

Optimal long-distance transport systems in nature: control and applications

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Long-distance conducting systems in high plants and animals are presented by networks of rigid tubes with porous walls (in plants) or distensible tubes with impermeable walls (in animals). Geometrical relationships between the diameters, lengths and branching angles of separate conducting vessels have been studied and the results of the comparative analysis are presented. It was shown that the principles of construction of the transport systems are similar in animals and plants and correspond to the optimal pipelines with impermeable and permeable walls accordingly. The optimization criterion is the total energy expenses W for the fluid delivery and construction of the system. Global optimality at the systemic level is provided by local optimality conditions in each conducting element. It is shown that complexity of the branching system of the optimal tubes leads to certain regularities in the hydraulic and wave properties of the systems. The obtained regularities and the principles of design of the long-distance transportation networks in Nature can be used in biomedical applications and technique.

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1 Experimental study of the systemic arterial tree

The results of measurements of the lengths and diameters of the arterial segments in the plastic casts of the arterial beds of the inner organs and muscles of 5 corpses (with age ranging from 38 to 62; the death was not connected with cardiovascular pathology) have been used for statistical analysis and numerical calculations of the pressure and flow wave propagation in the realistic models of the vasculatures. The lengths and diameters of the arterial segments have been measured to 0.1 mm. The parameters of the systemic arteries have been measured in the course of the post-mortem examination of the corpses that gave the database I. Each artery has been followed down to the place it penetrates into the organ. The measured diameters of the arterial segments in both replicas and corpses correspond to the inner diameters of the arteries at full dilatation. The diameters and lengths of the systemic arteries and feeding arteries of the inner organs have also been measured in 5 healthy volunteers (with age ranging from 18 to 42) using triplex scanner 'Sonoline Elegra Advanced' (Siemens) that gives the database II. The coronary arteries have been studied by transesophageal ultrasound monitoring. The flow waves in the middle sections of the corresponding arteries have been measured by Doppler ultrasound.

2 Analysis and biomechanical interpretation of pressure $P(t)$ and flow $U(t)$ curves

$P(t)$ and $U(t)$ signals measured in healthy patients and calculated on the models of the intraorgan arterial beds have been compared and investigated using the wave-intensity analysis and wave separation technique: $P(t) = P^+(t) + P^-(t)$ [1,2]. When $P(t)$ signal is measured in the feeding artery of the organ the parameters of the forward wave are determined by the upstream conditions while the backward wave $P^-(t)$ carries information about the intraorgan circulation. The intensities $dI^+(t) = dP^+ dU^+$ and $dI^-(t) = dP^- dU^-$ of the forward and backward waves reveal the forward and backward compression and expansion waves and the distance H to the reflection site can be estimated as $H = (t_2 - t_1)c$ where the wave speed

$$c = \frac{1}{\rho} \frac{dP}{dU} = \frac{1}{\rho} \tan(\theta)$$

is easily determined by the slope θ of the linear portion of the $P(U)$ [3]. The slope of the long axis of the $P(U)$ loop and its inner area are important parameters for diagnostics. The computational results have been compared to the measurement data. It was shown that the proposed analysis of the $P(U)$ loops, wave separation and analysis of the wave intensities gives a useful tool for differential diagnostics of the wave reflection in the large intraorgan arteries (stenosis, wall rigidity) and in the small arteries and arterioles (microcirculatory state).

3 Transport system organization in plant leaves

The lengths and diameters $L_{j,0-1}$, $D_{j,0-1}$ of the leaf veins have been measured on the scanned images of the leaves using image analysis software [4]. The total number of elements of each branching order $i=1-5$ was calculated. The dependencies $N_i = N_i(D_i)$ and $L_i = L_i(D_i)$ have been obtained in the form $L_{1,2} = \alpha_{1,2} D^{\beta_{1,2}}$ and the corresponding coefficients

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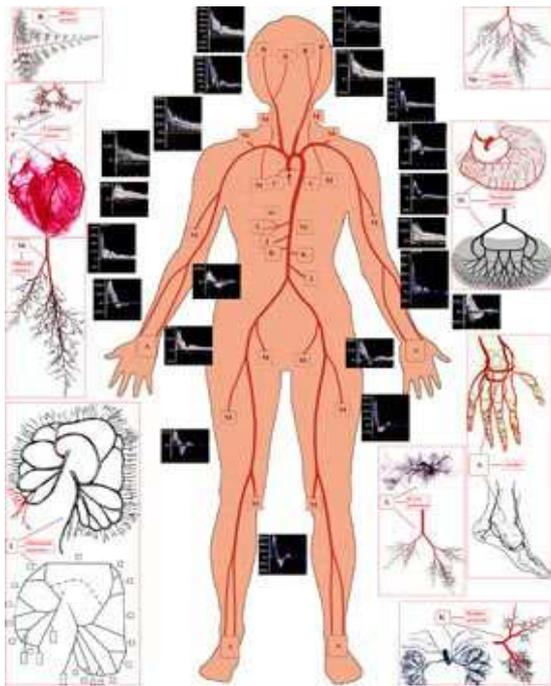


Fig. 1 Schematic representation of the human arterial system.

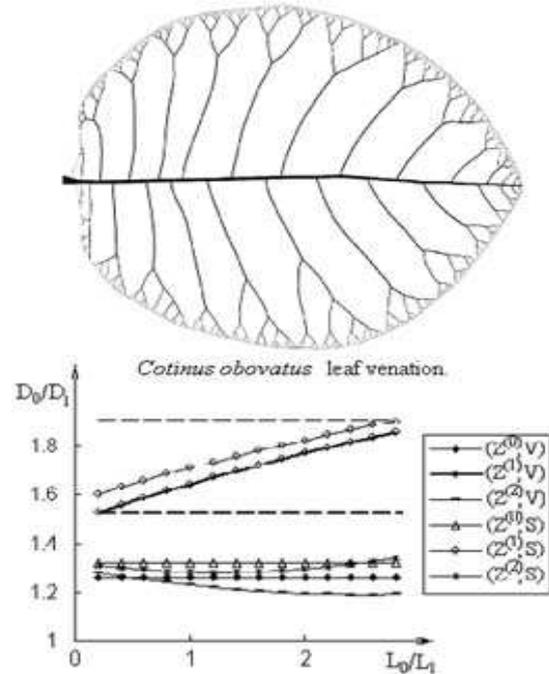


Fig. 2 The dependences $D_0/D_1(L_0/L_1)$ for the optimal symmetric bifurcation at different optimization criteria.

$\alpha_{1,2}, \beta_{1,2}$ have been calculated. Two subsystems can be distinguished: the system of the so-called distributing vessels with $\beta_2 = 3.2$ and the delivering vessels with $\beta_2 = 1.6$ [5]. The same subsystems were found in the coronary arterial bed [6]. The function of the distributing veins is to convey the fluid into different zones of the leaf blade, while the function of the delivering veins is uniform delivery of the fluid into each cell. The relation between the length L_j of the separate conducting element and its domain of influence (i.e. the area S_j of the leaf blade supplied with water through this element) have been obtained in the form $\sqrt{S_i} = k_i L_i$ of the Hack's law. The comparative analysis of the data obtained for the conducting systems of leaves and mammalian vascular systems reveals, that both of them are statistically similar and the principles of design of the long-distance transport systems in animals and higher plants are the same.

4 Control over organization of the transport system

The arterial system formation in a developing tissue is provided with mechanoreceptors in the vessel wall. The mechanoreceptors can control the network self-organization by keeping the shear stress at the wall τ_w within certain limits. At a steady flow condition (Poiseuille's flow) $\tau_w = 32\mu Q/(\pi D^3)$. When $\tau_w = const$ it gives $Q \sim D^3$, that corresponds to the optimal tube in which the total energy costs $W \rightarrow min$. In such a manner the mechanoreceptors provide the local optimality conditions in the developing branching vascular tree. For a bifurcation j of the optimal vessels with $Q_{j,0-2} \sim D_{j,0-1}^3$ the continuity condition $Q_{j,0} = Q_{j,1} + Q_{j,2}$, where $Q_{j,0-2}$ – volumetric rate in the tube with diameter $D_{j,0-1}$ leads to the Murray's law $D_{j,0}^3 = D_{j,1}^3 + D_{j,2}^3$ [7]. Then the global optimality conditions for the whole transport system are the same and the transport system possessing the minimal hydraulic resistance at the given total volume develops in the tissue. The mechanisms of the vein systems with the same geometrical properties formation in plant tissues are unknown yet. The hypothesis of the optimal transport structure formation in plant tissue was proposed in our previous works. It is based on the model of the branching pipeline with permeable walls. The control over the optimal transport system construction is provided by prevention the vessels' desolation by means of regulation of balance between the plant sap inflow and consumption [7,8].

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