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A hydraulic model of cardiovascular physiology and pathophysiology embedded into a computer-based teaching system for student training in laboratory courses

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Christ A, Barowsky D, Gekle M, Thews O. A hydraulic model of cardiovascular physiology and pathophysiology embedded into a computer-based teaching system for student training in laboratory courses. Adv Physiol Educ 44: 423–429, 2020; doi:10.1152/advan.00069.2020.—Functional understanding of the different parts of the cardiovascular system is essential for an insight into pathomechanisms of numerous diseases. During training cardiovascular physiology, students and early-stage medical personnel should understand the role of different functional parameters for systolic and diastolic blood pressure, as well as for blood flow. The impact of isolated parameters can only be studied in models. Here physical hydraulic models are an advantage in which the students have a direct contact to the mechanical properties of the circulatory system. But these models are often difficult to handle. The aim of the present study was to develop a comprehensive model of the cardiovascular system, including a mechanical heart with valves, an elastic aorta, a more rigid peripheral artery system, a total peripheral resistance, and a venous reservoir representing the variable cardiac preload. This model allows one to vary systematically several functional parameters and to continuously record their impact on pressure and flow. This model is embedded into a computer-based teaching system (LabTutor) in which the students are guided through the handling of the model (as well as the systematic variation of parameters), and the measured data can be analyzed. This hybrid teaching system, which is routinely integrated in physiology laboratory courses of medical students, allows students to work with a complex hydraulic model of the cardiovascular system and to analyze systematically the impact of influencing variables (e.g., increased peripheral resistance or changed cardiac preload) as well as pathophysiologically (e.g., reduced aortic compliance).

blood flow; blood pressure; cardiovascular system; computer-based learning platform; hydraulic model

INTRODUCTION

Profound knowledge of the cardiovascular system (CVS) is essential for the understanding of pathomechanisms underlying several disorders. However, the understanding of distinct functions (e.g., mechanical heart function, regulation of the vascular resistance in arterioles) alone will not yield the necessary insight in the overall, complex, and nonlinear regulatory function of the CVS as a functional unit. Students often have problems with understanding the interaction of the pumping heart with different sections of the circulatory system. Even though the underlying physical laws are known, the overall resulting effect of the complete mechanical system determining systolic and diastolic blood pressure is difficult to understand, especially from a theoretical description in textbooks only. For this reason, models of the CVS were introduced into teaching. Most of these models are mathematical descriptions used for numerical simulation of the time course of changes for different physiological parameters. The most elaborated simulation model was originally described by Guyton et al. (12). But these models were then further developed as a tool for teaching cardiovascular physiology (1, 13). The main focus in these simulation approaches laid in the regulatory component integrating heart, vascular system, and kidney. But mathematical models were also developed to simulate the beat-to-beat changes in the vascular system, e.g., course of the arterial pressure, pressure volume diagram of the heart (11), or the venous return (10). However, the disadvantage of simulation models is that students work only with abstract graphs and numerical inputs, which are difficult to follow for some individuals.

For this reason, hydraulic models of the circulatory system have been developed as suitable tools for teaching cardiovascular physiology (2, 3, 7, 16–18). Using these models, students have a more direct contact with the mechanical properties of the circulatory system, e.g., by tactile experience of different blood pressure qualities. With a hydraulic model, the students can change relevant parameters and directly measure the impact of these factors on systemic variables, such as blood pressure or flow in different sections of the CVS. However, the most important problem of using complex hydraulic models is the complexity of operation, especially if several variables have to be measured simultaneously.

The aim of the present study was to develop a complex hydraulic model of the mechanical properties of the CVS in which 1) the cardiac output [stroke volume (SV) and heart rate], the compliance of the aorta, the total peripheral resistance (TPR), and the venous return (cardiac preload) can be varied. 2) Furthermore, pressure sensors in the ventricle, the aorta, and the peripheral artery, as well as a noninvasive flow sensor in the arterial system, allow the continuous measurement of these parameters. 3) Finally, the physical model has been integrated into a computer-based learning platform (LabTutor script) in which the students perform systematic experimental variation of the relevant parameters to analyze their impact on blood pressure and flow. LabTutor (as well as its successor Lt as a teaching software) offers an environment in which the data can
be acquired easily and the analysis of the measurements is supported.

**MATERIALS AND METHODS**

**Hydraulic Model of Circulation**

The cardiovascular model described here is a further development of that described by Wiggers (19), Rothe and Gersting (15), Bauereisen (2), and Blasius (3). Figure 1 shows the setup of the model that simulates the pressure and flow dynamics of the systemic circulation (the pulmonary circulation was omitted). The heart (Fig. 1Ae, Supplemental Fig. S1; Supplemental material is available at https://doi.org/10.6084/m9.figshare.12136359) is realized by a Perspex tank covered with a silicone membrane. The membrane is elastic so that an increasing pressure leads to a higher filling volume of the ventricle. For pumping, the silicone membrane is pressed in by a mechanical stamp connected to programable linear DC servomotor (type LM 2070–080–11, Faulhaber, Schönaich, Germany) (Supplemental Fig. S2). The motion controller of the motor (type MCLM 3006 S RS, Faulhaber) stores movement profiles for different stroke length and contraction rates. The various profiles can be activated by different voltages at the input channel of the controller. Thus heart rate and contraction strength can be varied from within the LabTutor software (see below). The shape of the contraction profile varies with different heart rates simulating the increasing systole-to-diastole ratio at high frequencies (Supplemental Fig. S3). The stamp of the motor is not fixed with the membrane, so that during retraction of the motor the membrane is not actively drawn back. Filling of the ventricle is obtained only from the positive pressure resulting from the venous return.

Two valves ensure that the fluid is pumped from the heart into the aorta. At the inlet of the heart, a reed valve mimics the mitral valve. At the outlet, an artificial mechanical heart valve for children (diameter: 18 mm) represents the aortic valve (Supplemental Fig. S1). The aorta (Fig. 1Ab, Supplemental Fig. S4) is realized by a highly elastic silicone tube. The tube is surrounded by two metal plates (half pipe shaped) whose distance can be varied by two adjusting screws. By changing the distance of the metal plates, the elasticity and by this the compliance of the aorta can be varied. For a reduction of the compliance, the plates are converged; however, they will not be closed completely (minimum: 6-mm distance). Under this condition, the remaining open part of the flexible aorta still provides a sufficient compliance to mimic the elastic properties of the aorta. The metal plates reduce the compliance but do not eliminate it completely.

Following the aorta, a more rigid silicone tube (inner diameter 14 mm, wall thickness 1 mm) with a length of 75 cm simulates the peripheral arteries (Fig. 1Ac), which show a lower compliance than the aorta. An adjustable flow resistance representing the main peripheral resistance at the arterioles follows the peripheral artery (Fig. 1Ad, Supplemental Fig. S5). With the needle valve (type AS2210FS-01–06S, SMC Corp., Tokyo, Japan), the flow can be varied in a nonlinear manner using four different settings, leading to relative resistances of 94, 100, 134, and 228%. Finally, the circulation model contains a glass bottle representing the venous blood pool (Fig. 1Ae, Supplemental Fig. S6). With a scissor lift, the bottle can be raised to various heights, which changes the pressure of the fluid returning to the heart. Due to the elastic silicone membrane of the heart, a higher venous pressure increases the volume loading of the heart (preload) and by this increases the ejection volume (Frank-Starling law). With the model, it is also possible to change several parameters simultaneously to simulate complex alterations, e.g., during orthostasis in which, besides the preload, the sympathetic tone might change as a result of the short-term blood pressure control.

To follow hemodynamic parameters in the circulation model, the blood pressure is measured continuously (pressure sensors “P” in Fig. 1; type ADP5120, Panasonic, Osaka, Japan) in the ventricle of the heart, directly behind the aorta and in the peripheral artery directly in front of the variable resistance to flow. The blood flow is measured continuously with a noninvasive ultrasound flowmeter (Sonoflow type CO.55, Sonotec, Halle/Saale, Germany) between the aorta and peripheral artery (flow sensor “F” in Fig. 1). The sensors are connected to a PowerLab A/D converter (type 26T, ADInstruments Ltd., Oxford, UK), and the measurements are integrated in a LabTutor script (ADInstruments) of the student’s laboratory course. In December 2019, LabTutor was replaced by ADInstruments by its successor Lt. However, all LabTutor scripts can be easily transferred to the actual teaching environment Lt, maintaining the complete functionality of the teaching system described in this paper.

Since the pulse curves of the aorta and the peripheral artery are recorded simultaneously (Fig. 2), the pulse-wave velocity can be calculated from the time difference of these curves. However, since the tube representing the peripheral artery has unphysiological geometric and elastic properties, the resulting value is higher (∼18–20 m/s) than in reality.

**Laboratory Course of Cardiovascular Physiology**

The model is part of a student’s laboratory course on mechanical properties of the cardiac function and on the interaction between heart
In this course, three or four students work with the hydraulic model, which is connected to a computer via the A/D converter. On the computer, the LabTutor script leads the students through the different experiments and explains how to systematically vary the different parameters. The measured results of the pressure and flow sensors in the different parts of the hydraulic model are displayed in graphs of the LabTutor script.

**Prerequisite student knowledge.** Before students undergo the laboratory course, they should be familiar with the following:

1. Physical laws of fluid dynamics resistance to flow
2. Definitions of blood pressure, pulses, pulse wave velocity, elastic modulus of vessels, and vascular compliance
3. Regulation of the CVS

**Time required.** This experiment with the hydraulic model is part of a 4-h practical course on the circulatory system and takes ~1 h, including data analysis. The students should have been prepared with the theoretical background by visiting the main physiology lecture and with the basic experimental setup, which is distributed as a laboratory course manual.

**Experimental setup.** The hydraulic model is integrated in a PowerLab/LabTutor environment. All data measured with the PowerLab (pressure, flow) are directly linked to respective charts in the LabTutor environment. For documentation, a button box is also linked to the PowerLab, which allows the labeling of the LabTutor recordings. During the experiment, the students vary one parameter, and, by pressing the respective button on the control panel (Supplemental Fig. S7), a label indicating the changed parameter is included in the LabTutor chart.

The LabTutor script starts with a short introduction of the hydraulic model in which all components of the model (Fig. 1), as well as the handling of the operator panel, are explained. In the next step, the basic setup (“normal” conditions) is explained, and the students register the arterial blood pressure and flow. The values obtained are used as reference for the subsequent parameter variations. In the next five steps, the students change each parameter one by one and register the resulting arterial blood pressure and flow (some screenshots of the LabTutor script are shown in Supplemental Figs. S8–S10). In the first step, the compliance of the aorta is reduced by narrowing the distance of the two metal plates around the elastic tube representing the aorta by 5 mm (Supplemental Fig. S8). The students can also palpate the strength of the aortic pressure pulse on the surface of the silicone tube (Supplemental Fig. S4). Afterwards, the students return to the control setting. The next parameter to be changed is the contractility (ejection volume) of the heart. By selecting the respective setting in the LabTutor script, the contraction depth of the linear servomotor representing the heart is changed, resulting in a ejected volume varying from 4.2 to 6.6 ml (increase by 57%). Afterwards, the students change the heart rate within the LabTutor script from 30 to 120 beats/min. The respective setting also changes the shape of the contraction curve of the motor, reflecting a reduced diastole duration at high frequencies (Supplemental Fig. S3). The next parameter to be varied is the TPR. The resistance can be varied from 94 to 228% of the control value by using the adjustable valve (Supplemental Fig. S9). The last parameter to be varied is the venous return to the heart and by this the cardiac preload. The students have to lift the “blood” reservoir with the scissor lift by 10 cm (Supplemental Fig. S10), resulting in an increased filling pressure and thus volume of the ventricle.

For data analysis, the students extract the systolic, diastolic, and mean arterial blood pressure, together with the cardiac output and the ejection volume from the recordings of the different experiments (Supplemental Fig. S11). The values are collected in a table, together with a brief description of the parameter changed. For the final report, these data were used to calculate the relative changes to the control conditions, and these results are shown in a bar chart.

In the end, the students should understand the principles of vascular mechanics and hemodynamics. They should explain how changes in relevant parameters (e.g., cardiac output or TPR) affect the pulse pressure curves and flow.
In principle, the hydraulic model could also be used without the LabTutor (or Lt) teaching environment. In this case, the values from the pressure or flow sensors have to be displayed on a chart recorder. But integrating the physical model into a broadly used teaching environment allows one to easily use the complex model in a structured didactic concept. Academic institutions using LabTutor or Lt in physiology courses often exchange the developed teaching scripts within the community.

RESULTS

Under “resting” conditions (all variable parameters in the initial position), the motor of the heart had a frequency of \( \sim 60 \) beats/min, and the ventricle had an ejection volume of \( \sim 5.55 \) ml, resulting in a cardiac output of \( \sim 330 \) ml/min. The pressure in the heart oscillated from 1 (diastolic) to 51 (systolic) mmHg and in the aorta from 35 to 43 mmHg (Fig. 2, A and B). During the systole, the aortic pressure did not reach the value in the ventricle, which was caused by the unphysiological large volume of the aorta compared with the SV, but the pressure difference was rather small. Figure 2C shows the course of the pressure in the peripheral artery, which varied between 37 and 45 mmHg. Due to the increasing stiffness of the tubes between the aorta and peripheral artery, the systolic pressure increased along the arterial system. The pressure curve of the peripheral artery showed a clear dicrotic wave (recoil wave; Fig. 2C). Since in contrast to the physiological situation the total radius of many parallel peripheral arteries was lower than the aorta, the course of the aortic flow differed from the in vivo situation. Because the volume of the aorta (as a blood reservoir for the following arteries) is much larger compared with the physiological situation in vivo, the flow remained elevated during the entry diastolic interval (Fig. 2D). With this model, it was possible to vary the relevant parameters systematically.

Heart Rate

Figure 3, A and B, shows the impact of the heart rate on the arterial pressure. With rising heart frequency, the pressure in the aorta and the peripheral artery increased. However, at the highest frequency (120 beats/min), the pressure dropped, which was the result of a too short filling phase of the ventricle. As shown in Fig. 3C, the SV decreased markedly at high heart rates, resulting in a reduction of the cardiac output, which then led to a drop in arterial pressure.

Stroke Volume

By varying the contraction depth of the motor, the contractility of the heart can be varied. Starting from a SV of 5.6 ml,
A reduction of SV by 26% reduced the mean pressure in the peripheral artery from 40 to 34 mmHg, whereas an increase of SV by 18% increased the pressure from 40 to 46 mmHg (Fig. 4). A reduced contractility can be used as a model for cardiac insufficiency, whereas the increase may reflect an activation of the sympathetic nervous system.

Aortic Compliance

The compliance of the aorta is varied by changing the distance of the metal plates around the aorta. The lower the distance between the plates is, the stiffer the aorta is (reduced compliance). Figure 5 indicates that, with decreasing compliance, the blood pressure amplitude increased in a nonlinear manner. The peripheral pressure changed from 47/37 mmHg under control conditions (distance of the metal plates: 10 mm) to 53/31 mmHg during reduced compliance (plate distance: 6 mm). Reduced aortic compliance also led to a slight decrease in SV and cardiac output by ~10% (Fig. 5C).

Peripheral Resistance

As was expected, the TPR had a strong impact on the systolic, diastolic, and mean pressure in the aorta and the peripheral artery (Fig. 6, A and B). The model showed an almost linear relation between TPR and blood pressure. The blood pressure amplitude in the peripheral artery was only slightly dependent on the TPR. Besides, the higher the TPR was, the more pronounced was the dicrotic wave seen in the peripheral pressure pulse curve (Fig. 7). In addition, with increasing TPR, the SV and the cardiac output were markedly reduced. Increasing the TPR by only 33% lowered the SV by ~15% (Fig. 6C).

Preload

The cardiac preload is varied in the model by increasing the height of the venous blood reservoir, resulting in a higher filling...
pressure. As expected, increasing the preload led to higher SV. Increasing the preload by 10 cmH2O increased the SV by 15% (Fig. 8C). The magnitude of this effect directly correlates with the stiffness of the silicone membrane on the heart. With a weaker membrane, the slope between preload and SV can be steepeened. As shown in Fig. 8, A and B, the preload also increased the blood pressure in the aorta and the peripheral artery.

**DISCUSSION**

The hydraulic model described here, integrated in a LabTutor script, is a very efficient and demonstrative method to teach the systemic behavior of the mechanical properties of the CVS. Compared with previous approaches (2, 3, 7), the flow measurement using a noninvasive sensor for a continuous recording is a relevant improvement. Another advantage is the use of a linear motor for heart contraction. In previous approaches, the movement was obtained from an eccentric cam fitted to an electric motor. This resulted in a sinus-shaped contraction of the heart. With the linear motor, specific frequency-dependent profiles of the contraction are realized, reflecting the change in the systole-to-diastole ratio at high frequencies (Supplemental Fig. S3). Another important advantage of this system is the integration into the computer-based learning platform (LabTutor). With this step, students can work with the model independently, doing all recordings and analyses. In addition, with this teaching tool, explanations about the structure of the model and also about the handling are shown interactively. Due to the complex handling of the model formerly, it was used only as a demonstration experiment (with a teacher and a small group of students). By combining the model with the data acquisition tools of LabTutor, students work on their own. Evaluating the comments of the students after the laboratory course revealed that they like the physical properties of the model (seeing the heart pumping, touching the pulsatile aorta) and performing systematic measurements to obtain the functional characteristics of the system. On the other hand, integrating the hydraulic model in a computer-assisted learning platform was positively rated because the students’ attention was focused on the relevant changes in the model and not on its handling. Recent studies indicate that multimodal integrative teaching concepts combining classic lectures with interactive components can improve the students’ learning process and, by this may advance, the integrative understanding of the physiological context (4, 14).

In the past, hybrid approaches by integrating a hydraulic model into a computer environment have not been used in teaching cardiovascular physiology. Only for scientific purposes have models been combined with computer programs that simulate the short- or long-term closed-loop control of blood pressure. In these hybrid models, the pulsatile changes of the blood pressure in the hydraulic model were measured and served as input variables for the control units (5, 6, 9).

**Other Applications of the Model**

Besides the use in compulsory physiology laboratory courses as part of the medical study, the hydraulic model of the CVS can also be applied for postgraduate training in the clinical environment. As refresher courses, it may remind physicians of the physiological basics and may also give an insight into pathophysiological mechanisms of diseases. In addition, it is possible to modify the model to simulate specific disorders. For instance, if the opening of the aortic valve is restricted, the situation of an aortic stenosis results. With the...
model, pressure and flow measurements under these conditions can be obtained and compared with the physiological situation.

Limitations of the Model

The model represents the principle components of the human CVS (heart, elastic aorta, peripheral arteries with resistance, venous capacity). However, some details, especially with respect to the size and functional properties, cannot be transferred directly from the model to the in vivo situation. The most important difference is the structure of the peripheral arterial system. In contrast to the real situation, the peripheral artery consists of only one vessel showing no breakdown in parallel branches. For this reason, the total cross-sectional area of the peripheral artery and, therefore, the total artery volume is much lower. In contrast, the volume of the aorta is much higher, both resulting in a slower drainage of the blood from the aorta to the peripheral vessels. This results in a continuous positive flow during the diastole (Fig. 2D), whereas in vivo the aortic flow returns to low values shortly after the end of the ventricle systole (8). In experimental data, the drop of flow varied between different positions within the aortic diameter, being most pronounced at the convex curvature of the aorta (8). The rapid initial decrease of flow after the end of the ejection phase of the heart is not seen in the model arteries. For this reason, the model does not reflect real flow data exactly, which has to be explained to the students.

The model in its present form just demonstrates the mechanical properties of the CVS and their role for the blood pressure and flow. It is not able to illustrate the regulation of the arterial pressure (e.g., baroreceptor control loop). However, the knowledge of hemodynamics presented in this model is essential for the understanding of the actuators in the blood pressure control circuit. With some modifications, the model could also be used to simulate the impact of properties of the peripheral artery on blood pressure and flow by using tubes with different diameters, materials, or elasticity.

In conclusion, using a comprehensive hydraulic model of the CVS offers a good opportunity for students to learn the functional interrelation of relevant parameters that determine the systolic and diastolic blood pressure in different sections of the arterial system. The most important aspect is that the students can handle the model on their own. This requires an automation for continuous measuring of pressure and flow at different positions in the circulatory system. In addition, a well-defined protocol is needed for the students to systematically vary parameters and observe the resulting systemic changes. The combination of a hydraulic circulatory model with a computer-based learning platform fulfills these requirements in an optimal way. This hybrid training system allows students to work with a complex hydraulic model of the CVS and to analyze systematically the impact of influencing variables as well as pathophysiological dysfunctions.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

A.C., D.B., M.G., and O.T. conceived and designed research; A.C., D.B., and O.T. performed experiments; A.C. and O.T. analyzed data; O.T. interpreted results of experiments; O.T. prepared figures; O.T. drafted manuscript; A.C., M.G., and O.T. edited and revised manuscript; A.C., M.G., and O.T. approved final version of manuscript.

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