Using Simulation to Develop Solutions for Ventilator Shortages From the Epicenter

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Summary Statement: The COVID-19 pandemic threatened to overwhelm the medical system of New York City, and the threat of ventilator shortages was real. Using high-fidelity simulation, a variety of solutions were tested to solve the problem of ventilator shortages including innovative designs for safely splitting ventilators, converting noninvasive ventilators to invasive ventilators, and testing and improving of ventilators created by outside companies. Simulation provides a safe environment for testing of devices and protocols before use on patients and should be vital in the preparation for emergencies such as the COVID-19 pandemic.

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Key Words: Ventilation, innovation, high-fidelity simulation, rapid prototyping.

In March 2020, the Mount Sinai Department of Anesthesiology's Human Emulation, Education and Evaluation Lab for Patient Safety and Professional Study (HELPS) found itself in the center of the COVID-19 pandemic. As the volume of critically ill COVID-19 patients increased throughout New York City, the very real threat of ventilator shortages loomed. Ventilator shortages were reported worldwide, and at the time, very few solutions existed in the United States.

Our simulation laboratory is staffed by full-time clinical anesthesiologists who found themselves caring for COVID-19 patients throughout the hospital. Despite clinical duties, we worked in collaboration with trainees within our department as well as outside departments at our institution to develop and test solutions for ventilator shortages. Our faculty split into teams to tackle multiple potential solutions to the ventilator shortage problem.

The first team aimed to develop a method for safely allowing one ventilator to be used for 2 patients simultaneously. Before the pandemic, splitting ventilators between 2 patients was used for mass casualty events and presented problems because of variability in each patient's lung volumes, compliance, and disease severity. The initial prototype was developed using plumbing gate valves from a local hardware

store to control flow to each patient. Using our simulation laboratory's 2 high-fidelity simulation mannequins (HPS Simulator Mannequin Systems; CAE Healthcare, Sarasota, FL), we were able to titrate the appropriate tidal volumes to each simulated patient across a variety of programmed lung compliances. Using the data from these experiments, we worked with industry to rapidly prototype a 3-dimensional-printed needle valve, which then underwent further testing in the simulation laboratory and design modifications based on the results. After institutional approval and legal consent, these valves were then successfully tested in vivo using a standardized protocol on human patients.

A second team worked in collaboration with the Department of Sleep Medicine at Mount Sinai to repurpose readily available noninvasive Bilevel Positive Airway Pressure machines into functioning invasive bilevel ventilators after the Food and Drug Administration's emergency use authorization. First, the porous mask system was replaced by a closed circuit capable of connecting to an endotracheal tube. Next, the circuit was modified to allow for measurement of inspired oxygen concentration, tidal volumes, and expired carbon dioxide on capable monitoring devices. The bilevel ventilator was then tested on our high-fidelity mannequins with good results. Similar to the first team, these modified bilevel ventilators were successfully tested in vivo on human patients after legal consent.

Finally, a third team aimed to use simulation to test and troubleshoot numerous ventilators developed outside of our institution. Many of these ventilators were developed by companies traditionally operating outside of healthcare and needed collaborators within healthcare for insight. Two styles of ventilators were commonly tested and included low-cost automated manual self-inflating resuscitation bag ventilators and small ventilators similar to portable ventilators used for patient transport. This team was able to test and review each ventilator using high-fidelity simulation to find problems and solutions, which allowed for rapid prototyping of an improved iteration

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of each device. One of the ventilators tested was developed by the National Aeronautics and Space Administration's Jet Propulsion Laboratory. With our simulation-based testing and clinical insight, they were able to develop, troubleshoot, and refine a fully functioning ventilator in only 37 days.

These experiences have reinforced our belief that simulation provides a limitless potential for testing and design of new devices and technology. Just as simulation for educational purposes provides a “low stakes” environment, we must remember that this same “low-stake” environment exists for the testing of devices and technology to improve processes and patient care. The use of the simulation environment was vital in testing and improving upon ventilator solutions before use on human patients and without simulation likely would have dangerous. In addition to the example provided by our team, the use of in situ simulation

to test protocols and team work is a great example of using this “low-stake” environment to test and improve processes.

Although none of the previously discussed innovative solutions to a lack of ventilators were required for clinical care at our institution, the devices and protocols now exist for institutions worldwide. It is our hope that the advancements made in simulation at our institution and institutions everywhere during the COVID-19 pandemic will allow for healthcare systems across the globe to better prepare for future healthcare emergencies, equipment shortages, and prevent the rationing of potential life-saving equipment. Additional information is available as supplemental digital content (see Text, Supplemental Digital Content 1, <http://links.lww.com/SIH/A584>, which provides more information on development and testing of split ventilation, Bilevel Positive Airway Pressure ventilators, and testing of novel ventilators).