SIMULATION OF THE TRANSIENT FLOW OF BLOOD THROUGH THE HUMAN ARTERIAL SYSTEM

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Abstract: A hydrodynamic blood flow model for the human arterial system is presented. It is based on the theory of transient flow through highly flexible tubes. A special concept of fictitious arteries is used to model the resistance of the capillaries and the network meshes in parts of the arterial system, which are not take into account. Including only the most important arteries leads to a network of about 150 vessels. Such a model can be used to investigate the effects of different pathological situations (valvular defects, stenoses, ...) on blood transportation and pulse forms.

Introduction

The reasons for performing simulation experiments on the blood flow in human arteries are the investigations of the propagation of pulse waves within an arterial network. The main part of literature about that theme concentrates on a *microscopic* view, i.e. only small parts of an artery or one specific arterial bifurcation were analyzed. In our work we tried a *macroscopic* way by including a whole network of arteries in our models in order to simulate also different pathological situations and their influence on the pulse waves in the different parts of the body [1,2].

Materials and Method

Based on the theory of transient flow through highly flexible tubes, a model for the propagation of pulse waves in a network of arteries is derived. Some changes are necessary to adapt the theory for that purpose, those are dynamical changing diameters and wave speeds depending on the pressure values and a variable Darcy-Weisbach friction factor, because during one pulse beat flows are changing between laminar and turbulent state. So the basic equations for the transient flow through an artery are (H – pressure head, V – flow velocity)

$$g\frac{\partial H}{\partial x}+\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+\frac{V|V|}{2D}\lambda(V)=0$$

$$\frac{\partial H}{\partial t}+\frac{a_o F(H)}{g}\frac{\partial V}{\partial x}+V\frac{\partial H}{\partial x}-V\sin\alpha=0$$

This system of partial differential equations can transformed into a system of ordinary differential equations using the method of characteristics. The solution can be approximated on a x-t-grid by integrating stepwise along the time axe [1,5].

The above equations can be used for describing the flow through normal arteries, but for the aorta it is necessary to include additional air chambers in between in order to model the damping property of the aorta.

For calculating a whole network the boundary conditions of the single arteries are connected. Only at the inflow and outflow points of the network external boundary conditions must be provided. The condition at the inflow point is simply the flow curve of the heart, but it is not possible to determine such flow curves at all end points. Therefore additional (fictitious) arteries are included, which collect all outflows in one point, and it is assumed that there is a constant discharge of blood (see figure 1). Although those fictitious arteries have no real counterpart, they simplify the boundary conditions for the outflow, and by varying the diameters of the fictitious arteries the resistance of other parts of the arterial system can be introduced in an easy way.

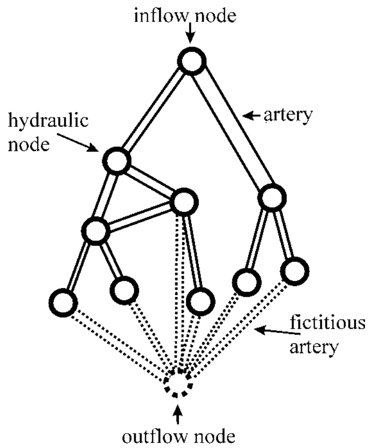

Figure 1: Schematic Network

A hydrostatic blood flow model is used to get mean flow and pressure values in order to initialize the dynamic calculation [5,6].

The main calculation program was written in C++ in order to minimize the computation time. The network structure is mapped on an object hierarchy consisting of different classes for arteries, nodes and the whole network. The integration algorithm includes also a time step control in order to minimize the numerical failures and to optimize the calculation time.

There are two different ways for data I/O: a MATLAB interface and a simple ASCII file interface. So the features of MATLAB can be used for data pre- and postprocessing, also the integration into other models is possible using the MATLAB interface. But because of the ASCII file interface it can be connected very easily with any other software.

Results

For simulation experiments a network of about 150 arteries of a standing person was used (see figure 2). In this case two air chambers along the aorta were used to model the special elastic behavior of that vessel.

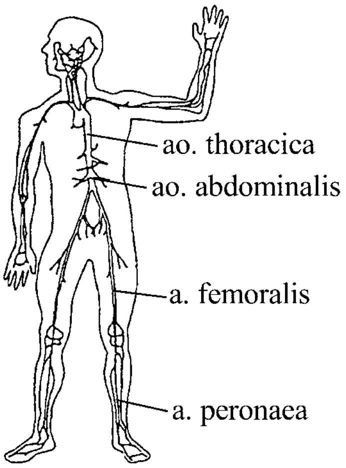

Figure 2: Human arterial network

A normal blood flow curve with a frequency of 75 Hz was assumed at the heart. The pulse curves recorded in 4 different vessels are shown in figure 3.

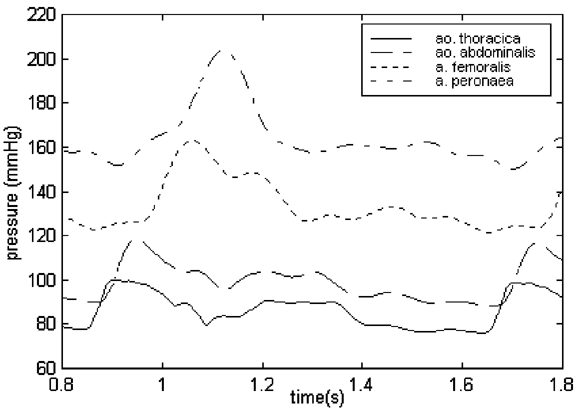

Figure 3: Pulse curves in different arteries.

Because of the hydrostatic pressure the pulse curves in the leg are on a higher level. The pulse curves in the aorta show clearly the dicrotic notch (at about 1.1 sec.) and a slow pressure decrease during the diastole (1.1 – 1.6 sec.).

It is also possible to record the flow or the flow velocity in the arteries, or the changes of the diameters. Hence, such simulation experiments allow investigations of the blood supply in different parts of the body, or on special forms of the pulse curves, depending on the different conditions of the arterial system (reduced compliance and closed vessel because of arteriosclerosis, valvular defects).

Conclusions

Many different parameters have to be identified for that model. Therefore it is very complicate to gain individual models for a patient because of lack of data, but general examinations can be realized with standardized models. A possibility would be to try an semiautomatic parameter identification using an expert system. But the success depends mainly on the quality and the amount of measurements available in each case.

The computation time for such rough networks is about 10 minutes on a common personal computer (P2 400MHz) for a simulation run of 5 seconds. So it is also possible to perform long-term experiments in order to investigate the effects of tachycardias or arrhythmias.

So this computer model offers the opportunities of investigating the effects on the blood flow caused either by normal or pathological processes going on in the human body.

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