

Mechanical Simulators of the Cardiovascular System: An Alternative to Research Subjects and Patients

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Before the development of electrical analog and digital computer-based simulations of the cardiovascular system, animal models were the most common tools for investigating the detailed properties of the cardiovascular and cerebrovascular circulations, especially when human experimentation was not possible. However, as far back as the 16th century, William Harvey developed the concept of a mechanical analog to describe heart function and blood flow,^{11,13} though there is no evidence he constructed any such devices. In 1850 Weber²⁸ published a description of what appears to be one of the first working mechanical analogs, using portions of the small intestine with natural valves, to investigate the concept of the hydrostatic mean pressure. It was not until 1940 that Starr and Rawson developed a detailed mechanical model of the circulatory system in order to investigate congestive heart failure.²² Their model included mechanical versions of all four heart chambers, systemic and pulmonary circulations, capillary beds, flow meters, and the ability to regulate vascular resistance. Advances in materials and computer technologies have the potential to enable the development of much more sophisticated mechanical models for basic research, validation of computer based simulations, and training of physicians.

Cardiovascular Simulators for Teaching

Computer simulations of the cardiovascular and cerebrovascular systems are used as clinical teaching tools, including simulated pathologies.¹⁴ However, for training of medical students and physicians in hands-on procedures for radiology, cardiology, and cardiovascular surgery, mechanical systems that simulate the structure and fluid dynamics of some segments of the cardiovascular and cerebrovascular systems are becoming more common.^{1,6,17} Angioplasty, insertion of stents, and the use

of other vascular probes and catheters can be demonstrated and practiced on mechanical analogs prior to real-world application, with the obvious advantages of increased patient safety and the ability to provide training when patients are not available. The use of 3D printing technology has allowed custom models that faithfully reproduce the vascular systems of individual patients, allowing clinicians to practice customized procedures prior to real-world use.¹

Research Systems

Investigating the exposure of human volunteers to extreme environments such as sustained acceleration, or thermal stress, is becoming more difficult and expensive, as Institutional Review Boards impose more constraints and safety requirements become more stringent. Computer simulations can provide an alternative approach, especially in those cases where one wishes to extrapolate to stress levels that would not be possible with human subjects. Dozens of research papers have been published describing mathematical models of the cardiovascular system, including detailed models of heart mechanics, respiratory function, and the complexities of blood flow in the brain and the impact of cerebrospinal fluid pressure on cerebrovascular fluid dynamics.^{21,24,26,27} Most of these have addressed basic research goals in understanding the interactions between various components of the system, though some have been developed as teaching tools. These models do require experimental data on the constitutive properties of blood vessels, the heart, and other soft tissue in order to determine the resistance,

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Mechanical models can be used to provide an alternative method to validate the computer simulations, since the constitutive properties of the blood vessel and heart analogs can be readily quantified. Since the work of Starr and Rawson²² described above, few mechanical models have been used, as the computer simulations have become more sophisticated. During the early development of improved cardiac bypass systems for open heart surgery, Anderson developed a mechanical analog with a motor driven heart model.²⁻⁴ A YouTube video is available demonstrating the simulator.³ Anderson was particularly

consciousness (G-LOC).⁷ Determining jugular vein dimensions and blood flow velocity in humans during G_z exposures is not feasible. Therefore, to validate the role of the jugular vein collapse as the root cause of G-LOC, a mechanical surrogate of the head and neck was built⁸ incorporating a carotid artery, a jugular vein, a rigid skull with cerebrospinal fluid (water), and a linear cerebrovascular resistor (**Fig. 1**). Unable to test the system on a human centrifuge, the effect of G_z was simulated by incorporating a “heart” to “skull” distance approximately five times that of a human. Flow through the system was controlled by adjusting the height of the water-filled containers to adjust inlet and outlet pressures. The original mathematical model reproduced the fluid flow characteristics of the mechanical analog (with appropriate

changes in neck vascular length and the constitutive properties of the analog vein and artery), confirming venous collapse as the primary mechanism regulating flow. The constitutive properties of the vinyl and dialysis tubing (as analogs of the carotid artery and jugular vein) could be easily measured in the laboratory, whereas the mathematical model of the actual human system used data collected from human subjects under high levels of positive pressure breathing.⁹ Thus the mathematical model, which accurately predicted the G_z level at which G-LOC was likely to occur,¹⁰ was validated by the mechanical model.

Future Applications

With the advent of recent manufacturing technologies, more sophisticated mechanical analogs of the cardiovascular and cerebrovascular systems, complemented by advanced computer simulations, could be applied to research issues of high altitude exposure or sustained acceleration. The accurate models of the cardiovascular and cerebrovascular anatomy of individual patients produced using imaging data and 3D printers¹ involve producing detailed blood vessel structures with dissolvable substrates that are coated with silicon. Using various thicknesses of silicon coatings, a simulator can be configured with a system of blood vessels with constitutive properties similar to actual arteries and veins, allowing more advanced mechanical simulators for investigating the mechanisms involved in orthostatic intolerance following long-term microgravity exposure,²³ or for designing G-LOC prevention technologies, including anti-G suits and positive pressure breathing. Anderson's models and more recent clinical training simulators have focused on modeling the supine patient. Modifying a mechanical model to allow transition from supine to sitting and standing, incorporating the ability to provide counterpressure to various parts of the systemic and pulmonary systems, and incorporating controllable resistance and capacitance elements to simulate myogenic, neurogenic, and metabolic influences would result in a powerful tool to validate current mathematical models of the cardiovascular system and a much enhanced research and teaching tool.

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