MODELLING OF THE HUMAN ARTERIAL NETWORK FOR PREOPERATIVE PREDICTIONS

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ABSTRACT

The aim of this project was the development of a user-friendly software package for physicians that can be used as an advisor in vessel surgery and as a training tool for medical students. The tool contains a graphical user interface, a mathematical model that describes the relationship of morphology and hydraulics in human arterial networks and an expert system for managing automatic parameter identification and bypass optimization. This system enables physicians to calculate mean flow velocity, mean flow, flow direction and blood pressure at any point of a vessel network. By changing the topology of a network the hydraulic effects of stenoses and bypasses are simulated. The results of these simulation experiments may help physicians in their decisions, whether an operation is necessary and which kind of operation is to prefer.

INTRODUCTION

Most times modelling and simulation in human medicine is a very difficult task to do, because the human body is a complex system involving physical and chemical processes. Sometimes only inaccurate or even no explanations are available for things going on in the human body. The fact, that the physiology differs from person to person, makes it more difficult to develop general models which are valid for a large group of persons.

The main purpose of the model of the human arterial network is to describe the relationship of the morphology and the hydraulics. This model offers methods to calculate mean flow velocity, mean flow, flow direction and blood pressure in the arteries. The results are accurate enough to make fundamental statements on blood supply of specific parts of the arterial system and on the flow velocity through the arteries.

MODEL DESCRIPTION

A steady-state model is used to describe the hydraulics of the arterial network. It is based on the work of Martin Suda from the Austrian Research Centers Seibersdorf. (Suda et al. 1993, Suda 1995)

Physiology of the Human Arterial System

The vessels -- arteries, capillaries and veins -- together with the heart form the cardiovascular system. It is a transport system in which a pump (heart) transports blood through a closed system of flexible pipes. The main purpose of the system is to supply all cells in the organism with substances that are necessary for the normal function of the cells (e.g. oxygen, nutritive substances, ...) and to carry off the metabolic substances. (Schmidt 1983)

Picking out only the arterial system (capillaries excluded) of the systemic blood circulation, it can be described as follows: *The arterial system is a network of flexible pipes. At one point blood is pumped into the system. The same amount of blood, that enters the network, leaves it at the end points.*

The heart generates a pulsatile flow of blood through the arteries, but the compliance of the arteries smoothes this pulse. This fact causes a nearly steady flow in heart distant parts of the body.

The blood itself consists of blood plasma (56%) and different cells. Blood is not a fluid in the physical sense, but its characteristics are similar to that of a Newton fluid if it flows through large vessels.

Physical Model – Pipe Network

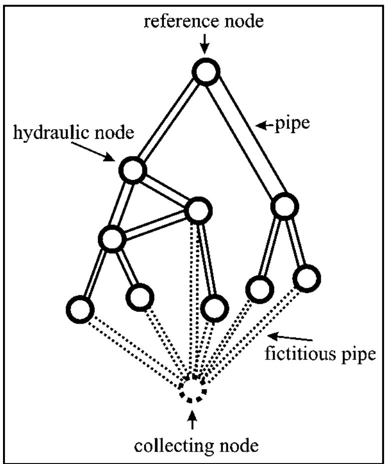

Figure 1 : Arterial system as pipe network incl. fictitious arteries

The physiological facts give the motivation for the identification of the arterial system with a pipe network. Every segment of an artery between two ramification points is represented by a pipe and every ramification point by a hydraulic node. The network is supplied with a constant inflow of fluid (blood) at one node. That means that the pulsatile flow from the heart and the compliance of the arteries are neglected.

The blood can leave the network at any node and flow into other parts of the arterial system or into the venous system which are not take into account. The amount of blood which is lost at the nodes is unknown. Therefore all blood is collected through fictitious arteries.(Almeder 1997)

This pipe network has the following features (see figure 1):

- There is only one node (reference node) with a constant flow into it and given pressure.
- The outflow of all nodes is collected in one fictitious node. The additional node is connected to the other nodes through fictitious vessels of the same length, but with variable diameters. Those are used to regulate the resistance of other parts of the arterial system.
- Blood is modelled as a Newtonian fluid.
- The arteries are hydraulic smooth pipes, that means that the roughness of the walls is zero.

Mathematical Model

Graph theory is used to get a mathematical representation of the network topology. The pipe network is translated into a directed graph and the structures is stored in a node-edge-incidence matrix.

The nonlinear hydraulic equations are based on three conditions:

Node condition:

The sum of inflows into a hydraulic node is equal to the sum of outflows.

Mesh condition:

The sum of pressure drops of each segment along any closed pathway in the network must be zero.

Hydraulic condition:

The pressure drop along a pipeline is proportional to its length and at constant flow inversely proportional to the density of the fluid and to the friction factor which distinguishes between laminar flow (Poiseuille's law) and turbulent flow depending on the Reynolds number

These basic conditions lead to a system of non-linear equations. The number of unknowns depends on the number of nodes in the network (usually between 150 and 300). In most cases when a arterial system is modelled, only laminar flows occur in the whole network. Then the resulting equation system is linear and sparse. If turbulent flows or flows in the transition range occur, the solution of the system is approximated using a fix-point iteration.(Almeder 1997)

Parameter Identification

Usually the parameter identification for this model is a difficult task, because most times only few data from measurements are available for a specific patient. Therefore standardized arterial networks are used as basic data. These networks has to be adapted to the physiology of a patient by data from X-ray pictures and ultrasonic Doppler measurements. Hence, only an approximation of the network topology and a few measurements of the flow velocity are available to model the arterial system of a patient. But as test have show, it is possible to get results which are accurate enough for fundamental statements on the blood supply in specific parts of the patient's body.

PROGRAM STRUCTURE

The implementation of the mathematical model is the basis of the software package, but some other modules are necessary so that the program can be used easily. Figure 2 shows the parts of the program and the communication between them and the user.

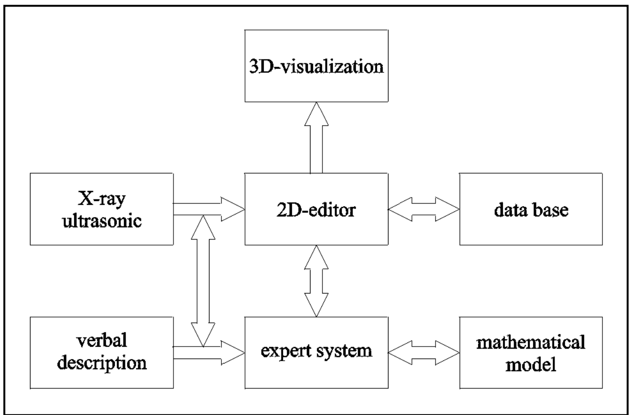

Figure 2: Functional diagram of program structure

EXPERT SYSTEM AND MATHEMATICAL MODULE

The mathematical module is the main part of the program. It contains the implementation of the model optimized with respect to calculation time and memory usage, so that this software can be used on a PC.

The expert system controls the mathematical module. It automates the parameter identification and adapts the standard networks to the measurements. Another task of the expert system is the processing of simulation experiments. So automatic bypass optimizations can be performed to find an optimal operation method.

USER INTERFACE

Our prime directive in user interface development was to implement a workplace that allows complete intuitive software usage, even the user is a "Non-Computer-Expert". To achieve this goal the tool supports Windows "Look and Feel" and a consistent realization in user guidance.

The user interface provides to main parts.

- Patient Database
- Graphical Editor

The patient database is designed to manage the personal data and the different vessel models. The editor workspace supports a corresponding visual description of real live vessel systems. Additionally there are several opportunities in editing the current model interactively by various mouse actions.(Almeder et al. 1998)

Graphical Editor

The editor enables interactive editing to the doctor in a 2D environment using a pointing device. All changes made are displayed in real time and full graphical representation (WYSIWYG). A simple mouse click over an desired vessel provides entire data manipulation facilities. Different individual model views are supported by scrolling and zooming capabilities. Flow charts and bar diagrams supply post processing support.

Object oriented design and development had been applied to this project. Subsequently we used C++ to its implementation. The algorithmic issues are covered through basic graph theory considerations. Each model consists of a finite number of edges (vessels) and a corresponding number of nodes (start/end point). Due this knowledge we are able to design the OMT object diagram (see figure 3).

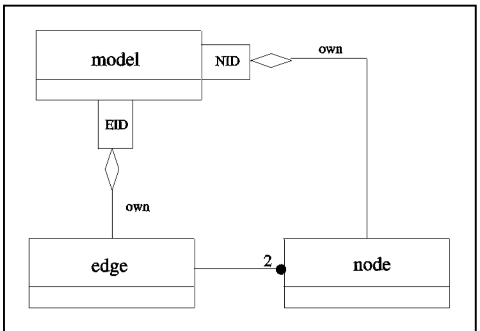

Figure 3: OMT-Diagram

As the reader sees, we deal with a well known "part of" problem. Due we don't have to consider n:m relations we can use template container structures provided by C++. Additionally we interconnect corresponding edges and nodes through pointer references.

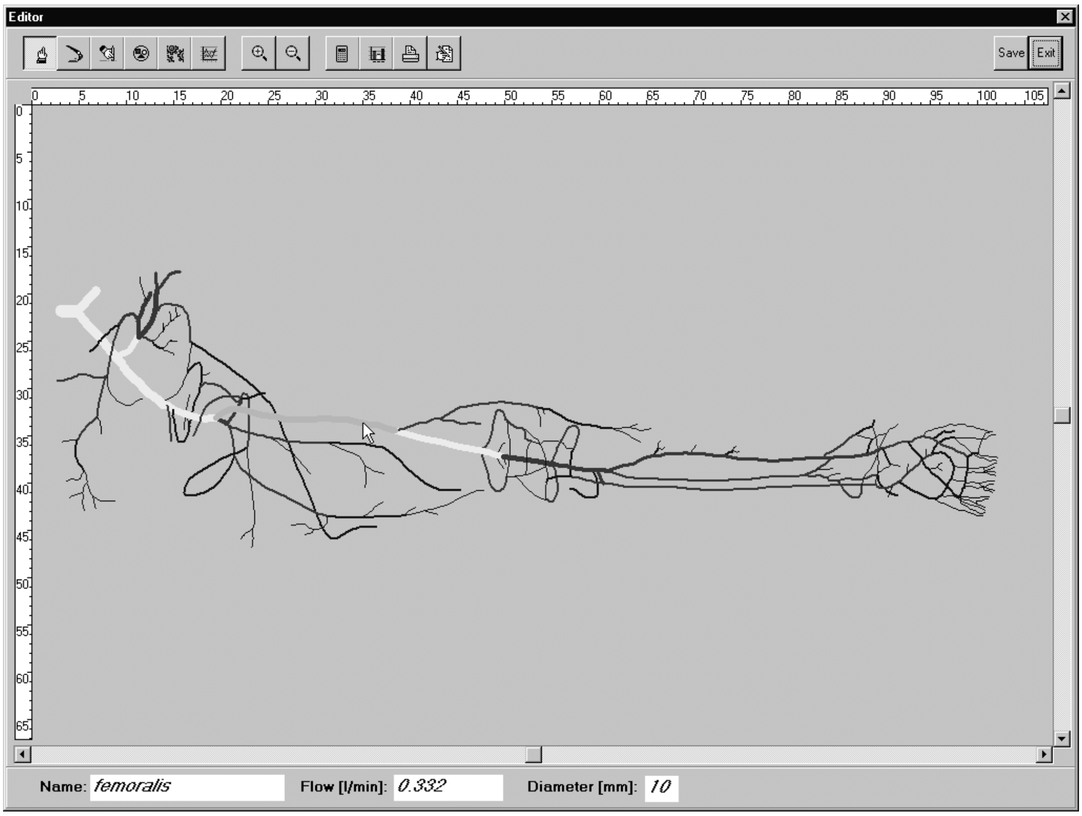

Figure 4 : Screen shot of Graphical Editor

Patient Module

The major purpose of the patient module is to provide easy to use features in data handling. The module enables to view all relevant patient data at once and edit it concurrent. To guarantee fast and easy data manipulation we support total browsing and indexed search.

Database Modeling and Implementation have been optimized concerning performance and resource requirements. To achieve this goals we implemented a hybrid database design using conventional, relational database design and persistent objects. Principal relations are shown in figure 5, whereby the entity Model is an persistent object unique to each tuple.

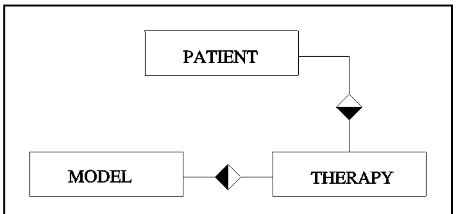

Figure 5: EER-Diagram

CONCLUSIONS

The model of the human arterial system described in this paper was designed to meet two expectations. The model includes all necessary physiological details so that the results can be used for general statements on the condition of a patient's blood circulation. On the other hand the model is simple enough so that it can be used for different patients. The experimental use of the model has shown that it is appropriate to fulfil both aspects.

The presented software realization of the model is already in use by physicians for scientific investigations. This tests have shown that this software package can be used as advisor for vascular surgery.

OUTLOOK

Our researches now concentrated on the extension of the model by the consideration of the pulsatile blood flow from the heart and the compliance of the arteries. But this leads to models with systems of partial differential equations. Therefore the model calculation will take much more time and also more and more precise data will be necessary to identify the parameters.

Another extension will be the connection with models that describe the regulation of the blood circulation and the heartbeat.

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