



The Analogous Human Arm Circulatory Model of Artificial Anastomosis

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The Analogous Human Arm Circulatory Model Of Artificial Anastomosis

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Abstract— The aim of this research is to design a computational model for study purposes of the pressure and flow waves in a human upper limb with dialysis vascular access. Model is based on electromechanical analogy. Human hand contains arteries and corresponding veins arches. Radiocephalic wrist arteriovenous fistulae (AVF) are a preferred choice to other types of vascular access for hemodialysis. In these models we can study the effect of arterial – venous anastomosis on blood pressure wave propagation in arterial and venous region

Keywords— analogous model, haemodynamics, electrical circuit, vessel segment, arteriovenous fistulae

I. INTRODUCTION

Models of the human cardiovascular have been the object of extensive research over the past few decades. Among all possible approaches has become quite popular application of electromechanical analogy. These models are built on analogy between hemodynamic processes in vessels and electrical circuits. Analogic principle there enables to transform physical process from one environment to another one, providing several computational benefits.

Whole circulatory system, as a complex system, becomes in detail modelling computationally expensive. Hence, detailed description is focused only on a small part of interest, separated from the rest of system. Its' relationship to the rest of the system can be well defined and described. For the investigation of haemodynamic processes in the case of artificial anastomosis was the arterial tree of human arm selected.

II. CREATION OF MODEL

A. Electro-mechanical analogy

Differential equations of hydrodynamic processes in a tube are similar to those describing transmission of electric charge in an electric line. The analogy of hydrodynamic process in a tube and transmission of electric current were demonstrated in a number of scientific works. [1, 2, 3, 4]

By deriving from equations describing haemodynamics (Navier – Stokes equation, continuity equation) applying electromechanical analogy the elements of equivalent circuit of blood vessel segment containing longitudinal and transversal

circuit elements are derived. Longitudinal impedances ZL represent conservative and dissipative components, transversal admittances YT describe cross elasticity and inter-wire capacity and cross losses. [1, 2, 4, 5] Circuit parameters of each analogous segment are calculated from the known mechanical parameters of the vessels, according to [1]. All parameters of the equivalent circuit are per-unit length.

$$R_n = \frac{8\eta}{\pi r_0^4} n \quad (1)$$

$$L_n = \frac{\rho}{\pi r_0^2} \frac{1}{2n-1} \quad (2)$$

$$C = \frac{2\pi r_0}{\kappa K_w} \quad (3)$$

$$G = \frac{2\pi r_0}{\kappa \eta_w} \quad (4)$$

r_0 - radius of the vessel, ρ - the blood density, η - dynamic viscosity, K_w - the volume stiffness of the tube wall, η_w - coefficient of internal friction (cause of deformation losses), κ - geometrical factor

Formulas for estimation of elements in longitudinal and transversal part of equivalent circuit are based on work of Gaelings [2].

Whereas cardiovascular system is complex net of the vessels model of each one is impractical and marginal parts of the system are usually lumped and the region of interest is described in more detail. The most frequently used model type of terminal segment is the 3-element Windkessel model. [6]

The total terminal load resistance, R_T is defined as:

$$R_T = \frac{\bar{p}}{\alpha \bar{q}} \quad (5)$$

where α is the percentage of cardiac output flowing through the vascular bed behind the end-segment, and \bar{p}, \bar{q} are the mean pressure and mean flow, respectively. For the estimation of capacitance of the terminal load is the impedance matching method used. [6]

B. Modelled circulatory system

The arterial tree of human arm is modelled. Two cases of the model were implemented, with and without AVF in order to show the influence of anastomosis on the blood pressure and blood flow propagation patterns.

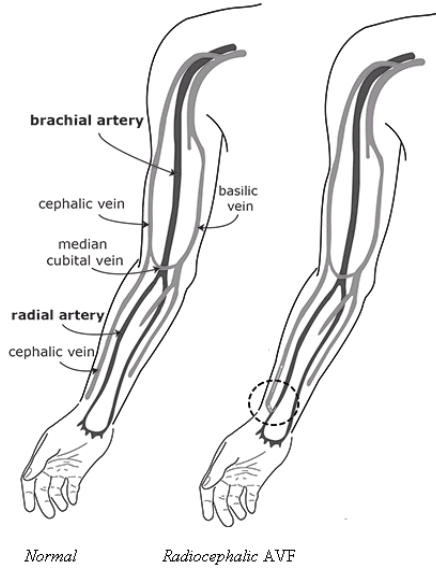


Fig. 1. Human arm arteries without and with AVF (in dashed circle)

Among other vascular accesses radiocephalic AVFs (shunts created among radial artery and cephalic vein on the wrist) are regarded as the best choice for haemodialysis patients. However, in quite large percentage of cases, shortly after the operation or even later, after maturation process, AVF fails and alternate solutions should be chosen. Selecting patients who would benefit from which type of AVFs, or if any, is a problem and there are no objective criteria. An electro-mechanic analogy model of the human arm blood vessels is developed in order to study the wave propagation in the region of radiocephalic AVF.

The input of the model is the brachial artery pressure wave adopted from [9]. In simulation model of human arm arteries the arterial tree including both palmar arches is considered. The blood pressure and flow changes in arteries caused by introduction of AVF in lower arm are computed. The segments representing cephalic vein are connected to the distal part of radial artery segments close to deep palmar arch.

III. SIMULATION RESULTS

A. Pressure and flow in time domain

Pressure and flow waves are computed at three equidistant points at radial artery and cephalic vein as well (7, 14 and 21 cm from AVF point). Parameters of blood vessels are adopted from literature. [1, 5, 6, 8]. Parameters of cephalic vein are supposed as for normal vein in both simulated cases, which corresponds with the situation shortly after operational creation of AVF.

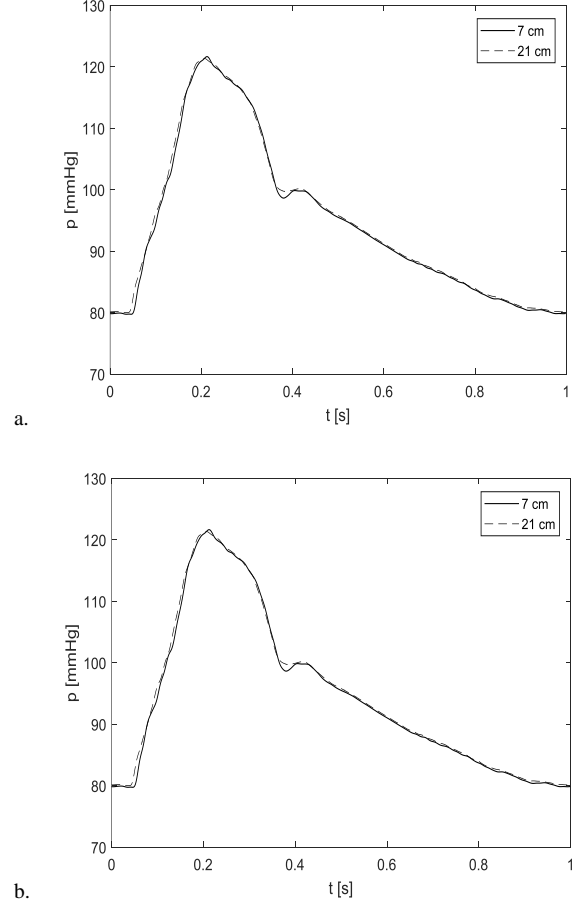


Fig. 2. Pressure wave in radial artery a. without and b. with AVF

Fig. 2 and 3 shows results of blood flow in radial artery and cephalic vein at the closest and furthest measured point on the corresponding vessel. Differences in pressure waveforms for radial artery with and without AVF are not as dramatic as for cephalic vein. Introduction of AVF creates direct connection between high pressure arterial system and low pressure venous system. It results in high increase in blood pressure and flow for the region. The influence of the increased pressure and flow is important among other forces, for the process of AVF patency establishment. The blood pressure waves in cephalic vein without and with AVF show good accordance to theoretical assumptions. [8]

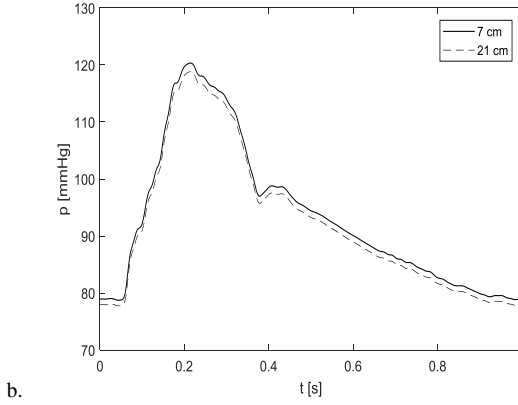
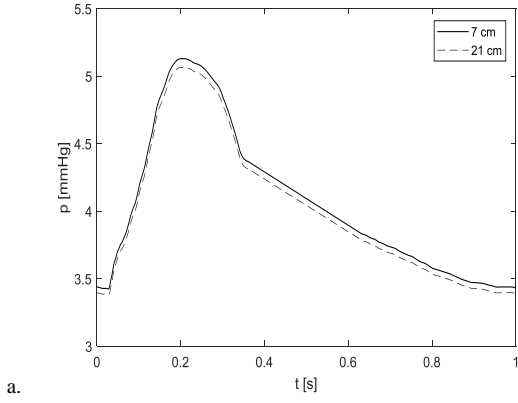


Fig. 3. Pressure wave in cephalic vein a. without and b. with AVF

B. Blood pressure and flow wave analysis

Of the two well established methods for blood pressure and blood flow wave analysis the Fourier transform method is chosen [5]. The Fourier spectrum of the pressure wave is determined on three different locations, z_{i-1} , z_i and z_{j+1} , by using a discrete Fourier transform. The dynamic pressure in the frequency domain can be expressed using

$$p(z, \omega) = p_+(z, \omega) + p_-(z, \omega) \quad (7)$$

where $p_+(z, \omega)$ is the progressive pressure wave and $p_-(z, \omega)$ is the back pressure wave. The transfer function H_{ij} of two measured signals in respect of position z (z_{i-1} – in the distance l before z ; z_{j+1} – in the distance l after z) is computed. By means of the transfer function the reflection coefficient is estimated. Then the forward and backward component of wave is evaluated in frequency domain. The inverse Fourier transformation of both the components gives the forward and backward blood pressure and flow waves on location z . [5]

Results of the pressure wave decomposition for both simulation cases with and without AVF are shown at the Fig. 4 and 6 for cephalic vein and radial artery respectively, and for of the flow wave decomposition at the Fig. 5 and 7 in same order. The influence of AVF on the blood pressure and flow wave propagation are visible for both examined vessels.

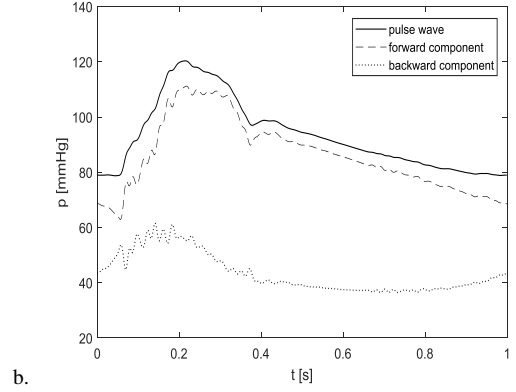
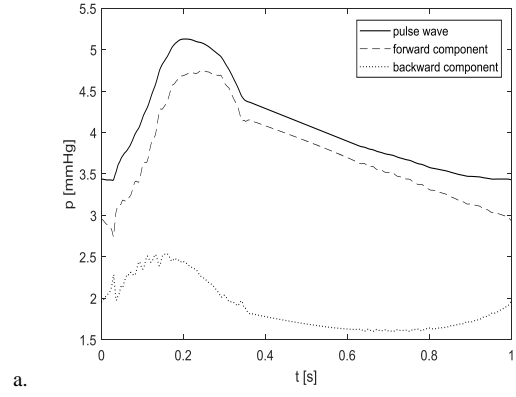


Fig. 4. Pulse wave components in cephalic vein a. without and b. with AVF

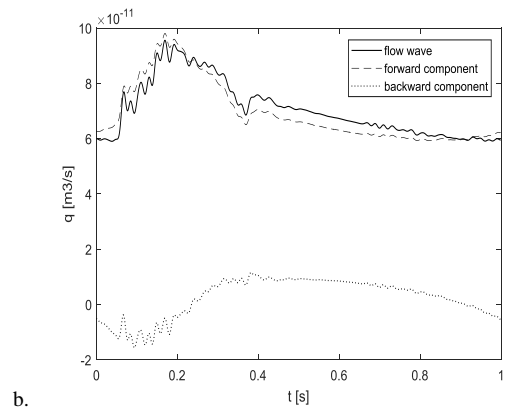
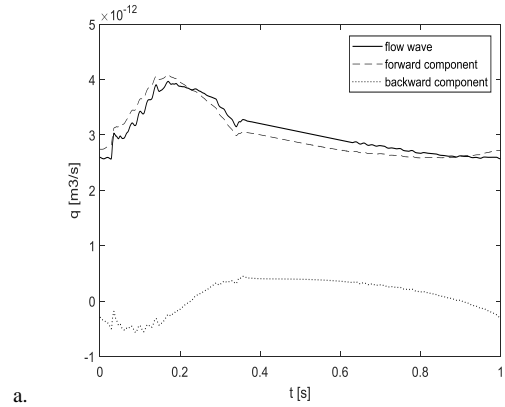


Fig. 5. Flow wave components in cephalic vein a. without and b. with AVF

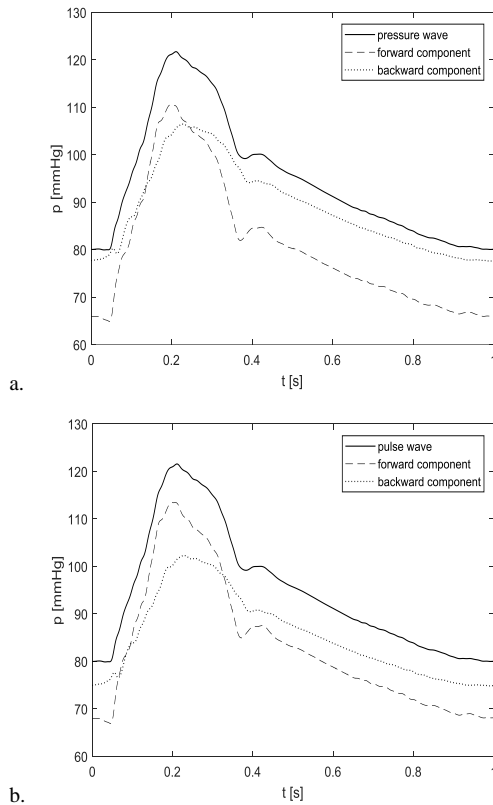


Fig. 6. Pressure wave components in radial artery a. without and b. with AVF

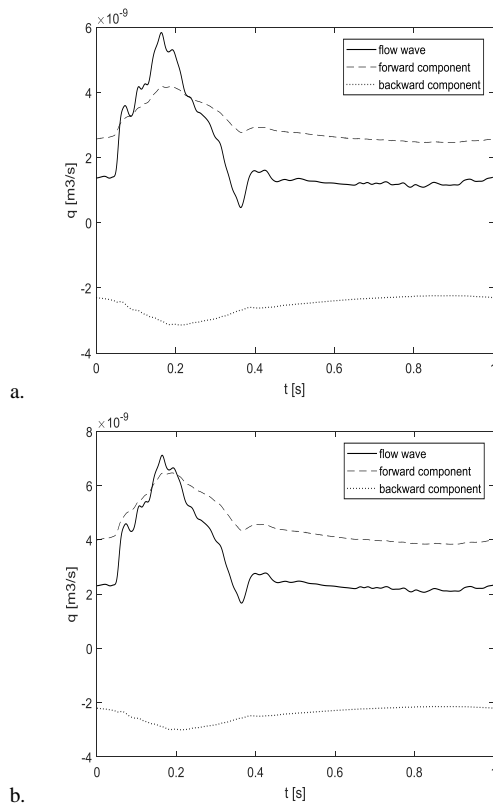


Fig. 7. Flow wave components in radial artery a. without and b. with AVF

IV. CONCLUSION

Simulations of two cases of model upper arm arterial vessels without and with AVF were performed and compared in order to examine its influence to the blood pressure and blood flow wave propagation patterns. The Fourier transform was used for the decomposition to the study of forward and backward travelling waves.

All two cases show good agreement of results for blood pressure curves and similar results for blood flow with theoretical assumptions. This provides a good starting point for further development of the model, for better understanding of AVF development. The present study is strictly theoretical and more development is necessary.

REFERENCES

- [1] L. O. Müller, E. F. Toro: *A global multiscale mathematical model for the human circulation with emphasis on the venous system* International In: Journal for Numerical Methods in Biomedical Engineering Int. J. Numer. Meth. Biomed. Engng. 2014; 30:681–725 Published online 15 January 2014 in Wiley Online Library DOI: 10.1002/cnm.2622
- [2] Gaelings E. W. *Numerische Simulation Haemodynamischer Prozesse in vascularen Netzen*. Shaker Verlag Aachen, 1996, ISBN-3-8265-1509-9, Germany.
- [3] Ketan Naik, P. H. Bhathawala: *Mathematical Modeling of Human Cardiovascular System: A Lumped Parameter Approach and Simulation*. In World Academy of Science, Engineering and Technology International Journal of Mathematical and Computational Sciences Vol:11, No:2, 2017
- [4] Westerhof N., Stergiopulos N., Noble M.I.M.: *Snapshots of hemodynamics*, ISBN0-387-23345-8
- [5] B. Czippelová, D. Gombárska, I. Čáp.: Wave propagation in cardiovascular model of human arm In: Physiological research. - ISSN 0862-8408. - Vol. 59, Iss. 5 (2010), s. 35P
- [6] Gombárska D., Czippelová B., Čáp I. Investigation of terminal segment influence in cardiovascular system modelling, Elektro 2010 Proceedings, 2010, p. TA5_38 – TA5_43, ISBN: 978-80-554-0196-6
- [7] A. Hughes, K. Parker, Forward and backward waves in the arterial system: impedance or wave intensity analysis? Med. Biol. Eng. Comput. 47 (2009) 207–210
- [8] Ali Kordzadeh, Jameson Chung, Yiannis P. Panayiotopoulos, *Cephalic vein and radial artery diameter in formation of radiocephalic arteriovenous fistula: a systematic review*, The Journal of Vascular Access, Volume: 16 issue: 6, June 2015, page(s): 506-511
- [9] Sackl-Pietsch E. Continuous non-invasive arterial pressure shows high accuracy in comparison to invasive intra-arterial blood pressure measurement, online, [1.4.2010] <https://www.biopac.com/Manuals/nibp100d_white_paper.pdf>