The Application of Complex Research Simulation Models in Education; a Generic Approach

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Abstract

Computer models are frequently used for scientific research. Since scientific models are usually targeted at a specific application, using them in an educational setting is not straightforward. At Maastricht University, the CircAdapt model of heart and circulation has been developed as a scientific research tool. The model describes hemodynamic interaction between the left and right ventricle as well as mechanical interaction of three wall segments. Pressure-volume relations are obtained by simulating the pulmonary and systemic circulations. To transfer this model to a user-friendly educational tool, an approach was chosen allowing stepwise definition of educational cases (e.g., exercise, hypovolemic shock, and cardiogenic shock) in teacher mode. In student mode, interactive simulation is possible by changing model parameters defined in teacher mode. Consistent use of the same graphical user interface throughout the curriculum familiarizes students with computer simulations.

1. Introduction

Many computer models of complex biological systems such as the heart and circulation have been designed to conduct scientific research. In theory, these models can also be applied for education. However, since scientific models are often designed to investigate a specific hypothesis, they may be either too complex or lay an emphasis on aspects that are not relevant for education. To facilitate teaching, often ad hoc solutions are created. On the one hand, such educational applications may not entirely fulfil the intentions of the teacher, while on the other hand the potential of the model and the skills of the developers are not fully utilized.

At Maastricht University the Department of Biomedical Engineering investigates various clinical aspects of the heart and circulation using the computational model CircAdapt [1, 2]. Among other applications, the model has been successfully applied to describe the transfer from fetal to newborn circulation [1] and the effects of right ventricular pacing in patients suffering from pulmonary arterial hypertension (PAH) [3].

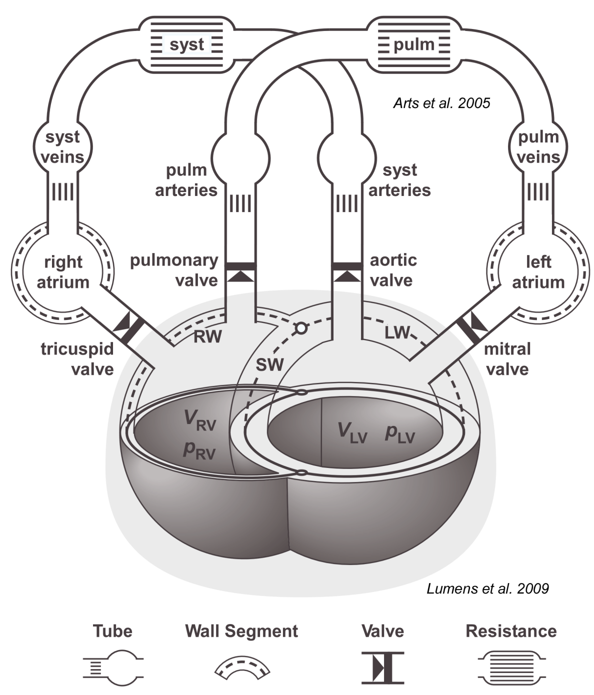

Figure 1. Schematic overview of the CircAdapt model. Cardiac hemodynamics was modeled by placing the ventricles in a systemic and pulmonary circulation including atria, valves, arteries, organs, and veins.

In order to transfer this sophisticated scientific model to a user-friendly educational tool, an approach was chosen in which educational cases are stepwise defined.

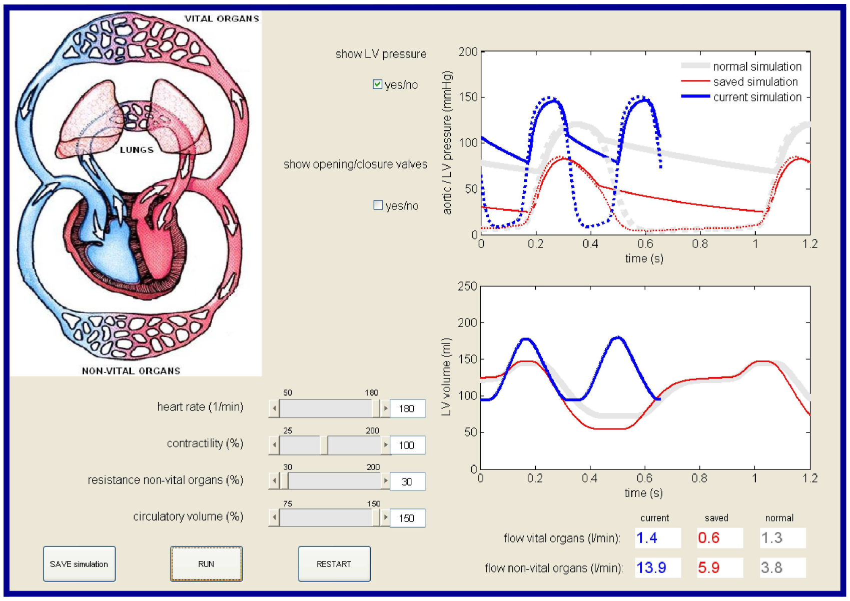

Figure 2. Screenshot from case *Exercise*. *Normal*: healthy person at rest. *Saved*: decreased resistance of non-vital organs. *Current*: increased heart rate and circulatory volume.

2. Methods

Our educational application will be based on the CircAdapt model of mechanics and hemodynamics of heart and circulation from Arts *et al.* [1]. The CircAdapt model comprises a number of basic modules that can be configured to form a network. Each of these modules belongs to one of the following main categories: 1) Tube, 2) Wall segment, 3) Valve, and 4) Resistance. Together, these modules represent the heart and the systemic and pulmonary circulations (Figure 1). Each of the CircAdapt modules has its own set of parameters describing mechanical and hemodynamical properties.

The model incorporates mechanical interaction of the left and right ventricle through the interventricular septum as well as hemodynamic interaction between both ventricles through the systemic and pulmonary circulation [2]. Global ventricular pump mechanics (pressure-volume relation) are related to myofiber mechanics (myofiber stress-strain relation) on the basis of the principle of conservation of energy. Active force generated by the myofibers is related to time of excitation, sarcomere length, and sarcomere shortening velocity using an empirical model [2].

An important aspect of CircAdapt is that material parameters can be automatically adapted to obtain physiological behavior of heart and vessel walls. For example, cardiac wall volume is adapted to obtain an optimal sarcomere length at end diastole. In a similar fashion, cavity volume is adapted on the basis of sarcomere shortening during ejection. Also, vascular material properties are adapted to shear rate and wall stress. With this approach only a few adaptation rules are required to obtain a physiological circulation without endlessly adjusting material parameters. Automatic adaptation of model parameters has been successfully applied to simulate the transition from the fetal heart and circulation to that of a newborn [1].

Adaptation of material properties requires proper boundary conditions. In CircAdapt these boundary conditions are realized by pressure control and volume control. With pressure control enabled, the systemic peripheral resistance is adjusted to maintain a predefined mean arterial pressure (MAP). Also the amount of circulating blood can be regulated to obtain the required cardiac output. The change in circulating blood volume represents the combination of short-term blood flow regulation (to control venous return) and long-term volume control by the kidneys. Using these regulatory mechanisms, material properties can be found by adaptation such that physiological behavior is obtained for given cardiac output, MAP, and heart rate. In a similar fashion, pathology can be simulated. For instance, pulmonary arterial hypertension (PAH) was simulated by increasing the pulmonary resistance. A simulation of compensated PAH was achieved by letting the model parameters adapt to the increased resistance [3].

Once the model parameters have been set to simulate a certain physiological (e.g., fetus, newborn, child, adult) or pathological situation (e.g., PAH), both pressure control and volume control can be switched off. The model will then remain in steady-state until a model parameter is changed. In this situation, the immediate effect of, e.g., a change in heart rate or a decrease in systemic peripheral resistance can be simulated.

From an educational perspective, two modes of application of the model are distinguished, the *teacher* mode and the *student* mode. In the *teacher* mode, the teacher can adjust any model parameter to simulate a certain physiological or pathological condition. Next, the remaining parameters are found by adaptation to obtain a steady-state situation to start the simulation in *student* mode. Depending on the case, the teacher decides whether pressure control and volume control will be turned on or off when running the simulation in *student* mode. Furthermore, the teacher can select a small number of input parameters which can be changed during the simulation by the student. These parameters represent, e.g., reaction of the autonomic nervous system or medical intervention, depending on the case at hand. Finally, the teacher can select a number of output variables that can be inspected by the student.

In *student* mode, the simulation starts with the steady-state situation defined in *teacher* mode. Usually, pressure control and volume control are disabled. Next, the student can change one or more input parameters (predefined in *teacher* mode) and inspect the effects on the output variables (also predefined in *teacher* mode). For example, the student can first simulate exercise by decreasing the systemic peripheral resistance and then simulate the response by the autonomic nervous system by increasing the heart rate. Output variables in this example may include aortic and LV pressure, and LV volume.

CircAdapt was developed in Matlab 7.1.0 (MathWorks, Natick, MA) [2]. To decrease computation time, optimized C++ code was written which uses ascii text files for input and output. A prototype of the educational version of CircAdapt was developed in Matlab and can be executed as a stand-alone application. In this prototype, an emphasis was laid on the user-interface, while the C++ implementation of the model was used for computation. The final educational version will be implemented in C++ and will support changing of model parameters during the simulation through user interaction.

3. Results

Using the prototype application, several educational cases have been developed that will be used in the the first year of the medical curriculum at Maastricht University. Three of these cases are described below.

Exercise
During exercise more nutrients and oxygen are required by (some) parts of the body. In these parts the arterioles relax and thereby increase in diameter (autoregulation). Consequently, blood flow increases and blood pressure drops, to which the autonomic nervous system responds by increasing the heart rate.

To simulate autoregulation, the student has to decrease the resistance of the non-vital organs. As a consequence, blood pressure will drop and flow through the vital organs will reduce (Figure 2, red lines). An appropriate action would be to increase heart rate and circulatory volume (to increase venous return). Since both LV pressure and volume are shown on the screen, the student can observe that when the resistance of the non-vital organs is decreased, not only pressure decreases, but also stroke volume somewhat increases. When heart rate and circulatory volume are increased, blood pressure increases (Figure 2, blue lines). The student can observe that flow through the vital organs returns to normal, while flow through the non-vital organs further increases.

Hypovolemic shock
During hypovolemic shock the amount of circulating blood is reduced due to severe bleeding. Thus, also the amount of blood flowing back into the heart (venous return) is decreased, which results in reduced filling and, therefore, diminished contraction (Frank-Starling law). The effect is a reduced cardiac output and blood pressure. The autonomic nervous system responds by increasing heart rate and resistance of the non-vital organs to increase blood pressure.

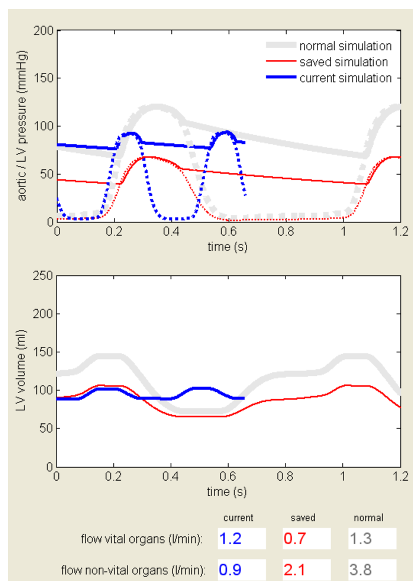

Figure 3. Case *Hypovolemic shock*. *Normal*: healthy person. *Saved*: decreased circulatory volume. *Current*: increased heart rate and resistance of non-vital organs.

To initiate a state of hypovolemic shock, the student can decrease the amount of circulating blood volume. As a result, blood pressure will drop to which the student has to take action (Figure 3, red lines). In such cases, the autonomic nervous system responds by increasing the heart rate and vasoconstriction to maintain blood flow to the vital organs at the expense of blood flow to the non-vital organs. This can be simulated by the student. The result can be described as a fast and weak pulse which is typical for patients who are in shock (Figure 3, blue lines). Moreover, these patients look pale due to the reduced blood flow through the non-vital organs.

Cardiogenic shock
During cardiogenic shock the contractility of the heart is reduced, e.g., due to a myocardial infarction. Thus, also stroke volume is decreased, which results in reduced cardiac output and blood pressure. As with hypovolemic shock, the autonomic nervous system responds by increasing the heart rate and the resistance of the non-vital organs.

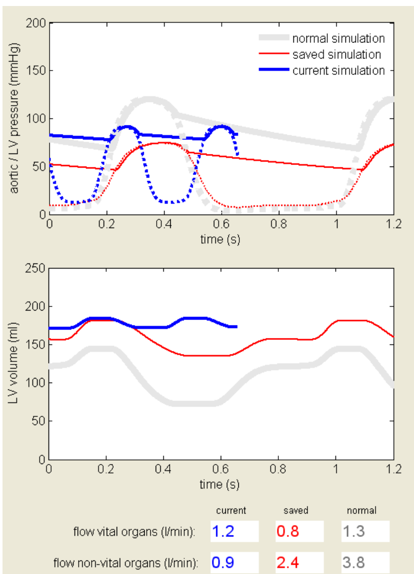

Figure 4. Case *Cardiogenic shock*. *Normal*: healthy person. *Saved*: decreased contractility. *Current*: increased heart rate and resistance of non-vital organs.

To initiate a state of cardiogenic shock, the student can decrease the contractility of the left ventricle. Stroke volume will be lower and blood pressure will drop to which the student has to take action (Figure 4, red lines). As before, the student can increase heart rate and resistance of the non-vital organs (Figure 4, blue lines).

4. Discussion and conclusions

In a scientific model, a large number of input parameters and output variables are available. For a student such a large number of possibilities may become overwhelming and distract the student from the task. In our approach, the *teacher* mode allows to selectively show input and output relevant for a specific case. In *student* mode, the user can interactively change model parameters while the simulation runs.

Interactive simulation requires that the model should react instantaneously on changes in parameter settings, while still giving reasonable results. In addition, steady-state should be reached within a limited number of cardiac cycles. Furthermore, computational load should be limited such that the simulation can be performed in real-time on a PC. The empirical approach of modeling excitation-contraction coupling in combination with the C++ implementation of the model enables real-time calculations. In the current prototype version, model parameters can be changed upon which 10 cardiac cycles are simulated to ensure steady-state. Only the results of the last two cycles are shown on screen. In the final version it will be possible to monitor variables such as pressures and volumes continuously while playing with model parameters.

Our approach is not only suitable for cardiology, but can also be used in other disciplines in medicine. By consistent use of the same graphical user interface throughout the curriculum, it is expected that students familiarize themselves with computer simulations.

Acknowledgements

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