An inexpensive bidirectional ventilator tube insertion flowmeter

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Abstract

We report results from our tests of a novel low-impedance bidirectional flowmeter that could be used to monitor the gas flow between a mechanical ventilator and an intubated patient. Under emergency conditions, when a ventilator must be shared among several patients, separate flowmeters could be placed in each patient's oxygen lines to provide patient-specific information. Our flowmeter uses the Bernoulli principle to determine the flow rate through a tube of varying cross-sectional area; it can record (and store) flow rates twice per second with an accuracy of approximately 5%, and transmit patient data to a base station at an intensive care unit's command center every few seconds. At the present time there appear to be no devices able to fulfill this pressing clinical need that have received approval from the U.S. Food and Drug Administration, even at the Emergency Use Authorization level.[2]

Introduction

During the first months of the covid-19 pandemic, some hospitals in the United States found that they were caring for more patients in need of intubation and ventilation than the available supply of mechanical ventilators would permit. In response, some hospitals jury-rigged sharing arrangements in which several intubated patients would receive oxygen from a single ventilator whose supply lines were split using T-junctions.[3]

This worrisome ventilator shortage is considerably more severe in the developing world: In early 2020 the Liberian Public Health Institute's Director of the Infectious Diseases and Epidemiology Department stated that "there is just one ventilator in the country,

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[2] U.S. Food and Drug Administration, "Emergency Use Authorization," March 24, 2020. (https://www.fda.gov/media/136423/download)

[3] See, for example, Jeremy R. Beitler et al., "Ventilator Sharing Protocol: Dual-Patient Ventilation with a Single Mechanical Ventilator for Use during Critical Ventilator Shortages," Columbia University College of Physicians & Surgeons, New York Presbyterian Hospital, March 24, 2020 (https://www.gnyha.org/wp-content/uploads/2020/03/Ventilator-Sharing-Protocol-Dual-Patient-Ventilation-with-a-Single-Mechanical-Ventilator-for-Use-during-Critical-Ventilator-Shortages.pdf)

located at a hospital outside of the capital…"[4] Even now, nearly two years into the pandemic, only 9.2% of all Liberians have received the full course of vaccinations against SARS-CoV-2, the virus causing covid-19.[5] Many other countries in Africa—Ghana, Ivory Coast, Senegal, Sierra Leone, Ethiopia, Malawi, Nigeria, and more—have vaccination rates below 10%.

According to a news story last year, "South Sudan, a nation of 11 million, has more vice presidents (five) than ventilators (four). The Central African Republic has three ventilators for its five million people… In all, fewer than 2,000 working ventilators have to serve *hundreds of millions of people* [emphasis added] in public hospitals across 41 African countries, the World Health Organization says."[6]

In February 2021 the U.S. Food and Drug Administration posted "Using Ventilator Splitters During the COVID-19 Pandemic - Letter to Health Care Providers."[7] This document also links to the FDA's Emergency Use Authorization (EUA) concerning ventilators, modifications to devices capable of oxygenating an intubated patient, and ventilator accessories such as tubing.[8]

The list of accessories includes only one flow monitor, the "PEEP-Alert Pressure and Flow Monitor." (PEEP is an acronym for "positive end-expiratory pressure.") The device is unidirectional and attaches to the exhalation side of the gas system oxygenating a patient. It reports the pressure and flowrate averaged over three-second intervals, with a flow range of 25 to 150 litres per minute, a display resolution of one litre per minute, and an accuracy of 10% - 15%, depending on conditions. The device reports its readings on a display built into its case, but cannot transmit information to medical staff not at a patient's bed side. The manufacturer lists the PEEP-Alert's price as $390.[9]

We note that average adult "tidal volume"—the volume of air inhaled in a single breath—is 0.5 litres, and that a typical respiratory rate is 15 breaths per minute.[10] If an

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[4] Lucinda Rouse, "Liberia braces for coronavirus with defunct health system," *Aljazeera*, April 3, 2020. (https://www.aljazeera.com/news/2020/4/3/liberia-braces-for-coronavirus-with-defunct-health-system)

[5] Josh Holder, "Tracking Coronavirus Vaccinations Around the World," *New York Times*, November 29, 2021. "(https://www.nytimes.com/interactive/2021/world/covid-vaccinations-tracker.html)

[6] Ruth Maclean and Simon Marks, "10 African Countries Have No Ventilators. That's Only Part of the Problem," *New York Times*, May 17, 2020. (https://www.nytimes.com/2020/04/18/world/africa/africa-coronavirus-ventilators.html)

[7] U.S. Food and Drug Administration, "Using Ventilator Splitters During the COVID-19 Pandemic - Letter to Health Care Providers," February 9, 2021. (https://www.fda.gov/medical-devices/letters-health-care-providers/using-ventilator-splitters-during-covid-19-pandemic-letter-health-care-providers)

[8] U.S. Food and Drug Administration, "Emergency Use Authorization," March 24, 2020. (https://www.fda.gov/media/136423/download)

[9] PEEP-Alert Pressure and Flow Monitor web site, (https://www.peep-alert.com/products/peep-alert)

[10] https://en.wikipedia.org/wiki/Lung_volumes, visited November 29, 2021.

adult spends half of each minute inhaling and half exhaling, we can make a rough estimate that the average inhalation flow is 7.5 litres over 30 seconds. This corresponds to an instantaneous inspiratory flow rate of 15 litres/minute, or 0.25 litres/second. The expiration flow is about the same. As a result, the PEEP-Alert's minimum flowrate (25 litres/minute), its three second averaging interval, its unidirectional nature, and its flowrate accuracy (±3.75 litres/minute for pure O_2 at 25 litres/minute) make it unsuitable for use as a flowrate monitor for an intubated patient. (We note that typical peak inspiratory flow rates discussed online are higher than this, typically 1 litre/second.[11])

Initial tests of our device show it capable of measuring air flowrates of 8 litres/minute with an accuracy of ~3%, and reporting these measurements twice per second. The device's minimum useful flowrate is limited only by the instrumentation noise in the device's sensors, which corresponds to approximately 0.25 litres/minute. In addition to a thin film transistor screen that displays its measurements, our device is capable of transmitting them over a LoRa ("Long Range") radio link that can service multiple flowmeters (perhaps a dozen, or more), and inform medical personnel of the near-real-time status of the oxygen flow to each patient. With further development and optimization in the manufacturing, it might be possible to produce our flowmeters for less than $100 per unit.

Principles of operation

Fluid flow and the Bernoulli Equation

The behavior of fluids, both compressible and incompressible, are well described by the continuity, Navier-Stokes, and Bernoulli equations as long as a number of simplifying approximations are valid.[12] In our case, flow velocities are small compared to the speed of sound, while variations in pressure inside our device are at most a few percent of atmospheric pressure. These allow us to approximate the velocity-dependent pressure at two points along a tube of varying cross section with the Bernoulli Equation:

$$P_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 = P_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2,$$

where P is pressure, ρ is density, v is fluid velocity, and h is height. Since the change in pressure inside our device will be small, $\rho_1 \approx \rho_2$; assuming the flow is horizontal so that $h_1 = h_2$ we have

$$P_1 - P_2 \approx \frac{1}{2}\rho[v_2^2 - v_1^2].$$

[11] See, for example, Mark A. Warner and Bela Patel, Chapter 48, "Mechanical Ventilation" in *Benumof and Hagberg's Airway Management (Third Edition)*, 2013.

[12] See, for example, K.R. Symon, *Mechanics, 3rd edition*, Addison-Wesley Publishing, 1971. See also Harlan H. Bengtson, "Orifice and Venturi Pipe Flow Meters - For Liquid and Gas Flow," available online at https://www.suncam.com/courses/100222-06.html (visited November 30, 2010).

Effecting a fluid flow of Q cubic meters per second through a tube with cross sectional area A square meters requires a flow velocity (in meters per second) of

$$v = Q/A.$$

An inspiratory flow rate of 0.25 litres/second corresponds to $Q = 2.5\times10^{-4}$ m^3/s. This flow, passing through a tube with cross sectional area 1 cm^2 (10^{-4} m^2) would yield a flow velocity of 2.5 m/s, while an area of 5 cm^2 would produce a flow velocity of only 0.5 m/s. Note that quadrupling the flow rate to 1 litre/second would quadruple the flow velocities to 10 m/s and 2 m/s.

In tests of our device, we pumped air through a tube whose cross-sectional area was 5 cm^2 (2.5 cm × 2 cm) at the inlet, narrowing to 1 cm^2 (0.5 cm × 2 cm) in the tube's center. From the Bernoulli Equation, we expect (when Q = 0.25 litres/second) the pressure difference between these two regions of the tube to be

$$\Delta P \approx 3\rho = 3.6 \text{ Pa},$$

assuming that the atmospheric density at sea level[13] is about 1.2 kg/m^3. (For Q = 1 litre/second we find $\Delta P \approx 57.6$ Pa.) Recall that 1 Pa is a pressure of 1 N/m^2, and that atmospheric pressure is very close to 10^5 Pa, or 10^3 hPa. Near sea level, the decrease in pressure with altitude is about 12 Pa per meter, or 0.12 Pa per centimeter.

We determine the airflow through the device by measuring the pressure difference between the inlet and central region of the flow tube with DPS310 pressure sensors. These are manufactured by Infineon Technologies AG and mounted onto small "breakout boards" (and sold) by Adafruit Industries LLC.

It is likely that other sources of pressure drop (such as turbulence and dissipative losses from air flow over rough interior surfaces) will contribute to ΔP, perhaps making the potentially observable effect larger.

Turbulent flow

The Bernoulli equation applies to fluids undergoing smooth, laminar flow. But the full range of behaviors available to a moving fluid includes chaotic, turbulent flow. A rough gauge of the likelihood of a fluid's transition to turbulent flow is the Reynolds number of the fluid and the channel through which it passes. Systems with Reynolds number R_e less

[13] https://en.wikipedia.org/wiki/Density_of_air, visited November 30, 2021.

than 2,300 (for which viscous forces dominate) will usually exhibit laminar flow, while those with R_e greater than 2,900 will tend to show turbulence.[14]

For our system, the Reynolds number is[15]

$$R_e = \frac{ud_h}{v}$$

where u is the fluid's velocity, d_h is the "hydraulic diameter" of the flow tube, and v is the "kinematic viscosity" of air (or humidified oxygen, when used in a hospital setting). For air at room temperature, v is approximately[16] 1.5×10^{-5}. The hydraulic diameter of a rectangular pipe[17] of cross-sectional area A and interior circumference C is $4A/C$ so our flow tube has hydraulic diameters of .0222 m and .0067 m in its wider and narrower regions. These values yield Reynolds numbers of $R_e = 740$ and $R_e = 1{,}117$ respectively, suggesting that the air flow in our device is laminar, not turbulent, when $Q = 0.25$ litres/second. Note that quadrupling the flow rate to 1 litre/second will quadruple the Reynolds number, perhaps resulting in turbulent flow in the device.

Device geometry and pressure sensors

A photograph of a version 1 prototype is shown in Figure 1. The reduction in cross sectional area in the middle of the white portion of the flow tube is clearly visible.

In the figure, air enters from the left; three DPS310 pressure sensors are inside the tube, while a fourth, external to the flow tube, allows us to gauge local atmospheric pressure. The pressure sensors' green status lights are visible through the translucent walls of the tube. The cross-sectional areas of the wider and narrower portions of the flow tube are 5 cm^2 and 1 cm^2.

From left to right, modules on the main circuit board are a RadioFeather M0 microcontroller, an I2C multiplexer, a GPS module, a microSD memory card, a real time clock (RTC) module, and a liquid crystal display. Most of the modules are available from Adafruit Industries, while the LCD is a Crystalfontz America product. We use the GPS module to set the RTC to the correct Coordinated Universal Time (UTC, formerly known as Greenwich Mean Time).

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[14] https://en.wikipedia.org/wiki/Reynolds_number, visited December 9, 2021.
[15] https://www.engineeringtoolbox.com/reynolds-number-d_237.html, visited December 9, 2021.
[16] https://www.engineeringtoolbox.com/dynamic-absolute-kinematic-viscosity-d_412.html, visited December 9, 2021.
[17] https://www.engineeringtoolbox.com/hydraulic-diameter-rectangular-ducts-d_1004.html, visited December 9, 2021.

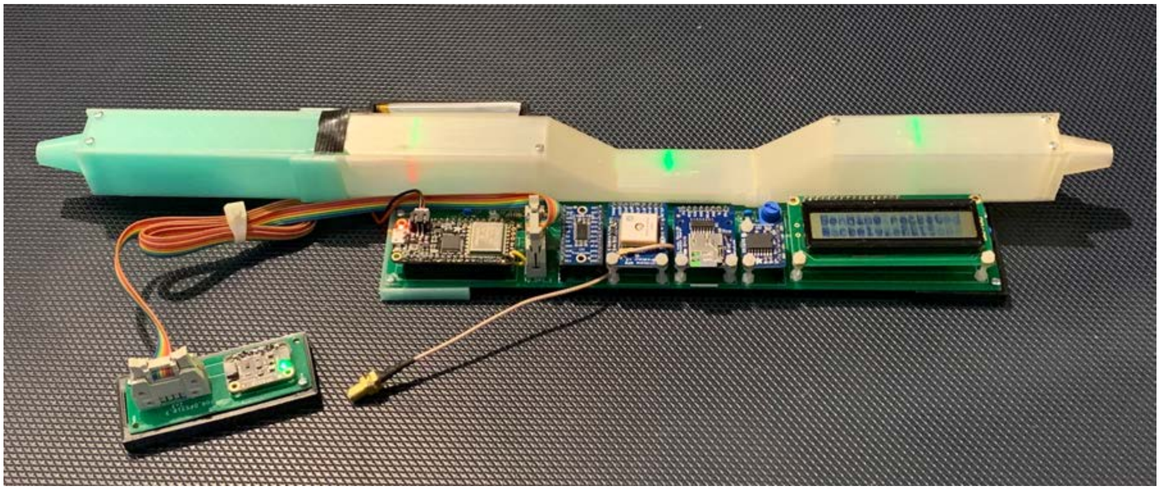

Figure 1. Ventilator tube insertion flowmeter. Air enters from the left; three DPS310 pressure sensors are inside the tube, while a fourth is held outside, to gauge local atmospheric pressure. The small coaxial connector at the end of the thin cable allows attachment of an optional GPS external antenna.

The flow tube itself is designed using the Tinkercad rapid prototyping design tool from Autodesk. The tubes are fabricated from PLA (polylactic acid) plastic on Ultimaker 2+ 3D printers.

DPS310 pressure sensor

The DPS310 is manufactured by Infineon Technologies AG, a multinational technology producer with headquarters in Germany. The device includes both pressure and temperature sensors; according to Infineon, the "relative accuracy" and "precision" of the pressure sensor are 6 Pa and 0.2 Pa respectively.[18] The relative accuracy describes the variation in readings from uncalibrated out-of-the-box components. It is the precision figure that is important for us, since this sets the limit on how well we can interpret the difference between readings from calibrated sensors as arising from a true pressure difference.

The remarkable precision of 0.2 Pa corresponds to a change in altitude of 2 cm at sea level and is adequate for our purposes. The manufacturer describes the device as using a "capacitive sensing principle" to determine local pressure.

The DPS310 pressure measurement is temperature sensitive,[19] with a manufacturer-specified "Pressure temperature sensitivity" of 0.5Pa/K. It is possible to compensate for this on a device-by-device basis by loading appropriate values into a seven-word "Calibration Coefficient" register. We have not tried to correct the raw pressure values using the calibration registers, and do see device-to-device pressure variations that

[18] https://www.infineon.com/cms/en/product/sensor/pressure-sensors/pressure-sensors-for-iot/dps310/, visited December 1, 2021.
[19] https://www.infineon.com/dgdl/Infineon-DPS310-DataSheet-v01_02-EN.pdf, October 15, 2020.

accompany changes in temperature. We show this in the following figures, in which measurements from the three pressure sensors inside the flow tube were recorded at approximately 1.7 Hz for eight hours. Since no air was injected into the horizontal flow tube, the actual pressures at each sensor were identical.

In Figure 2 we display the uncorrected temperatures from the three devices, as well as the differences between pairs of devices. Take note of the nearly identical temperature dependences of devices 1 and 2: the lower graph in the figure shows a nearly horizontal band of green points, with which we show the p1 – p2 pressure differences recorded over eight hours. Also note that the p0 - p1 and p0 – p2 bands both peak up at the time of lowest temperature. We believe it will be possible to correct for the different temperature dependences *in situ*, during field operation of the ventilator flowmeter.

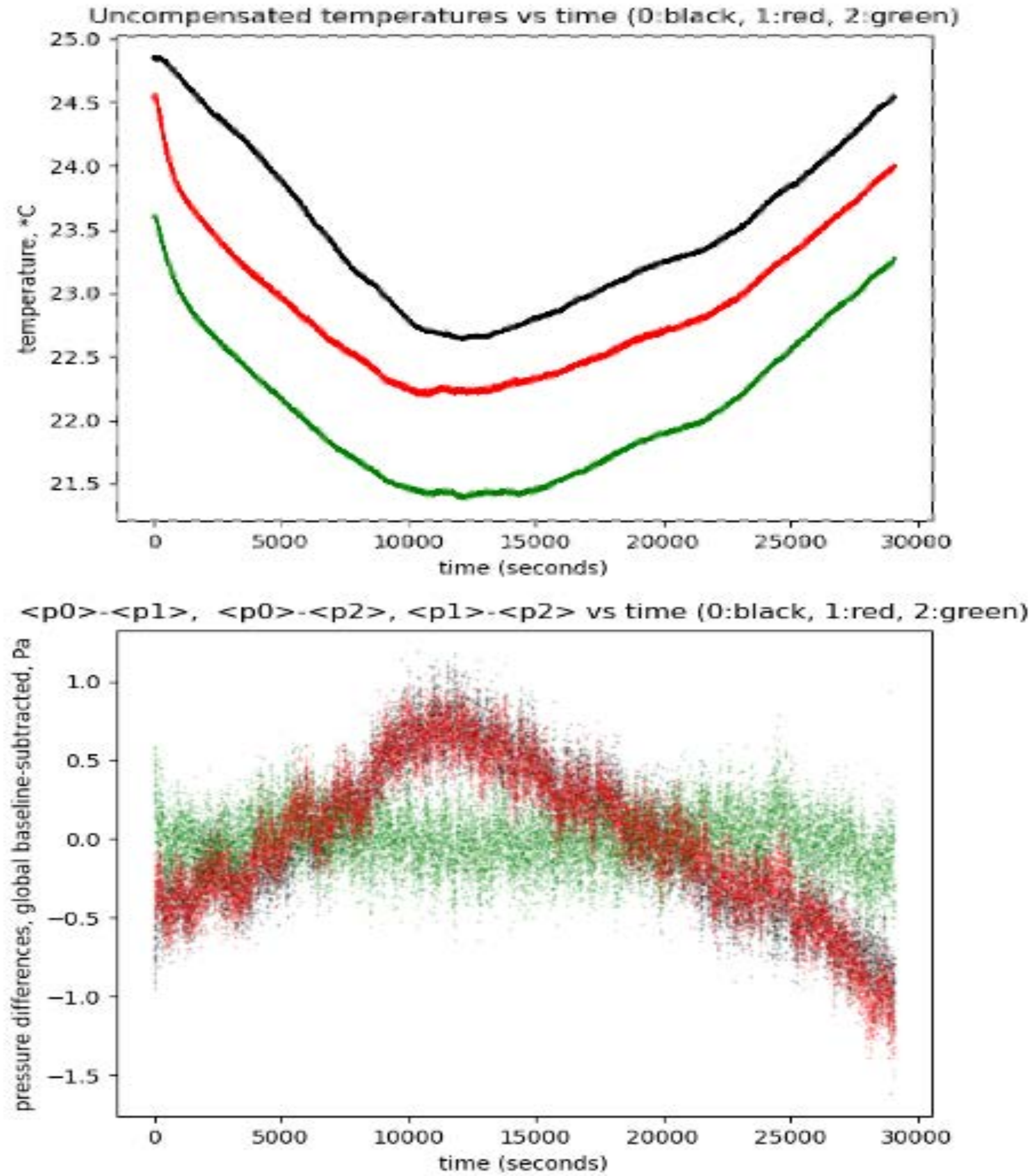

Figure 2. Top: raw temperature readings from three DPS310s. The three sensors are inside the flowmeter tube, which is held in a horizontal orientation. It is reasonable to assume that the true temperatures and pressures at each sensor were identical. Data were collected overnight, for about eight hours. Bottom: differences in pressure between pairs of sensors, after subtracting the eight-hour means from each of the sensors' measurements. Note that the temperature dependences of devices 1 and 2 (shown as green dots) are nearly identical, since the populated band is approximately horizontal. However, the differences between devices 0 and 1 (black dots) as well as devices 0 and 2 (red dots) shift by roughly one Pascal between times 0 seconds and 12,000 seconds, during which time the local temperature fell by about two degrees centigrade.

In Figure 3 we show as a histogram the uncorrected (but mean-subtracted) difference in pressures p1 – p2. This is equivalent to a projection on the vertical axis of the second graph in the previous figure. Even neglecting the small amount of temperature dependence evident in Figure 2, we find excellent agreement between devices 1 and 2: the RMS width of the plot in Figure 3 is 0.178 Pascals, about 5% of the expected pressure difference with a flow rate of 0.25 litres/second.[20]

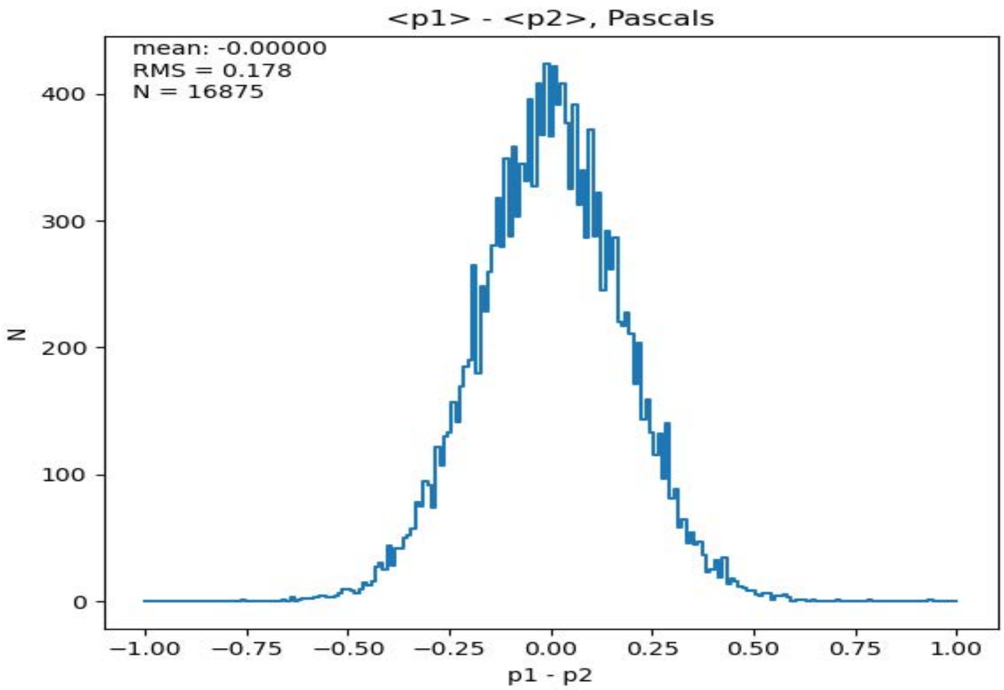

Figure 3. Differences in raw pressure between sensors 1 and 2, after subtracting the eight-hour means from each of the sensors' measurements. The RMS width of 0.17 Pa can be interpreted as limiting the system's precision when determining a flow rate that corresponds to about 0.0125 litres/second.

System architecture

A block diagram of the system is shown below in Figure 4.

The entire device is run by an Adafruit RadioFeather M0, a versatile microcontroller built around an Atmel SAMD21 processor clocked at 48 MHz. The microcontroller board includes an RFM95W radio module, which uses the unrestricted 915 MHz band to communicate with other devices, such as a general-purpose base station (an in-house design) we have used for other projects. We program the M0 using the well-supported Arduino Integrated Developers Environment (IDE), along with various Adafruit libraries that facilitate communication with the sensors and other modules.

[20] Analysis code: bernoulli_flowmeter_noise_study3.py. Flowmeter data acquisition code: bernoulli_flowmeter_noise_study3.ino. George Gollin, December 2021.

We use the GPS module to synchronize the real time clocks on various flowmeters, since the LoRa radio protocol forces us to communicate with only one device at a time. In other projects we have done this by having each "field station" schedule its time of next transmission to avoid conflicting with transmissions from other devices. (A more sophisticated wireless protocol, such as a cellular data network employed by some hospitals would obviate the need for this scheduling.)

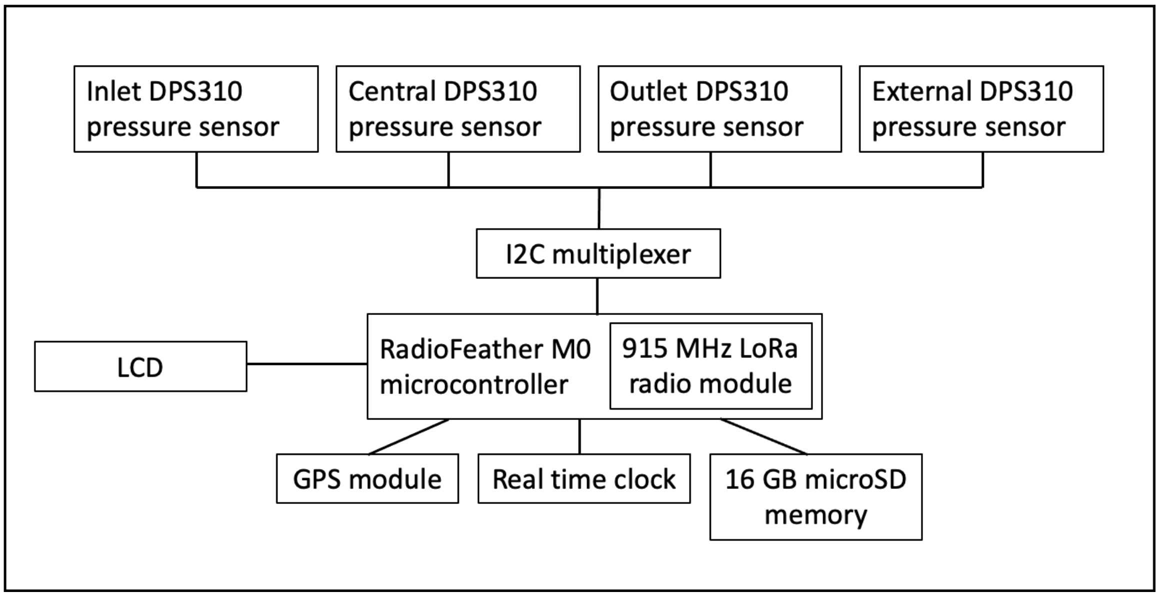

Figure 4. Ventilator tube insertion flowmeter system architecture.

We use the I2C protocol to move data from the pressure sensors into the microcontroller. Since the DPS310 I2C hardware address is fixed by the manufacturer, we use an I2C multiplexer so that up to eight devices with the same I2C address can communicate with the RadioFeather M0.

We expect that medical personnel who might use flowmeters of the sort we are developing would access their measurements primarily through an interface to a base station that was communicating with several flowmeters. Even so, we have included a microSD memory in the design so patient data can be stored locally, for offline analysis if desired. Since the data rate from a flowmeter is only a few hundred bytes per second at most, a 16 GB memory card could hold over a year's worth of measurements before running out of space.

An enlarged portion of Figure 1, cropped to show most of the device's electronic components, is shown in Figure 5.

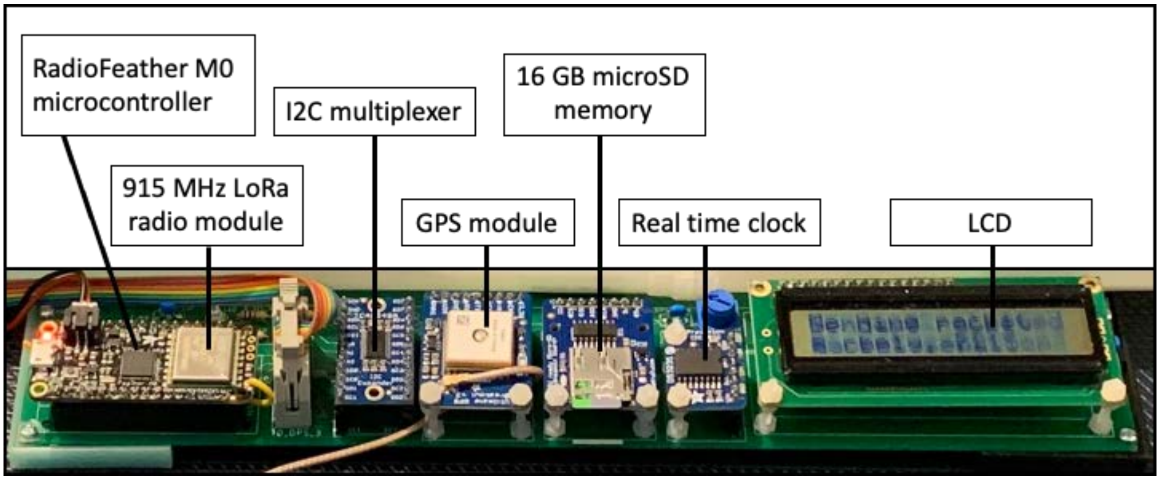

Figure 5. Flowmeter electronic components.

Second prototype

In January 2022 we built a second prototype with a shorter flow tube and only two DPS310 modules. (This version is otherwise identical to that described above.) We sealed leaks in the flow tube with mounting putty and used a battery-powered air mattress pump to push air through a column flowmeter and into our device.

This prototype with its cover removed is shown in Figure 6.

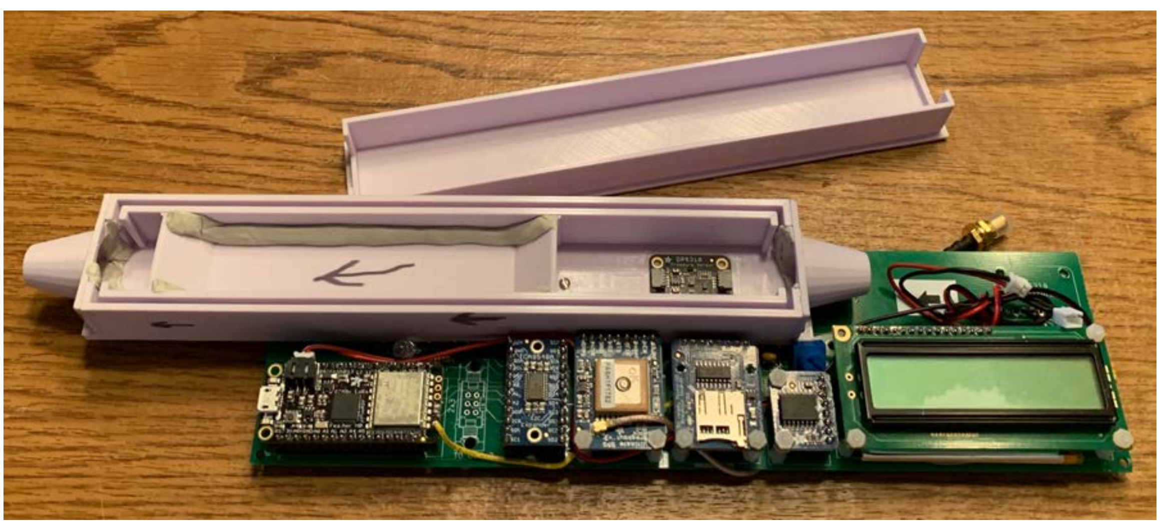

Figure 6. Second prototype.

The test setup used with this prototype is shown in Figure 7. The column flowmeter, near the top of the figure, can admit a maximum flow of 25 litres/minute.

Figure 7. Testing the second prototype.

Testing the second prototype

The pressure difference between the two sensors in the device is plotted as a function of time in Figure 8. After a brief interval of calibration for times near 0, the pump and flowmeter were set to pass approximately 22 litres/minute through the device. After recording data for a few minutes, we reduced the flow to 15 litres/minute, then 10 litres/minute, then 5 litres/minute, then 0. We found that the flow rates weren't especially constant: the indicator bead in the column flowmeter would bobble around a bit, perhaps by about one litre/minute.

Data from individual flow rates are shown in Figures 9 through 13. A quadratic fit to the means of these five flow rates is shown in Figure 14. Note that typical flowrates to an intubated patient are roughly in the range 15 litres/minute to 60 litres/minute.

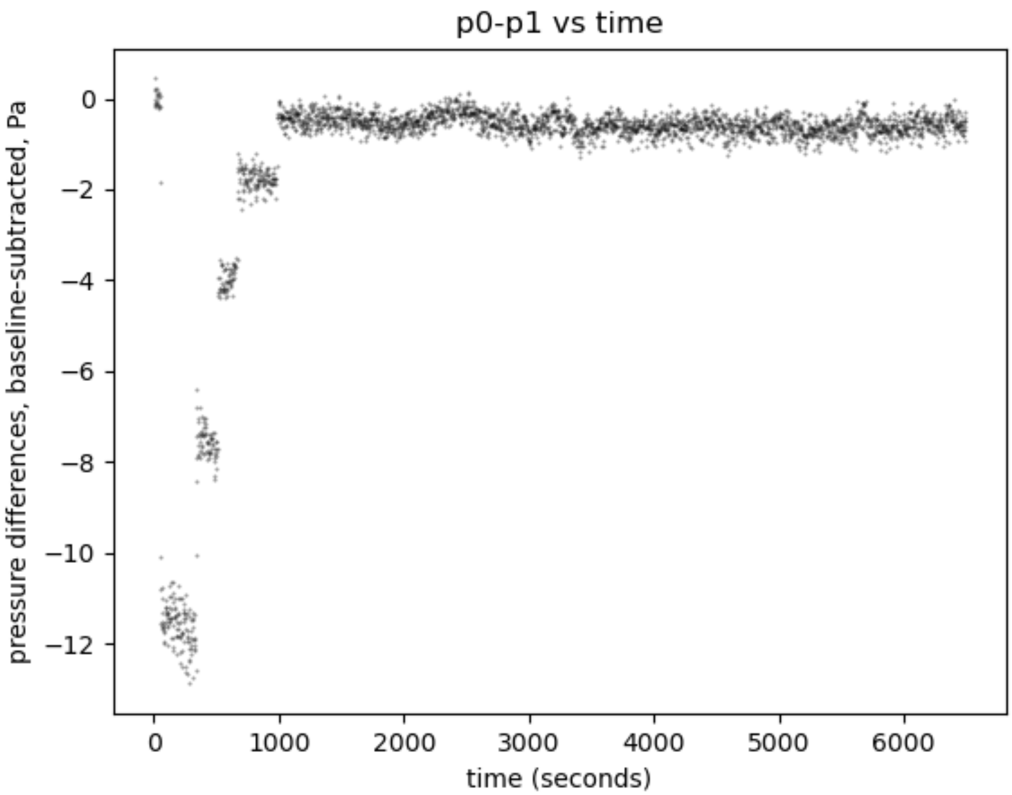

Figure 8. Test data. After a brief interval of calibration for times near 0, the pump and flowmeter were set to pass approximately 22 litres/minute through the device, then 15 litres/minute, then 10 litres/minute, then 5 litres/minute, then 0.

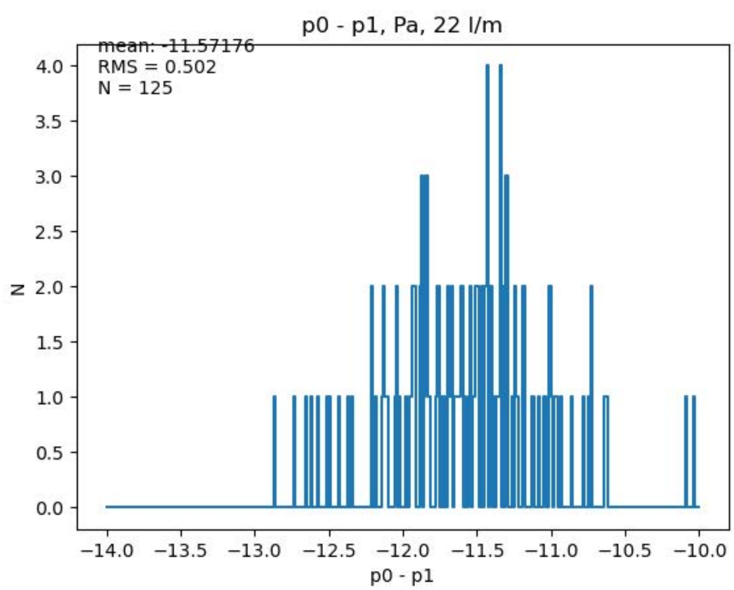

Figure 9. 22 litres/minute pressure difference.

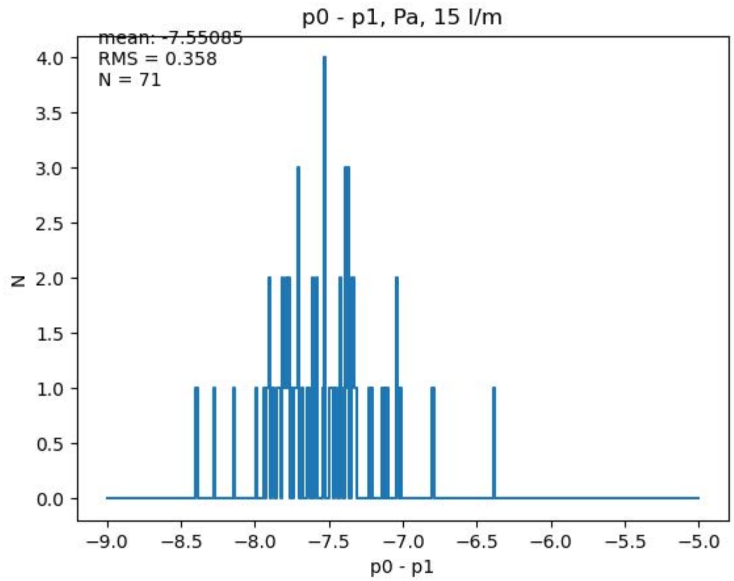

Figure 10. 15 litres/minute pressure difference.

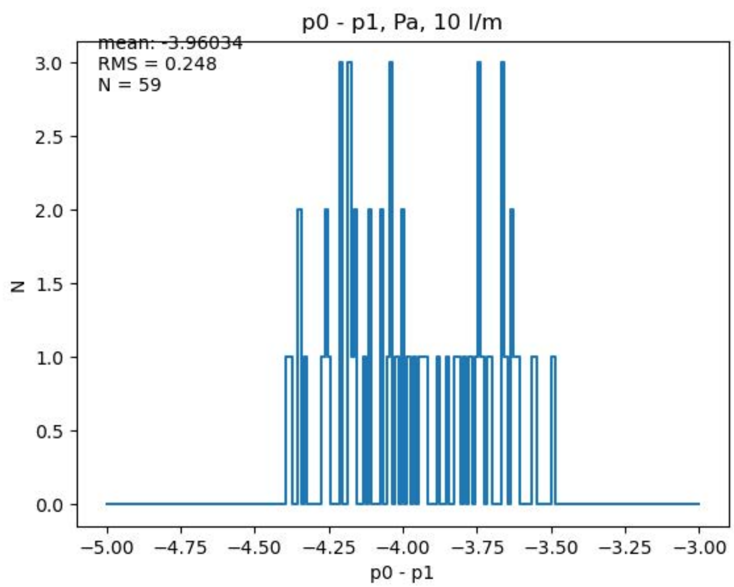

Figure 11. 10 litres/minute pressure difference.

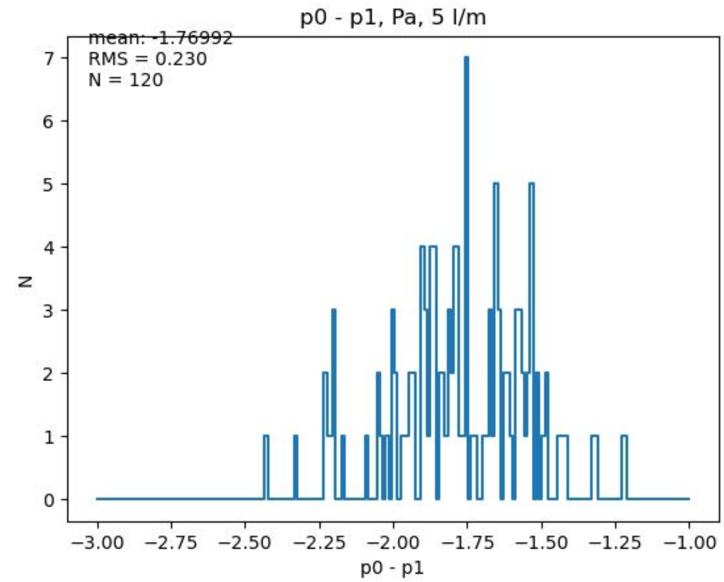

Figure 12. 5 litres/minute pressure difference.

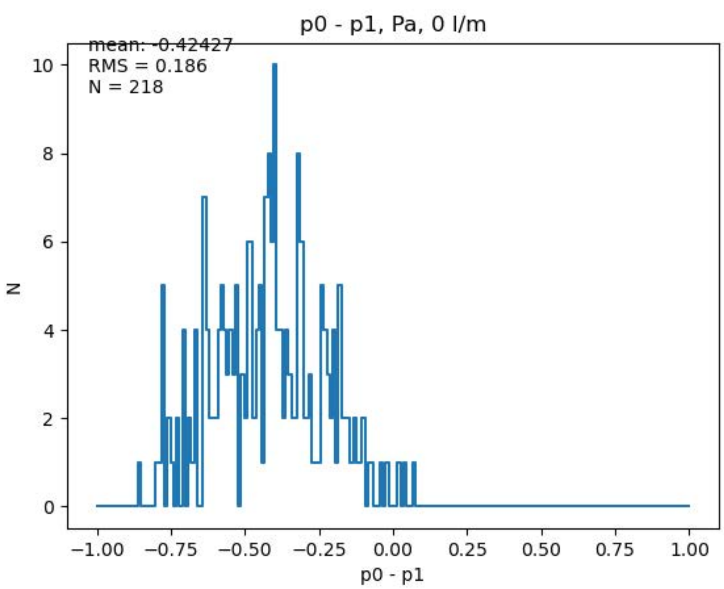

Figure 13. 0 litres/minute pressure difference.

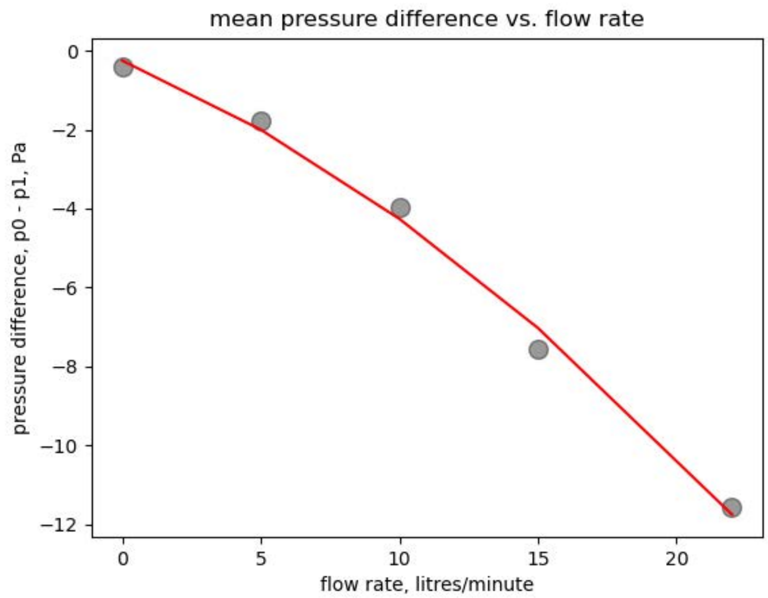

Figure 14. Mean pressure difference vs. flowrate, quadratic fit. Recall that typical flowrates to an intubated patient are roughly in the range 15 litres/minute to 60 litres/minute, and that the noise in our pressure difference measurements is typically 0.2 Pa. (The diameter of the markers in the plot is about the same as the typical pressure difference noise.)

Third prototype

ID bit switch
TFT display
Two flow tubes

Future directions and refinements; conclusions

Cost of components

Component price for one version 1 flowmeter

items for one flowmeter; unit price based on ten pieces included in a large order	price
Adafruit Feather M0 microcontroller with RFM95 LoRa Radio (1 required)	28.
Adafruit DPS310 pressure sensors (4 required)	23.
Adafruit DS3231 real time clock (1 required)	11.
Adafruit microSD card breakout (1 required)	6.
Lithium-ion battery, 3.7V, 2000 mAh (1 required)	10.
3D-printed flow tube (1 required)	2.
Adafruit I2C multiplexer (1 required)	6.
printed circuit board (1 required)	5.
Adafruit GPS module (1 required)	24.
Crystalfontz liquid crystal display (1 required)	4.
Miscellaneous resistors, capacitors, connectors, etc.	10.

total	129.

Component price for one base station

items for one base station	price
Adafruit Feather M0 microcontroller with RFM95 LoRa Radio (1 required)	28.
Adafruit DS3231 real time clock (1 required)	11.
Adafruit microSD card breakout (1 required)	6.
Lithium-ion battery, 3.7V, 2000 mAh (1 required)	10.
3D-printed enclosure (1 required)	2.
printed circuit board (1 required)	5.
Crystalfontz liquid crystal display (1 required)	4.
Miscellaneous resistors, capacitors, connectors, etc.	10.
total	76.