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Gravity influence in one-dimensional blood flow modeling

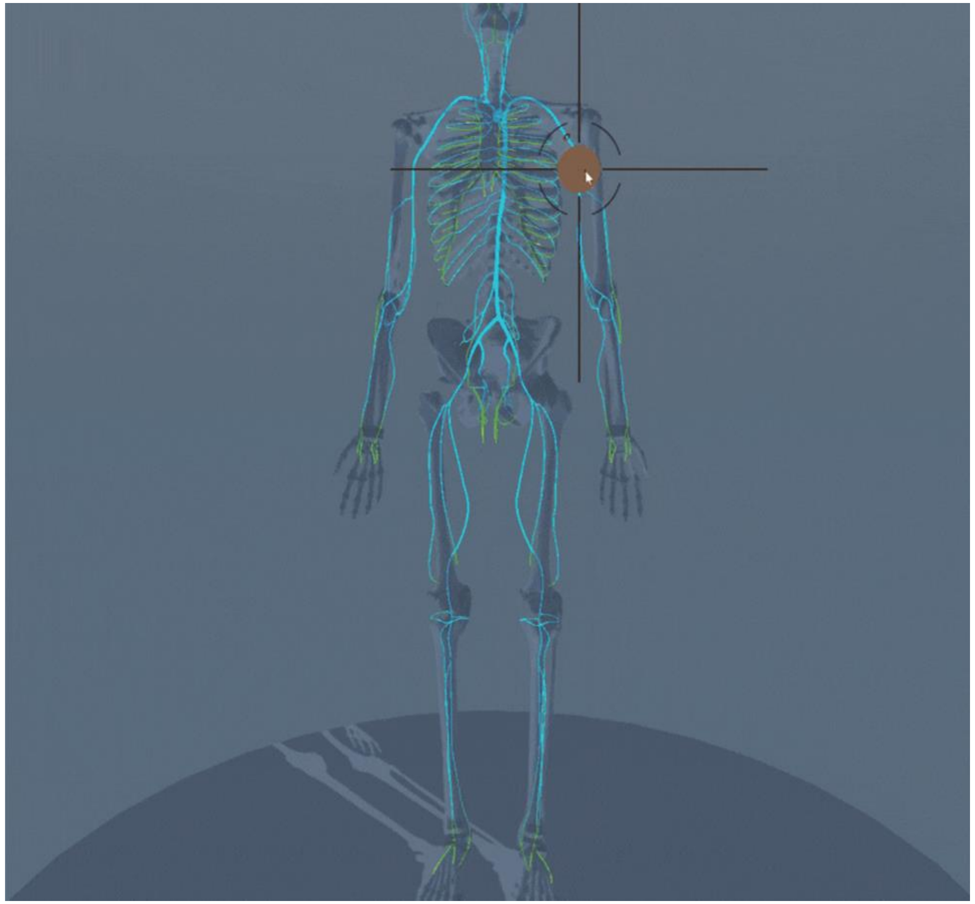
Oleg Shramko, Andrey Svitenkov, Pavel Zun

ITMO University

YSC young scientists conference

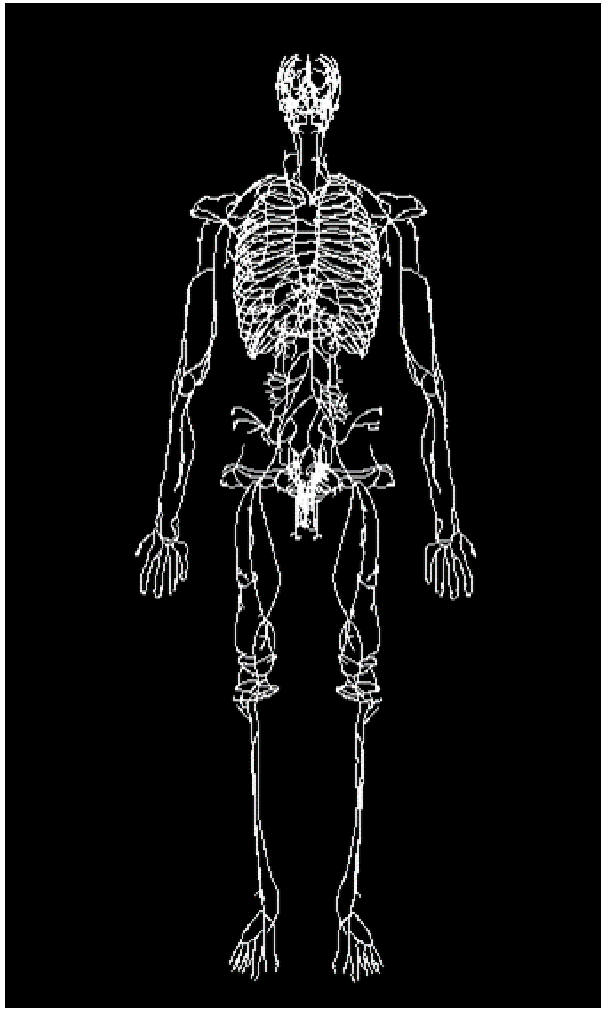
Introduction

In the past 10 years blood flow modeling became a routine and powerful tool to study the circulatory system for scientific applications. We suggest the idea and methodology for how a gravity field can be added to a 1D blood flow model while also accounting for the boundary conditions (peripheral vessels) reaction. We demonstrate our concept on the well-known ADAN56 model of human arterial system for verification purpose, keeping in mind that a high-detailed arterial model can be used as well.



Methodology

The general idea



Accounting for the gravity influence in blood flow simulations of human circulatory system requires more than just the inclusion of the gravitational force in the calculations.

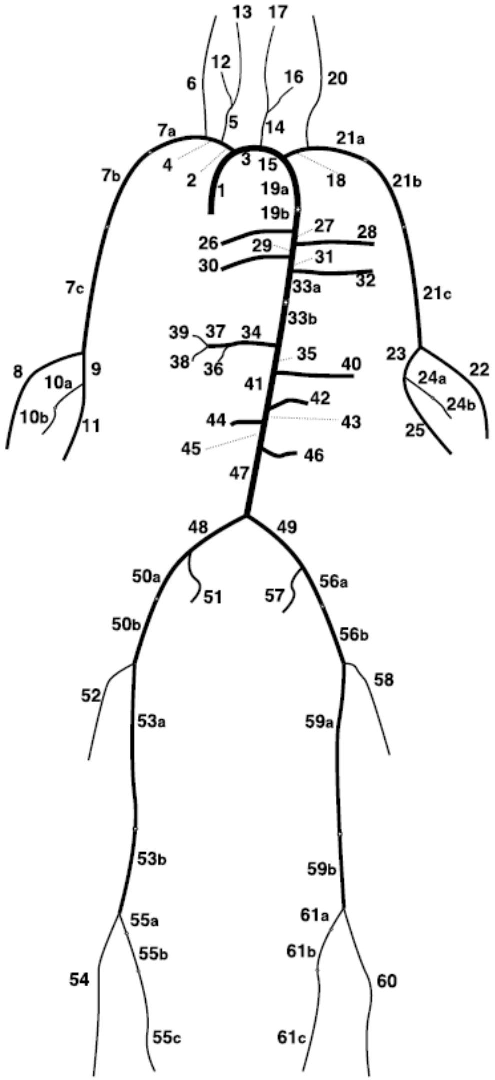
The smallest arteries, arterioles are boundary conditions (BC) for the 1D blood flow model.

BC can be represented in a 0D form similar to electrical circuits.

For more correct accounting of the gravity influence on blood flow, it is also necessary to change the boundary conditions following the changes in gravity.

Methodology

Model implementation



The ADAN56 arterial model includes 30 bifurcations and 31 outlets. We initially take all parameters of the model from the benchmark paper [Boileau et al., 2015] to verify the simulation results and make them easily repeatable.

Governing equations relating the average velocity U and the area of the vessel lumen A :

$$\begin{cases} \dfrac{\partial A}{\partial t} + \dfrac{\partial (AU)}{\partial x} = 0 \\ \dfrac{\partial U}{\partial t} + U\dfrac{\partial U}{\partial x} + \dfrac{1}{\rho}\dfrac{\partial P}{\partial x} = \dfrac{f(U)}{\rho A} + \dfrac{\partial (\boldsymbol{rg})}{\partial x} \end{cases}$$

t – time,

x – the longitudinal coordinate relative to the artery,

ρ – the blood density,

P – the pressure in the discretization point,

r – 3D space position of the artery elementary segment,

g – the vector of gravity acceleration,

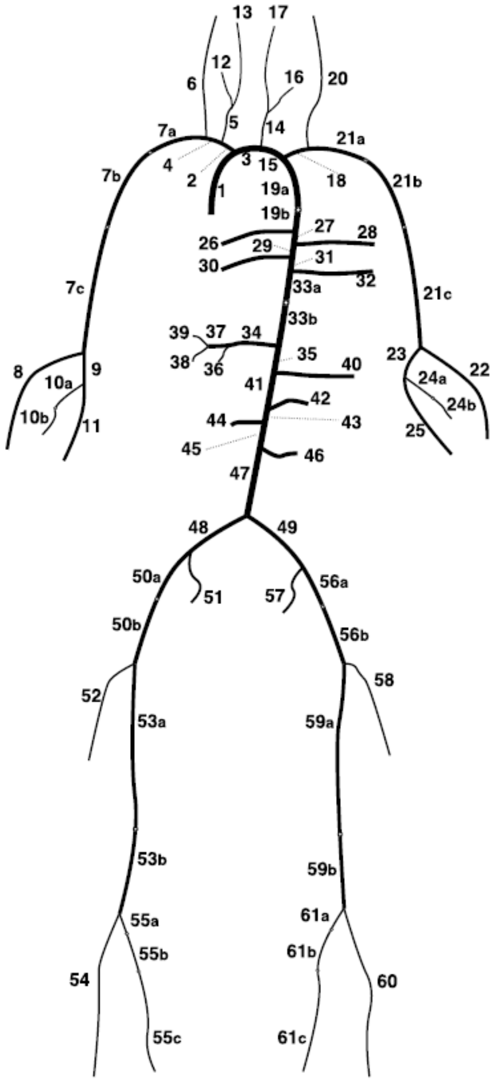
the friction term *f(U)* is defined in the assumption of a Poiseuille parabolic velocity profile.

$$f(U) = -8\mu\pi U$$

μ – the dynamic blood viscosity

Methodology

Model implementation



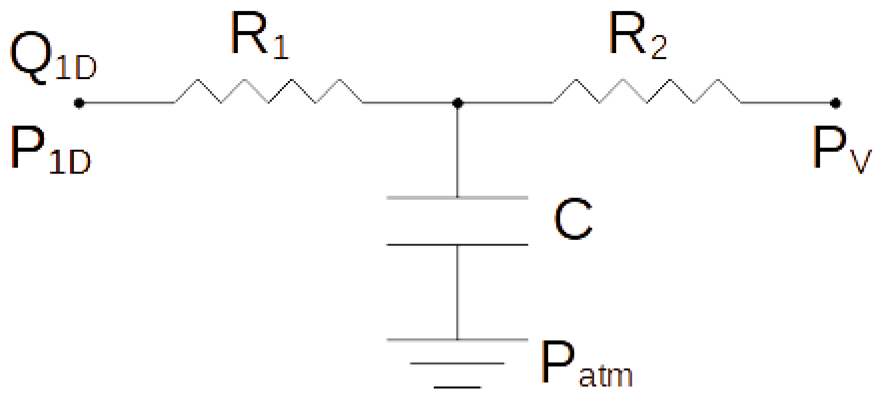
Parameters of the model

Property	Value
Blood density, ρ, kg·m^{-3}	1040
Blood viscosity, μ, mPa·s	4.0
Young’s modulus, E, kPa	225.0
Acceleration of gravity, g, m/s^2	0 or 9.8
Space discretization step, mm	2.5
Time discretization step, ms	0.01

Methodology

Model implementation

Q_{1D} – the outlet flux of the 1D model,
P_{1D} – the outlet pressure of the 1D model,
P_V – the venous pressure,
P_{atm} – atmospheric pressure,
R_1, R_2 – hydrodynamic resistances,
C – arterial compliance.



$$R = R_1 + R_2$$

R is total terminal resistance of one outlet, R_2 is adjustable.

We initially take R_1, R_2, C of the model from the benchmark paper [Boileau et al., 2015].

Methodology

Model implementation

$$R' = R \cdot \frac{(\Delta P_0 - P_{term\ av}) + \Delta P_g}{(\Delta P_0 - P_{term\ av})}$$

R' – the total terminal resistance of one outlet after the change of gravity,
ΔP_0 – the pressure drop between the heart and the veins in case with no gravity,
ΔP_g – the pressure of the liquid column, appearing when there is gravity,
$P_{term\ av}$ – the average for the cardiac cycle pressure in the terminal artery.

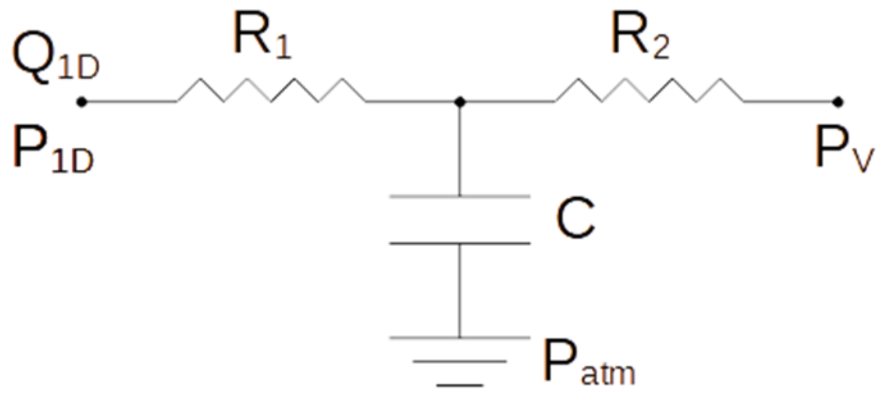
$$\Delta P_0 = \frac{\int_0^T P_h Q_h dt}{\int_0^T Q_h dt}$$

P_h – the pressure in the heart,
Q_h – the flux in the heart,
T – the time period (cardiac cycle).

$$\Delta P_g = \mathbf{r} \cdot \mathbf{g} \cdot \rho$$

So, recalculated R_2:

$$R_2' = R' - R_1$$



Calculation results

For the study we have chosen 3 model configurations:

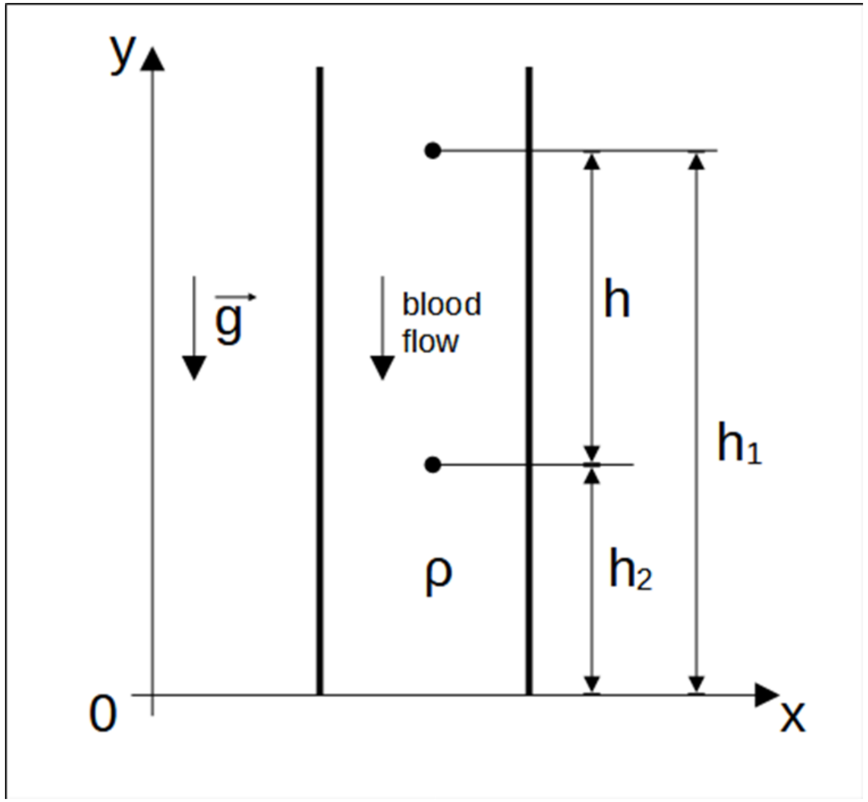
- No gravity, no BC parameters optimization – model configuration 1
- Gravity, no BC parameters optimization – model configuration 2
- Gravity, BC parameters optimization – model configuration 3

For the verification of our implementation of gravity influence on blood flow we checked two things. First, the pressure in legs is greater in case of gravity directed vertically to the legs than one in case of zero gravity. Second, with gravity there is an additional ρgh term:

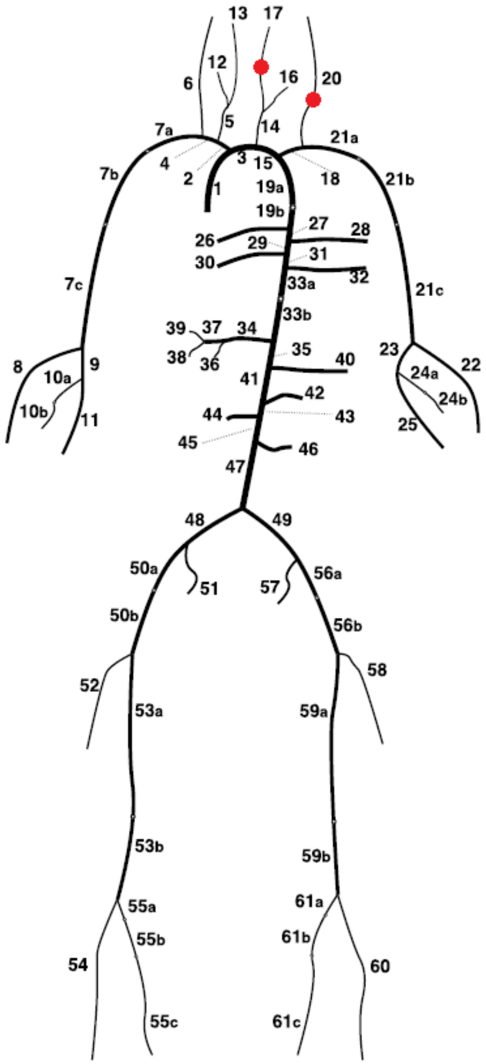
$$(P'_2 - P'_1) - (P_2 - P_1) = \rho g h$$

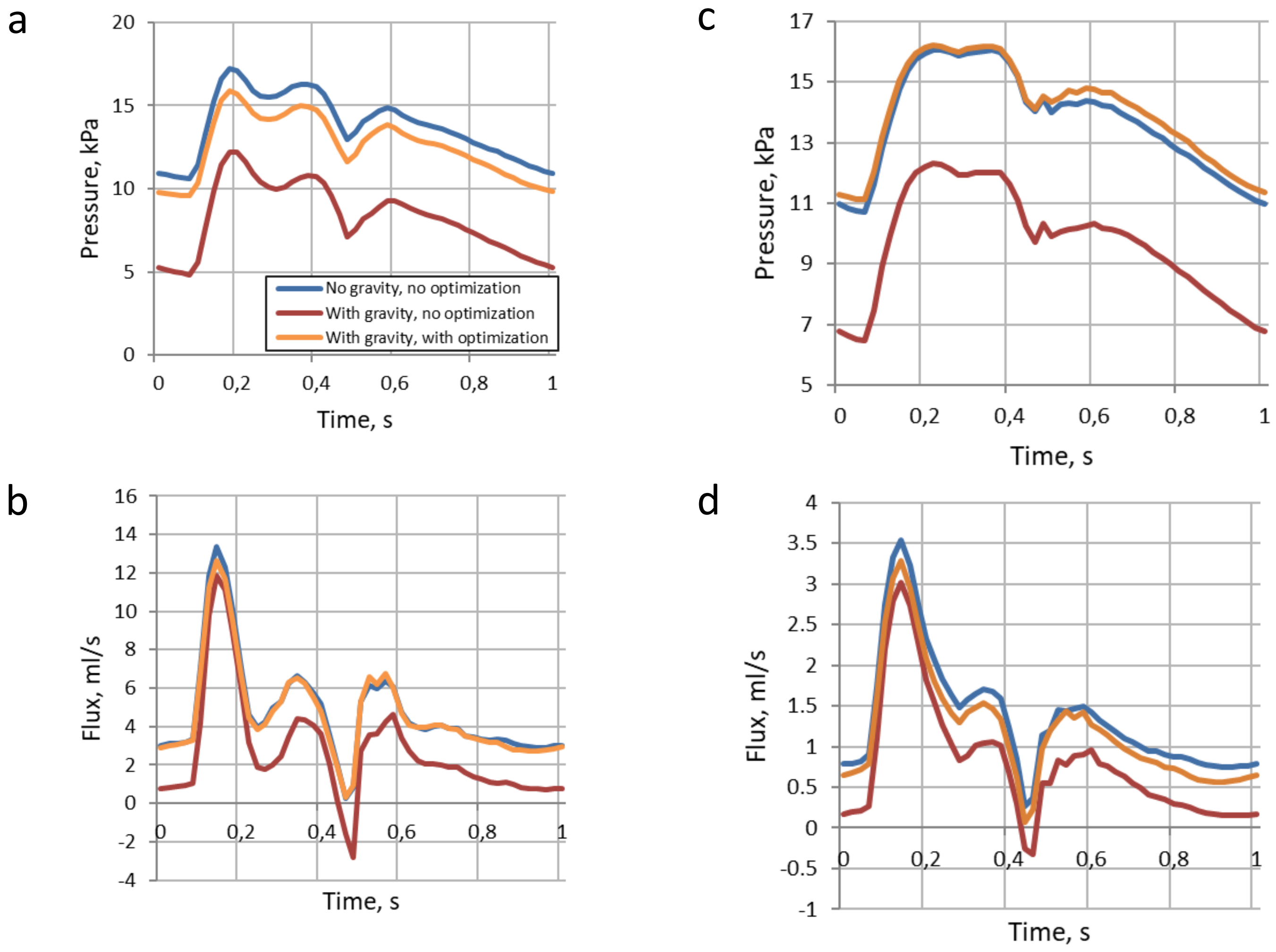
where

P_1 is the pressure in the aorta without gravity,
P_2 is the pressure in the leg without gravity,
P'_1 is the pressure in the aorta with gravity vertically directed to the legs,
P'_2 is the pressure in the leg with gravity vertically directed to the legs,
h is the height of liquid column.



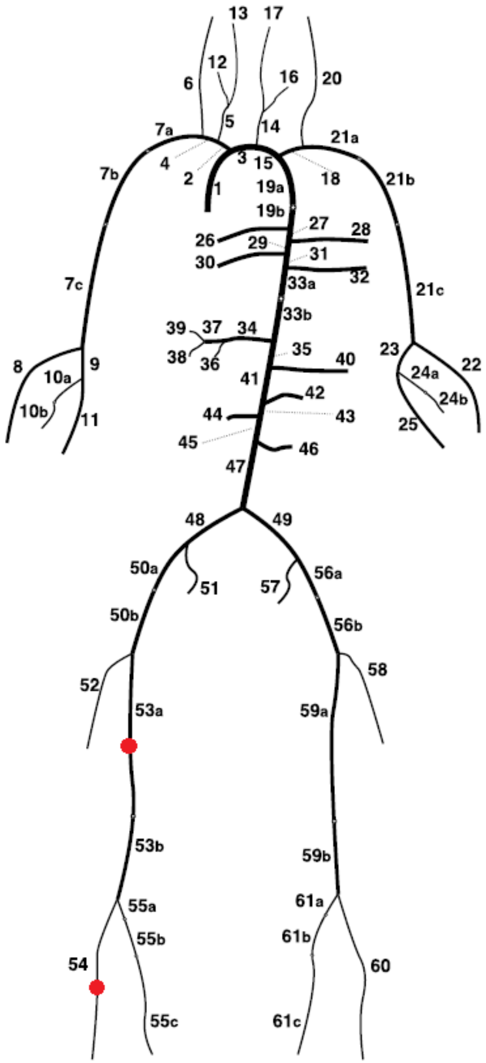
Calculation results

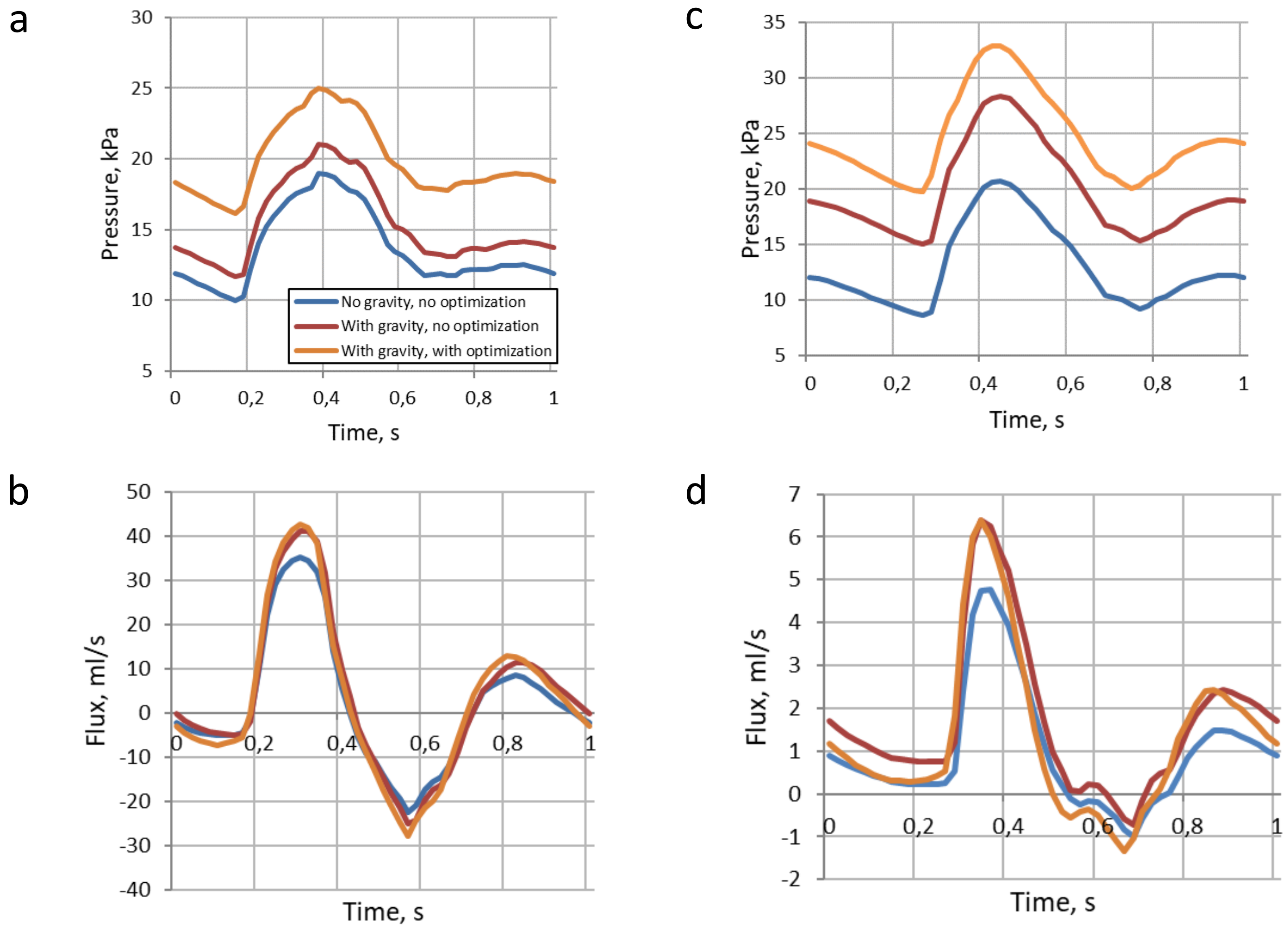




(a) pressure waveforms in the point of the left internal carotid artery; (b) flux waveforms in the point of the left internal carotid artery; (c) pressure waveforms in the point of the left vertebral artery; (d) flux waveforms in the point of the left vertebral artery.

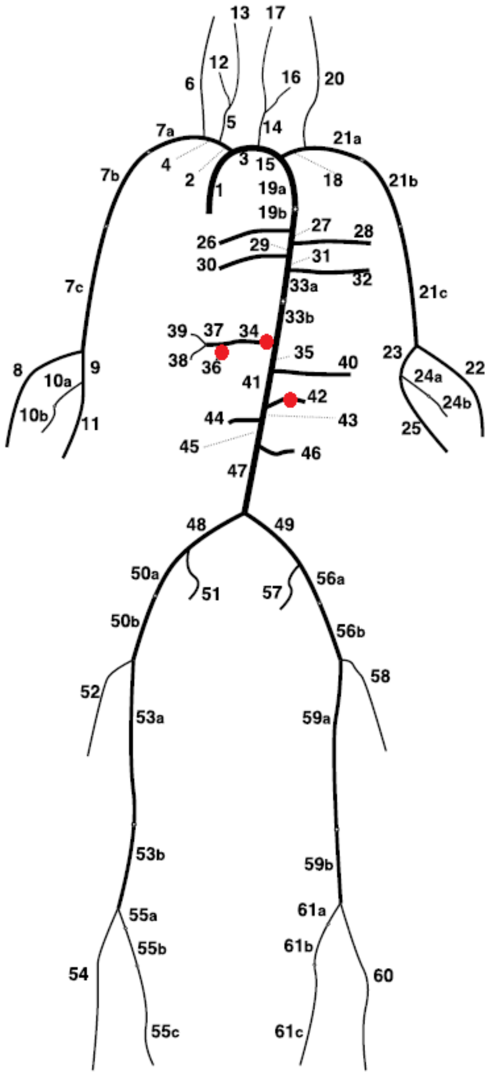
Calculation results

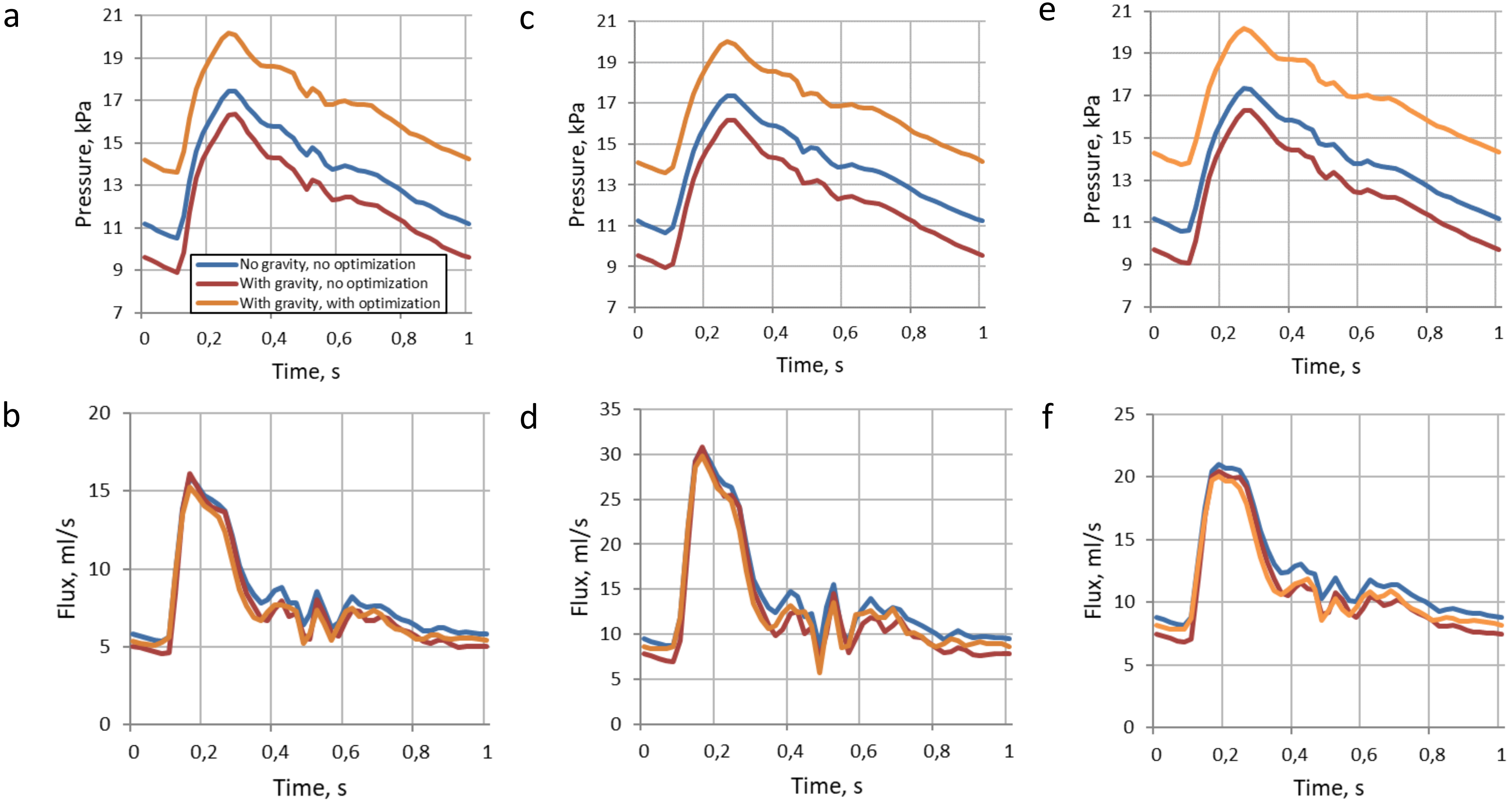




(a) pressure waveforms in the point of the right femoral artery; (b) flux waveforms in the point of the right femoral artery; (c) pressure waveforms in the point of the right anterior tibial artery; (d) flux waveforms in the point of the right anterior tibial artery.

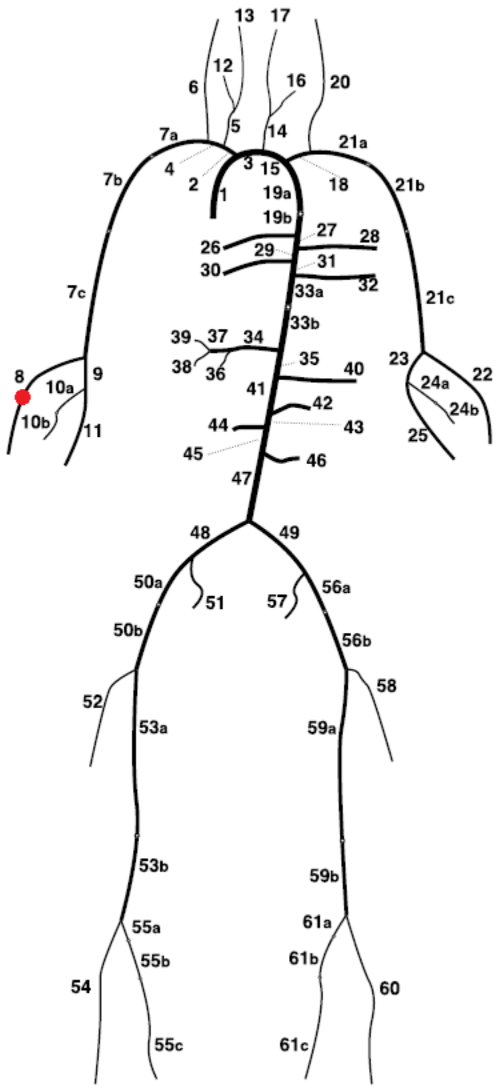
Calculation results

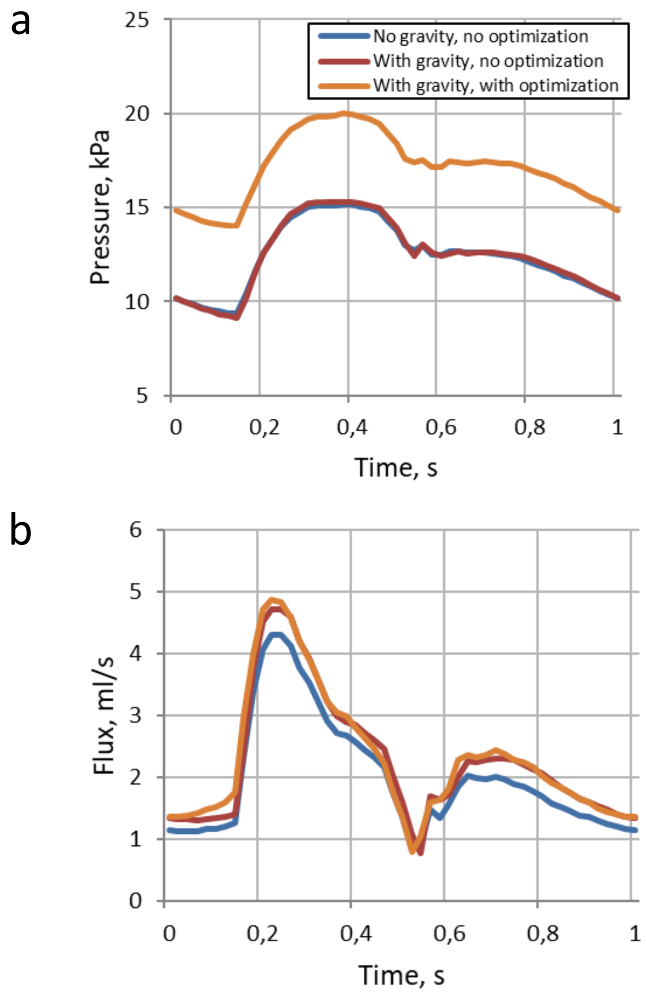




(a) pressure waveforms in the point of the common hepatic artery; (b) flux waveforms in the point of the common hepatic artery; (c) pressure waveforms in the point of the celiac trunk artery; (d) flux waveforms in the point of the celiac trunk artery; (e) pressure waveforms in the point of the left renal artery; (f) flux waveforms in the point of the left renal artery.

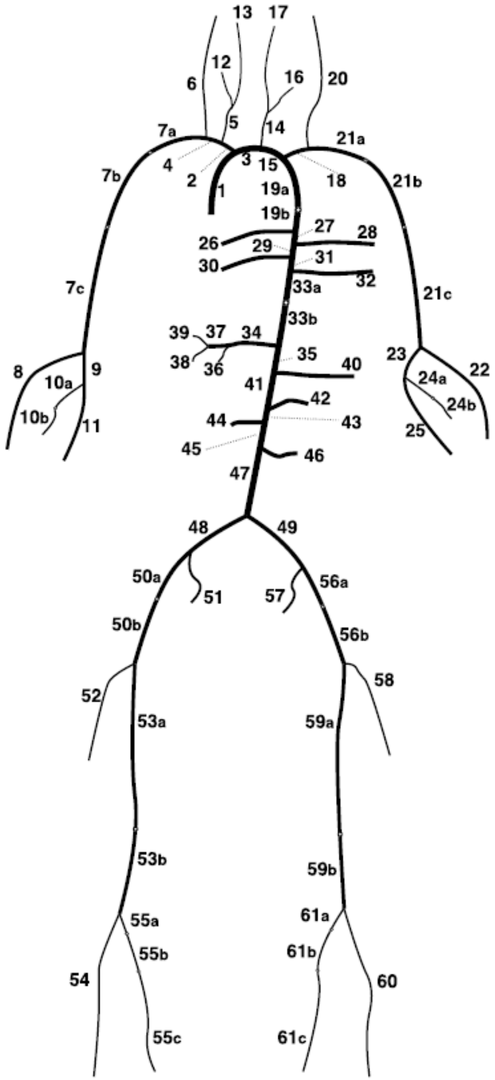
Calculation results





(a) pressure waveforms in the point of the right radial artery; (b) flux waveforms in the point of the right radial artery.

Discussion



We validated our method using data for normal blood perfusion of a brain.

Cerebral blood flow of 50 *ml/100 g/min* is a threshold for normal functioning of the brain. Average mass of the brain is 1310 *g*, and our simulations was made for an average healthy body. So, in our case the average cerebral blood flow should be equal or higher than 10.9 ml/s. For the second configuration cerebral blood flow is equal to 6.9 ml/s and for the third configuration cerebral blood flow is equal to 11.6 ml/s.

Conclusions

- We introduced the gravity influence in the blood flow model.
- We presented the methodology for simulating the reaction of the body to the changing gravity.
- Our experiments showed that when preserving the same flux an organism increases the mean pressure in cases of all considered arteries.
- We validated our technique using the data for normal blood perfusion of a brain.
- We proved that to account for the effect of gravity on blood flow in the human body, in addition to introducing a summand into the governing equation, it is necessary to adjust the boundary conditions.

https://github.com/ITMO-MMRM-lab/Complex_bloodflow_model

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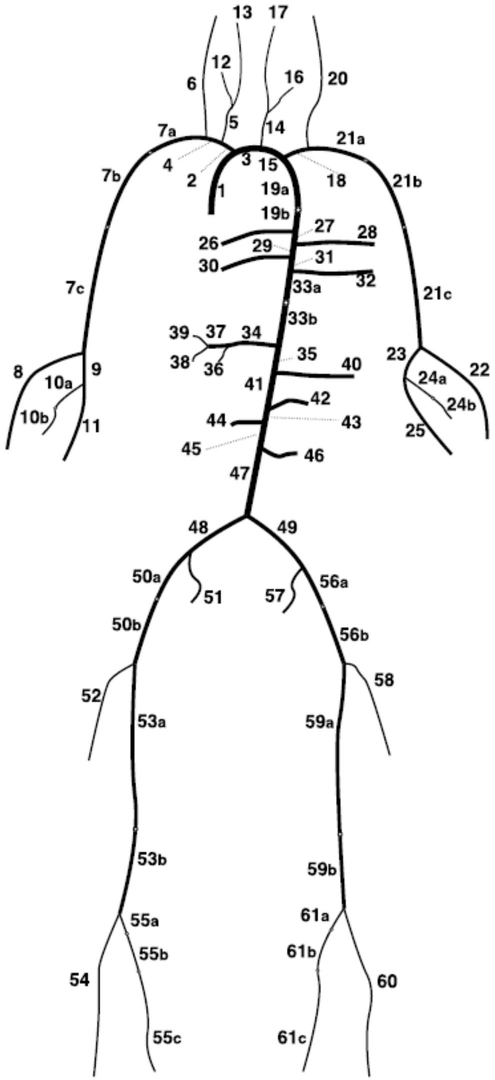
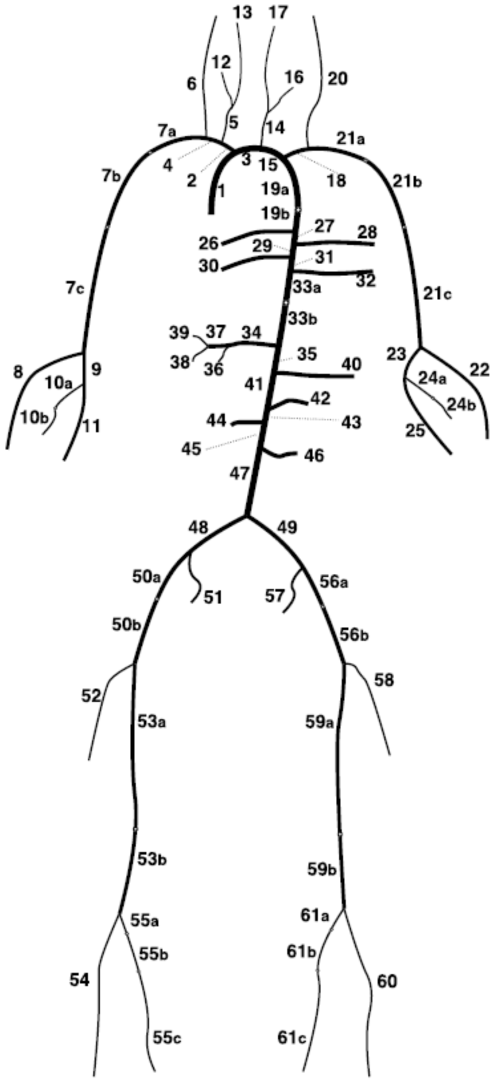
Thanks for your attention

Additional slide



- the left internal carotid artery – 17
- the left vertebral artery – 20
- the right femoral artery – 53a
- the right anterior tibial artery – 54
- the common hepatic artery – 36
- the celiac trunk artery – 34
- the left renal artery – 42
- the right radial artery – 8

Additional slide



Relation between the pressure *P* and the vessel lumen area *A* is:

$$P(A,x) = P_0 + \frac{4\sqrt{\pi}E(x)h(x)}{3A_0(x)}\left(\sqrt{A} - \sqrt{A_0(x)}\right)$$

To reduce the number of parameters in the model we use a phenomenological relationship between the reference radius of the vessel and the wall thickness:

$$h = R_0\left[\tilde{a}\exp(\tilde{b}R_0) + \tilde{c}\exp(\tilde{d}R_0)\right]$$

where *h* is the wall thickness, R_0 is the reference radius of the vessel, $\tilde{a} = 0.2802$, $\tilde{b} = -5.053\ cm^{-1}$, $\tilde{c} = 0.1324$, $\tilde{d} = -0.1114\ cm^{-1}$.