DIAGNOSTIKA ĽUDSKÉHO CIEVNEHO SYSTÉMU POMOCOU POČÍTAČA
COMPUTER-AIDED DIAGNOSTICS OF HUMAN ARTERIAL SYSTEM

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Summary. The paper deals with the modelling and the simulation of physiological fluid systems laying emphasise on the human vascular system. The presented simulation method has been developed as a helpful tool for the computer-aided non-invasive diagnostics of living bodies. Using the electromechanical analogy between physiological and electrical values the introduced method makes possible the description and 3D representation of the non-linear characteristics of the human haemodynamics as well. The simulation procedure and the obtained results verified by the experiment enable to visualize all physiological and pathophysiological states of the human vascular system.

Abstrakt. Článok pojednáva o modelovaní a simulácii sústavy fyziologických tekutín, s dôrazom na cievny systém človeka. Uvedená simulačná metóda bola vyvinutá ako nástroj pre počítačom podporovanú neinvazívnu diagnostiku živých objektov. S použitím elektromechanickej analógie medzi fyziologickými a elektrickými veličinami umožňuje uvedená metóda opis a 3D zobrazenie nelineárnych charakteristík haemodynamiky človeka. Simulačný postup a získané výsledky, verifikované experimentom, umožňujú vizualizovať fyziologické a patofyziologické stavy ľudského cievneho systému.

1. INTRODUCTION

Due to the increasing importance of utilization of the computer assistance in medical applications the numerical simulation has become an important method for the interpretation of biomedical experimental data. Considering the fact that not all circulation states can be analysed directly in living beings the virtual vascular modelling has been developed for both the calculation and the visualisation of blood characteristics. The introduced simulation procedure enables to describe all physiological states in various vessels between the heart and microcirculation.

2. MODELLING

Following from the formerly obtained progress dealing with the use of the electromechanical analogy between the fluid mechanical and two-port electromagnetic systems [1], [4], [5] and [7], the complex electromagnetic model of the human vascular system has been created. The corresponding mathematical model has been developed on the basis of the analogous transmission propagation equations in the state space. The time continuous description realized by the set of differential equations has been transformed into the general time discrete mathematical model and the corresponding block representation according to Fig. 1, where **A(k)**, **B(k)** are the system matrixes the elements of which are dependent on the equivalent parameters of the analogous electromagnetic system [1], [2], [6] and [8]. The input and output values $u_i(k)$, $y_i(k)$ are connected with the boundary conditions, the state values x_i correspond to analogous electromagnetic ones and k represents the instant of time.

The most important haemodynamic values are the blood pressure, volume and flow, which are analogically represented by the electrical potential, charge and current, correspondingly. The system dynamic behaviour depends on the morphology and topology of the cardiovascular system. The described method for the modelling of single vascular segments enables to create the modelling of the vascular network space structures. The base of the realization of the stochastic topology model consists in the growth of an initial tree of a real vessel structure. The used algorithms describe the growth within the determined volume under hypothetical optimisation criteria. The aim of the modelling is to keep both the real input behaviour and the proper division of the pulsating blood flow in various perfusion areas, [6]. The backward influence of control processes on the blood flow dynamics in the big vessels have been simulated and the local blood division up to the capillary level can be represented in this way [3].

The described modelling method involves also the non-linear system characteristics due to the non-linear vessel walls resistance. The non-linear processes have been described by both the continuity and the motion equations considering the pressure-volume (P-V) relations in vessels where the non-linear P-V dependence is caused by the vessel dilatation. In addition the dynamic changes of the pressure and volume lead to the time delay between the vessel dilatation and pressure which is represented by the P-V diagram in the form of the open hysteretic curve. Both the hysteretic and the non-linear properties have been involved in the mathematical model and the block system representation by the additional variables and the additional partial subsystems $f(x_l)$, $f(x_t)$ in Fig. 1, correspondingly.

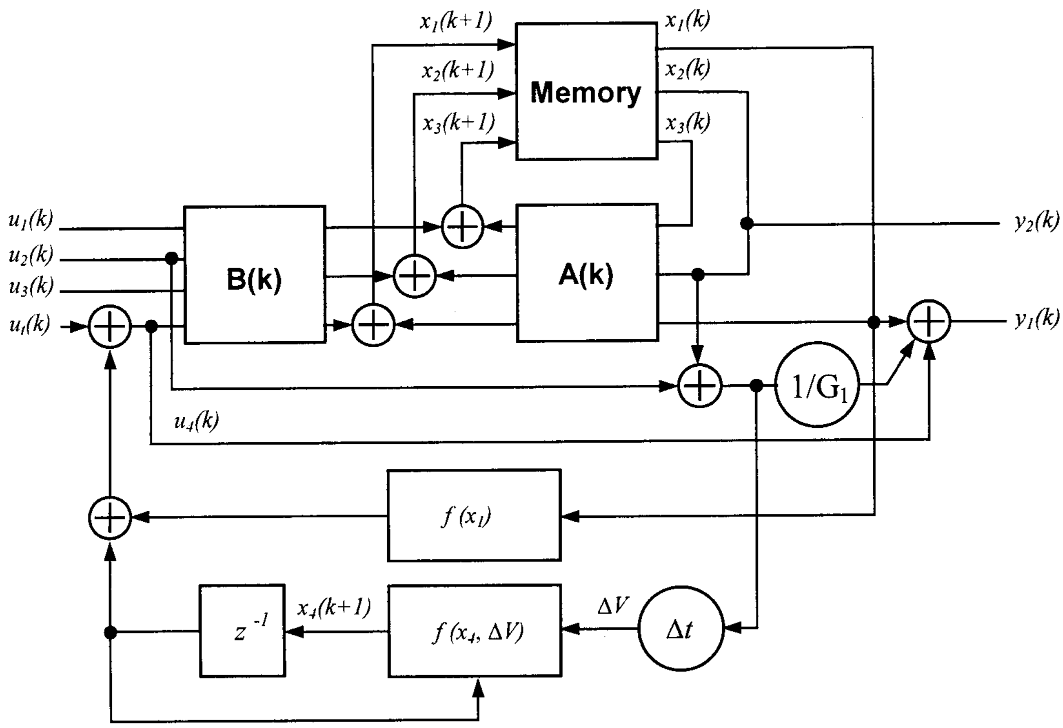

Fig. 1. Block representation of the time-discrete model of one vessel segment.

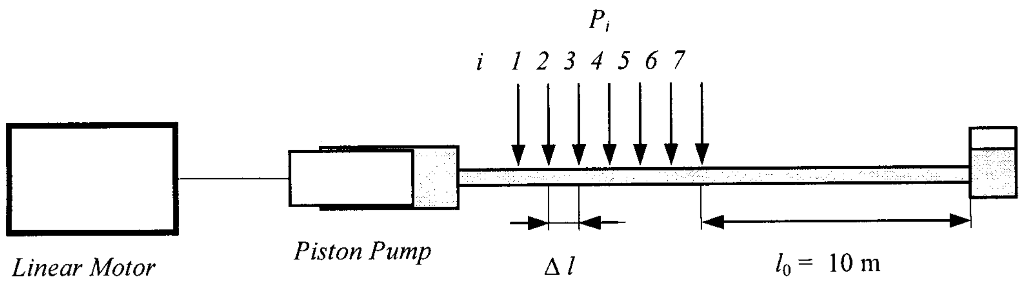

Fig. 2. The experimental model for the measurement of the pressure pulses propagation.

3. SIMULATION AND EXPERIMENTAL RESULTS

According to the Fig. 1 the time discrete representation of one vessel segment has been considered. The whole vessel tree has been divided into single elementary segments. Using the analogy to the transmission lines theory the whole system consists of the cascade connections of many elementary segments. The input periodic or aperiodic pulse sequences produce transmitted pulses which propagate along the vessel tree through all inhomogeneities, e.g. ramifications or stenosis, resulting in the multiple reflections of the propagating waves which determine the system dynamics.

In order to confirm the computational results many experimental measurements using the artificial vessel model have been performed. The main goal of the presented experiment was to verify the characteristics of the pressure pulses propagation along the vessel obtained by the used simulation algorithms. The experimental set up is shown at Fig. 2.

The computer-aided linear motor could generate both the pressure and volume pulses or pulse-sequences, which were transmitted by the pump along the aorta

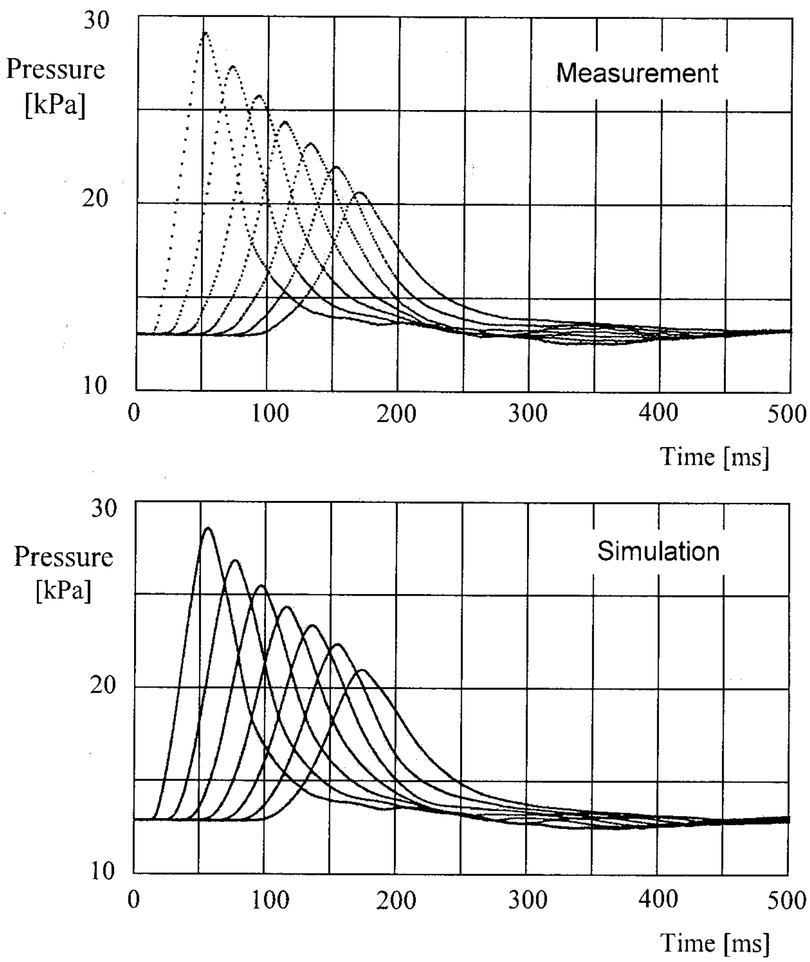

Fig. 3. Measured and simulated pressure signal time-dependence detected by the pressure sensors P_i according to Fig. 2.

model created by the silicon rubber tube with the length of 2 m and the radius of 3 mm. The blood flow was substituted by the glycerine-water mixture. The pressure sensors P_i were placed in the regular intervals along the model the ending of which by the very long (10 m) silicon tube had to suppress the pulse reflections.

The simulation and measuring results, Fig. 3, have been obtained using the input signals created by the short volume flow pulses with different pulse lengths and amplitudes. The measured volume signals were used as the input signals for the simulation procedures.

One example of the corresponding 3D simulation image, Fig. 4, represents the pressure pulse propagation from the aorta to the leg vessels under normal conditions, Fig. 4(a), in the case of higher elasticity of the aorta, Fig. 4(b) and in the case of the higher elasticity of the leg vessels, Fig. 4(c).

4. CONCLUSION

The modelling and simulation method of physiological dynamic fluid system by the electromechanical analogy using transmission characteristics have been used and experimentally verified in the paper. According to the mechanical blood flow properties the electromagnetic and corresponding mathematical models of the human vascular system have been created involving also the non-linear and hysteretic behaviour of the blood characteristics in vessels.

The fluid physiological systems cannot be investigated and visualized "in vivo" during the dynamic changes in a living body. For the comparison of the simulation results with the experimental measurements it is necessary to use the standard vessel models with the reasonably estimated vascular parameters in a close co-operation with physicians. The model measurements offer the possibility of the qualitative investigation and the enlightenment of the similarity to the introduced mathematical model.

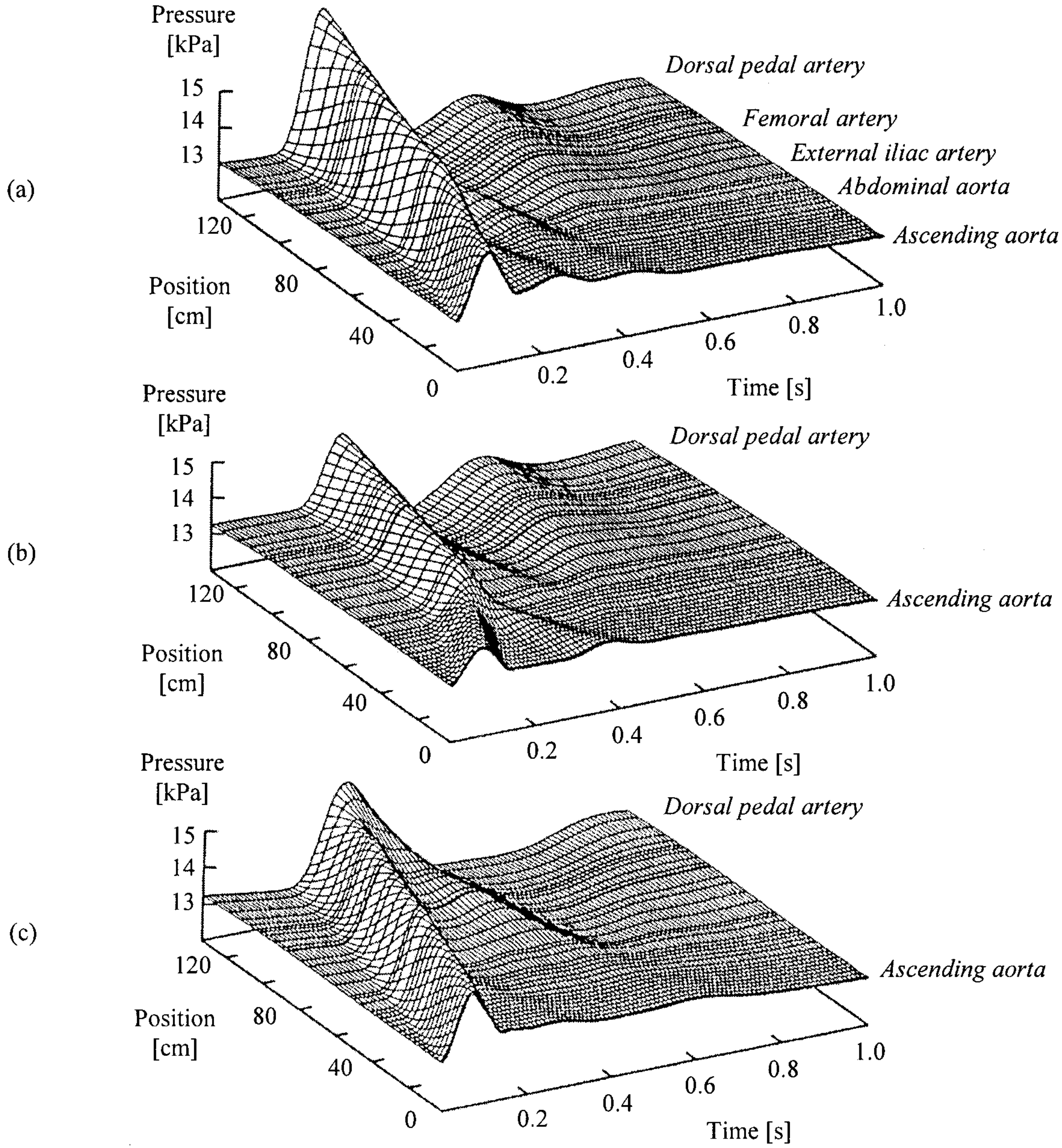

Fig. 4. Propagation and reflections of the pressure pulse in different parts of the arterial system from the ascending aorta down to the dorsal pedal artery under normal conditions (a), in case the of higher elasticity of aorta (b) and in the case of higher elasticity of pedal artery (c).

The 3D representation of the pressure pulses propagation and reflections of the vessel system were performed under various physiological and pathophysiological conditions. The example introduced in the paper represents the pulse propagation under changing elasticity of various parts of the vascular system.

The adequate agreement of the simulation and the experimental results of the human haemodynamics predetermine the described universal simulation method as a helpful tool for the computer-aided non-invasive diagnostics of living linear and non-linear dynamic systems. In the co-operation with other diagnostic methods in the clinical medicine the described simulation results give the useful recommendations for the decision and planning of the proper cardiovascular system treatment.

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