BME 5742 Biosystems Modeling and Control

Lecture 46

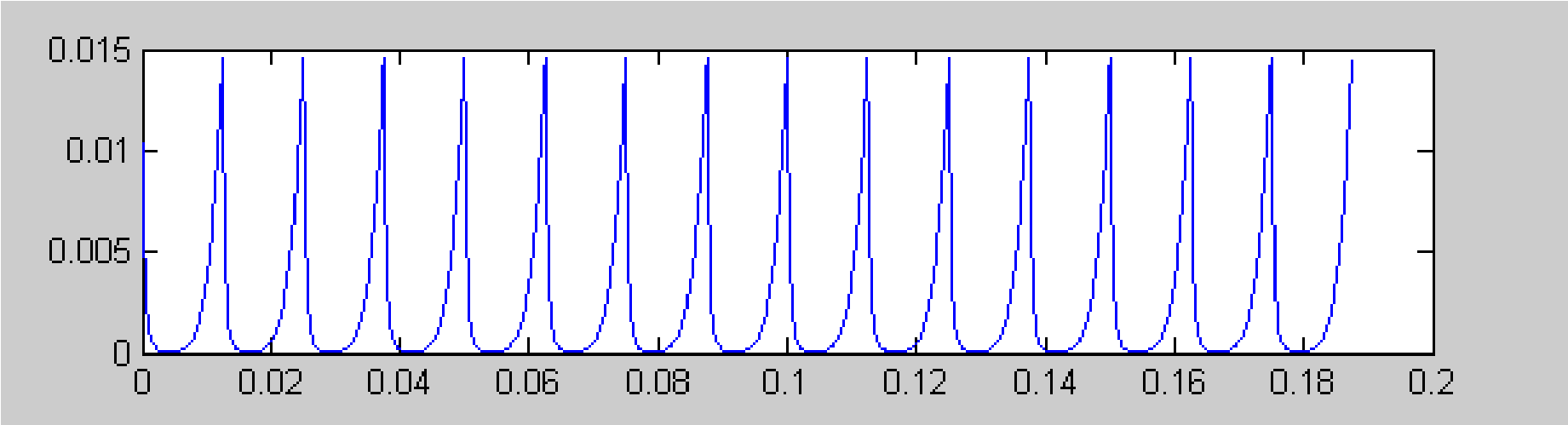
The Hoppensteadt-Peskin Heart and Blood Circulation Simulator: General Purpose Simulator of the entire Circulation system

Heart-Valve-System Simulator Structure (m files)

- PLV_Psa_new.m performs the numerical differential equations updates at each time step, assuming some fixed binary values of the valves' indicator functions.
- PLV_Psa_new.m has a sophisticated self-checking mechanism.
- File set_SMi_Sao.m set the correct valve indicators, by checking the pressure inequalities. There are 4 configurations: (0,0),(0,1),(1,0),(1,1).
- LV_sa.m is the main script. It is initialized by in_LV_sa.m.

Output Graphs of LA_sa.m

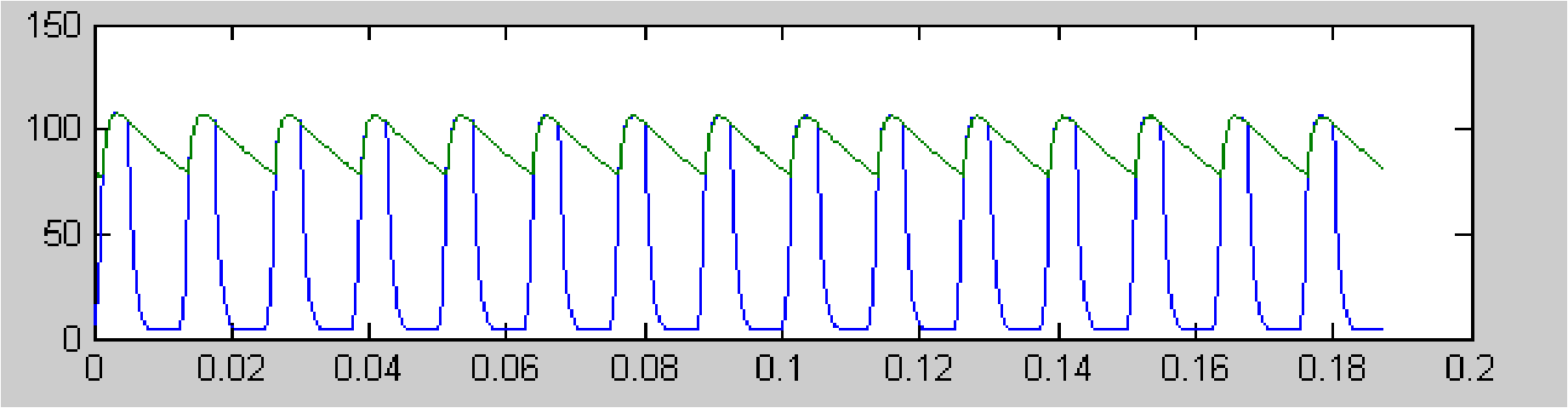
Plot of the input function $C_{LV}(t)$:



Program's first output figure contains three stacked plots. Here we separate it.

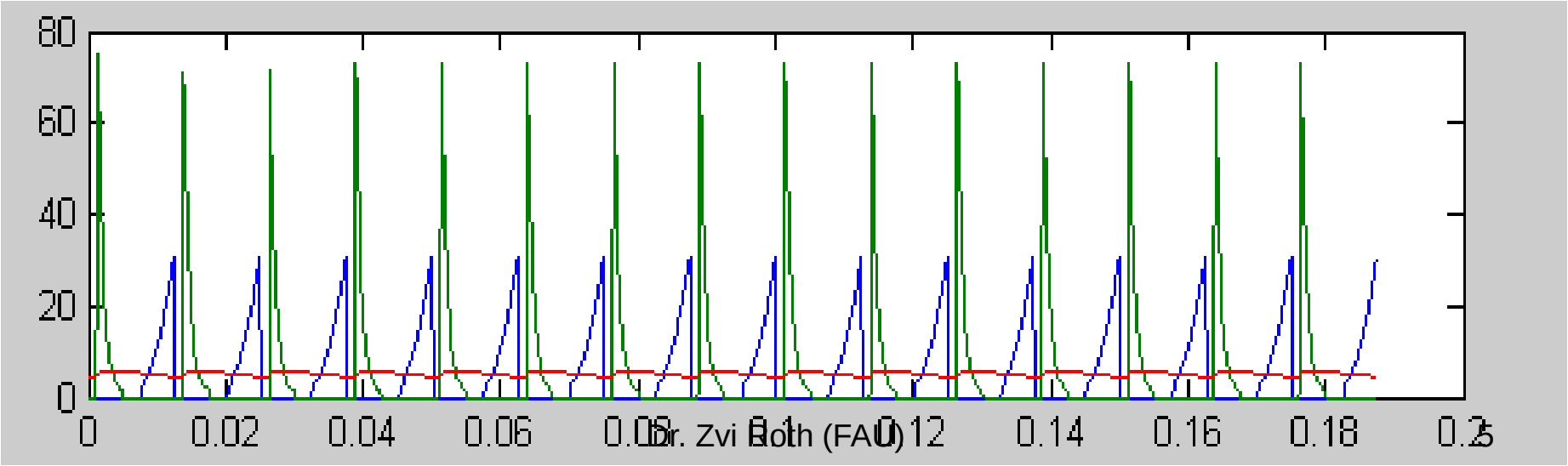
Output Graphs of LA_sa.m

Blue- P_{LV} –left ventricular pressure,
Green-Psa- systemic arterial pressure

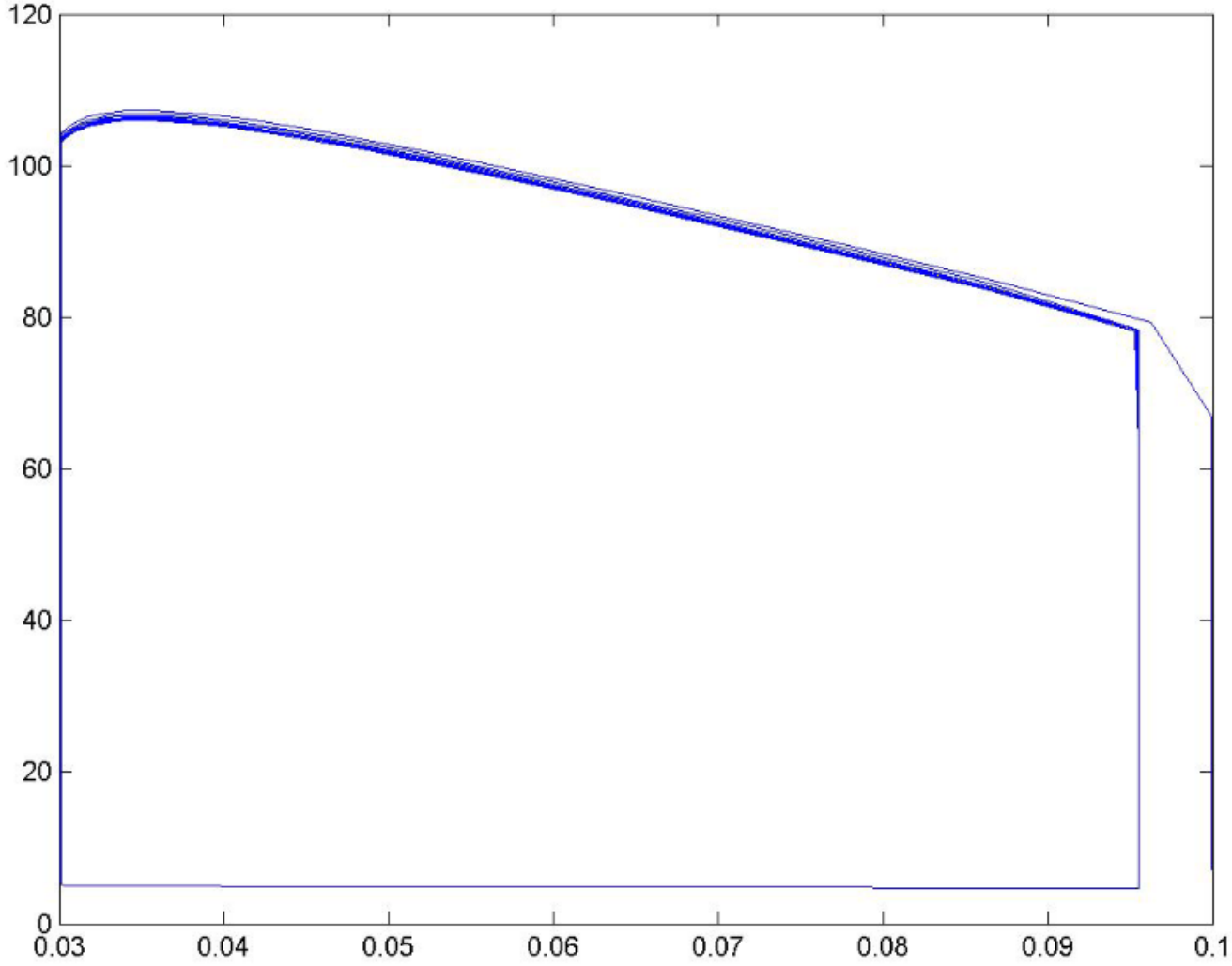


Output Graphs of LA_sa.m

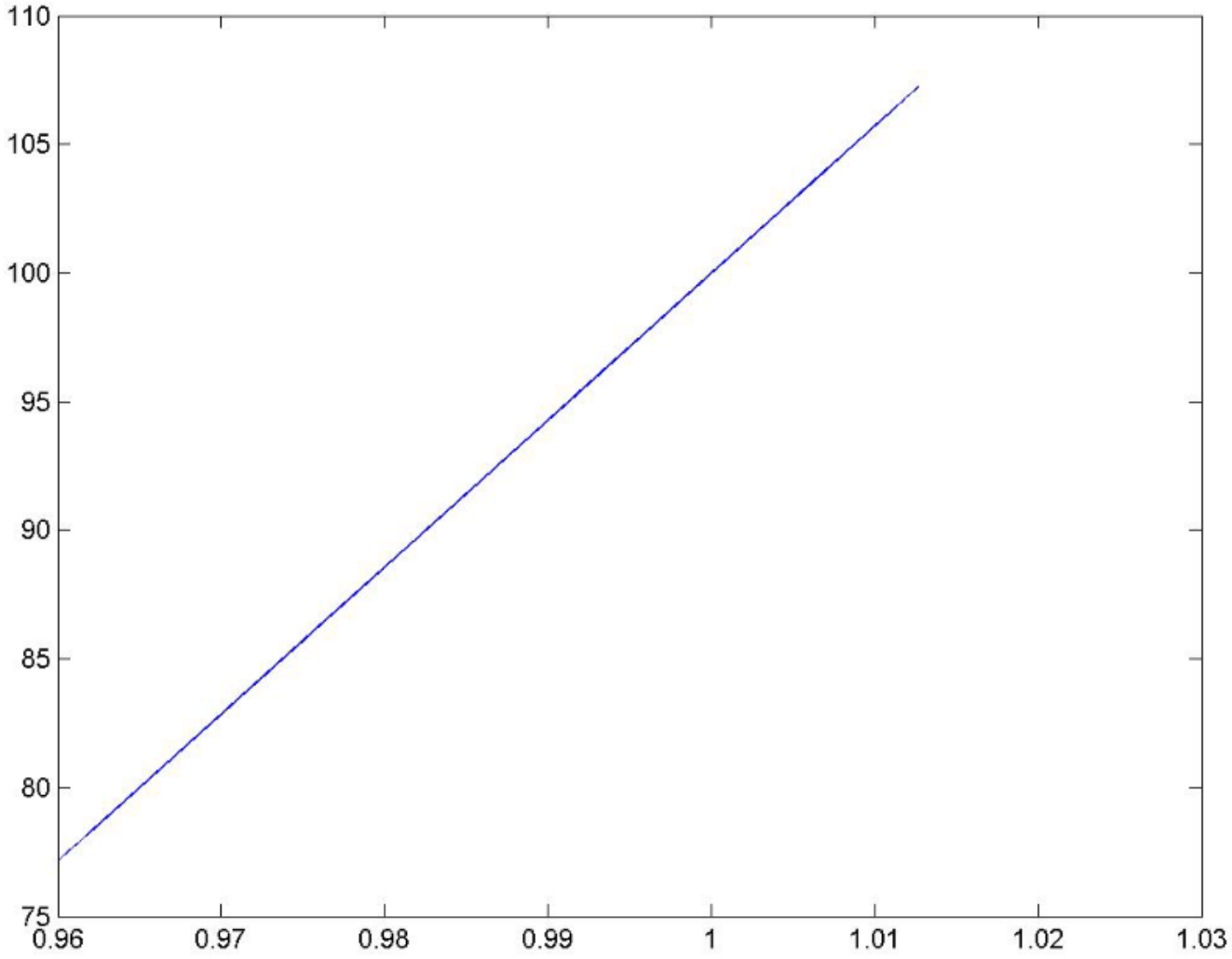
QMi- lines in blue- flow through the mitral valve
QAo- lines in green – flow through the aortic valve.
Qso- lines in red – flow through the systemic arterial tree.



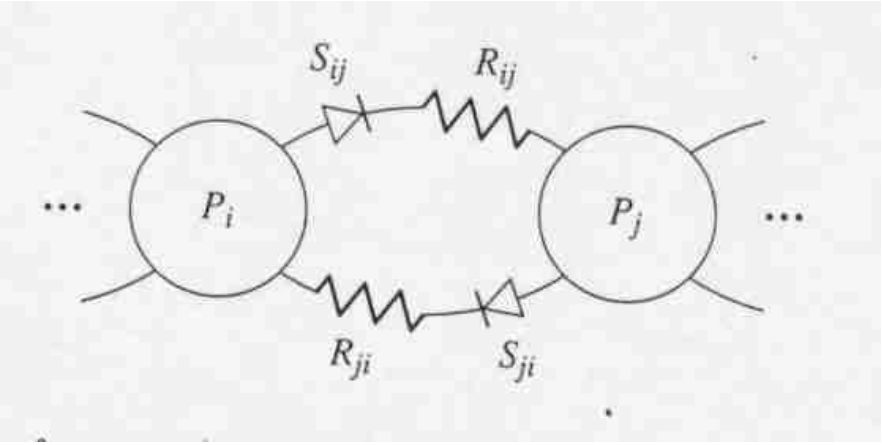
Second output figure shows the left ventricular pressure-volume loop



Third output figure: systemic arterial pressure-volume loop

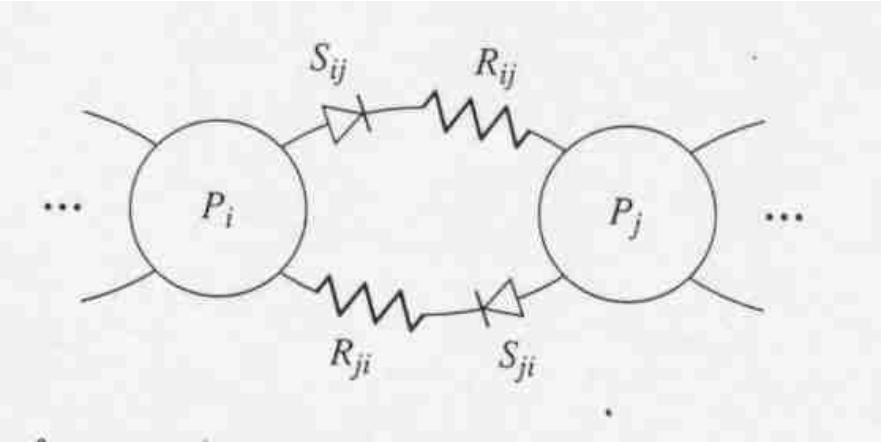


General Purpose Circulation Simulator Goal



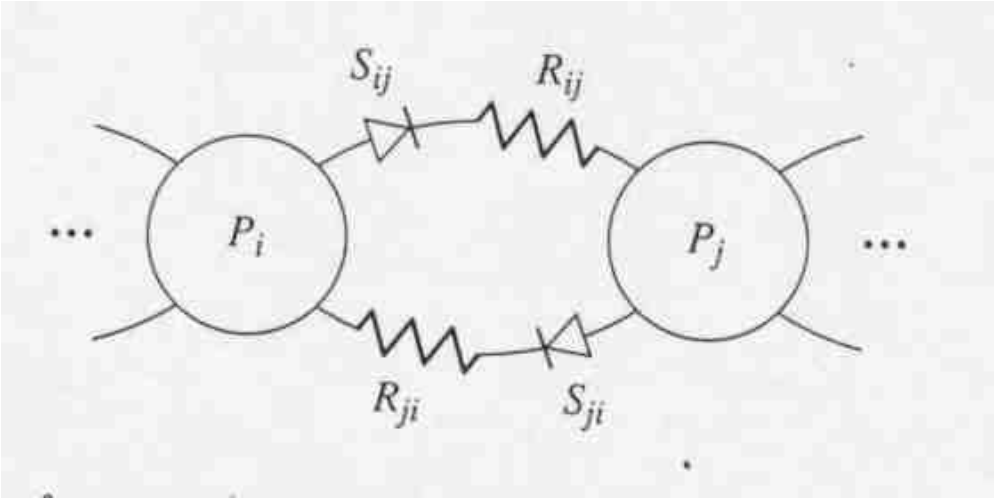
- So far the simulator served the highly simplified flow model of the heart and circulation.
- A general purpose simulator can allow the user to choose the level of detail: Studying more blood vessels, adding specific organs etc.

Examples to modifications or level of detail enhancement that can be added:



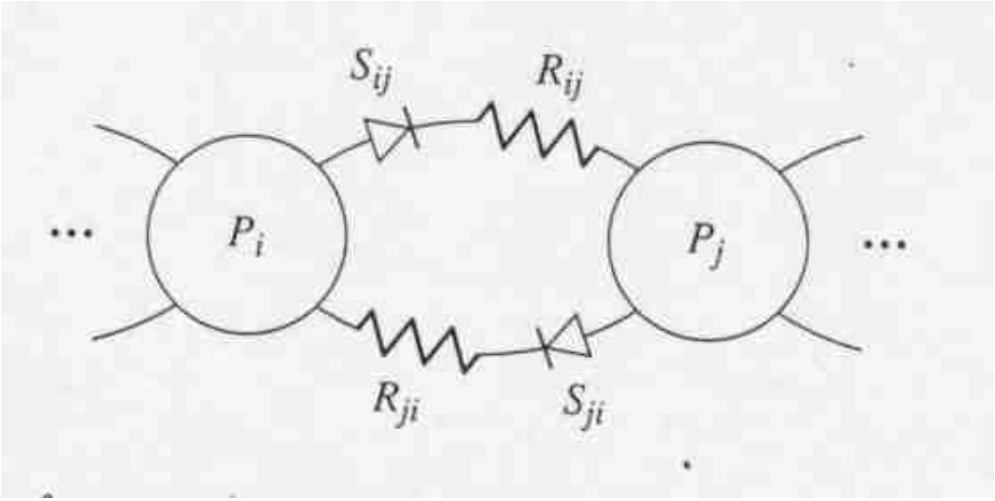
- Fetal Circulation (to be discussed later).
- Modeling a congenital heart disease.
- Atria and veins may be lumped together, or be separated.

Modular Design of the Simulator -1



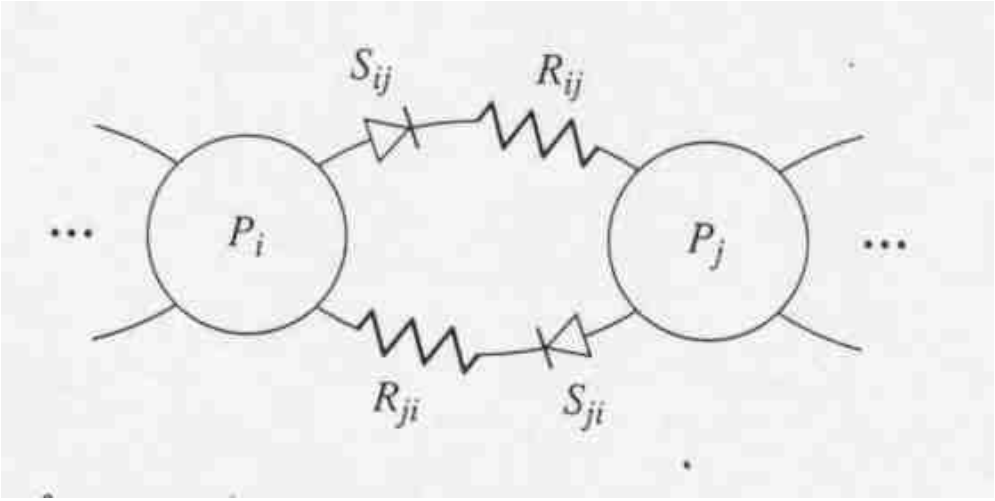
- Model contains an arbitrary collection of N Compliance Vessels, connected by Resistance Vessels equipped with valves.
- Compliance may be time-dependent, if one of such vessels is a heart chamber.

Modular Design of the Simulator -2



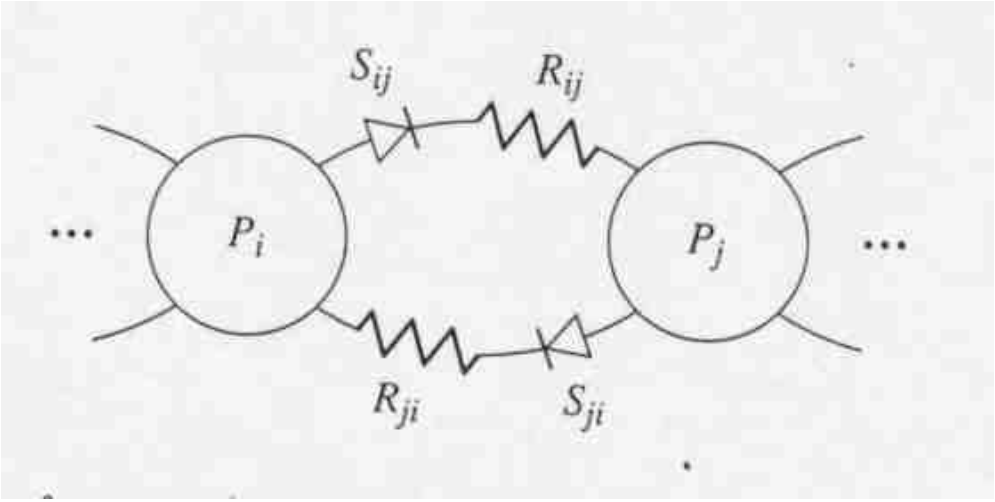
- If any of the connections (shown in the figure) are not wanted, we can make the respective resistance infinite.
- If a resistive connection, <u>without a valve</u> is needed, we make the two resistances <u>equal</u> !

Modular Design of the Simulator -3



- When the two resistances are <u>not equal</u> , the arrangement models a <u>leaky valve</u>.
- The leak becomes worse and worse, as the two resistance values come closer to each other.
- <u>No connection</u> is modeled by making both resistances infinite.

Module Equations – Conservation of Volume

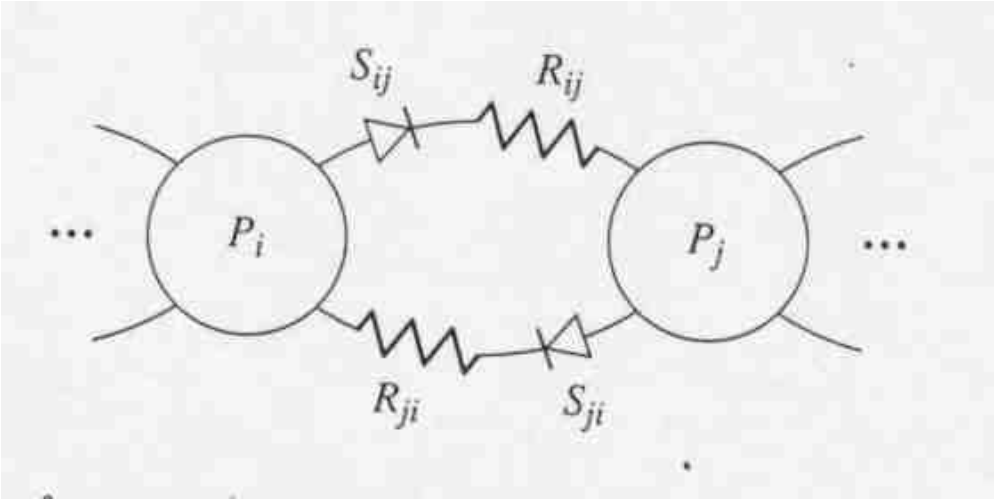


A compliance vessel may be connected to N other vessels simultaneously

$$\frac{dV_i}{dt} = \sum_{j=1}^{N} (Q_{ji} - Q_{ij}) \quad i = 1, \ldots, N$$

V_i is the volume of compliance vessel i. Q_{ij} is the flow out of chamber i into chamber j.

Module Equations – Compliance of the Vessel



C_i is constant for arteries and veins. It is time dependent for heart chambers.

$$V_i = (V_d)_i + C_i P_i \quad i = 1, \ldots, N$$

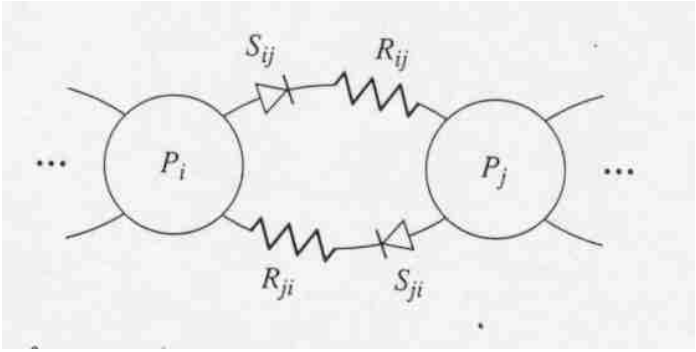
C_i is the compliance of vessel i. P_i is the pressure in vessel i. $(V_d)_I$ is the dead volume (when P_i=0)

Module Equations – Pressure-Flow relationship for each valve-equipped connecting resistance

$$Q_{ij} = \frac{S_{ij}}{R_{ij}}(P_i - P_j) _____ i, j = 1,\ldots, N$$

$$S_{ij} = 1 __ if _ P_i > P_j$$

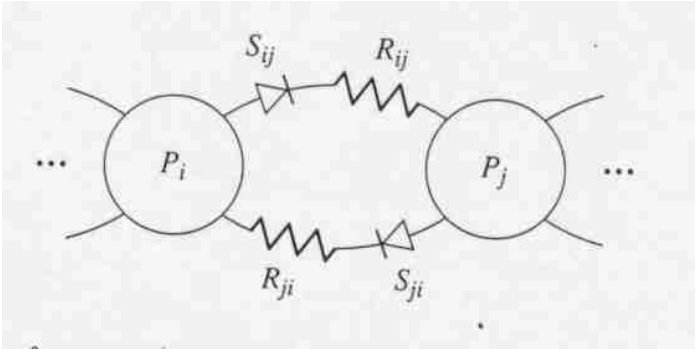
$$S_{ij} = 0 __ if _ P_i < P_j$$



Since the case of infinite resistance is quiet common, it is better to replace $1/R_{ij}$ by the conductance G_{ij}, which equals 0 whenever $R=\infty$.

Module Equations – Pressures Dynamic Model

N differential equations with N unknowns $P_1,\ldots,P_N$. Valve states are functions of the pressures.



$$\frac{d(C_i(t)P_i(t))}{dt} = \sum_{j=1}^{N}(S_{ji}G_{ji}(P_j - P_i) - S_{ij}G_{ij}(P_i - P_j))$$

$$= \sum_{j=1}^{N}(S_{ji}G_{ji} + S_{ij}G_{ij})(P_j - P_i))$$

Numerical Solution of Modules' differential equations

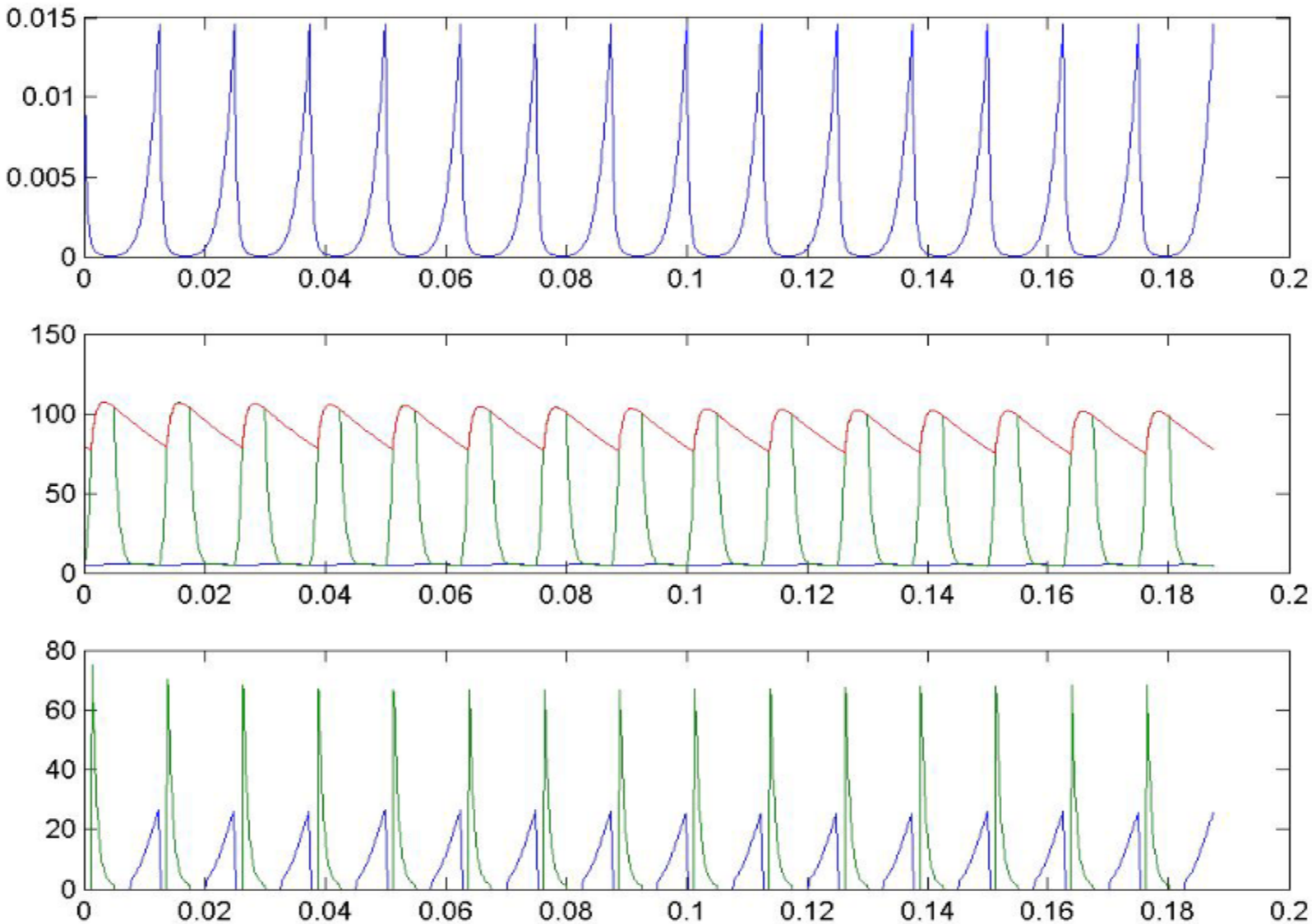
- See book (page 56) for the backwards finite difference approximation of the derivatives: N update expressions in the form of N equations with N unknowns.
- Program P_new.m uses Matlab's matrix algebra machinery to solve these equations.
- See page 57 for more discussion of the numerical details.

Circ.m

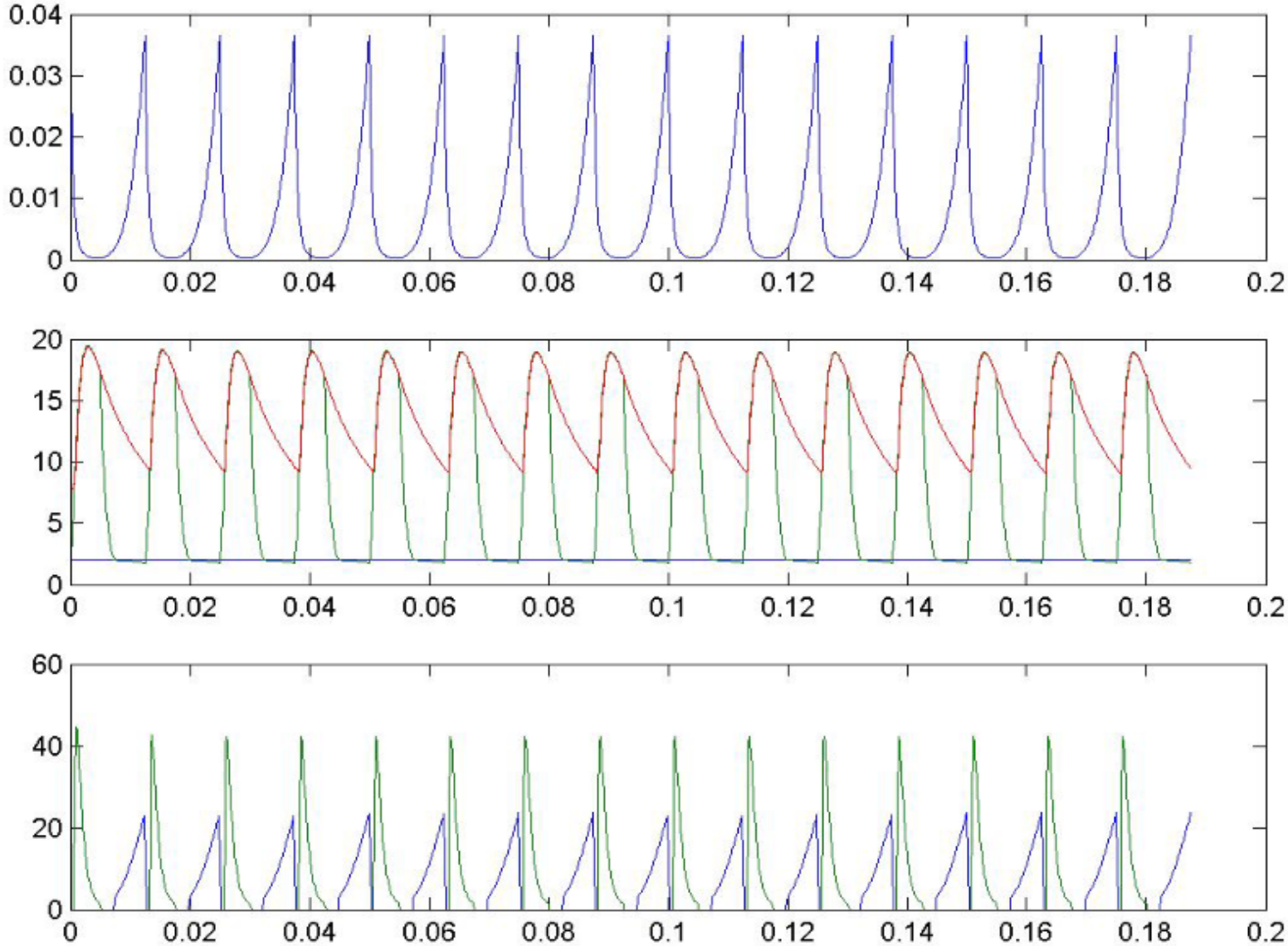
- This program circ.m is complete simulation of the circulation in heart
- The file circ_out.m is the file which plots all the graphs
- One can run one m file from another by mentioning the name in the first file, as shown below

```
%filename:  circ.m
clear all % clear all variables
clf       % and figures
global T TS tauS tauD;
global G dt CHECK N;
in_circ  %initialize
for klok=1:klokmax
  t=klok*dt;
  P_old=P;
  C_old=C;
```

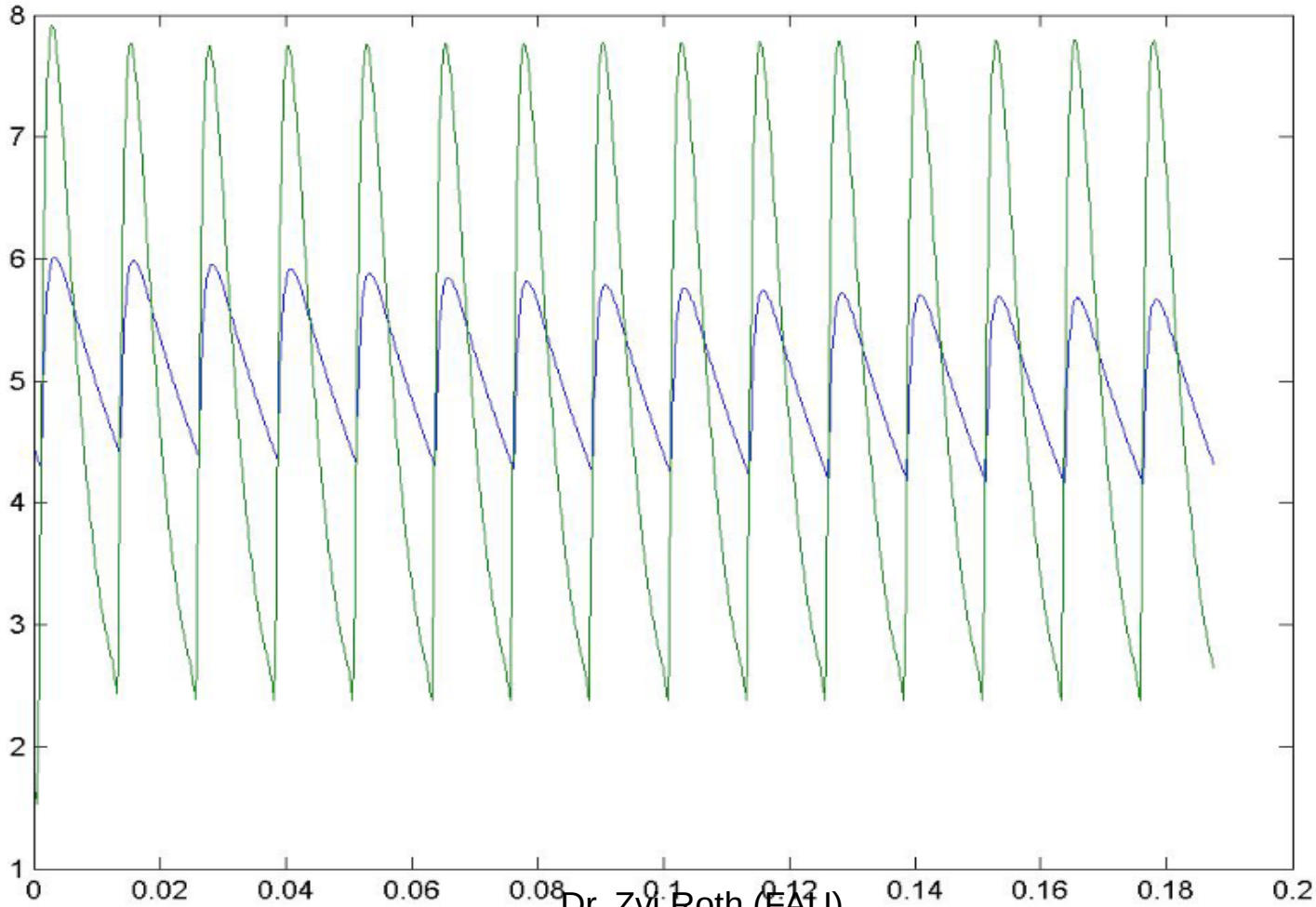
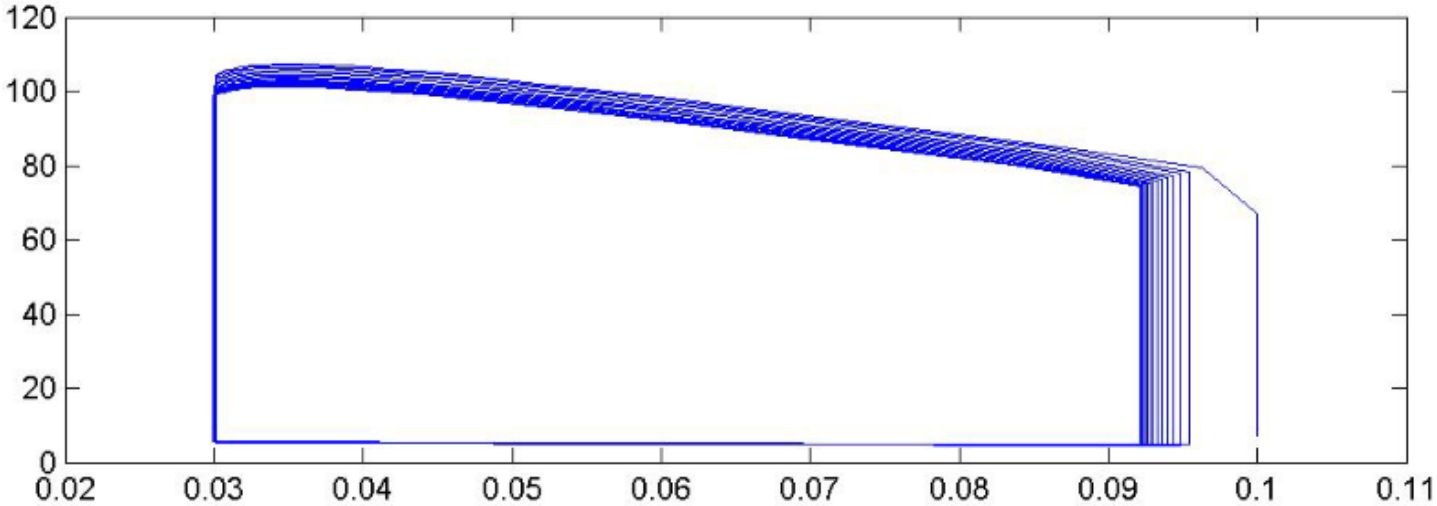
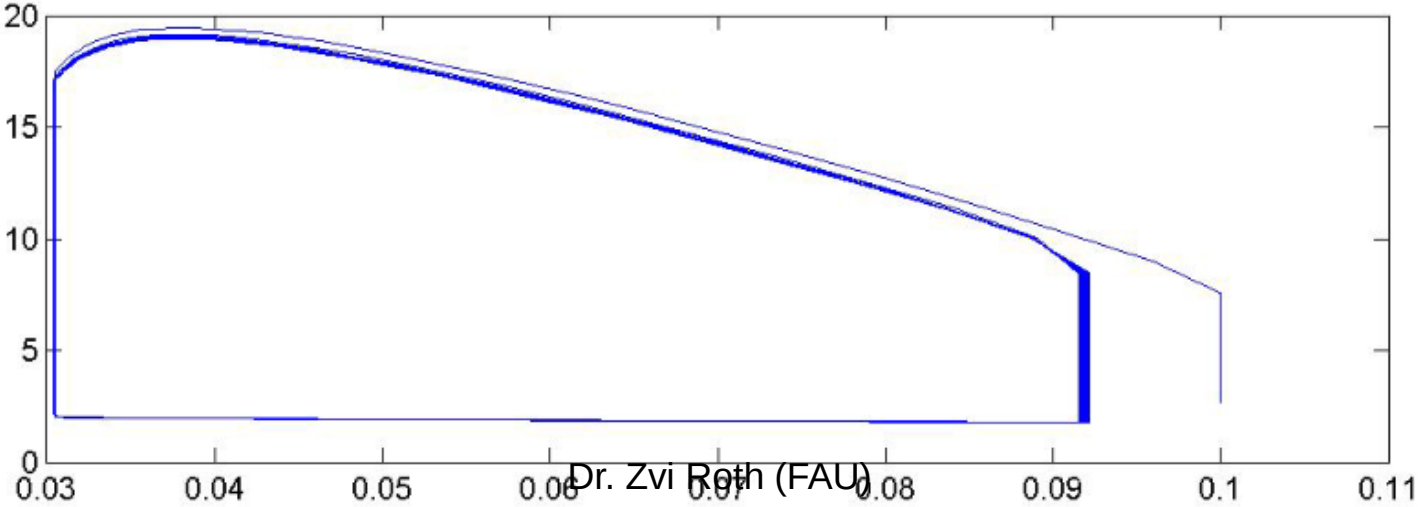
Left ventricular compliance, pressures, and flows:



Right ventricular compliance, pressures, and flows:



Systemic and pulmonary flows:



Pressure-Volume loops for both ventricles