PATHOLOGICAL DEFORMATIONS OF BRAIN VASCULAR SYSTEM MODELLING USING ANALOGOUS ELECTROMAGNETIC SYSTEMS

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Summary The contribution deals with the modelling and simulation of human brain haemodynamics using analogous electromagnetic systems characteristics especially propagation properties of distributed parameters circuits. The cascade connection of analogical transmission line elements represents the vascular tree both from the point of the parameters and the topology as well. In the paper there are presented simulation examples of the healthy cerebral system mainly in the big arteries in comparing with the pathologically changed ones. The various degrees of stenosis are considered for the simulations of blood pressure and blood flow velocity and the results are compared with the healthy arteries.

According to the last investigations the pathological deformations of brain arteries are the most frequently reasons of deaths in the world. The stenoses or aneurysms change the physical properties of arteries and they follow insufficient vascularisation of the brain. These computer-aided non-invasive methods together with the non-invasive experimental techniques represent a helpful tool both for the diagnostics and the treatment of vascular pathological deformations.

Keywords: electromechanical analogy, modelling and simulation, dynamic fluid systems, haemodynamics, equivalent electromagnetic system, transmission line propagation characteristics.

1. INTRODUCTION

According to the last medical investigations the pathological deformations of human brain arterial system represent one of the most frequent cause of a death in the world [1], [3]. Various kinds of stenoses, aneurysms or thrombi change the physical properties of vessels which result in variations of blood characteristics and following disorder of the brain area blood supply (vascularisation). In order to improve the situation, the most important step is the preventative efficient diagnostics of human haemodynamics, especially cerebral arterial system. With the aid of usual non-invasive diagnostic methods, nuclear magnetic resonance or radiological investigations, it is possible to obtain the necessary information for the creation of the individual physiological model of the brain haemodynamics.

Using the mentioned electromechanical analogy the equivalent electromagnetic system can be derived and consequently the computer modelling and simulation of the cerebral vascular system can be performed. It is not possible to develop the general simulation model for the whole vascular system, so that the computer modelling and simulation are limited for the descriptions of typical standard cases of the arterial system behaviour. Within the framework of the modelling and simulation, many influencing factors can be involved and calculated but the obtained results and following conclusions have mostly an individual character. The computer-aided non-invasive diagnostics of the arterial system enables to deduce how to treat the pathological arterial deformations from the brain arteries simulation results, especially in the case of their necessary surgical interventions.

2. FLUID SYSTEMS MODELLING

Modelling and simulation of physiological fluid systems on the basis of the electromechanical analogy consist in the creation of analogous equivalent electromagnetic systems, electromagnetic characteristics of which will describe the properties of the investigated physiological system, [3], [4], [5]. According to the analogy the electromagnetic propagation equations describe the mechanical properties of flowing fluids.

In our case, one part of the physiological system is one vessel segment and it can be equivalently replaced by one section of the elementary distributed parameter circuit characterised by the transmission propagation parameters and the corresponding relations, Fig. 1.

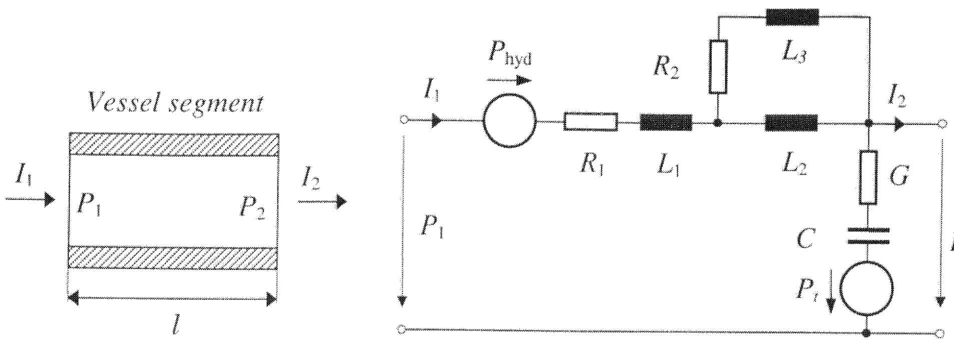

Fig. 1. The homogeneous vessel segment representation and its equivalent electrical two-port.

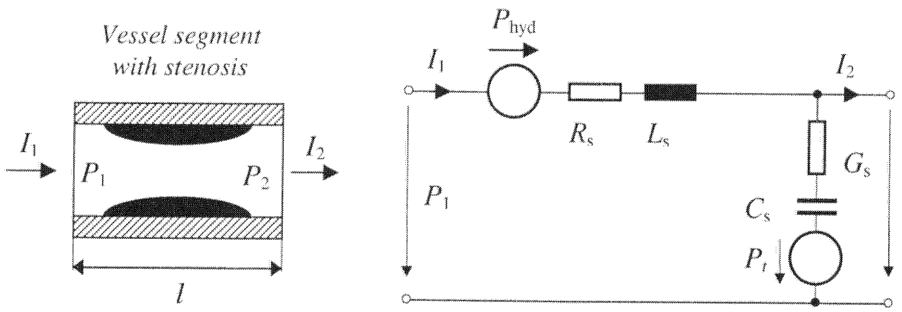

Fig. 2. The local arterial stenosis and its electric model.

The inductivities and resistances in the longitudinal branch depend on the system geometry and they describe the flow impedance of blood circulation. The non-linear vessel wall properties are represented by the series connection of capacity, loss resistance and controlled source, which are located in the transverse branch. The controlled source in the longitudinal branch describes the hydrostatic pressure.

$$R_n = \frac{8\eta}{\pi r_0^4} n \qquad L_n = \frac{\rho}{\pi r_0^2} \frac{1}{2n-1},$$

where $n = 1, 2, 3$

$$G = \frac{2\pi r_0}{k\eta} \qquad C = \frac{2\pi r_0}{k E_s},$$

where r_0 is the vessel radius, η and ρ are the blood viscosity and density, k is the vessel elasticity geometry factor and E_s is the vessel wall static elasticity modulus.

When the pathological deformation of a vessel segment occurs, the equivalent electromagnetic model will differ from the homogeneous one at Fig. 1. In the case of an arterial stenosis (a local narrowing of a vessel) the equivalent electric model is shown at Fig. 2, [1]. In comparison with Fig. 1 the elements $R_1 \to R_s$, $L_1 \to L_s$ and $R_2 = 0$, $L_2 = L_3 = 0$. The non-linear pressure drop ΔP_s dependent on the flow together with the hydrostatic pressure can be involved into the controlled source of voltage in the longitudinal branch.

In the case of an arterial aneurysm the local hollow of the vessel is present. The aneurysm usually causes the rise of a thrombus, the presence of which also causes the local narrowing of the vessel. The modelling and simulation are in the principle very similar to the case of a stenosis. The reasons of both kinds of arterial deformations are the changes of the pathological vessel walls properties, especially the lower elasticity and the higher stiffness of vessels. In the modelling the change of the wall elasticity is expressed by the higher value of the elasticity modulus E_s.

The human brain arterial system is shown at Fig. 3. The topological model of the basic brain arteries was used for the blood characteristics simulation. Both carotis interna arteries supply the front circulation and the arteries vertebralis supply the back cerebral circulation. The circulus arteriosus, which is the ring-shaped connecting system, can be individually very different one. The special importance of this system consists in the compensation possibilities if one or more basic feeding arteries are left. In such case the one-sided block of the carotis interna artery must not be a reason of an apoplexy, when sufficient amount of blood will flow through the connecting circulus arteriosus through the arteries communicans anterior and posterior, Fig. 3. It is very important to know the blood flow characteristics mainly in the basic arteries. From the clinical point of view it is necessary to know the way of the surgery treatment and its next influence on the blood supply of the brain.

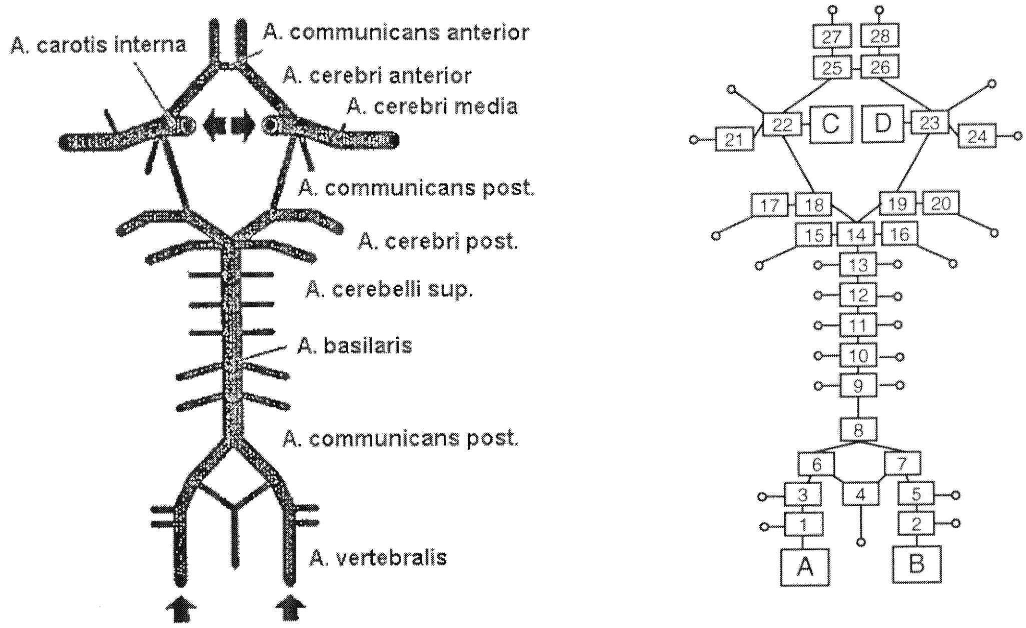

Fig. 3. Human brain arterial system and its topology.

3. SIMULATION RESULTS

In the following simulation experiments the estimation of the corresponding vessel wall elasticity was made. The supposed blood pressure increase 5 kPa leads to the enlargement of the cross-section of a vessel segment about 10%.

In the simulation experiments connecting with the estimation of vessel walls elasticity the necessary following assumption were made. If the wall elasticity increases to the value corresponding to the 10% volume expandability by the pressure rise of 5 kPa, the significant pulsation of the blood flow occurs while the mean values of the flow velocities are the same.

The blood supply of the brain is determined by the pressure course, the geometry of single vessel segments and by the boundary conditions of the terminal segments. The termination for every ending segment corresponds to symmetrical perfusion model [6].

In the second simulation experiment the stenosis in the area of artery carotis interna was modelled and the compensation properties of the connecting circle were investigated with regard to the various stenosis degrees. The placement of the stenosis was five centimeters behind the bifurcation of the artery carotis interna (before the segment C - 22), Fig. 3. The chosen relation of the stenosis length l_s and the vessel radius without stenosis r_0 was 4:1. The values of stenosis parameters K_v and K_u, [2], were elected according to the condition that in the case of vanishing stenosis the analogous circuit elements R_1, L_1 and L_2 become their usual values. The definition of the stenosis degree is expressed by the next relation $G_s = (r_0 - r_s)/r_0$ [2], where r_0 is the radius of healthy vessel and r_s is the radius of the vessel with stenosis. According to these assumptions the modelling of 60% and 90% stenosis were performed, Fig. 4, where the full line represents the blood flow velocity in the vessels without stenosis.

The Fig. 4 represents the fact that the 60% stenosis (dashed line) only slightly influenced the blood transportation. But the 90% stenosis (dotted line) caused significant differences of the blood flows and flow velocities especially of the both arteries carotis interna (C22, D23) and also in the connecting vessels (18-22, 19-23, 26-25) of the circulus arteriosus. The compensating flows in circulus arteriosus ran in spite of the strong occlusion in the artery carotis interna to undisturbed blood supply through the artery cerebri posterior (19-20), artery cerebri media (22-21) and artery cerebri anterior (25-27). According to the Fig. 3 and 4 the possible compensation path of the brain arterial system is shown.

4. CONCLUSION

The modelling and simulation of the human cerebral arterial system dynamics have been introduced and performed in the paper. In accordance with the electromechanical analogy, after which the flow mechanical blood characteristics are represented by the electromagnetic system propagation properties, the electrical model of the basic brain arteries has been created. Except of healthy elastic arteries the pathological vessel walls deformations, caused especially by the local stenosis of various stenoses degrees were simulated and evaluated. In the case of a stenosis both the circuit topology and the

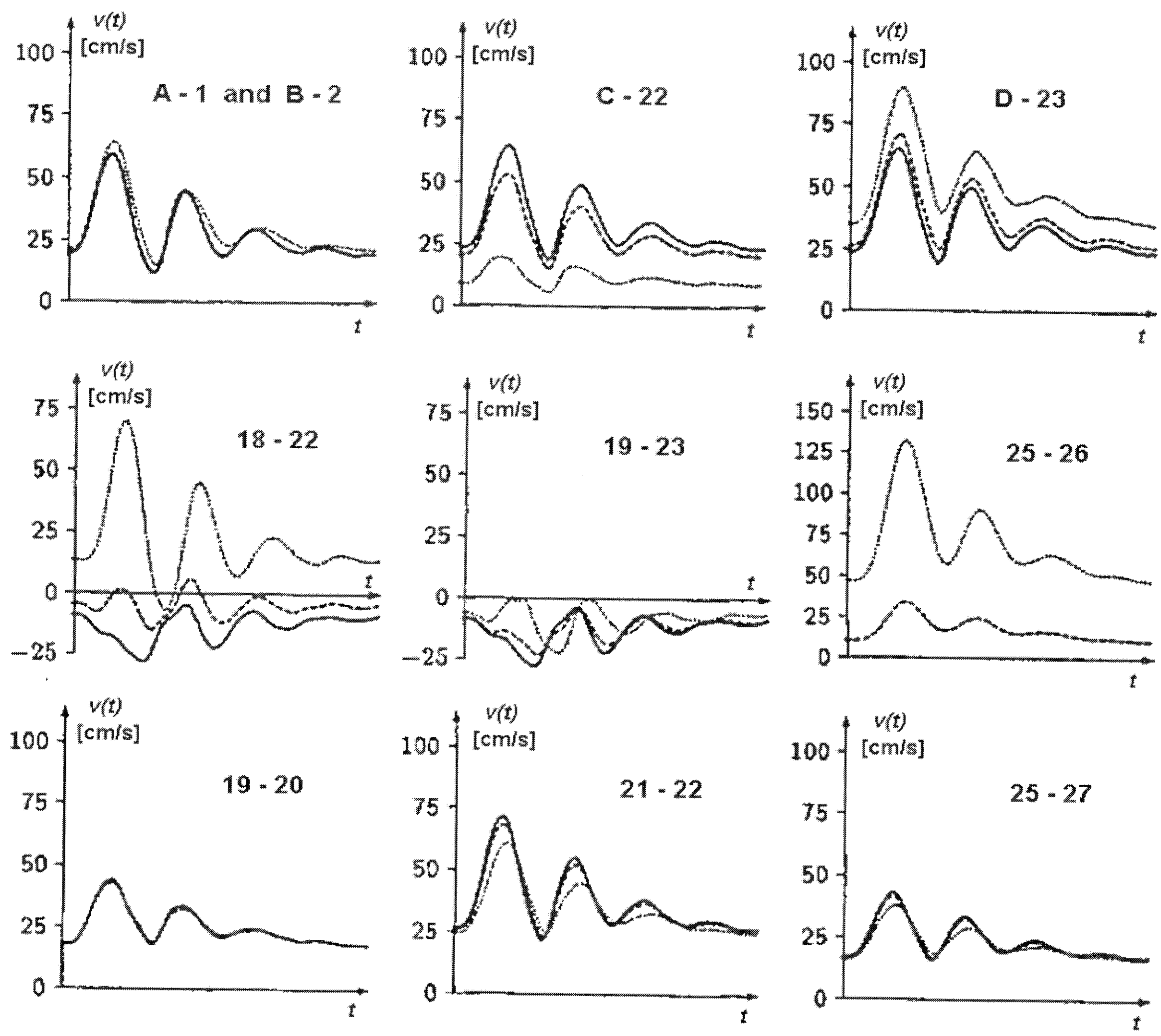

Fig. 4. The mean flow velocities in the basic brain arteries in the case of the stenosis in the artery carotis interna (0% - full line, 60% - dashed line and 90% - dotted line).

parameters values were changed according to the changes of the mechanical vessel walls properties. Following the simulation results (Fig. 4) the compensation possibilities for the blood supply of the brain arterial system in the case of a significant stenosis in the arteria carotis interna were shown and discussed.

The presented brain haemodynamics modelling and simulation in co-operation with medical investigation methods (EG, NMR, angiography) can offer a helpful tool for non-invasive computer-aided diagnostics of basic brain arteries.

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