CircAdapt

Manual CircAdapt Simulator v1.1.0

INTRODUCTION

The CircAdapt Simulator is an interactive simulation tool that can be used for education of cardiovascular physiology.[1] It is based on the CircAdapt model of cardiovascular system dynamics[2, 3] that is developed by the CircAdapt research team based at the Department of Biomedical Engineering, Maastricht University, The Netherlands. CircAdapt Simulator is freeware that can be downloaded through the CircAdapt portal www.circadapt.org. The development of the graphical user interface is funded by Stichting IT Projecten (www.stitpro.nl) and is realized by Peacs (www.peacs.nl) in close collaboration with the CircAdapt research team. The software is compatible with both Windows and Mac OS X.

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Background information CircAdapt model

The CircAdapt model enables real-time simulation of hemodynamic signals such as pressures in the cardiac chambers and large blood vessels, volumes of ventricles and atria, and blood flow rates through cardiac valves or shunts. It is configured as a network composed of a limited number of module types representing myocardial walls, cardiac valves, large blood vessels, and peripheral vasculature (Figure 1). Large arteries and veins are represented by non-linear elastic vessel modules having characteristic impedance for pressure-flow waves. Atria and ventricles are represented by chambers with a wall composed of contractile myocardial tissue. Three myocardial walls (i.e., the left ventricular free wall, the interventricular septum, and the right ventricular free wall) meet at a common junction and thereby form the left and right ventricular cavities. Mechanical ventricular interaction is incorporated by stating tensional force equilibrium at the junction. Myocardial tissue is simulated by a non-linear elastic material, harboring myofibers that contract after depolarization. Global left and right ventricular pump mechanics (pressure–volume relation) are related to myofiber mechanics (stress–strain relation) in the three ventricular walls, using the principle of conservation of mechanical work. Blood vessels and cardiac chambers are connected by valves, having inertia and Bernoulli pressure losses. Effective orifice area of a cardiac valve depends on direction and magnitude of flow through the valve and on pressure drop over the valve. Peripheral pulmonary and systemic vascular beds are modeled by non-linear resistances connecting the pulmonary and systemic arterial and venous vessel modules. The resulting pulmonary and systemic circulations allow hemodynamic interaction between the left and right side of the heart. Furthermore, the pericardium is modeled as a passive elastic sheet surrounding the entire heart (ventricles and atria).

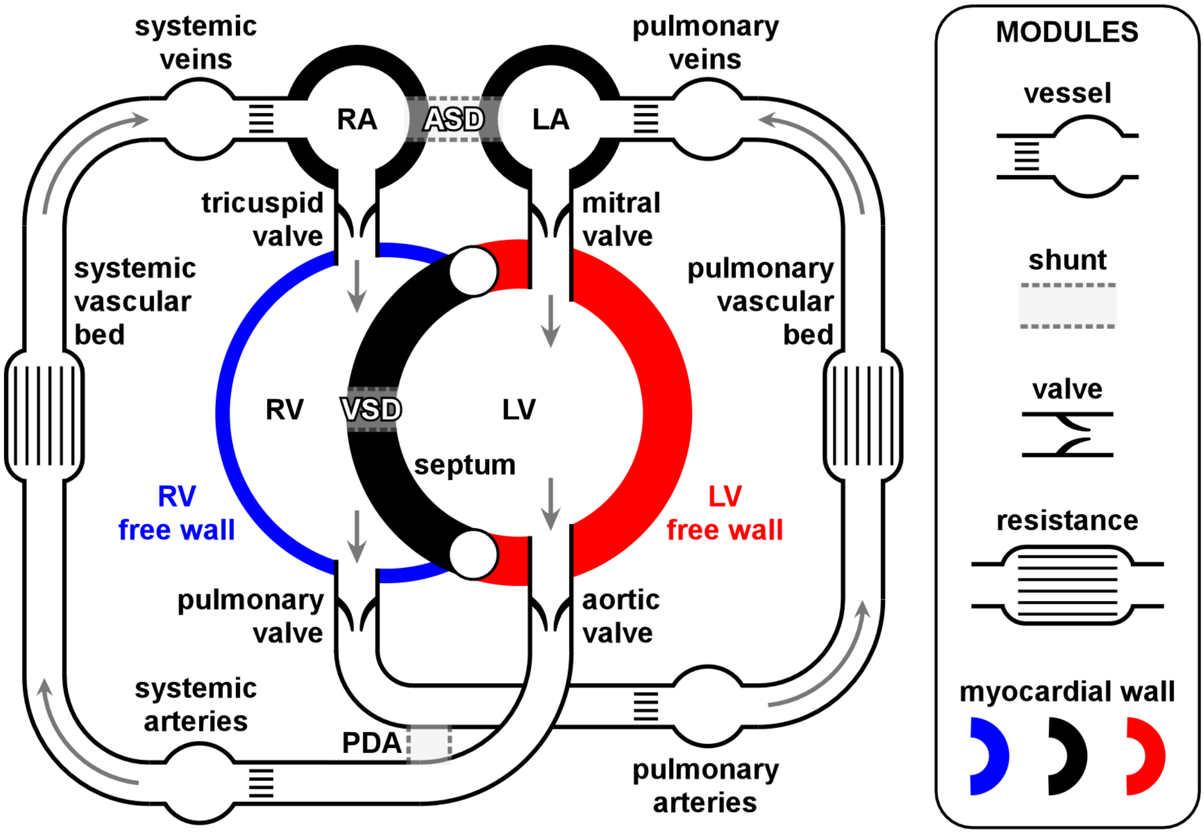

Figure 1: *Design of the CircAdapt model of the heart and circulation. The closed-loop circulation is configured as a network of modules representing myocardial walls (atrial and ventricular), blood vessels (arteries and veins), cardiac valves, shunts (optional), and peripheral vasculature. Adapted from Lumens et al.*[4] *Abbreviations: ASD, atrial septal defect; LA, left atrium; LV, left ventricle; PDA, patent ductus arteriosus; RA, right atrium; RV, right ventricle; and VSD, ventricular septal defect.*

GRAPHICAL USER INTERFACE

The CircAdapt Simulator user interface contains three panes (Figure 2):

A. The **Signals** pane displays hemodynamic signals such as pressures in cardiac chambers and large blood vessels, cavity volumes of atria and ventricles, and blood flow velocities in cardiac valves or in shunts.
B. The **PV-loop** pane displays pressure-volume relations of the atria and ventricles.
C. The **Controls** pane contains interactive tabs that enable manipulation of global and local properties of the cardiovascular system.
D. The **Values** pane shows absolute values of several hemodynamic variables derived continuously on a beat-to-beat basis from the running simulation. This pane is not being displayed at startup.

One can choose the panes to be displayed by selecting them in the *View* → *Windows* menu item. The boundaries between the different panes may be shifted by dragging them with the left mouse button.

***Figure 2:** General layout of the CircAdapt Simulator.*

Signals pane (A)

Hemodynamic signals available for display can be added or removed by placing the mouse in the relevant graph and clicking the right mouse button. The **Signals** pane contains three columns of panels:

- The **REFERENCE** column displays static signals of the reference case.
- The **SNAPSHOT** column displays static signals of any simulation that has been visually stored using the *snapshot*-button (see ***Snapshot function***).
- The **CURRENT** column displays the real-time simulated signals. The real-time nature of these signals makes that any manipulation of system properties immediately leads to a corresponding change of the hemodynamic signals.

PV-loop pane (B)

Ventricular and atrial pressure-volume relations can be added or removed by placing the mouse in the relevant graph and clicking the right mouse button. CURRENT signals are displayed as solid lines, SNAPSHOT signals as dashed lines, and REFERENCE signals as dotted lines.

Controls pane (C)

Several interactive tabs enable manipulation of global and local properties of the cardiovascular system. Default values in the reference CircAdapt case are given in Table 2. The following tabs can be used to simulate cardiovascular mechanics and hemodynamics under various (patho)physiological conditions:

- **general**
  This tab shows several homeostatic control settings. Homeostatic control of **mean arterial pressure** and **venous return** can be switched on by checking **pressure/flow regulation**. In that case, peripheral systemic flow resistance and total blood volume are regulated so that **mean arterial pressure** and **venous return** equal the desired values entered. Under steady-state conditions, **venous return** and cardiac output are equal in the absence of shunts. In the presence of shunts, however, **venous return** must be considered mean blood flow through the systemic capillaries (Qs) and can differ from cardiac output, which is defined as mean blood flow through the aortic valve. When **pressure/flow regulation** is switched off, peripheral systemic flow resistance and blood volume are constant and **mean arterial pressure** and **venous return** are not regulated but are variables that depend on the integral function of the cardiovascular system (interplay between cardiac chambers and large blood vessels). Note that **mean arterial pressure** and **venous return** cannot be changed when **pressure/flow regulation** is switched off. In the present version of the model, heart rate is not controlled by **pressure/flow regulation**, but can be changed manually.

- **ventricles**
  This tab enables manual manipulation of the **atrioventricular (AV) delay** and several myocardial tissue properties. Intrinsic AV delay is rate dependent (AV delay = 0.1765 * cycle time), however, one can change AV delay by choosing an offset (**extra delay**). The following myocardial tissue properties can be changed globally (by checking **All walls**) or for each wall individually (**LV free wall / septal wall** / **RV free wall**): passive stiffness, contractility (= ability of the myocardium to generate active myofiber stress), and wall mass.

- **atria**
  This tab enables manual manipulation of atrial myocardial tissue properties in a similar way as in the previously described **ventricles** tab. Note that the left atrium is default activated 20 ms later than the right atrium.

- **valves**
  This tab enables simulation of valvulopathies such as **stenosis** or **insufficiency**. Both valvular problems are expressed as percentage of the normal opening area of the valve. Default opening area of the mitral and tricuspid valves is 6 cm^2 and that of the aortic and pulmonary valves is 4 cm^2.

- **vasculature**
  The elastic behavior of the large pulmonary and systemic blood vessels can be manipulated by changes of the arterial or venous stiffness exponents. These exponents determine non-linearity of the exponential stress-strain relation of the vascular tissue. Vascular stiffening can be simulated by increasing the stiffness exponent. Given a flow through the pulmonary peripheral vasculature,

pulmonary vascular resistance can be manipulated by changing mean pulmonary arteriovenous pressure drop (= mean pulmonary arterial pressure – mean pulmonary venous pressure).

- **shunts**
  This tab enables simulation of three different shunts, i.e., atrial septal defect, ventricular septal defect, and patent ductus arteriosus. Diameters of shunts are expressed in mm. In default mode, all shunts are closed (0 mm).

- **adaptation**
  This tab offers the ability to apply structural adaptation of all vascular and cardiac walls. An automatic adaptation algorithm can be switched on or off by clicking the *adapt*-button. Summarizing, the algorithm continuously alternates between a predefined resting and an exercise state. During rest, reference blood vessel diameters are adapted until the time average of shear stress along the vascular inner wall reaches a physiological set point value. During exercise, wall thickness of a blood vessel is adapted to internal pressure so that maximal wall stress reaches a physiological set point value. Also mass, size, and passive stiffness of the atrial and ventricular walls are adapted in the exercise state so that mechanical load of the myocardial tissue (in terms of stress and strain) reaches physiological set point values. A transition simulation without adaptation allows for hemodynamic stabilization when heart rate and venous return are changed from resting to exercise values and vice versa. Duration of simulation can be defined in number of cardiac cycles for each condition (i.e., rest adaptation, transition, and exercise adaptation). Relative changes of atrial and ventricular wall mass and stiffness due to adaptation can be observed live (or retrospectively) in the **atria** and **ventricles** tabs. For more methodological details on the structural adaptation algorithm, we would like to refer to previously published studies by Arts *et al.*[2, 5, 6] and Lumens *et al.*[3]

Values pane (D)

This pane shows the absolute values of the hemodynamic indices listed in Table 1. These values are continuously derived from the CURRENT simulation on a beat-to-beat basis.

Table 1: Hemodynamic values

Symbol	*Name*	*Description*	*Unit*
CO	cardiac output	mean blood flow through aortic valve	l/min
Qs	systemic flow	mean blood flow through systemic capillaries	l/min
Qp	pulmonary flow	mean blood flow through pulmonary capillaries	l/min
LAP	left atrial pressure	mean left atrial blood pressure	mmHg
SBP	systolic blood pressure	maximum aortic blood pressure	mmHg
DBP	diastolic blood pressure	minimum aortic blood pressure	mmHg
MAP	mean arterial pressure	mean aortic blood pressure	mmHg
SVR	systemic vascular resistance	(MAP – CVP) / Qs	mmHg/l/min
CVP	central venous pressure	mean blood pressure in caval veins	mmHg
RAP	right atrial pressure	mean right atrial blood pressure	mmHg
sPAP	systolic pulmonary artery pressure	maximum pulmonary artery blood pressure	mmHg
dPAP	diastolic pulmonary artery pressure	minimum pulmonary artery blood pressure	mmHg
mPAP	mean pulmonary artery pressure	mean pulmonary artery blood pressure	mmHg
PVR	pulmonary vascular resistance	(mPAP – PVP) / Qp	mmHg/l/min
PVP	pulmonary venous pressure	mean blood pressure in pulmonary veins	mmHg
ASD flow		mean blood flow through atrial septal defect	l/min
VSD flow		mean blood flow through ventricular septal defect	l/min
PDA flow		mean blood flow through patent ductus arteriosus	l/min

Time markers
A time marker can be placed (Figure 2: circle 1) at any point in time of the hemodynamic signals both in the REFERENCE and in the SNAPSHOT column. The corresponding data points in the pressure-volume relations are indicated by black (REFERENCE) or gray (SNAPSHOT) bullets (Figure 2: circle 2).

Reading values
At any point in time, absolute values of the signals in the REFERENCE and SNAPSHOT columns can be obtained by placing the mouse at the desired time (Figure 2: circle 3).

Snapshot function
Any live simulation can be stored visually by clicking the *snapshot*-button. Then, the last two cardiac beats of the current simulation are visually stored in the static SNAPSHOT column. This function can be useful for comparison of a specific simulation either with a new CURRENT simulation or with the REFERENCE state.

Zoom functions
The scaling of the y-axis of a specific plot can be adjusted by placing the mouse in the plot and scrolling. The x-axis can also be adjusted by holding the *SHIFT*-button and scrolling. The origin of all axes can be shifted by simultaneously holding the *CTRL*-button and executing abovementioned zoom functions. Fully automatic scaling of axes can be achieved by clicking the *autoscale*-button.

Reset function
One can always return to the normal reference simulation by clicking the *reset*-button (NOTE: all previous simulations are lost, including the SNAPSHOT).

Image capture
At any time, one can capture an image of one of the panes by placing the mouse in the pane to be captured and pressing *CTRL-C*. Consequently, an image copy of that pane and all its content will be placed on the clipboard.

Table 2: Default values

Description	*Value*	*Unit*
general		
venous return	5.1	l/min
mean arterial pressure	92	mmHg
heart rate	70	bpm
ventricles		
AV delay	151	ms
offset	0	ms
atria		
interatrial activation delay	20	ms
valves		
mitral valve area	6	cm^2
aortic valve area	4	cm^2
tricuspid valve area	6	cm^2
pulmonary valve area	4	cm^2
vasculature		
arterial stiffness exponent (pulmonary & systemic)	8	-
venous stiffness exponent (pulmonary & systemic)	10	-
(pulmonary) arteriovenous pressure drop	11	mmHg
shunts		
ASD diameter	0	mm
VSD diameter	0	mm
PDA diameter	0	mm
adaptation		
heart rate (rest)	70	bpm
venous return (rest)	5.1	l/min
heart rate (exercise)	140	bpm
venous return (exercise)	15.3	l/min
number of cycles (rest, exercise, and transition)	100	cycles

OPENING & SAVING CIRCADAPT CASE FILES

The *Open* menu item starts up the “open case file” dialog that can be used to open any case files with extension *CircAdaptcase* at any location the user navigates to. The *Save* menu item can be used to save any current simulation as a *CircAdaptcase* file.

REFERENCE CASE FILE

The CircAdapt software includes a default reference case of a healthy adult at rest. This read only default case with file name *reference.CircAdaptcase* is located in the **cases** folder and should not be changed or overwritten.

PREFERENCES

The *Options* → *Preferences* menu item provides the ability to personalize display preferences such as:

- tab accessibility at startup
- font settings

- grid settings
- background color settings

Preferences are stored in the system's registry every time the application is being closed and are automatically applied at subsequent startup.

UPDATE FUNCTION

One can automatically check for newer versions of the CircAdapt Simulator freeware by running the "*CircAdapt update*" file that is included in the installation folder (folder in which the CircAdapt Simulator freeware has been installed). This file can also be accessed through the Windows *Start*-menu or the Mac *Applications*.

REFERENCES

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