Cardiovascular Simulation - Model Instruction

version 2.0

1. System requirements

The program has been tested in a Windows 8 environment or higher. It requires .NET4.5.1 or higher. When a lower release of .NET is active starting the program will initialise a Windows routine asking to download the latest update from the internet. The program works best at a screen resolution of 1550 x 850 or higher. In this version, the program window cannot be scrolled or resized. Therefore, lower screen resolutions result in less functionality.

2. Installation, activation and optimization

2.1. Installation

A demo version of the model can be obtained at www.neuromon.eu. It is downloaded as a .ZIP file. The folder contains 2 files. The executable file is called cardiovascularsimulation cs.exe (extension may or may not be visible). Double clicking this file will start the program. In the demo version the controls of the program allow settings to be changed for a period of 30s simulation time. After this the controls are locked.

2.2. Acivation

To unlock the controls the user needs to enter an email address and select a so-called Password_File. The combination of an email address with a correct Password_File will release the controls. For a working Password_File please contact info@neuromon.eu.

2.3. Optimization

It is important to realise that the model works on two separate processor threads: one calculating on a continuous basis the pressures and volumes for the different components and a second subserving the user-interface. The user interface on the one hand displays an animation of the model's calculation and on the other hand allows the user to change one or more of the various controls. Both threads will run simultaneously when the computer mouse is clicked without further moving. However, in order to change controls, the animation is interrupted as soon as the mouse is moved. This may have a stuttering effect on the graphing as well as on the animation that will disappear as soon as the mouse is left to rest. Because different computer systems may have different processor times the model can be optimised by selecting:

1. an optimal time step(ms): a larger time step will result in a faster but less accurate simulation; when chosen too large oscillations may occur. The time step can be changed in the main control box (see below).
2. an optimal refresh rate (Hz) for the volumes simulation (to be found in the Settings menu): a larger refresh rate will result in smoother animation but this goes at the price of lowering the simulation speed; both processes run on different computer threads that will compete in processor time. The refresh rate can be controlled in the Settings menu.

3. Model lay-out

The main window of the model contains a number of regions illustrated by figure 1. Basically, the model is based upon a simulation of blood volume in 8 different compartments: 7 compartments arterial (A - G) and 1 venous compartment V animated in the volume

simulation box at the lower mid. The colour of the volumes represents the CO2 level of the blood they contain: blue indicates high levels of CO2 and red indicates low levels of CO2.

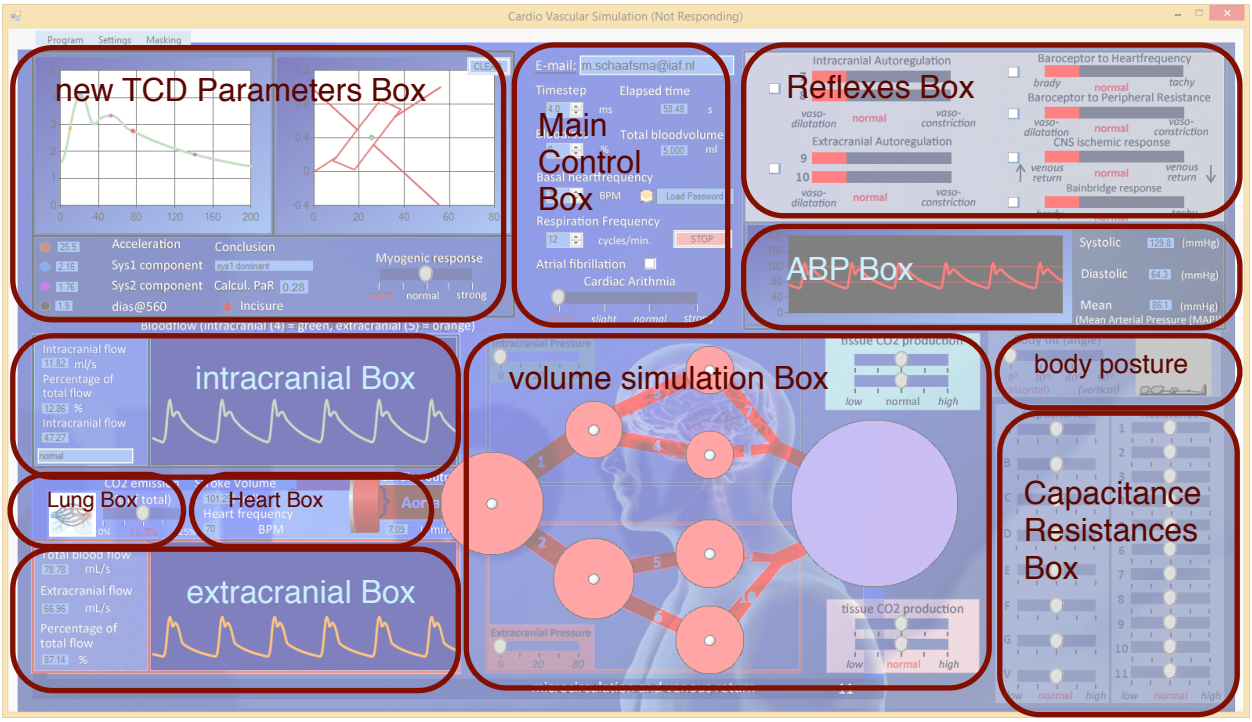

Figure 1

The model calculates the variation in volume of these compartments in response to the pulsatile output of a simulated heart, represented by a cylinder and piston in the so called heart box at the lower left. The remaining part of the window contains input controls as well as output indicators of flow velocity, pressure etc. represented by a graph or by a numerical value. The various components of the window will be discussed below.

3.1. Heart box

The heart box is the driving force of blood circulation in the model. Up to a maximum of 190ml the heart box will eject a fraction of the blood it is filled with. Filling of the heart only occurs during diastole. Therefore, the filling of the heart is dependent on heart rate: at lower heart rates the diastole will be longer, allowing more blood to enter the heart. The heart receives blood from the venous compartment V. Filling depends upon the pressure in this compartment: higher pressure will cause the heart to fill more rapidly.
This box also contains output indicators for heart rate, cardiac output and stroke volume.

3.2. Lung box

This model does not simulate the small circulation from right ventricle, via the lungs to the left atrium. It does, however, simulate the refreshment of the blood by this part of the circulation: by changing the slider inside this box 0-25% of all CO2 is removed from the volume entering the heart.

3.3. Volume simulation box

In this part of the main window the volumes are animated of the compartments of the arterial tree (A-G) and of the venous capacitance (V). The compartments are connected by resistances numbered 1-11. The arterial tree can roughly be divided in an intracranial part, accepting around 15% of cardiac output (CO) and an extracranial part accepting the remaining 85% of CO.
The refresh rate of the animation can be controlled from the Settings menu. It is usually set at 10Hz. Higher rates will favour the refresh rate of the animation but at the cost of a lower

simulation rate. Therefore, the user shall find an optimum between refresh rate and the simulated timestep (to be adjusted in the main control box).
This box also contains sliders for changing extracranial and inctracranial tissue pressure. And it contains sliders for metabolic activity in the tissue behind the volumes D-G, with D and E corresponding to the intracranial and F and G the extracranial circulation. The left two quadrants of the volume V represent the mixed CO2 level of the intracranial (top) and extracranial (bottom) venous return flow.

3.4. Main control box

This box contains several controls that alter the working of the model. First it contains an input box for the user's email address and a button that will start a dialog for selecting the corresponding Password_file to unlock all controls. When successful an indicator in front of this box will change from a warning sign to a cube.
It also contains a control for the timestep used for the cardiovascular simulation. A higher value will cause the model to make larger steps in time decreasing accuracy, a lower value will cause the model to become more accurate but slows down the simulation and thus the animation.
Furthermore, this box contains a control for adjusting the total blood volume (5 litres ± 5%). Changing this control will alter the total blood volume gradually. The total blood volume can be read from an indicator at the right.
Finally, the main control box contains controls for heart rate, respiration rate, respiratory arrhythmia and a checkbox for atrial fibrillation. The slider for respiratory arrhythmia will also control the heart rate variation during atrial fibrillation.

3.5. Body posture box

This box contains a control and an indicator of modelled body posture from recumbent to upright in 3 steps.

3.6. Capacitances and Resistances Box

The capacitances for the volumes A-G and V and the resistances 1-11 can be changed within this box.

3.7. Reflexes box

At the left side of this box 2 checkboxes can be selected to activate or de-activate autoregulation in intracranial of extracranial tissue. Autoregulation matches regional blood flow to metabolic activity. At the right side 4 checkboxes can be selected to activate or de-activate various cardiovascular reflexes, to be discussed below. The red horizontal bars on a black background represent the relative activity of each response.

3.8. Intracranial box

This box contains a graphical representation of the flow over resistance 3 (from volume B to D). The time resolution of this graph can be adjusted by selecting another value from the Settings menu.

3.9. Extracranial box

This box contains a graphical representation of the flow over resistance 5 (from volume C to F). The time resolution of this graph can be adjusted by selecting another value from the Settings menu.

3.10. ABP box

This box contains a graphical representation of the blood pressure in volume A (representing the aorta).

3.11. New parameters box

In the new parameters box the mean flow over resistance 5 is graphed over the last 10s simulation time. In this graph coloured dots represent the location of the different parameter values: acc, sys1, sys2 and dias@560 (Schaafsma, UMB 2012, 38(8): 1451-1459). At the

right side a (x,y) graph shows the values of sys1-sys2 plotted against the value for acc. A green box represents the range for normal combinations of these values.
The numerical values for the new parameters are given below these graphs, together with the numerical value of a so-called status code. The status code provides information about the interpretation of the signal by the automated signal analysis software (the so called Neuromon_TCD_Analyzer.dll). From the options menu the indicator window can be selected to translate the status code to understandable text.
Finally, this box contains a slider for adjustment of the myogenic response. This is the temporary decrease in capacitance of all volumes of the arterial tree assumed by the theory of arterial acceleration. In reality, this myogenic response is assumed to spread over the arterial tree as a peristaltic wave. In the model all volumes will decrease their capacitance simultaneously to avoid oscillations.
In this box there is a checkbox 'Calculate PaR' this causes the model to analyse both the flow signal over resistance 5 and the ABP in volume A. From this, it calculates the pulsatile apparent resistance or PaR; a patented blood pressure corrected pulsatility index (for more info consult http://www.neuromon.eu).

If not so, please set the myogenic response to 'normal'.

4. Menu

The menu contains several submenus to adjust settings of the program or provide extra information on the programs working.

4.1. Program

4.1.1. Information

Information box.

4.1.2. Exit

Selecting this menu item will terminate the program.

4.2. Settings

4.2.1. Refresh

Within this submenu the refresh rate of the model animation can be changed from 5Hz to 100Hz. Depending on the computer system the model is running on these options may not all be as effective.

4.2.2. Graphing

Within this submenu the time sweep of the graphs in the intracranial and extracranial box can be altered from 2.5 to 10 seconds.

4.3. Masking

For education purposes different parts of the model can be masked by empty windows that appear in front of the main window. The windows can be closed by selecting the red checkbox at the upper right or by deselecting the corresponding window in the menu.

4.3.1. TCD analysis box

Selecting or deselecting a masking window for the new parameters box

4.3.2. Reflexes box

Selecting or deselecting a masking window for the new reflexes box

4.3.3. RC box

Selecting or deselecting a masking window for the resistances and capacitances box

4.4. Options

There are different options to be selected or deselected:

4.4.1. Simulation time

In this submenu the timing of the simulation may be turned to realtime, half or twice realtime or maximal. When selecting maximal, the model simulation is no longer in sync with the model animation. This setting makes it easier to rapidly evaluate the parameter output of the model in response to changing controls but makes the volume animation and the graphing of the signals inaccurate.

4.4.2. Status indicator

The status indicator translates the status output of the automated signal analysis to understandable text; the status indicator is an overlay of the sys1-sys2 versus acc graph

4.4.3. HR from trace 12

Selecting whether the automated signal analysis will derive its heart rate detection automatically of based upon the first or second signal. Selecting trace 1 will cause het heart rate (and signal averageing) to be derived from the flow over resistance 5 and selecting trace 2 from the blood pressure in volume A (only possible after selecting 'Calculate PaR'.

4.4.4. Display trace 12

Selecting the signal to be displayed in the New parameters window and by the status indicator. Selecting trace 1 will display the flow over resistance 5 and selecting trace 2 will display the blood pressure in volume A.

4.4.5. Add noise

Selecting or deselecting the occurrence of signal noise

4.4.6. Ejection fraction

Changing the ejection fraction of the heart from 65% (normal) to 25% or to a fixed residual volume of 50ml.

5. Basic parameters: heart rate and heart rate variability

In normal subjects heart rate is not stable but varies with respiration, physical and/or mental activity. The mean heart rate can be adjusted within the Main control box. Also heart rate variability can be selected. There is a check box for atrial fibrillation which result in a random heart rate with a variation selected by the slider for heart rate variability.

Model observation:
Selecting a lower heart rate (e.g. 65 BPM) will result in a longer diastole. During diastole the heart chambers will have more time to fill. This increases stroke volume. In contrast, selecting a higher heart rate (e.g. 85 BPM) will allow less time for filling of the heart chambers and result in a smaller stroke volume.
These effects are visible in the flow (velocity) as variations of sys2 relative to sys1 (at least when the myogenic response is activated). A decreasing heart rate will make the signal more sys2 (or less sys1) and an increasing heart rate more sys1 (or less sys2) dominant.
Selecting a different heart rate variation by moving the slider will simulate respiratory arrhythmia. The respiratory frequency is set at 12 per minute. This is the frequency with which heart rate will vary. It results in waxing and waning of the sys2 component relative to the sys1 component. This variation in the sys2 component during, for instance, deep breathing has very often been demonstrated in real subjects.

6. Basic parameters: stroke volume and cardiac output

The stroke volume (SV) and the cardiac output (CO) are calculated on a beat-to-beat basis and displayed numerically within the heart box.

Model observation:
When selecting a variable heart rate stroke volume (SV) will increase at lower and decrease at higher heart rates. In the model, cardiac output (CO) will vary in parallel, since it is calculated on a beat-to-beat basis. Usually, cardiac output is estimated over a longer period of time, e.g. over minutes. With or without respiratory variation, the average cardiac output should be roughly the same, since it mainly depends on the venous pressure (venous pre-load of the heart atria).

7. New TCD parameters

There are two graphs in the left upper corner that display the results of the so-called new TCD parameters. This analysis provides the maximal acceleration at stroke onset, the amplitudes of the sys1 and of the sys2 components within the intracranial flow velocity signal. These parameters are normalized by division through the dias@560 ms, which is the mean flow (velocity) over an interval of 520-600ms after stroke onset. This choice of parameters is explained in Schaafsma (UMB 2012, 38(8): 1451-1459). Apart from simulating cardiovascular physiology the model is also meant to illustrate how changes in these new parameters relate to the underlying physiology.
The graph at the far left displays the mean flow signal over a period of 10s. The location of the sys1, sys2 and dias@560 parameters are indicated by coloured dots. The red dot indicates the calculated incisure, which is the moment in time that the systole turns into diastole.
The graph at the right displays the difference between sys1 and sys2 versus acceleration. Under normal circumstances data will cluster within the oblique rectangle. The flow (velocity) signal can be qualified as sys1 dominant, sys2 dominant or sys12 balanced. This qualification is provided in text below both graphs.In extreme circumstances the signal may become sys1 or sys2 exclusively.

Model observation:
See how the relation between sys1 and sys2 varies at different heart rates. Investigate how the relation between sys1 and sys2 vary for different body postures (Body posture box). Investigate how the relation between sys1 and sys2 varies when the total blood volume is changed (Main control box).

8. Arterial acceleration: the myogenic response

An important, but still hypothetical, addition to the model is the Theory of arterial acceleration. This theory is explained in Schaafsma (Medical Hypotheses 2014, 82(5) 589-594). Basically, it assumes that the conducting arteries within the arterial tree support the pressure wave from the heart by briefly contracting at stroke onset. This is, presumably, the origin of the sys1 component within the flow signal. The sys2 component is the result of cardiac output in interaction with arterial compliance and peripheral resistance.
To demonstrate its effect, the myogenic response can be turned on or off. It can even be turned on in an exaggerated mode to more clearly demonstrate its action. The myogenic

response is implemented by a temporary reduction of the capacitances within the simulation model. Thereby, the arteries squeeze out a bit of volume that is present in the arterial tree. The pressure that results from this temporary contraction improves the penetration of the pressure wave into the capillary systems. This can later on be demonstrated by increasing the tissue pressure, either intracranial or extracranial (controls within the volume simulation Box).

Model observation:
Change the slider for the myogenic response in the New parameters window and relate this to the output graph. Optionally, select the status indicator to see how the signal may change from sys1 dominant to sys2 exclusive at different settings for the myogenic response.

9. Basic parameters: blood CO2 level

The cardiovascular simulation model integrates a crude simulation of metabolism. Basically, on the right side a waste product is produced by the intracranial and extracranial tissue (modelled as CO2 load) that requires transportation to and excretion by the lungs. The metabolic rate can be adjusted by sliders within the volume simulation box (right side). Its effects become visible by changing the colour of the venous outflow in the two left quadrants of the venous capacitance (V). A blue colour indicates high levels of CO2, a red colour low levels of CO2. There are two sliders for the intracranial (output from D and E) and two sliders for the extracranial circulation (output from F and G).
The excretion of CO2 by the lungs can be adjusted in the so-called lung box. Normally, 12.5% of the CO2 passing through the lungs is expired. This slider can be set to zero (causing suffocation of the model) or to 25% which simulates hyperventilation.

Model observation:
The colour of the volumes A-G and V will alter depending on the balance between CO2 production on the right side and CO2 excretion by the lungs at the left. By playing around with the sliders the blue or red blood can be shown to vary across the model's volumes. Since approximately 15% of all cardiac output passes through the intracranial tissue and 85% through the rest of the body, sudden changes in CO2 level will first have an effect on the intracranial and only somewhat later on the extracranial circulation. This is basically caused by more or less dilution of the effect relative to the blood volume in the two parts of the modelled circulation.

10. Basic parameters: venous capacitance

In the model, the cardiac output (CO) is highly dependent upon the venous capacitance. This can be demonstrated by changing the slider of volume V within the Capacitance and Resistances box.

Model observation:
When the slider of the volume V is set slightly to the left, the decrease in capacitance will cause an increase in pressure. This increase in pressure results in an increase in filling of the heart chamber: the stroke volume goes up and at identical heart rate, the cardiac output will increase. When the slider is set slightly to the right, the venous capacitance will increase causing less

filling of the heart chamber, and thus a smaller stroke volume and a smaller cardiac output, at least when the heart rate remains the same.
Similar to the effect of changing heart rate a larger stroke volume will cause the flow (velocity) signal to become more sys2 (or less sys1) dominant, whereas the smaller stroke volume resulting from an increase in venous capacitance will result in a more sys1 (or less sys2) dominant signal. Note that occasionally, selecting a different value for the venous capacitance will cause the model to oscillate. This has to do with the timestep (ms) the model is working at. When oscillating select a smaller time step to allow the model to perform a more accurate calculation of volumes and pressures. Usually, selecting 3 ms will prevent the model from oscillation.

11. Basic parameters: intracranial versus extracranial resistance

Normally, approximately 15% of cardiac output is directed to the intracranial tissues. Increasing the resistance within the intracranial arterioles may direct the blood away from the brain. Likewise decreasing this resistance will allow more blood to flow in.
From the viewpoint of the brain increasing total peripheral resistance will force the blood to pass through the intracranial tissues, whereas lowering peripheral resistance will decrease cerebral blood flow. Of course, changes in total resistance will have consequences for the arterial blood pressure (ABP).

Model observation:
increase the metabolic activity of the intracranial tissue by setting the sliders to the right of normal. See whether the colour of the outflow (upper left quadrant of volume V) can be turned to pink or red again by changing the resistance of the intracranial arterioles (resistance 7 and 8) or, alternatively, by changing the resistance of the extracranial arterioles (resistance 9 and 10), Observe what effects changes in resistance have on the arterial blood pressure. How can the arterial blood pressure be brought back to its original level? What about changing the venous capacitance (V)? What about changing heart rate?

12. Autoregulation: cerebral versus extracranial

Most tissues within the body have a so-called autoregulatory mechanism. For the brain this is known as cerebral autoregulation. It allows the blood flow to remain relatively constant despite changes in arterial blood pressure. It is likely that cerebral autoregulation, as meant in literature, is the result of a number of processes acting simultaneously. One of these is the so-called metabolic response: when a tissue, such as the brain, is more active it produces more metabolites. These metabolites trigger a local vasodilatation. Similarly, when the tissue is less active, a local vasoconstriction occurs. This metabolic response has been implemented within the cardiovascular simulation model for both the extracranial as well as intracranial tissue. The response can be activated by selecting the leftmost checkboxes within the Reflexes Box.

Model observation:
It is probably wise to put all sliders back in the normal position. Now select the intracranial and extracranial autoregulation. Adjust the timestep (ms) whenever necessary. Does the model settle to an equilibrium state? What happens after activating respiratory arrhythmia? Is the model still stable?

Now change the metabolic activity of one of the two sliders for intracranial tissue. What happens with the reflex output is indicated by the location of the red bar in the reflex slider. Does it move towards vasodilatation or towards vasoconstriction?
Move both sliders towards the right side. Is there a change in the sys1-sys2 parameter? What happens with the flow (velocity) when both sliders are moved to the right?

13. CNS ischemic response

After playing around with both autoregulation responses it will be clear that there may be circumstances that both intracranial as well as extracranial metabolism are increased. This, for instance, happens during physical activity. The resulting drop in peripheral resistance will cause blood pressure to decrease. This is an unwanted side-effect. Since a higher metabolic activity requires a larger cardiac output.
There is a well known but ill-defined response, called the CNS-ischemic response, that is known to cause an increase in blood pressure in response to an increase in CO2 (or metabolic acidosis).
The receptors for this response have not yet been identified but are possibly in contact with intracranial venous outflow. The way by which the CNS-ischemic response increases arterial blood pressure is not exactly known. In the model, the most effective way is to change the capacitance of the venous part of the circulation. In rest about 80% of the blood volume is in the venous phase. Decreasing venous capacitance will decrease the time the blood can remain within the venous compartment. The blood returns to the heart more rapidly. When heart frequency and contractility allow the venous blood to be pumped out (not, for instance, when ejection fraction is low) the cardiac output (and the circulation time) becomes higher. An increase in cardiac output allows the increase in tissue metabolites to be flushed away and transported to the lungs. If the lungs are also more effective in refreshing the blood all effects of the increased metabolism can effectively be counter-acted.

Model observation:
With intracranial and extracranial autoregulation turned on, increase the metabolism in both intracranial and extracranial tissue. What happens with the arterial blood pressure? Is there a rise in cardiac output? Leave the model for a while: is the excess in metabolites effectively removed? Now turn on the CNS-ischemic response. Observe in what direction the red bar moves: towards an increase in pre-load for the heart or towards a decrease? What happens with cardiac output? What happens with arterial blood pressure? Does the model find an equilibrium (remove the excess of metabolites)? Now increase the refresh-rate of the lungs. Does the model turn pink or red again?

14. Baroceptor reflex to heart rate

The above mechanisms are based upon the detection of metabolites. For high speed living organisms as we are, these responses are, though effective, rather slow. Possibly, this is the reason why there is a 2nd more rapid line of defense: the baroceptor reflex influencing heart rate and the barocepter reflex influencing peripheral resistance. If blood pressure drops in the cerebropetal vessels heart rate is increased instantaneously to pump blood out of the heart into the aorta as much as possible. If blood pressure increases the opposite occurs: heart rate is

lowered in order to allow more blood to flow out of the arterial tree before the next stroke volume is added.

Model observation:
With all sliders in the normal position, turn on the baroceptor reflex to heart rate. Now, observe what happens with the heart rate when blood pressure drops. This can be achieved by either increasing the venous capacitance (V) or by decreasing the total amount of circulating volume (the control for blood loss can be found in the main control box).
Also observe what happens with the heart rate when the arterial blood pressure increases, for instance by decreasing the venous capacitance (V) or increasing the amount of circulating volume. What are the effects on the wave morphology of the blood flow (velocity)?

15. Baroceptor reflex to extracranial resistance

For living organisms as we are it is of paramount importance to maintain consciousness under all circumstances (except when safely sleeping in our bed). In order to deal with environmental threats we need our consciousness to decide what action to take: stay where we are, run away or try to make the threat run away? Brain circulation is priority number one, probably together with heart circulation, since the first depends so much on the latter. A decrease in pressure within the cerebropetal vessels may cause a decrease in cerebral perfusion possibly resulting in a loss of consciousness. The blood needs to be directed to the brain. This is done by the baroceptor to extracranial resistance response: the percentage blood directed towards the intracranial tissues can be increased by increasing peripheral resistance (as we have seen in paragraph 11).

Model observation:
Now also turn on the baroceptor to peripheral resistance response. Apply similar changes to the total amount of circulating volume and/or to capacitance of volume V as in the former paragraph. What happens with cerebral blood flow? What happens with the wave morphology expressed by the new TCD parameters?
Is the model stable? What happens when increasing metabolic activity with all reflexes turned on? Is a new equilibrium found? What happens when decreasing metabolic activity?

16. Bainbridge response

The Bainbridge response causes heart rate to increase at larger atrial pressures. Atrial pressure depends on venous backflow to the heart and cardiac output. The Bainbridge response prevents the heart to reach it's maximal filling capacity: the increase in heart rate reduces the stroke volume.

Model observation:
With the CNS ischemic response turned on change the metabolic activity of the peripheral circulation. This is as if the model is performing physical activity. Now, the (somewhat delayed) increase in CO_2 will cause a decrease in venous capacitance (V). This increases the preload to

the heart and thus the stroke volume. See what happens with the stroke volume when the Bainbridge response is turned.

17. Ageing: decreased arterial compliance

Decreased arterial compliance is thought to be the main cause of an increase in arterial blood pressure pulsatility. In the model, the arterial compliance can easily be lowered by reducing the capacitance of volume A.
When accepting the Theory of arterial acceleration an alternative explanation is that over time the strength of the myogenic response is increased (this hypothesis can be supported by the observed proliferation of smooth muscle cells in the arterial wall of elderly patients with systolic hypertension).

Model observation:
What happens with the morphology of the arterial blood pressure wave? Is indeed, the pulsatility higher than before changing volume A? What happens when increasing the capacitance of volume A?
Turn the capacitance of volume A back to its original position. Now increase the myogenic response. What happens with the arterial blood pressure wave? Is the pulsatility higher than before? What happens when sliding the myogenic response to a lower value?

18. Intracranial pressure

For neurologists elevation of intracranial pressure by, for instance, an intracranial mass lesion, intracranial haemorrhage, sinus thrombosis or hydrocephalus, is a major challenge for the optimal treatment of an individual patient. The model simulates intracranial pressure elevation by locally increasing the outflow pressure for the tissues capillaries. This blocks flow at the lower pressures, while flow is still possible at high pressures. Therefore, intracranial pressure elevation will first decrease or totally block diastolic flow, then the flow during sys2 and only at very high pressure flow during sys1. This makes the flow velocity signal more pulsatile / more sys1 dominant.

Model observation:
Put all sliders to normal. Put all cardiovascular reflexes on. Then increase intracranial tissue pressures in small steps. See, what happens with the morphology of the flow(velocity) signal. What happens with the sys1-sys2 versus acceleration plot?
At very high intracranial pressures the flow (velocity) signal may become ‘sys1 exclusivel’. See whether this occurs at the current settings of the model. What happens when increasing the myogenic response? What happens when turning the myogenic response to zero?

19. Unilateral stenosis

In carotid artery disease there is an obstruction of flow via one of the feeding arteries to the brain. Note. that the obstruction itself is usually not the cause for neurological symptoms: TIAs and ischemic stroke are most often caused by a thrombo-embolic process. Nevertheless, a carotid stenosis may limit regional cerebral blood flow and can in some cases cause

hemodynamic TIAs. Carotid stenosis can be simulated by elevating one of the resistances 3 or 4.

Model observation:
Put all sliders to normal and put all cardiovascular reflexes on. Now increase resistance 3 or 4. Since in the present version of the model the venous outflow of capacitances 3 and 4 are combined it is not directly evident from the colour of the upper left quadrant of the venous capacitance (V) whether the flow drops below a critical level. This, however can be deduced from the red bars within the sliders for cerebral autoregulation. At the side of the stenosis, the arterioles will be more dilated than on the contralateral side. A reduction in blood pressure (e.g. increasing capacitance of volume V or decreasing the total amount of circulating volume) will cause an increase of intracranial vasodilatation up to the point that the vessels are maximally dilated: this is the lower limit of cerebral autoregulation: a further drop in blood pressure cannot be compensated for by further vasodilatation.

20. Body posture

Following this instruction from point to point has introduced you to almost all the model's controls. The last control to be discussed is body posture. Changing body posture from horizontal to vertical will introduce the effects of hydrostatic pressure: the weight of the blood volume will cause pooling of blood in the lower parts of the body. The joint effect of the cardiovascular reflexes is to maintain cerebral blood flow as constant as possible.

Model observation.
With all reflexes turned off, change the body posture from horizontal to vertical. What effects does this have on cerebral blood flow? What are the changes in the morphology of the flow (velocity) signal?
Now change the body posture back to horizontal. Put all reflexes on. Now change the body posture to vertical again. Do the same changes occur? Does the model find a new equilibrium? What happens with the morphology of the flow (velocity) signal?

21. Conclusion

Hopefully, playing around with the controls of the cardiovascular simulation model has learned you something about the complex interaction of chemical, physical and physiological processes all primarily aiming to keep cerebral blood flow as constant as possible.
The main goal of cerebrovascular regulation is not to maintain a certain target for arterial blood pressure but to ensure adequate perfusion of all bodily tissues, without leaving any part out.