CircAdapt: a User-Friendly Learning Environment for (Patho) physiology of Heart and Circulation

Nico HL Kuijpers[1], Willem Dassen[2], Peter M van Dam[3,4], Eelco M van Dam[4],
Evelien Hermeling[5], Joost Lumens[1], Theo Arts[1], Tammo Delhaas[1]

[1]Dept. Biomedical Engineering, Maastricht University, Maastricht, the Netherlands
[2]Dept. Cardiology, Maastricht University, Maastricht, the Netherlands
[3]Dept. Cognitive NeuroScience, Radboud University Medical Center, Nijmegen, the Netherlands
[4]Peacs, Arnhem, the Netherlands
[5]Dept. Radiology, Maastricht University, Maastricht, the Netherlands

Abstract

To understand physiology as well as pathophysiology of cardiac function, a learning environment is required in which the student can interactively induce pathophysiological alterations. Such learning environment has been created on the basis of the CircAdapt framework, which is a computer model simulating cardiovascular mechanics and hemodynamics. Physiological input parameters can be interactively manipulated while continuously running the model and displaying hemodynamic signals, so that the consequences of interventions for left ventricular (LV) pressure, aortic pressure, and LV volume can be evaluated. In the first-year medical curriculum, a prototype version of the software was used to teach cardiac (patho)physiology of exercise and shock. After evaluation of both software and training, the application software was further developed. The new application will be deployed in the second-year medical curriculum to improve understanding of pathophysiology of the valves of the left ventricle. By consistent use of the same learning environment throughout the curriculum, students will not only enlarge their knowledge of the cardio-vascular system but also get acquainted with interactive computer simulations.

1. Introduction

To really understand physiology as well as pathophysiology of the cardiovascular system, a learning environment is required in which the student can interactively manipulate model parameters that represent functional properties of the system, e.g., heart rate, peripheral resistance, cross-sectional area of the valves. Traditionally, this type of education was organized using phantom models. Although these models provide insight, they lack versatility. CircAdapt is a computer model that enables beat-to-beat simulation of cardiac mechanics and hemodynamics. By configuring modules representing cardiac walls, valves, blood vessels, and peripheral resistances, a simulation of the heart and circulation can be created. The model incorporates both the systemic and pulmonary circulation and realistically describes mechanical interaction between the ventricles. Global pressure-volume relations follow directly from local myofiber stress-strain relations on the basis of conservation of energy [1-3].

To introduce more flexibility in the medical curriculum, a prototype of the learning environment has been created on the basis of the CircAdapt framework [4]. This prototype has been applied to teach cardiac physiology during exercise and pathophysiology during hypovolumic and cardiogenic shock to first-year medical students [4]. The aim of the present study was 1) to evaluate the prototype used in the first year curriculum, 2) to define further requirements for the application software, and 3) to test the new version of the learning environment in the second-year curriculum.

2. Methods

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: A) Vessel, B) Wall segment, C) Valve, and D) 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 hemodynamic 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 vessels

[2]. The function of the baroreflex and kidneys can also be simulated by using “homeostatic pressure/flow control”. With this function enabled, the systemic peripheral resistance is adjusted to maintain a predefined mean arterial pressure. Moreover, the amount of circulating blood is regulated to obtain the required cardiac output.

Cardiac physiology during exercise and pathophysiology during hypovolumic and cardiogenic shock were taught to first-year medical students during a two hours practical training session (9 groups of 45 students supervised by 2 tutors). A few days after the training, the students were asked to fill out an on-line evaluation form to determine whether this type of education is of additional value for medical students. The evaluation form consisted of two parts. First students were asked whether

- the learning objectives of this training were clear;
- the simulation program was self-explanatory;
- the simulation program is a good tool to reach the learning objectives of this training; and
- the manual was self-explanatory and helped them to independently perform all simulations.

Furthermore, there was room for the student to give positive and negative remarks about the training and the simulation program.

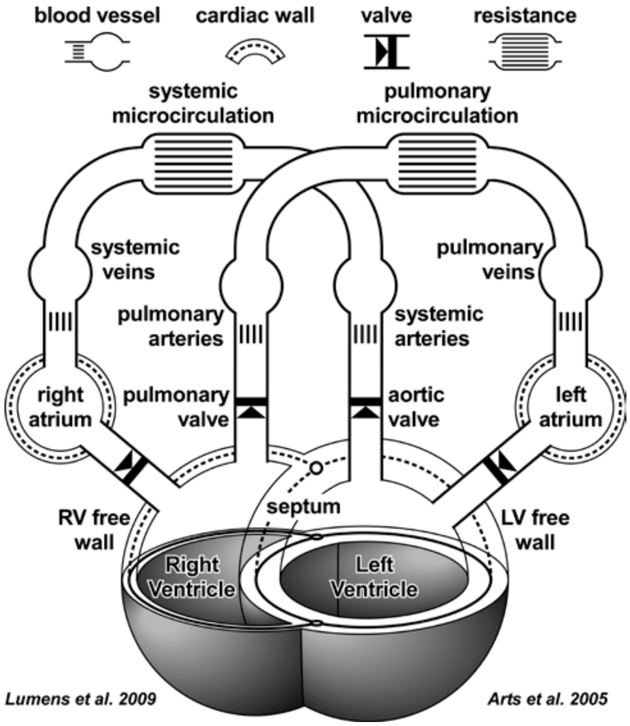


Figure 1. Overview of the CircAdapt model. The heart and systemic and pulmonary circulations are configured as a network consisting of vessels, wall segments, valves, and (peripheral) resistances.

The results obtained from the on-line evaluation were used to define points of improvement for the simulation program. The prototype and the points of improvement were used to define the software requirements. On the basis of these requirements, the educational software tool was developed by Peacs, Arnhem, the Netherlands.

The new software tool was extended such that it could be used for the second-year practical training session for medical students. The study objectives for this new training included pathophysiology of the aortic and mitral valves. During aortic and mitral valve stenosis, the cross-sectional area of the valve was reduced, whereas during aortic and mitral valve insufficiency, the valve was forced not to close completely. Valve deficiencies are well recognized by deviations in the LV pressure-volume relation. Therefore, graphical output not only included time plots of LV pressure and volume, but also o the LV pressure-volume relation. Moreover, the students need to become familiarized with blood flow velocity in the valves as these are usually measured in the clinic using (Doppler) echocardiography.

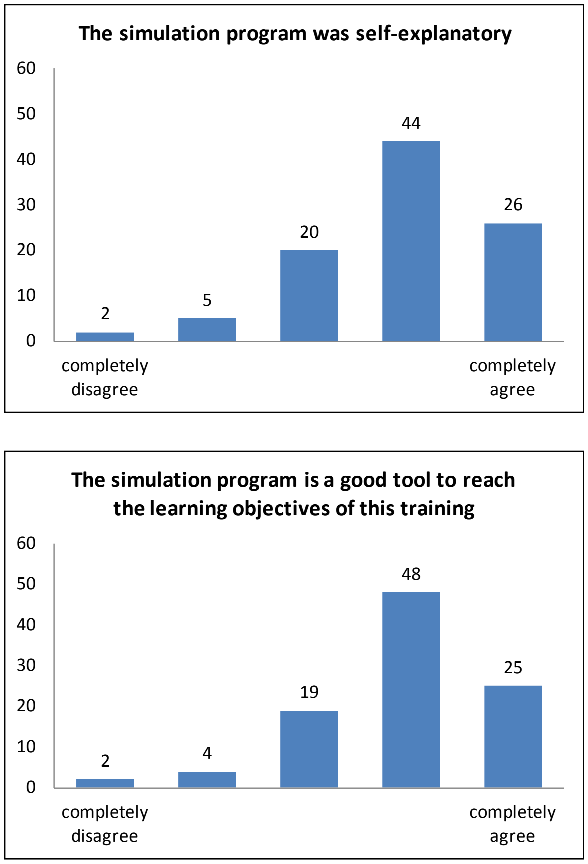
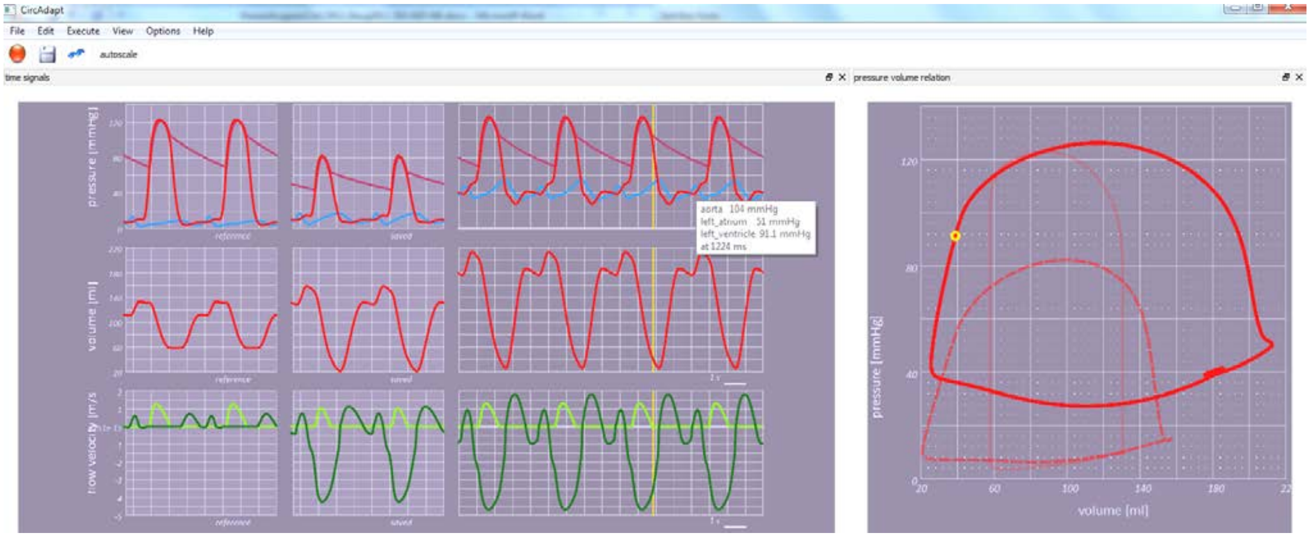


Figure 2. Overview of the results from the on-line evaluation form.



aorta 104 mmHg
left_atrium 51 mmHg
left_ventricle 91.1 mmHg
at 1224 ms

Figure 3. Screenshot of Case I: 15% mitral valve insufficiency. Left panel: time tracings of LV (red line), left atrial (blue line), and aortic pressure (top panel), left ventricular volume (center panel), and flow velocity through the mitral (light green) and the aortic valve (bottom panel). First column: normal healthy person; second column: acute hemodynamic changes during mitral valve insufficiency; third column: hemodynamics after pressure/flow control. Right panel: pressure-volume relation of healthy person (dotted line), acute changes (dashed line), and after pressure control (solid line).

3. Results

A preliminary version of the CircAdapt learning environment was used in the first year of the medical curriculum at Maastricht University (400 participants). Results obtained from the on-line evaluation forms spread among all participants (response 25%) indicate that the learning environment is a good tool to reach the learning objectives (73% of the responders agree) and that the user-interface is clear and intuitive (70% agree, Figure 2).

From the remarks of the students a number of points of improvements were subtracted:

a) the simulation tool should be available for the students after the training session;
b) the simulation should be real-time and beat-to-beat variations should be shown;
c) zooming functionality should be available to analyze signals in more detail.

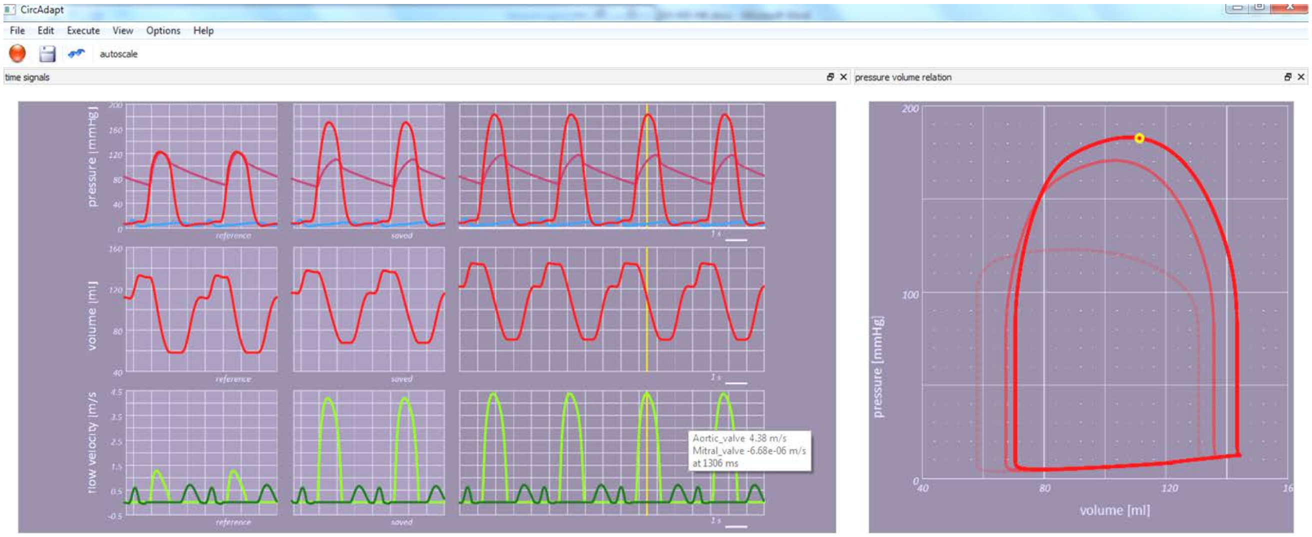
The software requirements were obtained from the prototype and the points of improvement as substracted from the evaluation form. The software was developed in the C++ programming language by Peacs. Using the new software, several educational cases were developed that will be used in the second-year curriculum at Maastricht University. Two of these cases are described below:

Case I: Mitral valve insufficiency

The mitral valve is usually bicuspid and separates the left atrium from the left ventricle. When this valve leaks, (mitral valve insufficiency) the left ventricle ejects blood back in the left atrium during systole. Consequently, aortic pressure is acutely decreased while atrial and LV diastolic pressures increased (Figure 3, left panel). The student can interactively adjust the severity of the mitral valve insufficiency and evaluate the effect on the pressure-volume relation (Figure 3, right panel). Moreover, by activating the pressure/flow control the student can evaluate the functional effects of the baroreflex and of kidney function. It should become evident that when the body regulates aortic pressure to normal values this occurs at the cost of an extreme increase of atrial as well as LV diastolic pressure (Figure 3). The normal therapy for severe mitral valve insufficiency, i.e., ACE inhibitors will counteract the regulatory processes and help to reduce atrial pressure.

Case II: Aortic valve stenosis

The aortic valve is normally tricuspid and separates the LV from the aorta. Impaired aortic valve opening, also called aortic valve stenosis, impedes the outflow of blood into the aorta. By adjusting the degree of aortic valve stenosis, the student can observe changes in LV pressure and analyze consequences of this increase for ventricular afterload (Figure 4). Moreover, the blood flow velocity (v) through the aortic valve is shown, and the student can observe a dramatically increase compared to normal. In the clinic the transvalvular pressure drop (Δp), and hence degree of stenosis, is often quantified by the formula $\Delta p = 4v^2$. By applying this rule of thumb, the student can get acquainted with clinically relevant measures and hemodynamic consequences of aortic valve stenosis.



Aortic_valve 4.38 m/s
Mitral_valve -6.68e-06 m/s
at 1306 ms

Figure 4. Screenshot of Case II: 80% aortic valve stenosis. See the legend of Figure 3 for panel descriptions.

4. Discussion

An important difference between the scientific version and the educational version of CircAdapt is characterized by user-interaction. For scientific purposes, the user is typically interested in certain output variables for a certain range of input parameters. Thus, the model can be run until hemodynamic steady-state is reached and only the output of the final cardiac cycle is of interest. In contrast, in the educational setting, the user can interactively change model parameters during runtime. Thus, 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. In the prototype version, model parameters could be changed upon which 20 cardiac cycles were simulated to ensure steady-state. In the current version it is possible to monitor variables such as pressures and volumes continuously while playing with model parameters. *In vivo*, the baroreflex and kidneys help to maintain proper mean arterial pressure and cardiac output. CircAdapt allows to selectively analyze acute consequences of pathophysiological abnormalities, e.g., valvular deficiencies. Moreover, CircAdapt also provides the hemodynamic changes when mean arterial pressure and cardiac output are restored by the physiological homeostatic control mechanisms and thereby allows direct comparison between *in vivo* findings and computer simulations.

By consistent use of the same learning environment throughout the medical curriculum, students will get acquainted with interactive computer simulations. Furthermore, the high degree of versatility of the CircAdapt model allows realistic simulation of many other cardiovascular abnormalities. This allows future development of many more educational cases.

Acknowledgements

The contribution of the StITPro Foundation in realizing this project is gratefully acknowledged.

References

[1] Arts T, Delhaas T, Bovendeerd P, Verbeek X, Prinzen FW.. Adaptation to mechanical load determines shape and properties Am J Physiol Heart Circ Physiol 2005;288:H1943–H1954.
[2] Lumens J, Delhaas T, Kirn B, Arts T. Three-wall segment (TriSeg) model describing mechanics and hemodynamics of ventricular interaction. Ann Biomed Eng 2009;37:2234–2255.
[3] Lumens J, Arts T, Broers B, Boomars KA, van Paassen P, Prinzen FW, Delhaas T. Right ventricular free wall pacing improves cardiac pump function in severe pulmonary arterial hypertension: a computer simulation analysis. Am J Physiol Heart Circ Physiol 2009;297:H2196–H2205.
[4] Dassen W, Arts T, van Dam PM, Kuijpers NHL, Hermeling E, van Dam E, Delhaas TD. The Application of Complex Research Simulation Models in Education; a Generic Approach. Computing in Cardiology 2011;38:465−468.

Address for correspondence:

Willem Dassen PhD
CARIM, Department of Cardiology
Maastricht University
P.O. Box 616, 6200 MD Maastricht, the Netherlands
willem.dassen@mumc.nl