Numerical Analyses And Researches Of The Human Greater Circulatory System

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Abstract.

The paper presents examinations of human's greater part of the circulatory system, modeled as an electric net. The similarities between human's greater circulation and the electric model have been evolved. The analysis of the greater circulation was performed in PSPICE – an environment of electric circuits modeling. The designed model allows to analyze human's greater circulation in physiological and pathological cases.

1. INTRODUCTION

The heart muscle is an extraordinary organ in the human body. Its function is blood pumping in the whole circulatory system to deliver oxygen and nutritive agents to all cells. Another important blood function is the transport of carbon dioxide and metabolism products. Significant aspects of analyzing the greater circulation comprise the possibility of simulating the operation of the circulatory system under various conditions: both, physiological and pathological ones [1-6].

In this paper the electric equivalent circuit of the grater circulation has been presented. Moreover, similarities between selected parts of the vascular system and their electric model have been derived. The electric equivalent circuit allows to simulate the biological vascular system in cases of its physiological and pathological status.

2. MATERIAL AND METHODS: SIMULATION OF HUMAN'S CIRCULATORY SYSTEM

In order to model the greater human circulation by means of an electric equivalent circuit it is indispensable to assign corresponding electric quantities to the physical parameters of the vascular system, its hydrodynamic impedance, the pressure and flow of blood. These assignments were performed on the basis of investigations presented in [3]. The final equivalences have been depicted in Table 1.

In the circulatory system the heart muscle operates as a positive-displacement pump. During the left ventricle systolic phase the blood is ejected to the aorta (stroke volume – SV) and the flow of blood (Q) is forced [4]. The time shape of volumetric blood flow just behind the aortic valve has been presented in Fig. 1. The response of the vascular system to this excitation is a higher circulation pressure (P). The shape of aortic pressure has been presented in Fig. 1, too. In the equivalent electric analogy of the circulatory system the heart function was modeled by the current source (I_s). Thanks to this the electric current time shape is the same as the blood flow Q behind the aortic valve (Fig. 1 and Fig. 3). The response of the electric equivalent circuit of human's greater circulation are voltage drops (U_{res}) (on respective components of the equivalent circuit), which represent the adequate blood pressures (Fig. 3).

Table 1 : Similarities between the physical parameters of the human vascular system and their equivalent electric parameters

| Hydrodynamic quantities – human circulatory system			Scale ratio	Electric quantities – substitute model of circulatory system		
Name	Symbol	Unit		Name	Symbol	Unit
Pressure	P	1Pa	wsp$_P$ =100	Voltage	U	1V
Blood flow	Q	1 m³/s	wsp$_Q$ =1	Current	I	1kA
Resistance	R_b	1MPa*s/ m³	wsp$_R$ =46,8	Resistance	R	1☐
Compliance	C_b	1cm³/ kPa	wsp$_C$ =15	Capacitance	C	1☐ F
Inertance	L_b	1kg/m⁴	wsp$_L$ =10^{-5}	Inductance	L	1mH
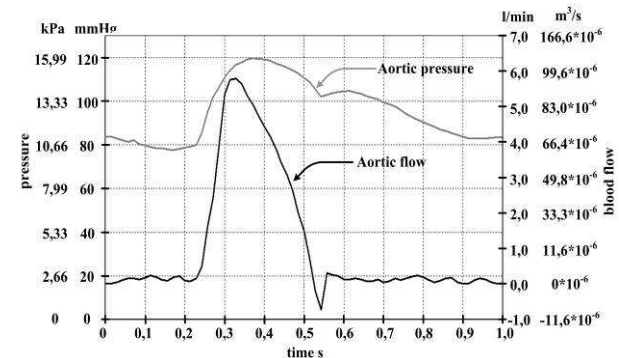
Figure 1 : The shapes of aortic blood pressure and flow vs. time in human's great circulation at a frequency f=1[Hz] (60 BPM) [2]

The idea of the equivalent electric circuit is to model precisely and accurately model the

hydrodynamic impedance of the human vascular system (seeing by the left ventricle which pumps blood to the ascending aorta), represented by the electric impedance of the equivalent circuit seeing through the terminals of the current source. This electric net consists of resistors (R), capacitors (C) and inductors (L), maintaining the character of significant human vessels and anatomical topology. The structure of the human aorta with principal systemic ramifications and its electric model have been illustrated in Fig. 2 [2,6,7]. In the electric model the aorta is divided into five elementary components (Fig. 2, dashed line), and several of these segments are split into smaller parts. The hydrodynamic impedance of any segment is represented by the elements R, L, C [8,10,11]. Additionally, to the respective aortic segments the elements R, C are attached, in order to simulate ramificationes of the greater circulatory system. The values of resistance, capacitance and inductance of the equivalent components of the circuit correspond to the values of physical properties of the circulatory system. The capacitances and resistances of aortic segments and whole vascular system have been derived from [3,8]. The parameters R_i, L_i, C_i of the substitute electric circuit are based on the assumption that blood is a Newtonian liquid and its flow through the respective segments of aorta is laminar (for details cf. [3,12]). In the presented elaboration of equivalent circuit (Fig. 2) one has been used information presented in [8,9].
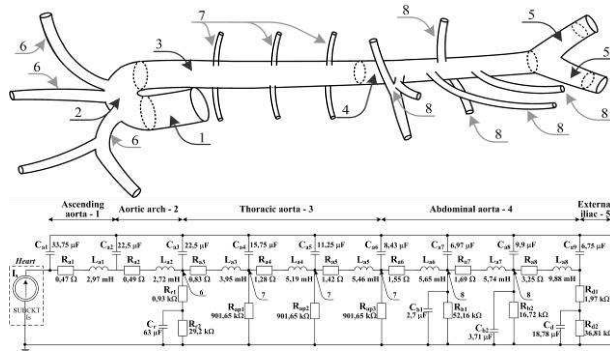

Figure 2 : Human aorta (top) and electric equivalent circuit (bottom). Own elaboration [3] based on [8]

3. RESULTS

First, the time shape of the current and voltage signals in the electric substitute model of the greater circulation were computed. The parameters of the model correspond to the human physiology. The electric model was stimulated by forcing the current signal I_s, which has the same pattern as the blood flow signal in the aorta Q, behind the aortic valve (Fig. 2). The response of the electric model was the voltage signal U_{res}. As a reference, the U_{ref} voltage signal was utilized, which had the same pattern as blood pressure in the human aorta [2] (Fig. 3).
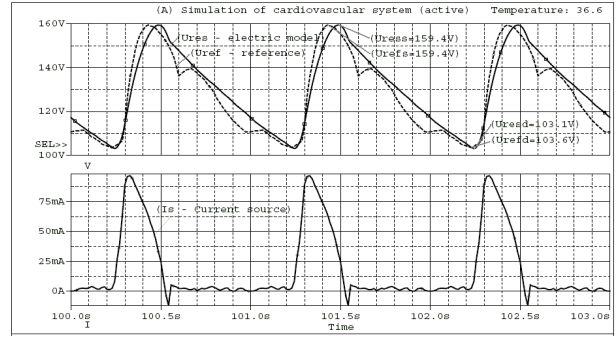

Figure 3 : Signals in the course of time: (top): U_{res} – voltage response of the greater circulation equivalent model U_{ref} – voltage corresponding to the pressure pattern in the aorta (bottom):I_s – stimulation current vs. time, corresponding to the blood flow in aorta [3]

One has been performed the comparison of the hydrodynamic impedance (seeing by the left ventricle during blood pumping into the ascending aorta) to the impedance of the equivalent electric model (seeing from current source's terminals). The obtained results provide the basis for the Fourier's spectral analysis of the vascular system of the hydrodynamic impedance and the input impedance of electric model. The results have been presented in Fig. 4 – nine harmonic components of the human hydrodynamic impedance and the impedance of the electrical equivalent model were compared.

Up to the eighth harmonic component a good correlation with reference has been observed (Pearson's correlation factors are: $CF_a = 0.9919$ and $CF_p = 0.8324$, for amplitude and phase spectrum, respectively).
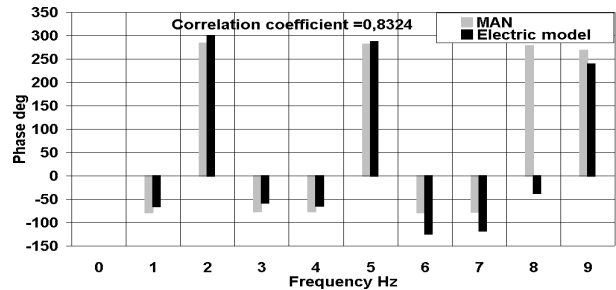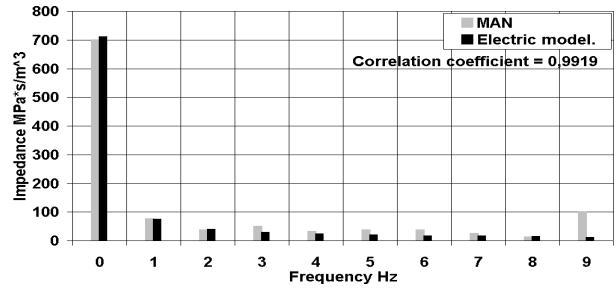

Figure 4 : Amplitude and phase spectrum of greater human circulation and electric substitute model [3]

4. CONCLUSIONS

The performed analyses revealed the similarity of human's greater circulation and the electric equivalent model. The correctness of the invented model was confirmed by a comparison to spectral hydrodynamic impedance (Fig. 4). The obtained Pearson's correlation factors for the amplitude CF_a and phase CF_p were really very high. The invented electric model of the human circulatory system was also applied to examine the pathology of the great circulation. The results of the modeling and numerical investigations will be presented in the next papers.

Acknowledgement

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