Novel methods of pulse wave diagnostics based on compression of a superficial artery

Natalya Kizilova *

Kharkov National University, Svobody sq., 4, 61077 Kharkov, Ukraine.

Pulse wave propagation and reflection in the branching systems of viscoelastic tubes and complex resistances as a model of arterial vasculature is considered. Axisymmetric wave motion of a viscous incompressible liquid in the system is investigated in application to the pressure and flow wave propagation in the system. Expression for the input admittance of the system taking into account wave reflection at the end of the tube is obtained. The dependence of the input admittance on the geometrical and mechanical parameters of the system is investigated. It is shown that the parameters of the pressure wave (the modules and phases of different harmonics) at the inlet of the system give information on the state (normal or pathological) of the inner organs. It is shown that after a proper compression (slight or deep) some harmonics can be amplified while the others are attenuated. Based on the theory of resonant harmonics of different inner organs the novel method of pulse wave palpation is proposed. The results are compared to some other methods as separation of the pressure wave into the forward and backward components, estimation of the parameters of the reflected wave and wave-intensity analysis.

1 Introduction

Wave propagation in the arteries is widely investigated in application to medical diagnostics. Important diagnostic information about the inner organ state can be obtained by analysis of the pressure P(t) and flow U(t) curves measured non-invasively by ultrasound devices in certain cross-section of an artery [1]. The diameter oscillation curve D(t) contains useful information on the systemic circulation, intraorgan blood flow conditions, microcirculation, blood distribution between the organs and viscoelastic parameters of the vessel wall. Due to significant individual variations the influence of geometry of the vasculature and pathological conditions has to be separated for the correct analysis of the curves. Determination of the diagnostically important parameters and their biomechanical interpretation are connected with mathematical approach to data analysis and solution of the corresponding coupling problem for the blood flow and vessel wall movement. Some novel aspects of the wave propagation in the arteries are connected with wave separation into the forward and backward running components, wave-intensity analysis, estimation of the resonant harmonics, analysis of the pressure-flow P(U) curves and the curves dD/dt(D) have been recently studied in [2-4]. It was shown that negative wave reflection which amplifies the blood inflow due to the sucking effect is proper to the intraorgan vasculatures. Analysis of the intensities $dI(t) = dP{\cdot}dU$ of the forward and backward waves gives the estimations of the distances to the occluded vessels. The area and the slope of the P(U) loop are significantly defined by the resistance and compliance of the terminuses. Non-invasive measurements of the pressure-flow curves in the feeding artery of an inner organ is proposed for recognition the pathological variations and separation the influence of the altered wall properties, vessel occlusion and the microcirculation state.

2 Materials and methods

The replica of the intraorgan arterial beds have been made using a polymerized liquid plastic. The inner organs have been got by autopsy from cadavers (death of young healthy subject had been caused by asphyxia). The casting liquid polymer was injected through the feeding arteries at a physiological pressure 80 mm Hg. After polymerization of the compound the organs have been kept into the sulphuric acid for 72 hours, then rinsed with water. As a result the accurate 3d replica of the networks have been obtained. The diameters of the separate elements of the replicas correspond to the inner diameters of the fully dilated arteries of the network. The successive nodes of each cast have been enumerated and for the purpose of measurements the replicas have been broken into pieces [5].

3 Statistical relationships for intraorgan vasculatures

The relationship $d_{max} = a \cdot d_0^b$, $b \sim 1$ has been obtained for all the investigated vascular beds. The dependences $d_{min}/d_0\,(\xi)$ and $d_{max}/d_0\,(\xi)$ are close to the optimal relations $d_{min}/d_0 = \xi\left(1+\xi^3\right)^{-1/3}$ and $d_{max}/d_0 = \left(1+\xi^3\right)^{-1/3}$ predicted by Murray's law [3]. Wave reflection coefficient $\Gamma \sim 0$ for the feeding artery and its branches whereas the big scatter $-0.6 < \Gamma < 1$

* Natalya Kizilova E-mail: nnk_@bk.ru, Phone: +38 057 707 5287, Fax: +38 057 714 1408

has been observed for the small arteries of all the vasculatures. Branching optimality for the steady flow correlates to its optimality for the wave propagation.

4 Relationships for dead and alive patients: what is the difference?

The next parameters have been calculated for each tube from the measurement data:

Branching asymmetry $\xi_j = min\left(d_j^1, d_j^2\right)/max\left(d_j^1, d_j^2\right)$;

Branching coefficient $K_j = \left(\left(d_j^1\right)^2 + \left(d_j^2\right)^2\right)/\left(d_j^0\right)^2$;

Optimality coefficient $\mu_j = \left(\left(d_j^1\right)^3 + \left(d_j^2\right)^3\right)/\left(d_j^0\right)^3$;

Hydraulic conductivity $Y_j^h = 128\eta\left(d_j\right)L_j/\left(\pi d_j^4\right)$;

Wave input admittance $Y_j^{in} = \pi d_j^2/\left(4\rho_f c_j\right)$

where η and ρ_f are viscosity and density of the blood, c_j is the wave velocity.

It is shown that there is a good correlation between the diameters of an artery in its dilated d_j^I (database I) and normal d_j^{II} (database II) state. In that way the values d_j^{II} may be calculated form d_j^I data. The individual variations are significant but the linear dependence $< d >^I \left(< d >^{II}\right)$ between the averaged values has been obtained.

The dependence $d_{max} = \alpha d_0^\beta$ has been found ($\alpha = 0.883$, $beta = 0.99$, $R^2 = 0.915$ for database I; $\alpha = 0.756$, $\beta = 1.05$, $R^2 = 0.902$ for database II and $\alpha = 0.873$, $\beta = 1.01$, $R^2 = 0.933$ for the Westerhof data [6]). In that way $d_{max} \sim d_0$ and the scatter in the dependence $d_{min}\left(d_0\right)$ is bigger. The vessel junctions which are optimal for the steady flow (Murray's law, $\mu \sim 1$) are well-matched and exhibit the zero wave reflection coefficient $\Gamma_0 \sim 0$. The dependencies $\Gamma_0\left(d_0\right)$ and $\Gamma_0\left(\xi\right)$ show that the large systemic arteries are well-matched with slight tendency towards the negative wave reflection while the smaller systemic arteries possess both negative and positive reflection coefficient $-0.5 < \Gamma < 0.6$ and their averaged values $< \Gamma_0^I > = < \Gamma_0^{II} > \sim 0$. Deviation from $\Gamma_0 \sim 0$ is more prominent for the database II.

5 Models and equations

Five models of the systemic arteries (731-883 arteries, database I); 5 more models (87 arteries, database II) and the 5 sets of the models of intraorgan vasculatures have been considered as the branching systems of straight cylindrical tubes from the viscoelastic material. The software for visualization of the arterial beds with given sets of diameters d_j, lengths L_j and terminus of the segments N_j^{in}, N_j^{out} has been elaborated. Womersley model of the axisymmetric wave propagation in the fluid-filled tube has been used for calculations the flow rate Q_j and pressure P_j waves in the systems:

$$P_j\left(t, x_j\right) = P_j^0\left(e^{i\omega(t - x_j/c_j)} + \Gamma_j e^{i\omega(t + (x_j - 2L_j)/c_j)}\right), \quad Q_j\left(t, x_j\right) = Y_j^0 P_j^0\left(e^{i\omega(t - x_j/c_j)} - \Gamma_j e^{i\omega(t + (x_j - 2L_j)/c_j)}\right)$$

where $P_j^0 = P_j|_{x_j=0}$ is the pressure amplitude, Y_j^0 is the characteristic admittance of the tube, Γ_j is the wave reflection coefficient. The input wave admittance $Y_{in} = Q/P$ of the systemic tree and the intraorgan beds have been calculated. The corresponding numerical procedures for the tree-like models and the systems with anastomoses are based on pressure and flow continuity conditions in the vessel junctions [3].

The results of computations of P(t), U(t), P(U) curves for the models have been compared to the measurement data. It was shown that analysis of the P(U) curves, wave separation and wave intensity analysis give a useful tool for differential diagnostics of the wave reflection site (due to stenosis, atherosclerosis, occlusion) in the large intraorgan arteries and at the terminuses (microcirculatory level). Basing on the models and morphometric data the resonant harmonics of the intraorgan vasculatures [3,4] have been computed and the method is proposed for clinical diagnostics. The distributed models of the intraorgan vasculatures are preferable to be used as the terminal elements in the model of systemic arterial tree. The developed models based on the presented data possess negative wave reflections and give realistic computational results which correspond to the ultrasound measurements in the arterial of alive patients.

References

[1] N. Kizilova, Intern.J.Fluid Mech.Res. **31**, 608 (2004).
[2] M. Bondarenko, and N. Kizilova, Russian J. Biomech. **4**, 52 (2002).
[3] N. Kizilova, J.ChineseInst.Eng. **26**, 869 (2003).
[4] N. Kizilova, Fluid.Dyn. **41**, 444 (2006).
[5] O. K. Zenin, N. Kizilova, and E. N. Philippova, Biophysics **52**, 924 (2007).
[6] N. Westerhof, F. Bosman, C.J. de Vries, and A. Noordegraaf, J.Biomech. **2**, 121 (1969).