IMPACT OF DIFFERENT HEART RATES AND ARTERIAL ELASTIC MODULI ON PULSE WAVE VELOCITY IN ARTERIAL SYSTEM MODEL

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Abstract

The article describes the analysis of a pulse wave propagating through arteries towards periphery. For this analysis the model of arterial system based on the electromechanical analogy was used. Using the theory of transmission lines we estimated phase and group velocity of the arterial pulse wave. Both types of velocities were compared and dispersive properties of the selected arterial segments were evaluated. Pulse wave velocity corresponding to group velocity was calculated. We performed simulations for different heart rates and for different arterial elastic moduli. An increase in the heart rate causes that phase and group velocities converge to the same values. The higher magnitude of the arterial elastic module has the impact in the form of the increase in the both types of pulse wave velocities indicating the pathological state of the arterial system – arteriosclerosis.

Keywords

arterial system, group velocity, modelling, phase velocity, pulse wave

Introduction

Pulse wave velocity (PWV) is classified as a significant indicator of an arterial system state. Depending of its concrete magnitude it is possible to predict pathological processes impacting on the arteries. There are two ways how to assess current state of the arterial tree. The first way is a direct measurement of the pulse wave velocity by using conventional diagnostic methods like photoplethysmography [1], [2]. The modelling of arterial system and backward comparing simulated and measured values represent another approach. Using model of arterial system based on the electromechanical analogy allows us to evaluate properties of the selected arteries according to the transmission line theory.

Materials and Methods

Arterial system model based on electromechanical analogy

Using electromechanical analogy, we are able to transform mechanical properties of the arterial tree to their electrical equivalents. Then it is possible to use of the ordinary methods for electrical circuits analysis (e.g. theory of transmission lines) to obtain characteristic properties of the system such as voltage and current corresponding to their mechanical opposites which are pressure and current [3 - 6].

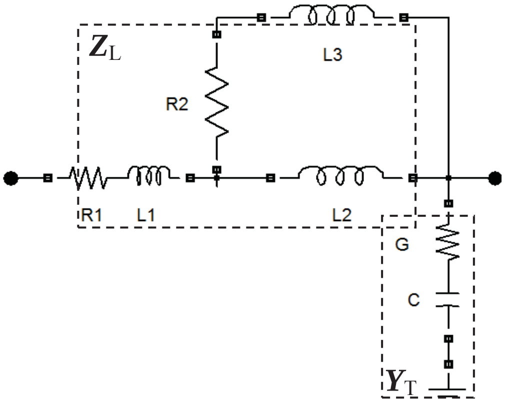

Fig. 1: The model of the arterial segment.

The model describing the arterial segment consists of three basic electrical elements: resistor, inductor and capacitor (Fig. 1). Calculation of their values can be found in [3 - 6].

Phase and group velocity

Phase velocity is defined as the velocity of the points of a wave (in our case it is the electromagnetic wave) with the same phase and it can be calculated [7 - 9]:

$$v_\mathrm{f} = \frac{\omega}{\alpha}, \tag{1}$$

where ω is angular frequency in rad/s and α is imaginary part of wave number (see Eq. 3) – propagation constant in rad/m.

Group velocity corresponds to the whole signal shape velocity and corresponds also to the pulse wave velocity (PWV) which propagates in a human body from aorta towards the periphery [7]. Its calculation is [8 - 10]:

$$v_\mathrm{g} = \frac{\mathrm{d}\omega}{\mathrm{d}\alpha}. \tag{2}$$

According to the transmission line theory, complex wave number is defined:

$$\boldsymbol{k} = \beta + \mathrm{j}\alpha = \sqrt{\boldsymbol{Z}_\mathrm{L}\boldsymbol{Y}_\mathrm{T}} \tag{3}$$

and the Equation 2 can be transformed to:

$$v_\mathrm{g} = \frac{\mathrm{d}\omega}{\mathrm{d}\left(\mathrm{Im}\left\{\sqrt{\boldsymbol{Z}_\mathrm{L}\boldsymbol{Y}_\mathrm{T}}\right\}\right)}, \tag{4}$$

where $\boldsymbol{Z}_\mathrm{L}$ is the longitudinal impedance of the appropriate arterial segment and $\boldsymbol{Y}_\mathrm{T}$ is the transversal admittance of this segment (see Fig. 1).

Results

For modelling of the impact of the heart rate and elastic moduli changes on the phase and group velocity, we used model of the arterial system (described in the previous sections) based on electromechanical analogy. The Fig. 2 shows the changes of PWV by changing heart rate for the selected arteries. The basic trend, which we can observe, is that phase velocity is in the all cases always higher than group velocity except PWV calculation for aortic segment. From the physical point of view, these observations tend to assume that a. subclavia, a. brachialis and a. radialis represent dispersion environments. Dispersive properties of the aortic segment are negligible.

Changing heart rate in interval starting at 0.5 Hz and ending at 3 Hz represents physiological operating condition of the heart activity. We can see also that phase and group velocities converge to the same value.

By changing of the arterial elastic moduli we can simulate a pathophysiological state (arteriosclerosis) of arteries. The arteriosclerosis is connected, for example, with arterial aging [7], [11], [12]. We started the simulation at physiological value of the arterial elastic moduli (adopted from [5]) for each arterial segment. The calculation ends at decuple of the physiological value. Changes between phase and group velocity in the small arteries like a. radialis are sizable when comparing to changes in aorta or a. subclavia. We can also see that all investigated arterial segments become more dispersive by increasing their arterial elastic moduli (see Fig. 3).

Conclusion

Within this article we performed the simulations for the physiological and pathological states of the arterial system. The physiological changes were provided by changing of the heart rate in physiological interval (from 0.5 to 3 Hz). Phase and group velocities converge to the same value and it follows that by the increasing the heart rate, the dispersive properties are minimalized by the arterial walls physical limitation to contract and dilate (corresponding to the energy losses). The simulation of the pathological state was performed by increasing of the elastic moduli of the selected arteries and we can observe increasing pulse wave velocity which is the significant indicator of the arterial disease – arteriosclerosis.

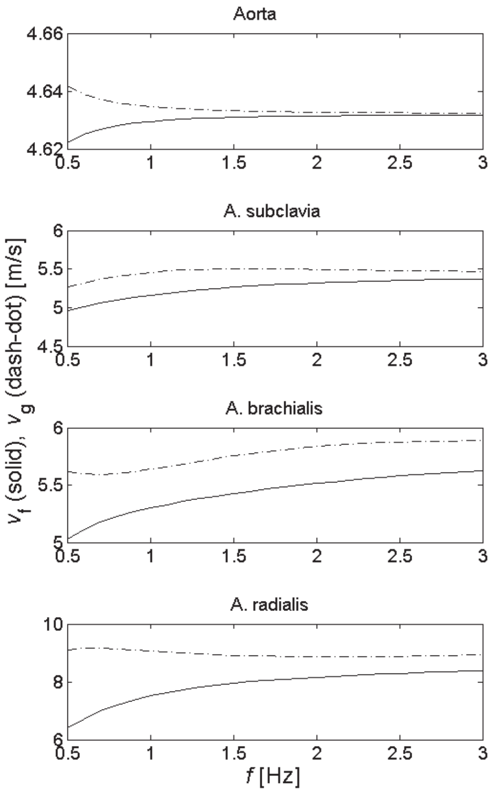

Fig. 2: Dependency of the phase and group velocity on the heart rate changes.

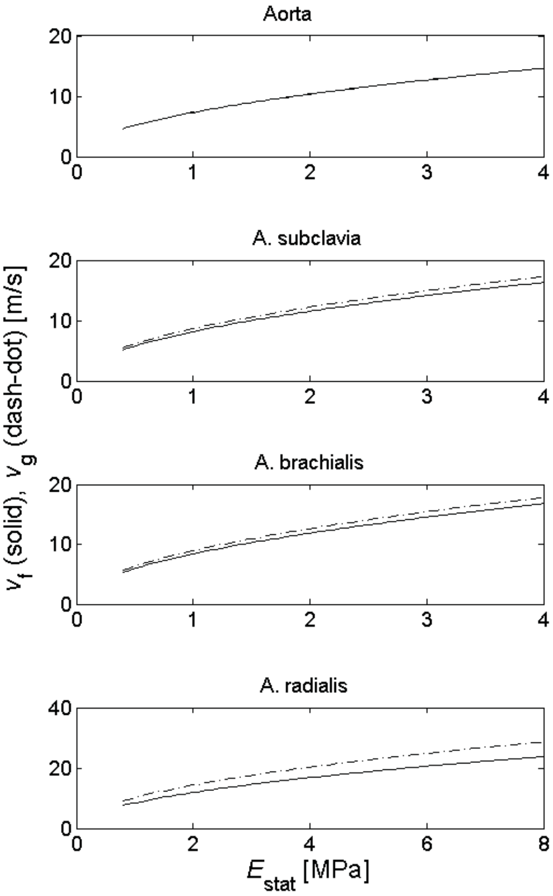

Fig. 3: Dependency of the phase and group velocity on the elastic moduli changes.

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