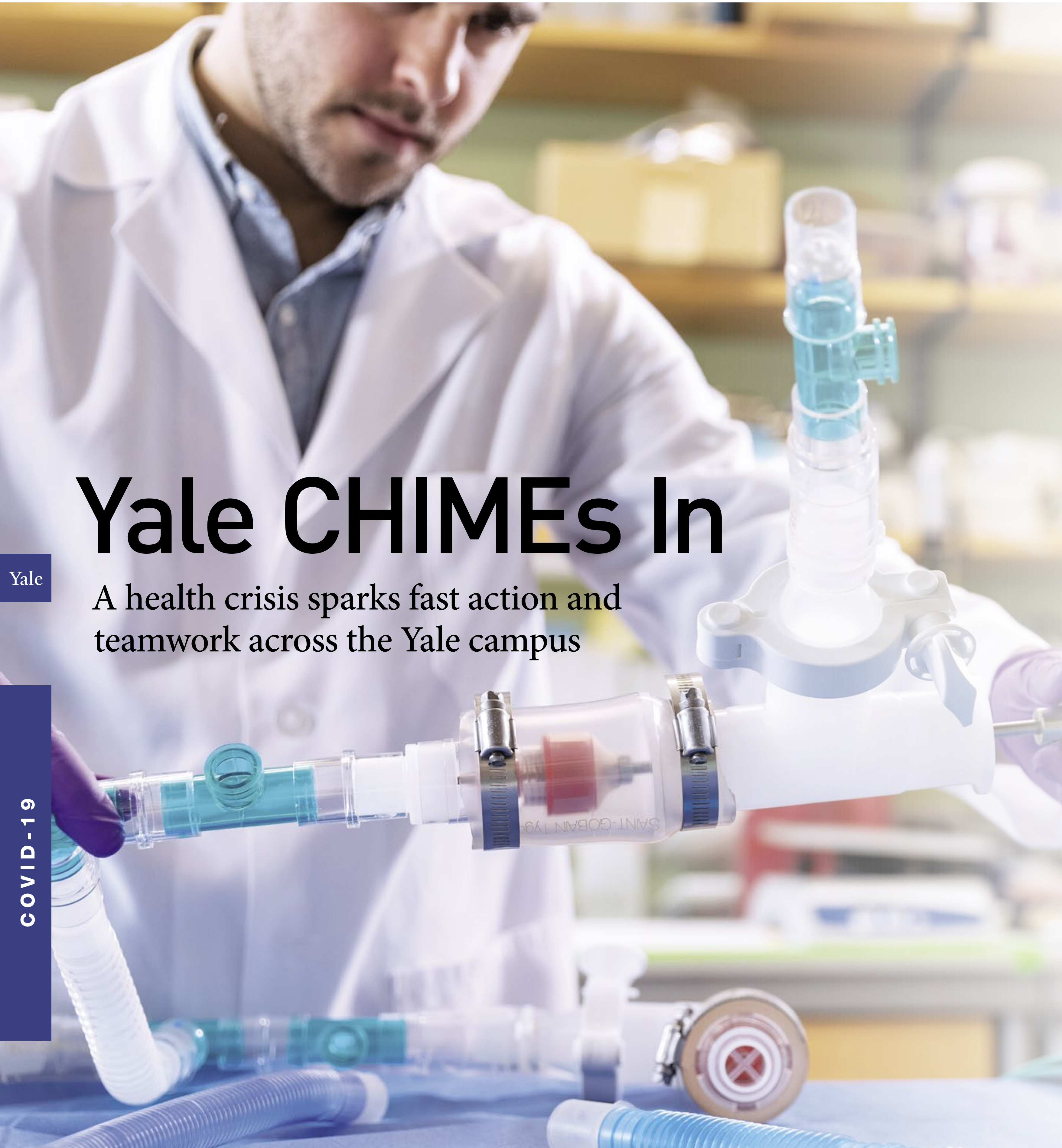

Yale CHIMEs In

A health crisis sparks fast action and teamwork across the Yale campus

In March, days after Yale and most of Connecticut went into lockdown to curb the spread of COVID-19, there was an increasing concern that hospitals might run out of supplies critical to fighting the disease.

In response, Yale faculty and staff from a wide range of disciplines quickly pooled their skills and resources to come up with solutions. This group, the Coalition for Health Innovation in Medical Emergencies (CHIME), brought together engineers, physicians, nurses, and many others to identify the most crucial shortages facing healthcare workers — and then, ways to increase those supplies. This included expanding access to personal protective equipment, ventilators, respirators, and nasopharyngeal swabs. Organized by the staff at the Center for Engineering Innovation & Design (CEID), rapid progress was made on a number of projects, from the creation of a device and a protocol for measuring the reliability of non-certified respirators, to work on the design of ventilator systems that treated more than one patient at a time.

"We've seen as our faculty turned on a dime to take projects they were working on that were non-COVID-19-critical and repurposed them — repurposed their labs, and repurposed the work they were doing — to address what could have a tremendous and important impact on the outcome of the pandemic," said Jeffrey Brock, Dean of the School of Engineering & Applied Science.

The coalition was formed to take advantage of Yale's culture of collaboration, and its diverse range of expertise which includes specialists in engineering, public health, nursing, medicine, and design. The coalition also leveraged Yale's significant fabrication resources, such as those at the Wright Laboratory, the School of Architecture, the Neurotechnology Core at Yale's medical campus, and the CEID.

"Innovative output requires diverse input, so we convened a multidisciplinary team that could look at problems from fresh perspectives," said Joe Zinter, assistant director of the CEID, who helped coordinate CHIME's efforts.

"Giving us More Options"

At a time when many hospitals were running low on personal protective equipment, a Yale-built system that tests non-certified respirators and masks opened up valuable new options for healthcare workers. Typically, hospitals have a steady supply of respirator masks certified by the National Institute for Occupational Safety and Health. At the height of COVID-19 cases in Connecticut, though, a shortage of these masks made finding suitable alternatives a must. Many non-certified masks in circulation, however, are of unknown quality and safety. To identify the most suitable products, Yale researchers developed a system to test the quality of these respirators. This solution to an unprecedented situation was made possible by the collaboration of researchers in different fields.

"Testing for masks on your medical campus isn't normal, but it's necessary right now — like many things we're doing now in the state of COVID-19, it's all about what we need to do for patients and our frontline healthcare workers," said Dr. Lisa Lattanza, chair of Orthopaedics & Rehabilitation at Yale's School of Medicine. "We want to protect our frontline heroes from getting sick, and the ability to test on campus just gives us more options to do that in the time of a really tight supply chain."

Stationed at the CEID, tests of the masks are run on the device and determine how well the respirators filter out aerosols, as well as how well they allow

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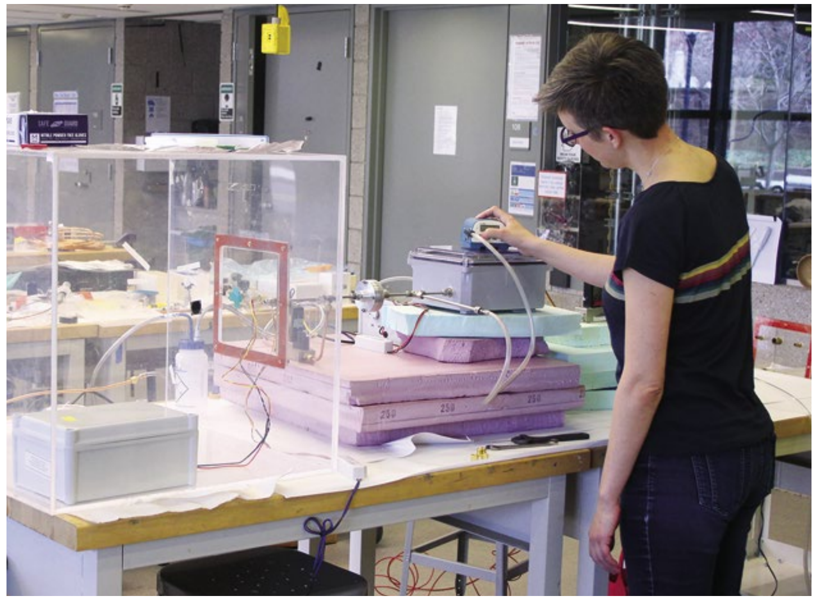

Senior research scientist Lawrence Wilen (left) and associate research scientist Katherine Schilling (right) conduct tests on the quality of non-certified respirators.

their wearers to breathe. They're conducted by senior research scientist Lawrence Wilen, associate research scientist Katherine Schilling, and CEID design fellow Antonio Medina, with guidance from Drew Gentner, associate professor of chemical & environmental engineering and the environment.

The results showed a wide range of quality and were shared with Lattanza and Yale Environmental Health & Safety, which conducts its own tests on how well the masks fit. Wilen said the tests at the CEID provide data that allow Lattanza and her colleagues to make informed decisions.

"We see this as sort of a pipeline — in the end, they're trying to come to some decisions about which ones have the best chance of being the highest quality," he said. "With this information, they can come up with a priority list, and if they start at the top and go down, it optimizes their chances of doing better."

Under the unique conditions, a lot of creativity and fast-thinking was required to build the device. Without the immediate use of an atomizer to generate an aerosol, they used incense instead. In the SEAS Machine Shop in the basement of Dunham Laboratory, research support specialist Nicholas Bernardo "scrounged up some materials" to fashion from scratch a new filter holder made out of aluminum (existing models are made out of Teflon, which wouldn't work for this device). He made the first component in six hours.

"It's was a time when we were all feeling unique pressures, but also finding unique solutions," said Vincent Wilczynski, SEAS Deputy Dean and the James S. Tyler Director of the CEID.

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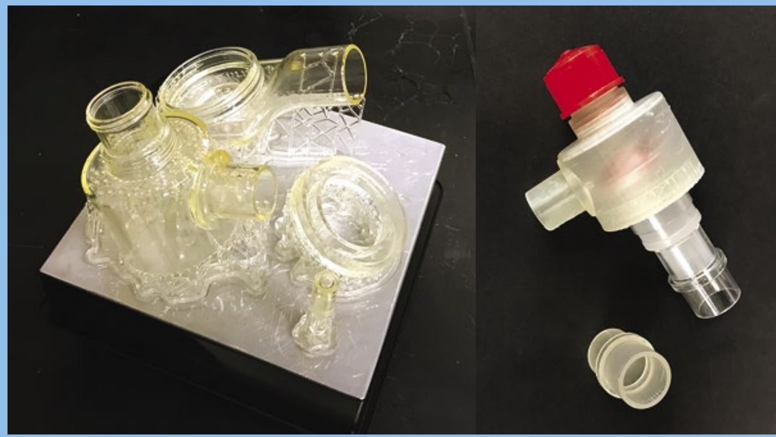
Above: *In the SEAS Machine Shop, research support specialist Nicholas Bernardo creates a new filter holder made out of aluminum to aid in respirator testing.*

Other CHIME-Associated Projects Include:

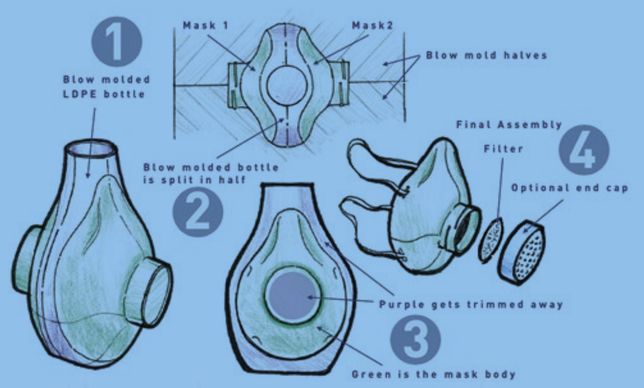
Moldable Face Shield Design

A partnership between Cisco Research Center, the Yale School of Nursing (YSN), and the department of computer science resulted in the creation of 1,000 injection-molded face shields. John Marshall, distinguished engineer at Cisco, said his team started work on the moldable face shield design and created a new design that allowed the use of alternate materials for the elastic strap as well as simplified construction to facilitate efficient injection molding. YSN Dean Ann Kurth said the face shields would be critical in supporting the personal protective equipment needs of students at clinical sites.



Local Industry Respirator Design

In another effort to increase access to face masks, staff and faculty at the School of Medicine, the CEID, and Yale Environmental Health & Safety, worked with Unilever to produce alternative respirators made with two distinct high-volume production methods: blow-molding and injection-molding.



Testing Mask Reuse with Computer Simulations

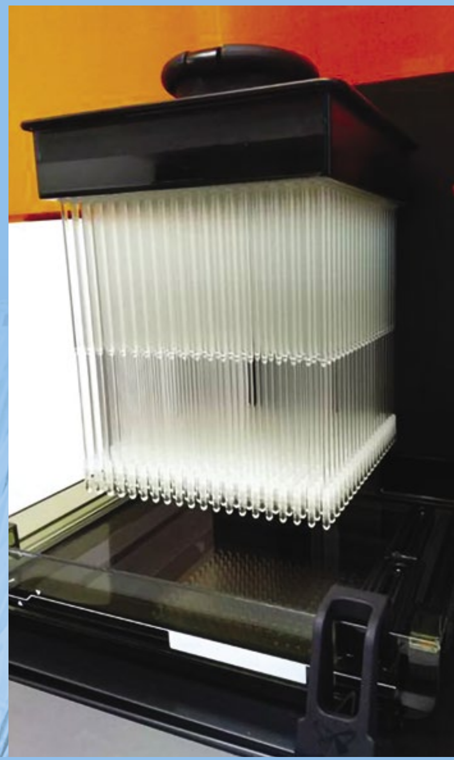
To help hospitals make the most of what supplies they have on hand, Yale alums and CEID staff developed computer simulations to predict the mechanical properties of single-use face masks when they're reused — a possible necessity due to shortages. The team's computer simulations took into account various failure modes of masks, such as contamination, strap breakage, and filter efficiency to determine the average number of hours a given mask can survive in a hospital.

Single-use Ventilator Components

In addition to a shortage of ventilators, single-use parts for ventilators such as tubing and connectors ran low in hospitals at the peak of COVID-19 cases. To relieve this shortage, Dr. Daniel Wiznia, assistant professor of orthopaedics and rehabilitation and mechanical engineering & materials science, worked with James Nikkel, associate director for instrumentation and education at the Wright Laboratory. After identifying eight ventilator parts as being in particularly short supply, the researchers used 3D printers to create prototypes of these parts.

Printing NP Swabs

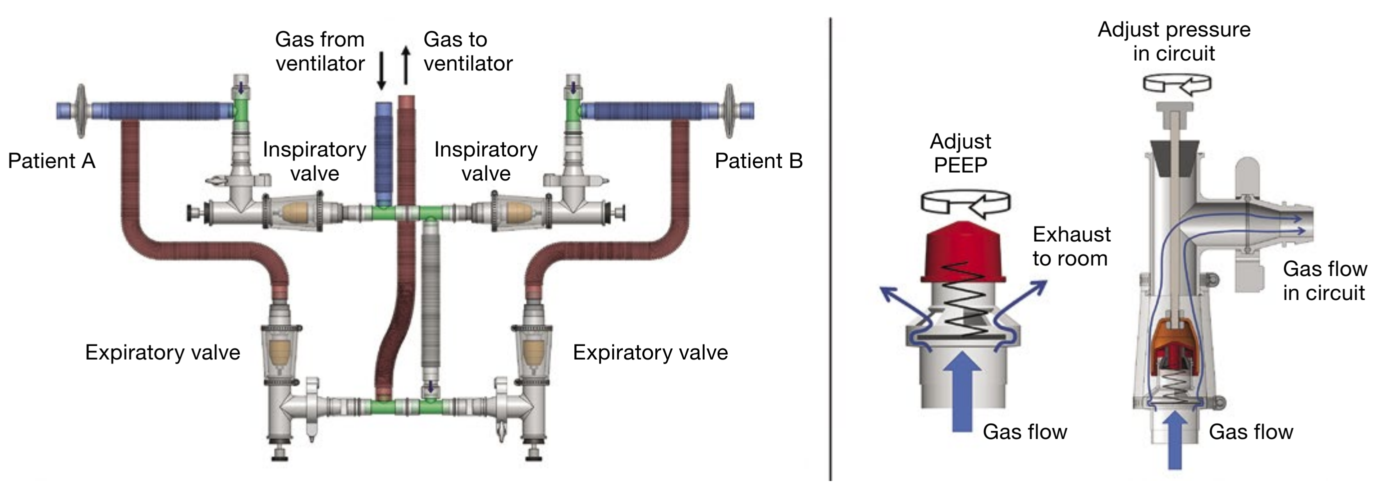
COVID-19 testing led to an urgent need for nasopharyngeal (NP) swabs, used to collect samples from patients. To alleviate the shortage, faculty in the departments of endocrinology, pathology, and biomedical engineering partnered to establish a local mechanism for 3D printing swabs based on an FDA-approved process. After local manufacturing in the department of endocrinology, the NP swabs were autoclaved, packaged, and then added to the hospital's inventory.



Ventilator Innovations

As COVID-19 cases rose, there were concerns that hospitals wouldn't have enough of the ventilators needed for the most severe cases. Rather than building new ones, which would take too much time and resources, some CHIME members focused on finding ways to modify existing ventilators. Because COVID-19 patients vary in their physiological and immunological profiles, though, simply dividing a ventilator's capacity between two patients isn't sufficient — a setting that stabilizes one patient could make another patient far worse. The problem called for a more nuanced solution.

One of these projects came out of the laboratory of Dr. Laura Niklason, the Nicholas Greene Professor of Anesthesiology and Biomedical Engineering. Their system, known as the Pressure Regulated Ventilator Splitting (PReVentS), allows one ventilator to not only treat two patients simultaneously, but in a way that fits both patients' physiological needs. While the PReVentS splitter is designed for simultaneous use by two patients, a study published by the team shows that the system could possibly allow a single ventilator to be used by up to four patients. The researchers note, though, that treating multiple patients with one ventilator would be for emergency situations only.

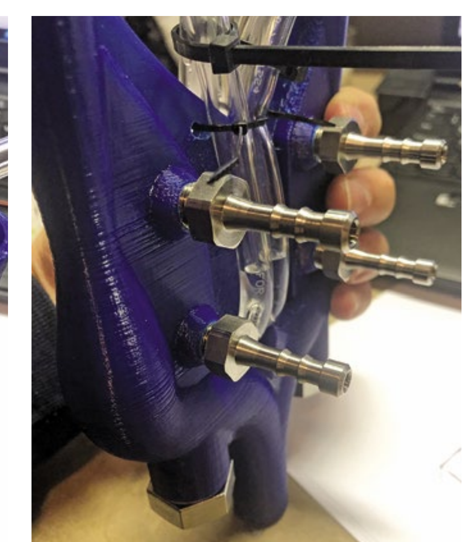


As COVID-19 cases rose, a shortage of ventilators become a critical concern for hospitals. The laboratory of Dr. Laura Niklason created a system that splits an existing ventilator to treat up to four patients simultaneously, but adjustable to fit all patients' physiological needs.

Left: *Sam Brickman Raredon, a member of the Niklason Lab, illustrates how PReVentS can treat multiple patients at the same time.* Middle: *PReVentS being tested and analyzed.* Top Right: *A design that was easy for hospital staff to quickly assemble in a high-stress environment was critical.* Right: *CHIME members also designed an adapter to convert an off-the-shelf positive end-expiratory pressure ventilator valve element into a device that can be used in the vent-splitting circuit.* Bottom: *An alternative multiplexing design that incorporated Venturi-based pressure measurements for each air pathway.*

Working with the Niklason group was Yale alum Joe Belter, director of actuator engineering with ClearMotion, who said they were aiming for a design easy for hospital staff to put together and use in a very high-stress environment. After creating some computer-aided designs, the team printed out prototypes at the CEID, the Wright Laboratory, the School of Architecture, and even Belter's home office. Those were then handed over to the Niklason group so they could review it and work through some of the layouts.

Belter and others at CHIME worked on a separate ventilator project, in which they looked into ways to design a device that can be 3D-printed, added to a standard ventilator, and allow for the ventilation of multiple patients while still independently controlling the air flow to each. When putting together some prototypes, a major part of the process involved consulting with another Yale alum, Becky Robinson-Zeigler, deputy chief regulatory officer with Advanced Regenerative Manufacturing, to advise on certifications and tests pertaining to the work.



"We're fortunate to be at a place like Yale, which maintains such strong connections to former students that they're willing to stop what they are doing to help out in a crisis," Brock said. "From alumni, to staff, and to faculty, it's been all hands on deck."