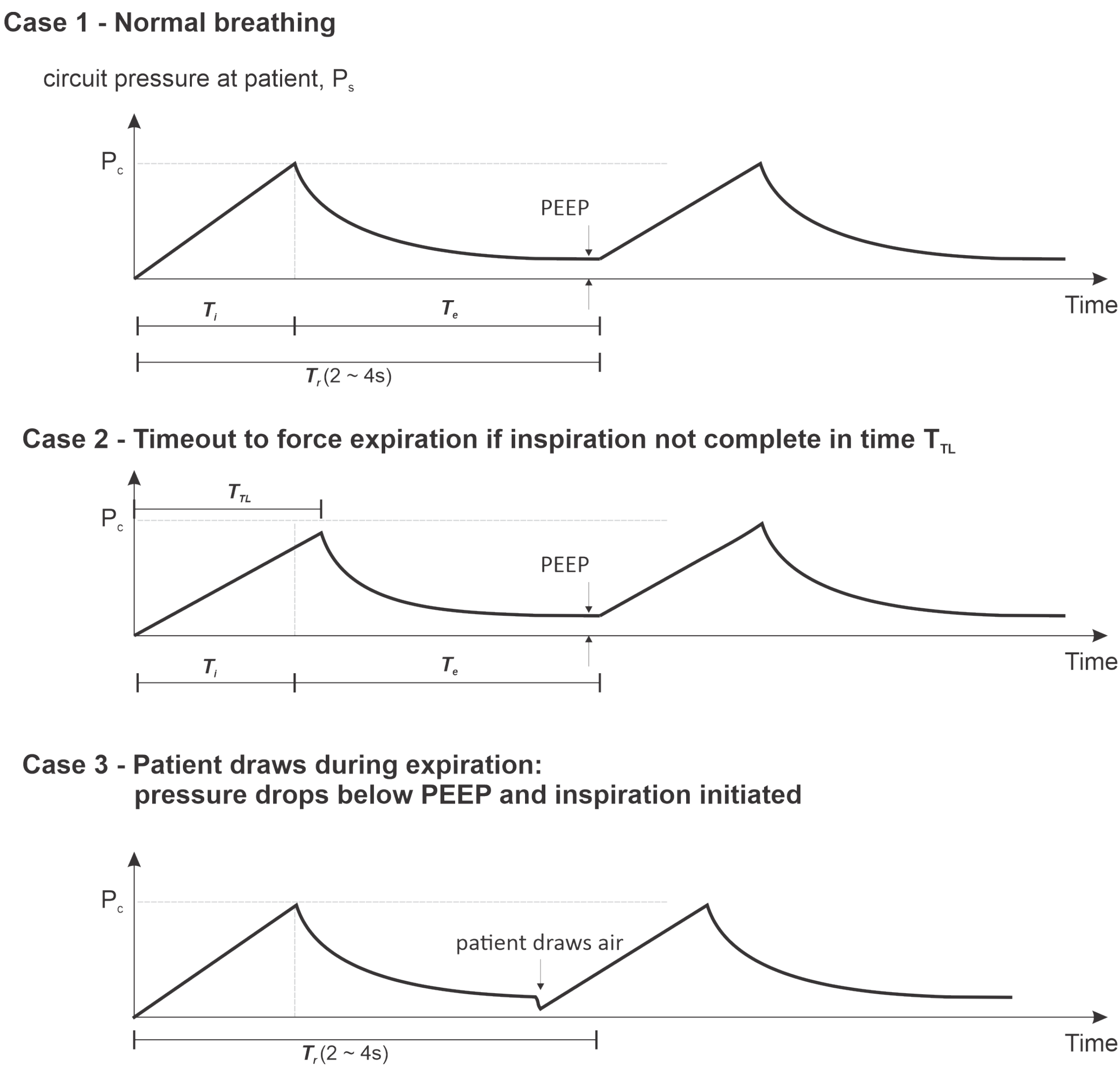

Figure 3. Ventilator operating modes. (top) Case 1 – normal pressure-cycled model, (middle) Case 2 – time-cycled mode. If target pressure not reached by time T_{TL}, expiration is automatically triggered, (bottom) Case 3 – Breathing-assist mode. if patient draws a breath during exhalation, inspiration is immediately started.

exhale. At time T_r=60/BPM where BPM is the preset breaths per minute rate, inspiration again starts, and the breathing cycle repeats. After one breath cycle the expiration time $T_e=T_r-T_i$. PEEP is typically desired for COVID-related ventilator applications and is provided through the addition of a manual, adjustable pop-off valve on the expiratory side of the breathing circuit (Figure 2). PEEP can be adjusted from 0 – 20 cm H_2O in this fashion.

2. Case 2 —Time-limit mode. Referring to the middle graph in Figure 3, if the target pressure is not reached by the timeout limit, T_{TL} (default of 1.4 seconds), then the inspiration valve is closed automatically, ceasing the inspiration event, and expiration commences. A time-out LED on the control panel is illuminated during this breath cycle to indicate that a timed-out breath has occurred. This LED light is cleared once the next normal breath occurs. When a time-limit breath occurs, the next breath cycle begins at the same time as the normal cycle, i.e., after time T_r=60/BPM elapses.

3. Case 3—Assisted-breath mode. If the patient attempts to take a breath during expiration, the circuit pressure will drop as a result of the patient drawing for air. If the controller detects such a pressure drop (default value set to 4 cm H_2O below the PEEP setting) then the next breath cycle is started immediately by opening the inspiration valve to provide air to the patient. The sensitivity of the pressure drop required for the assisted-breath mode can be adjusted from 0 – 6 cm H_2O below the PEEP value from the system menu.

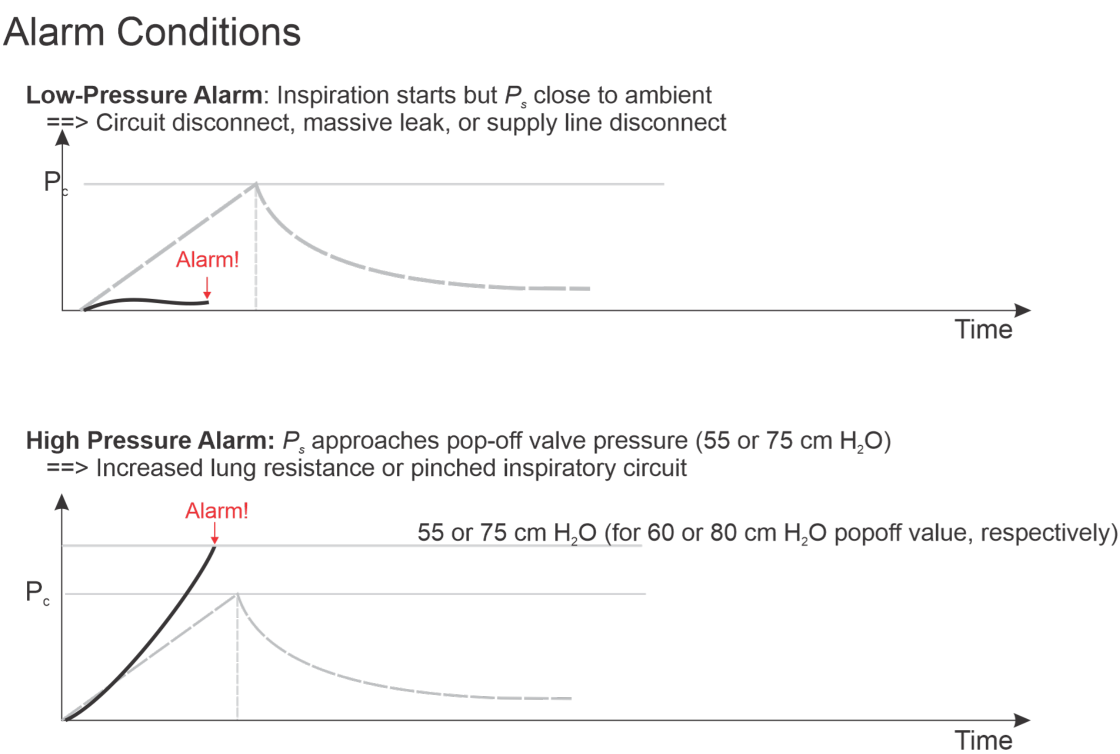

Figure 4. Alarm conditions. (top) **low-pressure alarm** – pressure is below 10 cm H_2O after inspiration timeout (1.2 seconds). (bottom) **high-pressure alarm** – patient pressure exceeds high-pressure alarm setting, typically 55 or 75 cm H_2O inspiration, at any point during inspiration.

Alarm Features

Referring to Figure 4, two alarm conditions are monitored. The first alarm condition is a low-pressure alarm that may occur if the circuit becomes disconnected, the gas supply is shut off, or the inspiratory circuit line becomes disconnected or obstructed. During inspiration, the target pressure is never reached, and a time-out condition is triggered. At this point, if the patient's pressure is below ten (10) cm H_2O, the low pressure alarm is triggered. An LED is illuminated to indicate the alarm condition as well as the sounding of a buzzer to notify healthcare workers. If the low-pressure event is resolved on the next breath the buzzer will stop; however, the LED light will remain on until the *Alarm Reset* button has been pressed. If the low-pressure event remains, e.g., the patient is being tended to by a healthcare worker for other matters, the buzzer can be silenced for 60 seconds by pressing the *Alarm Silence* button. The *Alarm Silence* button can also be pressed in anticipation of a

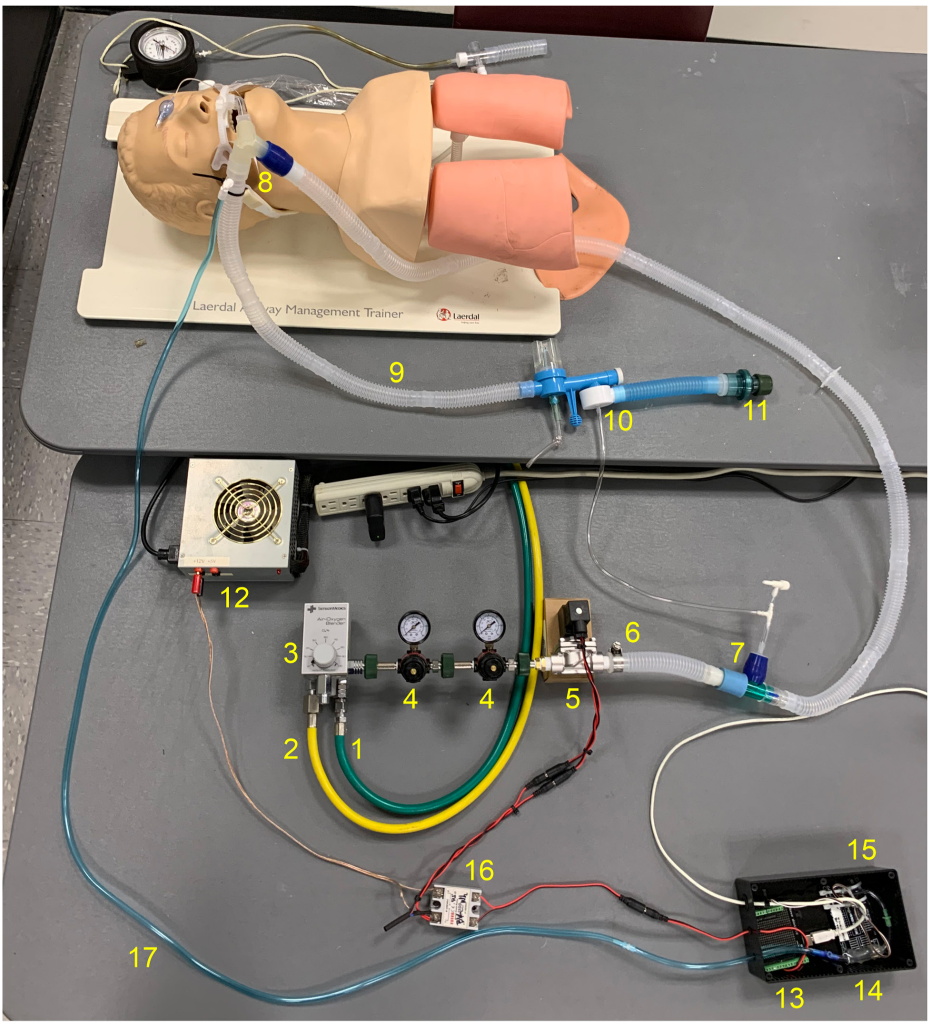

Figure 5. Functioning CV20 with all key components in place. Refer to text for label descriptions.

low-pressure event, e.g., temporarily disconnecting the breathing circuit for maintenance, repositioning, etc.

The second alarm condition is a *high-pressure* alarm, which occurs if the measured pressure exceeds a pre-set threshold amount (default = 70 cm H_2O) at any time during inspiration. A high-pressure alarm LED is illuminated for that breath and any subsequent breaths until the situation clears, in which case the high-pressure alarm LED turns off automatically.

Additional alarm and indicator functions include:

1. Alarm for loss of medical gases. The system uses 100% pure oxygen and medical air (21% oxygen) as inputs to the gas blender at a nominal pressure of 50 psig (350 kPa). If either gas pressure is lost the blender will sound an audible alarm.

2. Alarm for AC power loss. The Uninterrupted Power Supply (UPS) will issue an audible alarm if the AC main power is lost.

3. Normal and triggered breath indicators. Both normal and assisted-breathing modes are indicated with LEDs on the front panel. The indicators are updated for every breath.

RESULTS AND DISCUSSION

The completed CV20 ventilator is shown in Figure 5. Pure oxygen (1) and medical air (2) gas lines are connected to the blender (3), two regulators (4), and the inspiration solenoid valve (5). The inspiration leg of the breathing circuit (6) is connected to the inspiration valve followed by a T-connection (7) to actuate the exhaust valve, as described above. The inspiration leg is connected to the patient (8) and expiration leg of the breathing circuit (9). The mechanical exhaust valve (10) is attached to the end of the expiration leg, with an optional mechanical PEEP valve (11) connected to the exhaust valve.

The system is powered using a switching computer

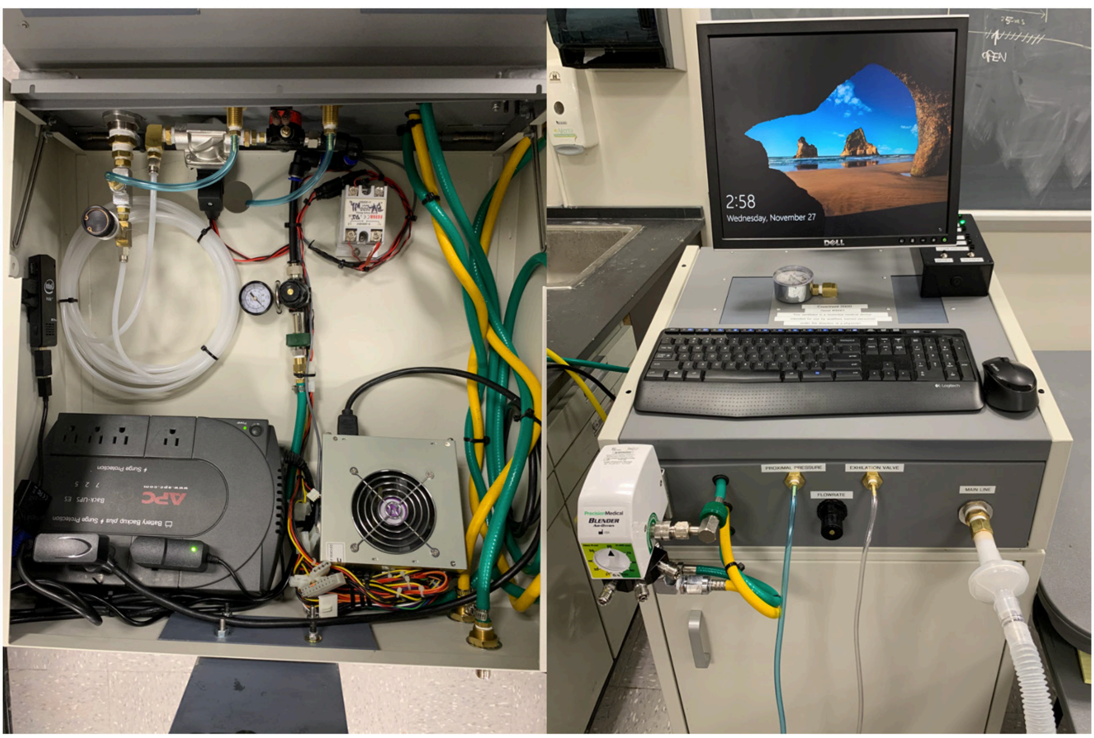

Figure 6. Packaged ventilator components into rollable cart for bedside use. (left) top view showing same key components as those in shown in Figure 5, (right) completed ventilator, ready for patient use.

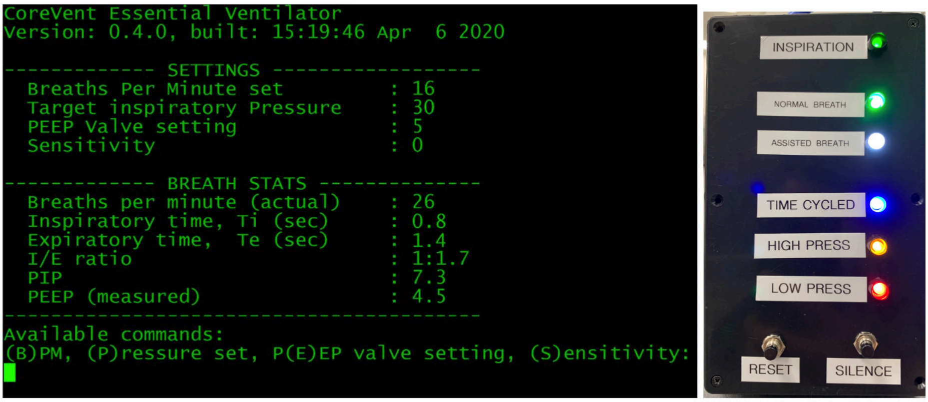

Figure 7. User interface for CV20, including computer terminal display/interface (left) and hardware control panel (right). In this instance, the ventilator was being tested in assisted-breath mode (Case 3), which explains a measured BPM of 26 versus the default setpoint of 16 BPM.

Day	Key Activities
1	Initial ventilator design concept developed
2	Basic operation established using parts from local hardware store
3	Assembled all components on bench and verified operation (Figure 5)
4	Manakin testing; troubleshooting and design revisions
5	Mechanical bellows testing; parts down-selection
6	Testing on ASL 5000 advanced lung device
7	Animal testing; final prototype complete; start build of final prototype
8	Prototype construction; additional testing
9	Prototype completion; hospital checkout for electrical safety
10	Final assembly and testing of patient-ready ventilator

Table 1. Development timeline for CV20

power supply (12) connected to line 120 VAC voltage, which provides both 5VDC and 12 VDC outputs. The Arduino controller (13) and electronic pressure sensor (14) are contained in the user control enclosure (15) and display (Figure 7, right). The solid-state relay (16) used to actuate the inspiration valve is connected to the 12V rail of the power supply while the 5V control is connected to the Arduino controller. Finally, the pressure reference from the patient is connected to the pressure sensor through tubing (17).

The prototype was packaged into a rollable medical cart suitable for bedside use with all hardware installed in the cart, as shown in Figure 6. The device also received medical device electrical safety approval by Stony Brook Hospital.

The user interface for the ventilator consists of a computer terminal (Figure 7, left) and hardware control panel (Figure 7, right). The control panel houses the LED indicators for operating modes and alarms, alarm reset buttons, and the buzzer, as well as the support electronics shown in Figure 5. The user screen is presented to the user through a standard monitor and a Windows 10 computer running PuTTY, which acts as a serial terminal. The Arduino provides all screen updates and accepts user input from a keyboard through a USB serial port on the Windows 10 computer. The user interface allows setting the

	Subject A			Subject B	
	Subject A Baseline	CV20 Test A1	CV20 Test A2	Subject B Baseline	CV20 Test B1
Vital signs					
Respiratory rate - observed (BPM)	54	25	25	38	25
FiO_2	1.0	0.40	0.40	1.0	1.0
Exhaled tidal volume (cc)	140	450	650	130	500
CV20 parameters					
Respiratory Rate Setting (BPM)	—	25	1	—	1
Pressure Control (Pc, cm H_2O)	—	25	30	—	25
PEEP (cm H_2O)	—	10	5	—	10
Arterial Blood gas					
pH	7.41	7.43	7.49	7.34	7.39
pCO_2 (mm Hg)	48	42	33	55	45
$p0_2$ (mm Hg)	216	190	187	323	435

Table 2: Arterial blood gas results for Subject A and Subject B during experimental testing of CV20.

breathing rate (breaths per minute), target inspiratory pressure (cm H_2O), manual setting of the PEEP valve pressure (cm H_2O), and the desired sensitivity for breath-assist mode (0–6 cm H_2O). The interface also reports several calculated values, including the measured breaths-per-minute, inspiratory time (sec), expiratory time (sec), the ratio of inspiratory to expiratory time (unitless), and the measured PIP (cm H_2O) and measured PEEP (cm H_2O) from the last breath.

Timetable

The ventilator development timeline over the ten-day period is shown in Table 1.

VENTILATOR TESTING

Respiratory Manakin Testing

Approximately 12–15 hours of testing were completed on an instructional manakin (AM-BU Manikin), as shown at the top of Figure 5. The manakin has rubberized lungs that emulate the approximate volume and compliance of a human patient. The manakin is intubated and represents a COVID-19 patient in need of a ventilator. All ventilator operating modes and alarms conditions were tested with this configuration. PIP, PEEP, and inspiratory time-limit operation were also confirmed at this stage.

Mechanical Bellows Testing

For quantitative tests of lung volume, lung compliance, and pressure during operation, a Michigan Instruments Dual Adult Test Lung bellows and springs system were used for approximately one to two hours of testing. This device provides a mechanical readout of volume and pressure during inspiration and expiration as well as PEEP. Lung compliance for normal lungs and those associated with COVID-19 can be adjusted via a pair of springs on each side of the device. While mimicking Acute Respiratory Distress Syndrome (ARDS), the CV20 was able to maintain adequate tidal volumes and PEEP regardless of lung compliance.

Advanced Lung Simulator Testing

Additional testing of the CV20 system was performed on an Active Servo Lung (ASL) 5000 advanced breathing simulator (IngMar Medical).

This device incorporates a piston-assembly driven by a closed-loop servo capable of reproducing lung behaviors for a variety of lung conditions, including normal lungs and ARDS (COVID-19) lungs. The device is also capable of drawing a breath to confirm the assist-mode of the ventilator. The instrument provides graphical and numerical data of the volume, pressure, and flow rates for each breath cycle. Using the ASL-5000, the CV20's ability to respond to a patient's inspiratory effort and deliver a mechanical breath was confirmed.

Animal Studies Testing

The CV20 was tested on two adult research swine subjects. The swine were approximately 45 kg in weight, anesthetized, intubated, and breathing spontaneously. Three tests were performed, two on subject A (A1 and A2) and one on subject B (B1). The goal of Tests A1 and B1 was to verify the CV20 was capable of successfully ventilating the animal as verified by arterial blood gas analysis. Test A2 was aimed at verifying the ventilator's ability to synchronize with the animals' breathing and assist the spontaneous efforts as verified by arterial blood gas analysis and direct observation. The results are shown in Table 2.

The CV20 performed as a pressure-cycled ventilator, as designed, in all of the testing indicated above. The device was demonstrated to transition to a timeout mode if inspiration did not complete within the allowed time, and the breath-assisted mode was also confirmed with the animal studies. The CV20 was able to adequately ventilate both swine subjects during all tests. The breath-assist mechanism was responsive and when used exclusively was able to adequately ventilate each swine, as shown by arterial Blood Gas Analysis for Case 2.

The CV20 has not been tested on human subjects. During the peak of the pandemic in the greater New York area, discussions were begun to explore the possibility of patient testing; however, the number of new infections per day was brought under control and, coupled with additional commercial ventilator reserves made available to the hospital, the immediate need for the CV20 was put on hold.

TROUBLESHOOTING

The following list common issues that can occur during ventilator operation and suggested remedies.

Low-pressure alarm

- Breathing circuit disconnected — confirm all connections
- Regulator pressure set too low — verify pressure settings and/or increase
- Tubing from breathing circuit to pressure sensor disconnected or blocked — inspect/reconnect
- Oxygen and/or medical air not connected to ventilator or is turned off — confirm connections and all valves on

High pressure alarm

- Breathing circuit pinched or obstructed — inspect breathing circuit
- Pressure regulator set too high — reduce second regulator pressure

Inhalation process not initiating

- Confirm ventilator settings correct in main menu
- Regulator pressure set too low — verify pressure settings and/or increase
- Oxygen and/or medical air not connected to ventilator or is turned off

Exhalation process not initiating

- Solenoid hose on exhaust valve breathing circuit disconnected or obstructed — check connections.
- Mechanical PEEP valve pressure valve setting too high — reduce/set to correct pressure
- Patient not receiving adequate breath during inspiration —confirm inspiration process working and no alarms present.

General ventilator operation

- No ventilator operation / no power — confirm power and UPS on, confirm all cable connections are intact.
- Screen inoperative by control unit working — computer/monitor has lost serial connection with Arduino. Re-establish connection and confirm menu operation.

A technical-support person, ideally one who was involved in the construction of the ventilator itself, should be made available for more serious issues such as component failures, more complex operating issues, and firmware updates. If possible, two extra ventilators are recommended to be kept on hand, with one used to swap out a non-functioning unit and a second dedicated for spare parts.

THINKING AHEAD — PREPARING TO INNOVATE UNDER DURESS

Innovating under duress can present unique and drastically different constraints on the innovation process versus normal situations. Factors include disrupted supply chains, critical components being out of stock, limited availability of personnel and expertise, compromised communications, limited available infrastructure for design and prototyping, physical and psychological stress, extremely short deadlines, lack of sleep and exercise and the reality of dealing with potentially life-or-death situations all can influence and challenge the ability to produce optimal solutions.

Training to innovate under duress is not taught or practiced in many, if not most, technical fields. With the pandemic receding, but still fresh in the collective mindset, it is proposed that efforts be made to develop training to innovate under duress. Some lessons may be drawn, e.g., from approaches used for airline pilots, law enforcement officers, and health/emergency personnel. Such training paradigms tend to be procedure-oriented and would be useful for aspects including organization, communication, and prioritizing topics in emergency situations. However, the more subtle question of preparing to successfully innovate under duress is less obvious. One challenge is in capturing a true duress environment, in which the consequences of decisions made have real, potentially serious consequences. In what ways can this be practiced? How can training for such events occur under realistic duress situations? What general principles and guidelines can be adopted in anticipation of a variety of unique duress situations that are likely to be vastly different from each other in terms of the stressors that they present?

There is an urgency to address these issues now, given that with time the memory and the ramifications of the current pandemic will fade. These are open questions, and it is the authors' collective hope that these issues will remain a vibrant discussion topic moving forward.

CONCLUSIONS

This work presents the development of an emergency-use ventilator developed during the initial COVID-19 pandemic. The ventilator was designed to be minimally viable, in that only the most essential capabilities were incorporated. The ventilator was developed, built, and tested over a ten-day period and features a pressure-cycled, time-limited device with a breath-assist mode that operates on standard pressurized oxygen and medical air. It includes high- and low-pressure alarm features, an adjustable PIP, and PEEP. The ventilator components and operating principles discussed were successfully tested on an educational manakin, a mechanical lung simulator, a computer-controlled lung simulator, and live animal studies. The unique circumstances that the pandemic presented impacted the design and fabrication process to keep the system simple, reliable, and to use readily available parts from multiple vendors with a flexible range of parameters, so that a high volume of devices could be fabricated quickly if needed. Finally, some thoughts on future training to innovate under duress situations are offered.

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APPENDIX

Component	Qty	Vendor	P/N	Ext Cost	Description
Medical Cart	1	Biodex Medical Sys.	132-503-A000	$700.00	Pulmonex Cart (Bare)
Spare Parts Organizer	1	Ridgid	238093	$34.98	Pro System Gear 10-Compartment, 22”
A/C power strip	1	Tripp Lite	PS-415-HG-OEM	$79.19	Medical-Grade Power Strip for Patient-Care Vicinity, 4x 15A Hospital-Grade Outlets, 15 ft. Cord
Bulkhead Pass-Through Out Fitting (Main Line)	1	McMaster	50785K273	$213.51	Low-Pressure 316 Stainless Steel Through-Wall Connector, 1” NPT Female
Bulkhead Pass-Through Inlet Fitting Rear	2	McMaster	50785K273	$17.64	High-Pressure Brass Pipe Fitting, Through-Wall Straight Connector, 1/4 NPT Female
Bulkhead Pass-Through Outlet Fitting Front	2	McMaster	50785K272	$12.78	High-Pressure Brass Pipe Fitting, Through-Wall Straight Connector, 1/8 NPT Female
Air/Oxygen Blender	1	Precision	BL-5200	$1028.00	High-Flow Oxygen-Air Blender, 2-120 LPM
O2, DISS Male Adapter #1	1	WT Farley	MF-0703	$5.00	Process Connection: 1/4” NPT Male
O2, DISS Male Adapter #2	1	WT Farley	MF-0713	$14.00	Demand Check Valve, Connection: 1/4” NPT Male
O2 DISS Female Assembly	1	WT Farley	MF-0110	$10.00	Handtight Nut & Nipple, Con.: 1/8” NPT Male, 1” Stem
O2, DISS Elbow	1	WT Farley	MF-0705	$18.00	O2 DISS Fitting, 90 Degree Elbow x Hex Nut
Medical Air, DISS Elbow	1	RC Medical	SP-93	$42.00	Air DISS Fitting, 90 Degree Elbow x Hex Nut
Medical Air, DISS Female	1	WT Farley	MF-0209	$14.00	Handtight Nut, Con.: 1/8” NPT Male, 1 1/2” long
Medical Air, DISS Male	1	WT Farley	MF-0743	$21.00	Demand Check Valve, Connection: 1/4” NPT Male
Oxygen Hose #1	1	WT Farley	OH-1800219	$98.00	Green, 15ft, DISS Female Handtight & Ohmeda Male
Oxygen Hose #2	1	WT Farley	OH-0600200	$39.00	Green, 5ft, DISS Female Handtight & Open End
Oxygen Hose #3	1	WT Farley	OH-720000	$27.00	Green, 6ft length, open ends
Medical Air Hose #1	1	WT Farley	AH-1800219	$103.00	Yellow, 15ft, DISS Female Handtight & Ohmeda Male
Medical Air Hose #2	1	WT Farley	AH-0600200	$39.00	Yellow, 5ft, DISS Female Handtight & Open End
Medical Air Hose #3	1	WT Farley	AH-720000	$27.00	Yellow, 6ft length, open ends
Hose Fitting (20mm I.D.)	1	McMaster	5361K182	$39.10	Barbed, 303 SS Adapter, 20 mm I.D. x 1 NPT Male
Hose Fitting (1/4” I.D.)	3	McMaster	5361K32	$27.06	Barbed, 303 SS Adapter, 1/4” I.D. x 1/4 NPT Male
Hose Clamp	3	McMaster	5407K57	$4.83	201 SS Worm-Drive Clamps, 3/8” to 7/8” I.D.

Table A1: CoreVent Bill of Materials

Adj. Pressure Regulator	1	Wilkerson	R03-01-L00	$193.00	Inline Wall Oxygen Regulator, 60 psig
Adj. Pressure Regulator	1	Parker Hannifin	14R110FC	$21.82	Series 14R Zinc Miniature FRL, 30 psig Pressure, Relieving Relief, 1/4" NPT Pipe x 1/8" NPT Gauge Port
Plug with External Square Drive (1/8" NPT)	3	McMaster	4464K231	$6.42	304 Stainless Steel Threaded Pipe Fitting, Low-Pressure, Plug with External Square Drive, 1/8 NPT
Analog Pressure Gauge (0-60 psi, 1/8" NPT)	1	McMaster	3847K71	$12.38	Single Scale Pressure Gauge with Plastic Case, 1/8 NPT Male Bottom Connection, 1-1/2" Dial, 0-60 psi
U-bolt Assembly	1	McMaster	8896T121	$5.03	1-1/2" I.D., 304 SS U-Bolt with Mounting Plate
Vacuum Pressure Gauge	1	Smiths Med.	55-6060	$105.81	Pressure Gauge, +60 to -60cm H2O
OMEGA-FLO 2-Way 316 Solenoid Valve	1	Omega	SV171	$397.32	2-Way, NC, Direct Acting, Stainless Steel , Solenoid Valves, Normally Closed, FKM wetted Materials
DC Coil for Solenoid Valve	1	Omega	SV-8COIL-12DC	$42.28	12Vdc, 8 W coil
Bushing Straight Reducing Adapter #1	1	McMaster	4464K268	$6.47	304 Stainless Steel Threaded Pipe Fitting, Low-Pressure, Bushing Adapter, 3/4 Male x 3/8 Female
Bushing Straight Reducing Adapter #2	2	McMaster	4464K263	$7.04	304 Stainless Steel Threaded Pipe Fitting, Low-Pressure, Bushing Adapter, 3/8 Male x 1/4 Female
Bushing Straight Reducing Adapter #3	4	McMaster	4464K261	$12.64	304 Stainless Steel Threaded Pipe Fitting, Low-Pressure, Bushing Adapter, 1/4 Male x 1/8 Female
Straight Connector, Female (1/4" FNPT)	1	McMaster	51205K212	$15.62	Extreme-Pressure 316 Stainless Steel Pipe Fitting, Straight Connector with Hex Body, 1/4 NPTF Female
Straight Connector, Male (1/4" NPT)	1	McMaster	4464K721	$5.38	304 Stainless Steel Threaded Pipe Fitting, Low Pressure, Straight Connector, 1/4 NPT Male
Straight Connector, Male (1/8" NPT)	4	McMaster	4464K711	$11.48	304 Stainless Steel Threaded Pipe Fitting, Low Pressure, Straight Connector, 1/8 NPT Male
Elbow Connector (1/8" NPT Female, 90°)	1	McMaster	4464K11	$5.67	304 Stainless Steel Threaded Pipe Fitting, Low-Pressure, 90 Degree Elbow Connector, 1/8 NPT Female
Street Elbow Adapter (1/8" FNPT Female x NPT)	1	McMaster	4464K35	$8.17	304 Stainless Steel Threaded Pipe Fitting, Low-Pressure, 90 Degree Adapter, 1/8 NPT Female x Male
Cross Connector	1	McMaster	4464K311	$14.07	304 SS, Threaded, Low-Pressure, 1/8" NPT Female
Tee Connector	1	McMaster	4464K47	$8.14	304 SS, Threaded, Low-Pressure, 1/8" NPT Female
Tube Fitting (3/8" O.D.)	2	SMC Pneumatics	KQG2H11-N02S	$39.10	1/4" Tube x 3/8" Universal Thread SS Male Connector

Air Hose Tubing (3/8" O.D)	1 ft	McMaster	5097T61	$4.08	Hard Nylon Plastic Tubing, 1/4" I.D., 3/8" O.D., Black
Push-To-Connect Union Elbow (3/8", 90 deg)	3	SMC Pneumatics	KQGL11-00	$147.90	Stainless Steel Material
Push-To-Connect Fitting (1/4" tube O.D.)	7	SMC Pneumatics	KQG2H07-N01S	$85.05	Universal-Thread Push-to-Connect Tube Fitting for, Stainless Steel, Straight, for 1/4" O.D., 1/8 Pipe Size
Nylon Plastic Tubing (1/4" tube O.D., >25 ft)	1	McMaster	5548K74	$21.30	Hard Nylon Plastic Tubing for Air and Water, Semi-Clear White, 11/64" I.D., 1/4" O.D.
Straight Adapters, Hose (3/16" I.D. x 18" NPT)	2	McMaster	5361K82	$24.72	Barbed Hose Fitting, Air and Water, 303/304 Stainless Steel Adapter, 3/16" I.D. X1/8 NPT Male
Plastic Tubing (3/16" I.D., 25 ft.)	1	McMaster	55485K73	$152.00	Continuous-Flex Soft Tygon PVC Plastic Tubing for Air and Water, Clear, 3/16" I.D., 5/16" O.D.
Straight Connector, Hose (3/16" I.D. hose)	1	McMaster	5346K782	$6.87	Brass Barbed Hose Fitting for Air and Water, Straight Reducer for 3/16" Hose I.D. x 1/8" Hose I.D.
Safety Release Valve	1	Stra-Val	RVi20-01T	$463.00	Accurate Relief Valve, Range: 0.3 - 1.3 psig, Process Connection: 1/8", Materials: 316 SS and Viton
Disposable Respiratory Breathing Circuit	1	Westmed	9147	$11.24	72" Adult Single Limb Circuit w/Exhalation Valve
One-Way Valve	2	Tereflex	1664	$1.04	One Way Valve, 22 mm O.D. to 22 mm I.D.
PEPE Valve and Adapter	1	Mercury Medical	1055330	$8.21	Manual Positive End-Expiratory Pressure valve with 30mm female fitting, Adj. range of 0–20 cm H2O
Bacterial Filter	1	Mercury Medical	1055376	$2.97	In-Line Filter (22mm I.D. X 22mm O.D. / 15mm I.D.)
Pressure Line Adapter	1	Tereflex	1642	$0.83	22mm I.D. X 22mm O.D., Elbow accepts 5-7mm I.D. tubing
Aerosol Tee	1	Westmed	0219	$0.34	Connector Tee, 22mm O.D. X 22mm O.D. X 22mm I.D.
Kink-Resistant Tubing	1	Westmed	0008	$10.99	7', 6-channel inner lumen design, Universal Connection
HME Filter	1	Ballard	150	$4.85	Ballard Flexible Heat/Moisture Exchange Filter, Blue
Breathing Circuit Filter	1	Pall	BB50T	$6.29	Hydrophobic bidirectional filter, > 99.999% efficiency, Connection: 22 mm O.D x 22 mm I.D.
Universal Cuff Adapter	1	Tereflex	1421	$0.52	Standard, 22mm ID Female Connections
Miniature Pres. Regulator	1	Omega	AR91-005	$44.40	0-5psig range, 1/16" NPT Female connections
Hose Fitting (6mm I.D.)	2	McMaster	4406T796	$32.74	SS, Barbed, Tube Fitting, 6mm I.D. x 1/16 NPT Male
Silicon Rubber Adapter	2	Instrumentation Industries	PF1515	$11.98	Connector, Silicone, Straight, 15 mm ID x 15 mm ID

Tubing Adapter (22mm ID x 5-7mm Taper)	2	Instrumentation Industries	BE145-1522	$7.66	Hose Connector, Reusable, Barb, 15 mm ID/22 mm OD to taper, Transparent, Polycarbonate
Battery Back-Up	1	APC	BE650G1	$87.12	APC Back-UPS ES, 120VAC, 8 Outlet Surge, 390W
A/C Plug w/ Switch	1	Belkin	F7C01008q	$40.53	120VAC, Remote Switch, Wireless
A/C Power Cord	1	Tripp Lite	P006-L03-HG10	$14.05	Hospital-Grade, NEMA 5-15P to Locking IEC C13 - Green Dot, 10A, 125V, 18 AWG, 3 ft. (0.91 m), Black
Tri-Tap Power Adapter	1	Watson	A-PTT-B	$5.95	Tri-Tap Power Adapter, 120VAC, 15A
Transparent A/C Plug	1	Leviton	8215-CAT	$12.44	15 Amp, 125 Volt, Hospital Grade, Angle Plug, Transparent
Universal Power Cord	1	Watson	PC18-6B	$5.89	18 AWG, 6', Black 3-Pin Male to 3-Pin Female
Monitor Cable	1	Pearstone	VGA-A303	$7.99	Premium VGA Male to VGA Male Cable (3')
Monitor Video Adapter	1	Belkin	F2CD058	$23.59	HDMI Male to VGA Female Adapter with Audio
Intel Pocket PC W5 Pro	1	Amazon	B07PXRTSC7	$159.99	Mini Computer Stick with Intel Atom Z8350 & Windows 10 Pro, 128GB ROM, 4GB RAM, 4K HD, Dual Band WiFi
5VDC Power Adapter	1	Intertek	5011274	$10.00	AC/DC Power Adapter, 2000 mAh
Micro SD Card 64 GB	1	SanDisk	SDSDXXY-064G-GN4IN	$13.99	SD Card, 64GB, Class 10
Keyboard & Mouse	1	Logitech	MK335	$24.99	Logitech MK335 Wireless Keyboard and Mouse Combo
Computer Monitor	1	Dell	1707 FPT	$185.00	17" diag, 4:3 aspect ratio
Articulating Monitor Mount	1	Pad Holder	PH-MT-9110	$82.08	Articulating VESA wall mount
Aluminum Plate	2	McMaster	9246K523	$49.50	Multipurpose 6061 Aluminum, 5/8" Thick, 6" x 6"
Bolts (1/4"-20 x 1.5")	8	McMaster	98164A226	$5.16	316 SS Button Head Hex Drive Screw, Super-Corrosion-Resistant, 1/4"-20 Thread Size, 1-3/4" Long
Washers (1/4".)	16	McMaster	90107A029	$7.11	316 Stainless Steel Washer for 1/4" Screw Size, 0.281" I.D., 0.625" O.D.
Nuts (1/4"-20)	8	McMaster	94819A043	$3.77	Super-Corrosion-Resistant 316 Stainless Steel Hex Nut, 1/4"-20 Thread Size, ASTM F594
Project Enclosure Box	1	RadioShack	2701807	$14.99	RadioShack Project Enclosure Box - 7 x 5 x 3"
Rubber Grommets	3	Radio Shack	6403025	$2.20	Assorted Grommets (31-Pack), 2 x 0.5", 1 x 0.25"
5V DC LED, 5mm	1	Sparkfun	COM-09881	$10.60	LED Mixed Bag - 5mm (26 LEDs)
LED Bulb Holders, 5mm	6	RadioShack	2760079	$7.68	RadioShack 5mm LED Holders (5-Pack)
Momentary Push Button	2	Radio Shack	2751549	$10.98	125VAC, 3A SPDT Momentary Switch
Arduino Uno Rev3	1	Arduino	A000066	$20.05	Microcontroller Microchip ATmega328P

Arduino Power Supply	1	Corporate Computer	LJH-186	$6.49	9VDC 1A Power Supply
USB 2.0 Cable	1	Belkin	F3U133B06	$7.00	Pro Series, Type A to Type B Device Cable, 6ft, Black
Arduino Prototyping Screw Shield	1	DIY More	10710	$5.99	Proto Screw Shield for Arduino, Breadboard 3.81 Terminal Double-Sided PCB SMT Solder
Buzzer Alarm Module	1	DIY More	10323	$4.99	Active Buzzer Alarm PCB Board Module, 3.3v-5V
PCB Breadboard (3”x2”)	1	DIY More	500295	$5.99	5PCS Double Side 50x70MM Prototype PCB Tinned Universal Glass Fiber Breadboard
Integrated Circuit Analog Pressure Transducer	1	Measurement Specialties	GA100-001PD	$20.30	Board Mount Pressure Sensors 1psi 0.5-4.5V
Buzzer/Siren Alarm	1	CUI Devices	CPS-4242-100T	$14.97	Piezo Buzzers & Audio Indicators 42.5 mm, 12 Vdc, 100 dB, Through Hole, Driving Circuit, Piezo Siren
DC Power Supply	1	RECOM Power	RACM100-12S	$157.25	Switching, Ground Isolated 100W 85-264Vin 12Vout 8.43A
Power Connectors	4	Centropower	1.92187E+11	$36.36	Male/Female Barrel Con., 5.5 mm x 2.1xmm, 12V, 5A
Button head screws	12	McMaster	94500A227	$8.88	316 Stainless Steel Button Head Hex Drive Screws, M4 x 0.7mm Thread, 10mm Long
3-Pin Power Supply Con.	1	JST Sales America Inc.	VHR-3N	$0.15	Connector Housing, JST VH series, 3POS 3.96mm, white
4-Pin Power Supply Con.	1	JST Sales America Inc.	VHR-4N	$0.19	Connector Housing, JST VH series, 4POS 3.96mm, white
Power Supply Con. Pins	7	JST Sales America Inc.	SVH-41T-P1.1	$0.35	Connector Socket16-20AWG Crimp Tin
Solid State Relay	2	Schneider Electric Relays	6325AXX-MDS-DC3	$159.86	SSR - Industrial Mount 6000 SSR MOSFET, SPST-NO, 25A, 3- 32 VDC control, 3-200 VDC Load
Aluminum Heat Sink	2	Auber Instruments	HS25	$21.18	Heat Sink for SSR, 25A, Top: 50x60mm, Base: 50x80 mm, Height: 50 mm, Screw thread: M4-0.7
Wire, Red, 18 AWG	1	Pomona Elec.	6733-2	$7.00	Hook-up Wire Silicon LD RED 50’
Wire, Black, 18 AWG	1	Pomona Elec.	6733-0	$7.00	Hook-up Wire Silicone LD BLK 50’
Heat Shrink	1	Qualtek	Q2-F-QK1-01-6IN-180	$23.43	Heat-Shrink Tube Assortment
Ring Terminals	10	RadioShack	6400047	$11.99	Heat Shrinkable Type 22-16 AWG/16-14 AWG
Spade Connectors	10	RadioShack	6400046	$11.99	Heat Shrinkable Spade Terminal Assortment
Solder	1	Kester	24-7040-7601	$10.52	Kester 275 No-Clean Sn96.5 Ag3.5 Soldering Wire, 58 Core (2.2%), 0.031 Inch Dia, 1 lb Spool, 0.1 lbs req.
Zip Ties	1	RadioShack	2780472	$9.89	Nylon Cable Tie Assortment (200-Pack)