LUMPED-PARAMETER HEMODYNAMICS OF NON-TRADITIONAL CIRCULATION SYSTEMS

M. Berk Yigit, Kerem Pekkan

Department of Mechanical Engineering, Koç University, Istanbul, Turkey

Introduction

In Nature, there are several circulation systems with different hemodynamics, functional requirements and network topology, than the normal human circulation. In this study, the lumped-parameter hemodynamics of 4 major phases of cardiac development, spanning the evolution of the cardiovascular system in fish (phase I), reptile (phase II), crocodile (phase III) and mammal (phase IV) with increasing sophistication are studied and compared. Lumped Parameter Models (LPM) have been widely used to analyze the normal and pathological human cardiovascular physiology [Ursino,2000] as well as assisted circulation in adults and infants [Pekkan, 2005] but not common in integrative biology.

Methods

We simulated an electric circuit analog of the cardiovascular system using a lumped parameter model (LPM) previously developed by our group [Pekkan, 2005]. This model is similar to the formulation described by Peskin and Tu [Peskin, 1986]. In this model, arteries, veins, and ventricles are treated as pure time-dependent compliance chambers with lumped capillary and valve resistances. We modelled the transition between phases by prescribing time-varying resistance functions for cardiac shunts.

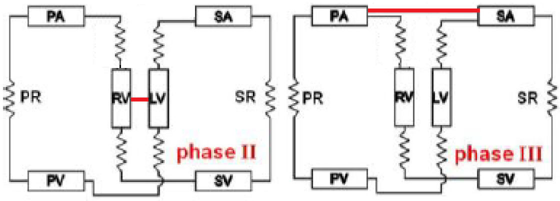

Figure 1: Phase 2 and Phase 3 circuits. (LV, RV: LeftRight Ventricles; SA, SV, SR: Systemic Arteries, Veins and Resistance; PA, PV, PR: Pulmonary Arteries, Veins and Resistance). Red lines are shunts which characterize each circulation.

Scaling with allometric relations, have been used in several studies [Pennati, 2001]. We non-dimensionalized the governing equations in order to compare hemodynamic performance indices. One non-dimensional parameter is the circulatory energy dissipation index, $CEDI = \left(\frac{E_V}{(\rho Q^3/BSA^2)}\right)$, which is the ratio of ventricle energy expenditure per unit time (E_V) to overcome frictional losses to a scale of total inertial power [Dasi, 2008].

Results

Overall pressure levels are lower in fish and reptile circulations. Pressure increases following the closure of intraventricular shunt. In case of reptile and crocodile circulations, low pulmonary resistance leads to a L→R shunting of the flow, which causes the imbalance between pulmonary (Q_{pul}) and systemic (Q_{sys}) flow rates with Q_{pul} being higher than Q_{sys}. CEDI is the lowest in Phase IV of evolution.

	Phase1	Phase2	Phase3	Phase4
P_{sys}-S	23.4	22.4	62.1	100.3
P_{sys}-D	17.6	16.6	34.1	74
P_{pul}-S	2.3	22.3	61.8	18.8
P_{pul}-D	2.3	8.4	34.1	9
Q_{sys}	1.0	1.0	2.7	4.9
Q_{pul}	1.0	7.1	17.8	4.9
E_V	0.35	2.1	13.3	8.1
CEDI	0.31	2.12	0.65	0.07

Table 1: Pressure and flow build-up due to network topology changes. (S: systole, D: diastole, P_{sys}, P_{pul}:systemic and pulmonary pressure (mmHg), Q_{sys}: mean systemic flow (L/min), E_V (mmHg.L/s), ρ and BSA are taken as unity, Q_{sys} is used for CEDI)

Discussion

Present study provided quantitative evidence on how mammalian circulation is evolved to yield high-pressure levels and the mechanism for achieving high cardiac output while still optimizing the energy efficiency. Surgically reconstructed univentricular circulation of congenital heart patients resemble the Phase I topology that is studied here which supported the requirement for venous compliance remodelling to regain high pressure levels and cardiac output. [Kelley, 1995].

References

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