New Researches on Mathematical Models and Numerical Simulations of Blood Flow in Human Vessels with Different Pathologies. Is the Stroke Predictable?

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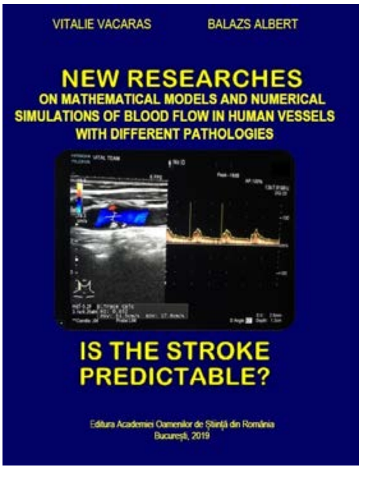

The current work offered for publishing is the result of in-depth interdisciplinary investigations performed by neuroscientists and cardiologists in cooperation with specialists in applied mathematics, fluid dynamics and numerical analysis.

The authors Vitalie VACARAS, M.D., specialized in neurosciences and the physicist Balazs ALBERT, Ph.D. in applied mathematics/fluid dynamics sought to construct mathematical models of the blood flow through various vessel types that would allow numerical simulations of the effective flow. Throughout the content organized in fourteen chapters the authors analyze large (arteries) as well as small (arterioles and capillaries) blood vessels in pathological circumstances often encountered in medical practice.

The numerical simulations performed using the package COMSOL Multiphysics (versions 3.3 and 4.4) yield supplementary information about the pathologies in question. Special emphasis is put on the numerical determination of the wall shear stress (WSS), one of the main pathogenic factors in the development of cerebrovascular accidents (strokes).

The first four chapters cover the necessary fundamental concepts of blood and blood vessels physics, dynamics of blood flow through the circulatory system and mechanics of the blood vessel walls. The rest of the work is devoted to the concrete implementation of the blood flow mathematical models using the COMSOL Multiphysics software. The step by step instructions allow users with no special mathematical or information science training to analyze specific medical cases involving blood vessel pathologies. That makes this work a valuable instrument for obtaining additional significant information that can be used to prescribe the appropriate course of patient treatment.

A major topic throughout the work is WSS, a main determinant of strokes – currently a major medical problem. The reader will be able to learn how to pinpoint the time and location of major risk events prior to the actual occurrence of a cerebrovascular accident as well as in a post-surgical environment.

The methodology presented in this work, which is addressed to cardiologists and neurologists, can be of real help in the treatment of patients. The work is an example of a truly interdisciplinary project. Besides the elegance of the mathematical models on which it is based, this approach can make a real contribution to the healing of gravely ill patients.

As far as we know there are no similar works in the literature that could serve as a useful instrument in dealing with pathologies of the type mentioned above.

Significant progress in understanding how the cardiovascular system functions in both normal and pathological physiological circumstances was achieved recently by using mathematical models combined with the appropriate numerical algorithms.

The resulting numerical simulations can aid physicians – neurologists, hematologists, surgeons – to choose the most appropriate treatments for patients with circulatory problems.

This new perspective gave birth to a new discipline -– computational hemodynamics. It is based on the mathematical models of fluid dynamics, particularly of blood flow, and the appropriate computational methods. Much progress has been made in both the modeling and computational aspects of hemodynamics. However, many difficulties related to the study of the cardiovascular system remain unresolved. Undoubtedly, they will be the subject of future research.

This book provides a practical instrument to neurologists, hematologists and surgeons for selecting the optimal treatment modalities of blood circulation pathologies. Identification of the maximum risk regions and assignation of specific values to the risk parameters at the earliest stages of treatment are crucial for a positive outcome. The techniques presented in this work are designed to achieve those objectives.

Using medical imaging information such as the geometry of the affected vessel, the shape of the stenosis or aneurysm, etc., the algorithm presented here makes possible the quantification of the immediate risk of potential, sometime lethal, complications.

Most of the models used in this work focus on the calculation of the wall shear stress (WSS) which plays a major role in the breaking off of atheromatous plaques. Besides wide vessels (arteries), we take into consideration narrow vessels (arterioles) and capillary vessels.

Throughout the work blood is treated as a non-Newtonian fluid (following a viscosity law of type Cross) flowing through vessels with viscoelastic, elastic or poroelastic walls, i.e., arteries, arterioles or capillaries, respectively.

The numerical simulations were performed running the Comsol Multiphysics 3.3 simulation software on a personal computer with an Intel Core 2 2.13 GHz processor, 3GB RAM memory and a 600 GB hard disk drive. There was no need for any specialized hardware.

The book presents succinctly basic relevant medical concepts, e.g., blood, blood vessels, stenosis, aneurysm. The reader is introduced also to fluid dynamics concepts such as the mathematical model for the study of fluid motions in wide, narrow and capillary vessels with initial conditions and at the adequate boundaries, and the analysis of the mechanical properties of the three types of vessel walls, i.e., viscoelastic, elastic or poroelastic, respectively.

All the mathematical and mechanical concepts are presented briefly and without proofs. No prior specialty training is necessary unless new approaches or different generalizations are attempted in response to new medical challenges.

Because of the interdisciplinary character of the work in-depth knowledge of the concepts mentioned above is not required unless potential extensions of the algorithm are attempted in face of significantly more complex medical circumstances.

The models effectively built in this study pertain to frequently encountered specific medical cases. The technique and steps to follow are the same in other similar or even more complex circumstances.

The following medical problems were analyzed and modeled successively: internal carotid artery (ICA) with stenosis; abdominal artery presenting a double aneurysm (AAA); pseudoaneurysm related to a prosthetic device; Fahraeus-Lindqvist effect in arterioles; blood flow in capillaries; an artery with stenosis in a post-stenting situation; obturation of arterioles; basilar artery with stenosis.

The majority of calculations were performed assuming a particular geometry, namely axial symmetry. This was done for logistical reasons but also because the objective was to allow anybody who wishes to simulate a problem related to the pathology of blood movement in vessels to do so even with limited computer resources. The same exact steps may be followed for any three-dimensional geometry but a faster computer with more memory should be used to allow the use of the Comsol 4.3, instead of the Comsol 3.3 package.

Special emphasis was put on cases related to pathologies in brain blood vessels implicated directly in cerebrovascular accidents (strokes). The research subjects were provided by the Neurology Clinic of the Iuliu Hațieganu University of Medicine and Pharmacy, Cluj-Napoca. The results of numerical simulations had a decisive influence during the treatment.

This works is addressed especially to physicians interested in the pathology of blood vessels: neurologists, hematologists, surgeons, etc. By following the prescribed steps, it allows them to pinpoint the regions of maximum risk, to assign the respective risk parameters and, implicitly, decide on intervention methods. This can be done without specialized knowledge in mathematics or fluid mechanics.

The book is also meant for specialists in computational fluid dynamics. They may be interested in developing the existing mathematical-mechanical models beyond the current pathologies covered by computational hemodynamics in order to meet new medical challenges.

This research was conducted under the auspices of the Academy of Romanian Scientists over a period of six years.

The authors are Vitalie VACARAS, M.D. specialized in neurology who provided the research subjects and the physicist Balazs ALBERT, Ph.D. (mathematics, specialized in fluid dynamics).

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