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„Computer-aided simulation of cerebral hemodynamics for preoperative risk-estimation of neuroradiological or neurosurgical interventions“

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ABSRACT

The development of a one-dimensional numerical model of the arterial network at the bottom side of the brain, called the circle of Willis, is described. Based on the Navier-Stokes and conservation of mass equations the hemodynamic properties of a vessel are expressed by linear differential equations describing an electrical circuit. The present model considers the elasticity of the vessel wall, pulsatile blood flow and Bernoulli's dynamic pressure leading to a nonlinear extension of the derived equations. The geometrical parameters and boundary values needed to run the model are determined non-invasively. In the treatment of many cerebrovascular diseases preoperative simulations with individual models can help to estimate the stroke risk of patients undergoing a neuroradiological intervention or neurosurgical operation.

INTRODUCTION

During the medical treatment of many cerebrovascular diseases it is often necessary to occlude one of the brain supplying arteries. The circle of Willis (CAW) connects the four brain supplying arteries annularly at the bottom of the brain. It thus compensates perfusion deficits so that such interventions involve no further consequences for the majority of patients. But sometimes due to an unfavorable vessel anatomy, a vessel disease or a decreased blood perfusion the compensating property of the CAW becomes insufficient and vessel occlusion causes an ischemia in the corresponding parts of the brain. In particular occlusions of the internal carotid artery frequently lead to neurological deficits or strokes.

Until now, this risk can only be estimated by invasive diagnostics such as temporary test occlusions containing the risk of cerebrovascular complications. Also, these methods are inaccurate. 5 to 20 % of the patients sustain strokes during a therapeutic vessel occlusion even if they passed the temporary test occlusion. Before doing interventional vessel occlusion it is therefore not possible to estimate the therapeutic risk for the patient non-invasively without any physical complications.

For this reason profound insights into the complex hemodynamical interactions within the brain were tried to enable by modelling the CAW. By replacing invasive diagnostics with computational simulations, a reliable and non-invasive diagnostic tool is obtained to estimate the hemodynamical effects of endovascular vessel occlusion.

METHODS

Figure 1 shows a schematic structure of the CAW and the analogy of hemodynamic and electrical state variables used.

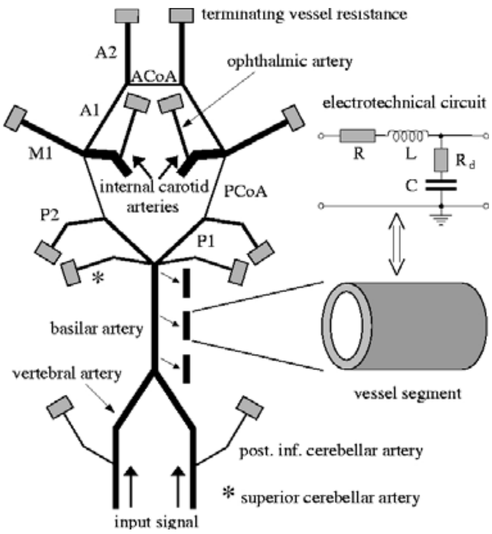

Fig: 1: The schematical CAW and the analogy of a vessel segment and an electrical circuit.

The designed model is based on linear differential equations (eqns. 1 to 3) describing the physiological behaviour of each vessel segment i. Their derivation can be found in the literature [Roessler1996].

$$I_i(t) = \int_0^t \frac{1}{L_i(t)} \left[P_{i-1}(t) - P_i(t) - I_i(t) R_i(t) \right] \, dt + I_i(0) \quad (1)$$

$$P_i(t) = \frac{2}{3} \rho \, l^2 \left(\frac{I_i(t)}{Q_i(t)} \right)^2 + R_{di}\left(I_i(t) - I_{i+1}(t) \right) + \frac{Q_i(t) - Q_{iu}}{C_i} \quad (2)$$

$$Q_i(t) = \int_0^t \left(I_i(t) - I_{i+1}(t) \right) \, dt + Q_i(0) \quad (3)$$

In terms of this electrical analogy the blood volume Q(t) corresponds to the charge, the blood flow I(t) to the current and the blood pressure P(t) to the voltage. The longitudinal resistance R(t) describes the friction between the vessel wall and the streaming blood. The inductivity L(t) stands for the inertia of blood. The transversal resistance R_d is the internal friction between the different layers of the vessel wall and the capacitor C reflects the ability of a vessel to store a certain amount of blood depending on

the intravasal pressure. ρ is the density of blood, r_0 and l are the radius and the length of the vessel segment and $Q_u = \pi \, l \, r_0^2$ is the blood volume in the unextended vessel.
The hemodynamic properties of a vessel can be determined by its geometrical parameters and the elasticity of its wall [Roessler1996]. By these means any given anatomical vessel structure can be designed, time continuous simulations of different states and the online observation of all calculated state variables such as blood flow in any modelled vessel become feasible.
To fit the model to the individual patient the vessel anatomy, the geometrical parameters and also the boundary values needed to run the simulation were determined by non-invasive measurements and imaging procedures.
Examinations were made with 6 volunteers all male, healthy and between 25 - 30 years of age. Using a 8 MHz Duplex-sonograph the velocity of blood flow was measured simultaneously in the internal carotid arteries and the vertebral arteries. They were used as input signals for the simulations serving as boundary values of the differential equations. The velocity of the blood flow in the middle cerebral arteries was also measured. These time series were used to evaluate the model by comparing them to the corresponding time series generated by the model.
The anatomical and geometrical data were obtained by 3-D-magnetic resonance angiography (MRA).
The elasticity of the vessels can be calculated using the pulse wave velocity (PWV) [Roessler1996]. The values for the PWV were taken from several publications [Li1987, SCHaaf1972].
It is not possible to model all vessels including capillaries and veins. The vessel network was therefore limited at several points and terminated with resistances describing the total peripheral resistance (TPR), represented by rectangles in figure 1 and 2. Their values were estimated by physiological considerations [Roessler1996]. By this procedure an individual model of the CAW for each volunteer was created.

RESULTS

As an example for the physiological behaviour of the model some generated time series for a volunteer who does not have a right anterior and posterior cerebral artery can be seen on the right side of figure 2. Mean values taken from the literature are shown as horizontal lines. On the left side a sketch of the individual model is shown. The radius and the length of each vessel are depicted corresponding to their real anatomical appearance. The arrows indicate the direction of blood flow as calculated by the model. The generated flow velocity in the left middle cerebral artery is compared with the corresponding time series measured at the patient.
The simulation shows a good agreement between modelled and comparative time series measured at the patient or taken from the literature. In the right posterior communicating artery (PCoA) a conspicuous high blood flow is simulated by the model. Normally the blood flow in this vessel is negligible, as it is simulated for the left side. But due to the missing right P1 the CAW supplies the right P2 by the right PCoA. This is a good reproduction of the volunteer's true physiological situation.

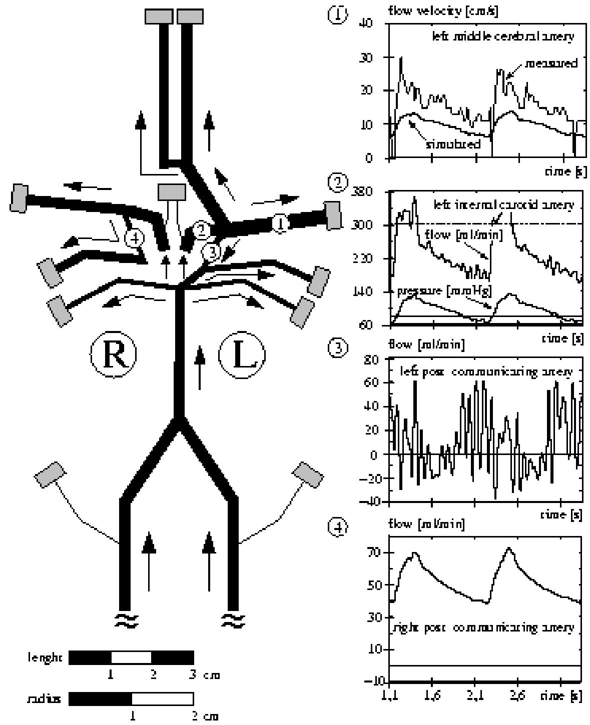

__Fig. 2:__ Model of a volunteer with simulation results

DISCUSSION

State variables generated by the model behaved physiologically and the reaction of individual cerebro-vascular systems in critical situations equal to the occlusion of different arteries could be investigated by special scenarios. By this preoperative information about the behaviour of the cerebrovascular system of patients undergoing therapeutic vascular occlusion can be obtained non-invasively. Due to the huge amount of system defining parameters and inaccuracies concerning their determination, agreement between the modelled data and those recorded from observations of the subjects were not reached in each case. It is conceivable that better results can be achieved shortly by using more suitable clinical techniques for the parameter measurement.

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