Simulator exercises are used at Midwestern University to augment academic and laboratory training toward consolidating particular skills, increasing situation awareness, and preparing the student for practice within the team environment of an operating room. This paper describes an enhanced cardiopulmonary bypass simulator consisting of a self-priming hemodynamic reservoir that includes an inline flow meter. A typical cardiopulmonary bypass adult perfusion circuit was assembled using a roller pump console and integrated oxygenator/heat exchanger/reservoir and primed with 2 liters of water. For patient simulation, a soft-sided reservoir bag was mounted onto an inclined platform. A 1-liter soft-sided bag was placed just above the reservoir, providing an overflow reservoir. The priming line extended to the head of the mannequin. The arterial, venous, and suction lines extended through the open chest. The primed perfusion circuit was connected to ports on the filled reservoir bag. To test the patient simulation, the arterial pump output was adjusted to flow rates ranging from 1–7 liters per minute, with a complete interruption (to zero flow) between each test run. An inline flow meter was added to the bypass circuit and an analog to digital converter board was used to pass flow data into the computer-based simulation program. The use of an inclined hemodynamic reservoir bag proved to be self-priming and functional without problems over a wide range of flows tested. By including a reservoir with the mannequin, plus processing and displaying real-time flow data using the CPB-Sim simulation program, a higher fidelity and more realistic simulation experience was created.

Keywords: cardiopulmonary bypass, patient safety, education, simulation.

Simulator exercises are used at Midwestern University to augment academic and laboratory training toward consolidating particular skills, increasing situation awareness, and preparing the student for practice within the team environment of an operating room. This paper describes an enhanced cardiopulmonary bypass simulator consisting of an inclined self-priming hemodynamic reservoir that includes an inline flow meter. The hemodynamic reservoir bag was proven to be self-priming and did not require any attention between pump-runs. Flow data was processed and displayed by the CPB-Sim software program. An inline flow meter was added to the bypass circuit and flow data was converted and passed into the CPB-Sim program. By including a reservoir with the mannequin, plus processing, and displaying real-time flow data, a higher fidelity and more realistic simulation experience was created.

Clinical perfusion training has traditionally relied on an apprenticeship model provided almost exclusively in a hospital setting. If a portion of teaching can be done more efficiently in a high-fidelity simulated environment out of the hospital, perfusion students should become more proficient with their skills earlier. This will expose patients to less risk and allow students to be better able to successfully manage stressful surgical scenarios when they move into the clinical environment.

Currently, cardiopulmonary bypass simulation training is not universally required by perfusion schools, perfusion societies, or accreditation programs prior to certification. From an historical perspective, the field of cardiology first developed a full-sized mannequin-based medical simulator called “Harvey” in 1968, which simulated 27 cardiac conditions (1). Over 20 years later, in 1987, Dr. David Gaba developed the CASE 1.2 (Comprehensive Anesthesia Simulation Environment) for the field of anesthesia (1). In that same year, the first computer-based surgical procedural simulator was described for training doctors performing endoscopic procedures.

A recent commercial effort in Australia resulted in the development of a product called the “Orpheus” cardiopulmonary bypass simulation system (ULCO Technology, Marrickville, Australia) (2). The simulator is hydraulic and...
very sophisticated, but does not include scenario-based simulation software. In addition to not meeting the needs of perfusion education programs desiring to simulate realistic procedural scenarios, the cost of the system is high.

Unfortunately, there is little sharing of medical simulation education information between the fields of anesthesia, cardiology, cardiovascular surgery, and perfusion, and even less sharing within the perfusion training community itself. Hopefully, since the authors began transferring lessons learned from U.S. Air Force flight simulations into academic perfusion training in 2002 (3), and with the advent of the Society for Simulation in Healthcare in 2004, a united effort to improve clinician performance and reduce patient errors will form between members of interdependent cardiovascular fields.

With few studies of the transfer of perfusion training to the operating room environment, and virtually no assessment of the effectiveness of simulation training in reducing risk or improving cardiac patient outcomes (4,5), this paper provides insights toward remedying the situation by documenting steps in developing an economical, scenario-based cardiopulmonary bypass simulator. The goals of this paper are to improve the fidelity of cardiopulmonary bypass simulation by integrating physical and sensor feedback components into a mannequin assembly. Cooper and Taqueti describe an electronic patient as a “replica of clinical site; mannequin-based; full virtual reality” (6). To achieve the objective of creating an electronic patient with many complex electromechanical functions, a modular and cost-effective approach was used.

The first step was reported previously by the authors and involved the development of exogenous sensor-based feedback to drive a software program that provides a high-fidelity simulation cardiopulmonary bypass training exercise for students (7). This paper is the second step in the modular integration process, and focuses on developing a self-priming hemodynamic reservoir and installing an improved inline flow meter for a cardiopulmonary bypass simulation program.

**DESCRIPTION**

Figure 1 shows the test circuit diagram with associated tubing diameters and lengths. The overflow bag was located at the same approximate height as the hemodynamic reservoir, which, according to Pascal’s law for incompressible fluids \( \Delta P = \rho gh \) (8), indicates the best height for excess fluid to flow from the reservoir into the overflow bag.

Figure 2 shows a close-up of the inclined self-priming hemodynamic reservoir in the lab with the suction line and overflow bag. The overflow bag acts as a buffer in case of excess fluid volume at high flow rates. The angle of inclination of the board relative to horizontal is about 10 degrees.

Testing the self-priming ability of the inclined hemodynamic reservoir began by priming a standard arterial-venous (A-V) loop with 2 liters of tap water. The roller pump flow was set to 4 liters per minute (LPM) and the entire circuit was de-aired. Next, all ports were closed/clamped on the soft-sided reservoir bag and suction and fill lines attached.

After running dropping 2 liters of tap water into the reservoir bag, the pump was stopped and the primary A-V lines were clamped and divided. Air-free connections were made from the divided A-V loop lines to the associated
patient reservoir A-V connections and the valves were opened on A-V lines at exit of hemodynamic reservoir. The valve on the suction line was opened next and the suction pump was run at 50 mL/min.

Several test runs were performed at .5 LPM intervals of arterial pump flow rates ranging from 1–7 LPM. This allowed for verification of the full range of typical perfusion simulator functions, including stopping the pump, clamping the venous line, (to simulate the venous reservoir emptying), and restarting the pump at a new flow setting without priming the hemodynamic reservoir.

The hemodynamic reservoir used to represent the patient consists of a 1600 mL adult-sized soft-sided “MVR” model venous reservoir bag, (Medtronic, Inc., Minneapolis, MN). The inclined reservoir bag support platform was fabricated from half-inch plywood with two 3-inch legs attached at one end to form a 10 degree elevation angle from horizontal. The heart-lung machine is a Sarns 8000, (Terumo Cardiovascular Systems Corp., Ann Arbor, MI) with four roller heads. The hard-sided venous reservoir is a Capiox model RX-25 (Terumo Cardiovascular Systems Corp., Ann Arbor, MI), with integral heat-exchanger and oxygenator. Circuit tubing is typical perfusion-grade tubing and the arterial line filter was a Medtronic Affinity model (Medtronic, Inc., Minneapolis, MN). The mannequin is a commercially available 6 foot tall fiberglass male model ($200) with custom modifications to accommodate arterial, venous, and suction tubing. The sub-platform assembly consists of commercially available coated wire shelving and baskets ($30) attached to the surface of a foldable 1.5 by 6 foot folding table with coated wire support structures attached.

Figure 3 shows the mannequin mounted on the wire support structure. For realism, note the endotracheal tube in the mannequin’s mouth and a simulated heart in the thoracic cavity with various cardiopulmonary bypass (CPB) lines emanating from the cavity. Figure 4 shows a general three-dimensional diagram of how the mannequin, coated wire support structures, and inclined hemodynamic reservoir platform were assembled onto the 1.5 foot by 6 foot folding table. The components are very cost-effective and the coated wire mesh supports easily accommodate the routing of circuit tubing while providing enough space for the inclined reservoir platform as well.

![Figure 3. Mannequin-support assembly with bypass simulation tubing.](image)

![Figure 4. Three-dimensional model of mannequin-inclined platform assembly.](image)
Figure 5 shows the complete CPB simulation assembly, including the Sarns 8000 heart-lung machine, associated circuit tubing, inclined hemodynamic reservoir, inline flow meter, and prone mannequin. An inline flow meter was added to the bypass circuit and an analog to digital converter board was used to pass flow data into the computer-based simulation program.

The inline flow meter sensor used in this investigation was model FLR 1001 ($240, Omega Engineering, Inc., Stamford, CT). The analog to digital (A-D) converter used in this investigation was model USB-6008, ($250, National Instruments, Austin, TX). Note in Figure 6 that the left arrow identifies the inline flow meter sensor. The ability to display inline flow rate data is important because it prompts the student to consider changes in the circuit (e.g., an open shunt) or changes in patient conditions (e.g., increasing systemic vascular resistance) before adjusting pump flow. The center arrow in Figure 6 identifies the A-D converter. This device converts and conditions the analog fluid flow signal from the inline flow meter into a digital signal that is fed into the CPB-Sim software program for processing and display.

The basic system design has been used for several years. Red food coloring and 10 mL of isopropyl alcohol is added to the 2000 mL water prime. The circuit volume is changed as needed.

Figure 7 is a screen snapshot of bypass simulation data presented by the CPB-Sim program. For the purposes of this paper, the key data on this screen is the real-time flow as displayed from the inline flow meter located just distal to the arterial outlet from the hemodynamic reservoir, (2.03 LPM in this case). The student can then compare the real-time flow displayed from the inline flow meter with the flow shown on the arterial pump head display and take appropriate action.

DISCUSSION

The methods outlined in this paper describe how a cost-effective, high-fidelity CPB simulation mannequin assembly was developed and tested, both with a self-priming reservoir and inline flow meter. The fidelity of the CPB simulation mannequin system is currently limited by a lack of sensors needed to provide timely data showing changes in the physical system (temperature and pressure) and changes in the physiological state of the simulated patient, particularly after student intervention. Coupled with the timely acquisition of data revealing changes in the system and condition of the simulated patient is the need to enhance the CPB-Sim software to process and display real-time trends to the student.

Future plans to further enhance fidelity include:

- The use of CPB-Sim software to simulate various cardiac rhythms (e.g., sinus, asystole, ventricular fibrillation, and ventricular tachycardia) to test student response.
• Mounting and testing of additional sensor components (e.g., temperature and pressure)
• Integration of additional sensor feedback with the CPB-SIM simulation software
• Pediatric simulation

The availability of economical flow and temperature sensors, combined with ever-decreasing costs of computing technologies has lead to rapid growth and advancement in the field of medical simulation. A paper published by thoracic surgeons at the March 2008 Visioning Simulation Conference states: “simulation of the physiologic events associated with instituting, monitoring and separating from cardiopulmonary bypass (CPB) can teach a trainee to recognize appropriate patterns of response. Once these patterns are learned, various alterations can be introduced into the simulations to help the trainee recognize an event that does not follow the usual pattern, identify the aberration, and learn corrective measures” (9). This means that the thoracic surgical community has opened the “simulation door” as well.

Since anesthesiologists have been simulating medical scenarios for more than 25 years, and the thoracic surgeons are just opening the simulation door, it is the ambitious goal of the high-fidelity cardiopulmonary bypass simulation program at Midwestern University to help perfusionists follow suit. As pilots and other health care professionals have already learned, high fidelity simulation contributes significantly to the preparation and competency testing of students and certified professionals (10). The topics described in this paper form the second of several steps toward advancing the fidelity of the cardiopulmonary bypass simulation to enhance the quality of perfusion training and certification, improving patient care and safety as a result.

REFERENCES
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