Simulation of Three-Dimensional Flow of Blood in Epicardial Arteries

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Abstract Several pathophysiological processes in the cardiovascular system are strongly influenced by hemodynamic factors. This is particularly true in the case of the formation and development of a thrombus in a stenosed epicardial artery. All investigations of such a thrombus formation must be based on a fair knowledge of the blood flow in the stenosed artery, especially of the three-dimensional flow characteristics around the stenosis. The paper deals with modeling and simulation of the three-dimensional flow of blood in stenosed epicardial arteries; the modeling approach is described and an overview of the simulation techniques is given. For the simulation of the flow, we employed "FIDAP" (Fluid Dynamics Analysis Package), a software package for computational fluid dynamics. We are able to carry out simulation studies for stenosed epicardial arteries with arbitrary geometry and dimension. Moreover, we can adapt our simulation system to the geometry and the dimensions of the stenosed epicardial artery of an individual patient on the basis of high-quality coronary arteriograms. In contrast, all previous simulation approaches to the three-dimensional blood flow in stenosed vessels suffer from considerable imperfections: many simulation models only allow axi-symmetric analyses. The simulation approach described by Ang and Mazumdar [1997] is one of the few which can investigate the flow around asymmetric stenoses; however, this simulation study is subject to constraints of the shape of the stenosis. There is another inherent and unsolved problem in all previous simulation studies of three-dimensional flow in stenosed (epicardial) arteries, namely the specification of meaningful boundary conditions. We were able to solve this problem rather easily by using a newly developed lumped parameter model (Quatember and Veit [1995]) of the entire coronary circulation to calculate the necessary boundary conditions for the stenosed artery. In the paper, the performance capacity of our simulation approach is demonstrated by presenting simulation results of the three-dimensional blood flow around a severe eccentric stenosis with an arbitrarily chosen and highly irregular shape.

1. INTRODUCTION

All early investigations in the domain of hemodynamics aimed at an insight into the behavior of the whole cardiovascular loop. They focused on the heart, the large blood vessels and on the majority of the other vessels distant from the heart, but neglected the specific characteristics of the coronary blood flow. The coronary circulation, which takes place in the vascular bed of the heart itself, is a component of the systemic circulation with unique properties that are quite different from those of all other vascular sections in the systemic vascular bed. In contrast to all other parts of the body, the perfusion of the myocardium occurs mostly during the diastolic phase, because the vascular compression caused by the contraction of the myocardium restricts the coronary blood flow during the systolic phase. The flow of blood in the coronary vessels is thus very complex and not yet very well understood. However, since the coronary flow amounts only to about 8% of the flow in the whole systemic circulation, it is not an influential factor in quantitative descriptions of the hemodynamics of the whole cardiovascular loop. Hence, the known simulation models of the whole cardiovascular loop do not consider the unique properties of the coronary circulation. Nevertheless, the coronary circulation is of particular importance, since the coronary vasculature delivers blood to the myocardium and thus covers its metabolic needs. The metabolic demands of the myocardium are very high; the functioning of the heart as a pump depends on unimpaired coronary circulation. A fair quantitative knowledge of the coronary blood flow and especially of pathophysiological changes of the coronary circulation is thus extremely important to clinical medicine.

The investigations of the coronary hemodynamics proved to be more difficult than expected. Reliable experimental investigations and measurements of the coronary flow are not yet practicable. Hence, the use of simulation models is the only way to arrive at quantitative results. However, the development of simulation models for the coronary circulation is a challenging task. Due to the highly complex structure of the coronary network, only a lumped parameter approach can be used to simulate the blood flow in the entire coronary system. The performance capacities of contemporary lumped parameter models of the coronary hemodynamics are rather limited (Fung [1997]; Spaan [1985]; Spaan [1991]; Wang et al. [1989]). We developed a lumped parameter model of the coronary hemodynamics (Quatember and Veit [1995]) which we are continuing to develop and refine. Even at its present stage of development, the model can be used to solve problems in the area of clinical medicine, e.g. the reduction of coronary blood flow caused by stenoses in the epicardial arteries. Fig. 1 shows simulation results that have been obtained with this new model, namely the patterns of blood flow into the capillary bed of the section of the myocardium supplied by the obtuse marginal branch of the coronary network. The flow patterns depicted in Fig. 1 refer to simulation runs for the case of physiological conditions and for two cases of relatively mild stenoses (55% stenosis and 70% stenosis). The results have been

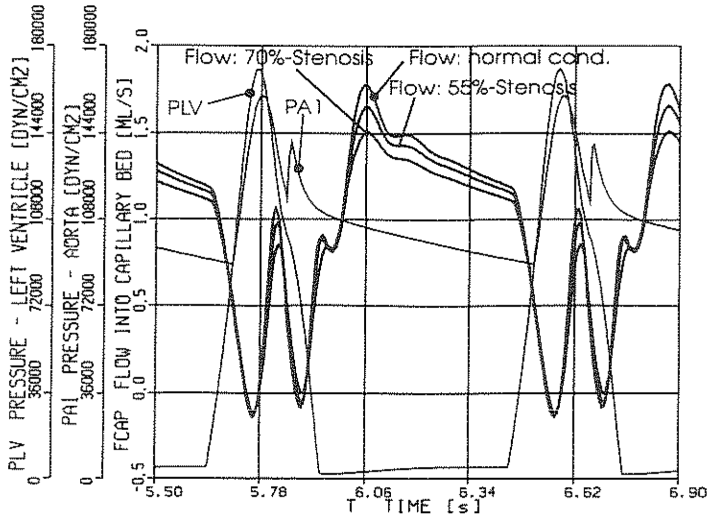

Fig. 1. Patterns of blood flow into the capillary bed of one of the 8 sections of the myocardium supplied by the left coronary network: comparison between physiological (normal) conditions, a 55%-stenosis, and a 70%-stenosis; (Left ventricular pressure curve "PLV" and aortic pressure curve "PA1": thin lines).

calculated under the questionable assumption that in these cases of mild stenoses, coronary regulatory mechanisms do not yet come into play.

In a lumped parameter model, the quantities describing the flow field only vary with time; they do not change from point to point over each section of the coronary circulation that is represented in the model as a lumped component. The blood flow is said to be uniform in such a region. This simplification of a uniform flow in each section can be justified for an overall description of the hemodynamic behavior in the entire coronary system. However, this simplification cannot be made in specific medical problem areas which require a detailed knowledge of the three-dimensional characteristics of the blood flow in particular sections of the epicardial arteries. In the following, two examples of such medical problem areas will be given, namely the assessment of specific adverse effects of stenoses and changes in coronary bypass grafts on the coronary flow. We will then confine ourselves to the case of stenoses, dealing with the simulation of the three-dimensional blood flow in the domain of a severe eccentric stenosis.

2. MEDICAL PROBLEM AREAS REQUIRING KNOWLEDGE OF THREE-DIMENSIONAL CHARACTERISTICS OF BLOOD FLOW

As already mentioned, there are several important medical questions that cannot be answered based on the assumption of a uniform flow in the individual regions (sections) of the coronary system. Examples of such medical problems are

Problem A: the assessment, therapy and prevention of thrombus formation and development in the domain of a stenosis (Gertz [1995]; Gould [1991]), and

Problem B: the assessment of the mechanisms of plaque formation and occlusion in coronary bypass grafts, especially determining the extent to which hemodynamic factors influence the progression of coronary bypass graft disease in the acute thrombotic phase as well as in the phases of intimal hyperblasia and atherosclerosis (Gertz [1995]; Lüscher et al.[1994]).

For such investigations, the above-mentioned simplification of a uniform flow in the individual sections of the coronary system is no longer permissible. Instead, we now need a fair knowledge of the three-dimensional flow of blood in the region of a stenosis (Problem A) and in the coronary bypass graft, especially in the regions of the graft-artery junctions (Problem B).

In this paper, we will confine ourselves to Problem A, namely the thrombus formation and development in the domain of a stenosis, and focus on the case of a severe eccentric stenosis in the circumflex artery. When blood passes through such a stenosis, it suddenly accelerates, and then decelerates as soon as it has passed the stenosis (Gould [1991]; Milnor [1989]; Seely and Young [1976]). At the center of the stenosis, we have to reckon with relatively high shear rates. Downstream from the stenosis, a recirculation zone (vortex) will be present. These unique flow conditions make the domain of the stenosis susceptible to thrombus formation and development. In the center of the stenosis, there is potential for growth of a "whitish" thrombus. Downstream from the center and close to the recirculation zone (vortex), a "reddish", fibrin-rich thrombus has great growth potential, as pointed out in Fuster and Verstraete [1992].

The processes in thrombus formation and development are very complicated and still not very well understood. More thorough investigations of these phenomena are necessary, and it is obvious that such investigations must be based on a fair knowledge of the three-dimensional flow.

3. MODELING APPROACH AND SIMULATION TECHNIQUES

We developed a simulation method that allows us to simulate the three-dimensional flow in a stenosed epicardial artery, especially in the domain of the stenosis which may have an arbitrary shape or, more specifically, arbitrary geometry and dimensions. In clinical medicine, we have to expect a considerable amount of inter-individual variability in the geometry and dimensions of stenoses as well as in the shape and branching structure of the epicardial arteries themselves. In our modeling and simulation approach, we can take these variations into full consideration by using clinical data obtained from a three-dimensional reconstruction of the stenosed vessel based on high-quality coronary arteriograms, preferably two views taken at a 90^{0} angle. This ability may be regarded as an improvement compared with the known simulation methods for the three-dimensional blood flow around a stenosis. As will be described in more detail below, other improvements could also be attained, especially the advantage of being able to calculate meaningful boundary conditions based on our above-mentioned lumped parameter model.

3.1 Properties of Coronary Blood Flow and Fundamental Equations

Our modeling approach, like most other simulations of coronary hemodynamics, is based on the assumption that the blood flowing in the coronary systems behaves like an incompressible Newtonian fluid. While this is certainly not completely true, it can be regarded as a very good approximation. Moreover, we justifiably assume that the coronary flow is laminar throughout the whole cardiac cycle, since the short bursts of turbulence which may occur are not really significant.

The flow field in the stenosed epicardial artery is derived here using the continuity and the Navier-Stokes equations in three-dimensional form. These are the governing equations of our simulation approach. They are solved numerically by employing the finite element method.

3.2 Previous Simulation Models of Three-Dimensional Coronary Blood Flow in Comparison with Our Modeling Approach

All previous simulation approaches to the three-dimensional blood flow in stenosed vessels suffer from considerable imperfections: many simulation models only allow axi-symmetric analyses. The simulation approach described by Ang and Mazumdar [1997] is one of the few endeavors to investigate the flow around asymmetric stenoses, but even it is subject to constraints of the shape of the stenosis.

In contrast to all previous simulation efforts, we are able to carry out simulation studies for stenosed epicardial arteries with arbitrary geometry and dimension. Moreover, we can adapt our simulation system to the geometry and the dimensions of the stenosed epicardial artery of an individual patient on the basis of high-quality coronary arteriograms.

There is another inherent and unsolved problem in all earlier simulation studies of three-dimensional flow in stenosed arteries, namely the specification of meaningful boundary conditions. However, we were able to solve this problem rather easily by using a newly-developed lumped parameter model (Quatember and Veit [1995]) of the entire coronary circulation to calculate the required boundary conditions required for the stenosed artery. In the paper, we demonstrate the performance capacity of our simulation approach by presenting simulation results of the three-dimensional blood flow around a severe eccentric stenosis with an arbitrarily chosen and highly irregular shape.

3.3 Pivotal Points of Our Modeling Approach; Assumptions, Simplifications, Approximations

The pivotal points of our simulation method are

(a) Finite element methods are used to solve the continuity and the Navier-Stokes equations.

(b) The software package "FIDAP" (Fluid Dynamics Analysis Package) is used

(c) The stenoses can have any geometry and dimensions.

(d) Our simulation system can be adapted to the shape of stenosis of an individual patient, using high-quality arteriograms.

(e) Appropriate boundary conditions can be computed with a newly-developed lumped parameter model of the entire coronary system (thus avoiding questionable assumptions of boundary conditions in previous simulation approaches).

However, at the present stage of the development, the following simplifications have been made:

(a) We assumed rigid walls of the stenosed epicardial artery; hence, we neglected the effects of fluid/structure interaction (blood/vessel interaction; Dankelman [1989]).

(b) the present studies refer only to the case of steady flow at the end of the diastolic phase; as can be seen in Fig. 1, the variations with time of the coronary flow at the end of the diastolic phase are moderate. Nevertheless, this simplification can only be regarded as a rough (but reasonable) approximation.

3.4 Software Package for the Simulation of Three-Dimensional Fluid Flow Based on the Finite Element Method

We solved the partial differential equation (Navier-Stokes equations and continuity equations for three-dimensional flow) with the software package "FIDAP" (Fluid Dynamics Analysis Package). "FIDAP" is a general purpose finite element program (programming environment) for simulating a wide variety of fluid flows.

The programming environment of "FIDAP" provides the user with advanced (automatic) mesh generators and other pre-processor program modules that allow the interactive specification of boundary conditions and other data required in the solution phase. These software modules facilitate an efficient method of working, but the data preparation and mesh generation phase consumed about 80% of the labor-hours required.

The finite element analysis of a fluid flow problem produces wealth of numerical data. This is particularly true in the case of our three-dimensional model of the blood flow through a stenosed epicardial artery. However, excessively long lists of numerical data are very difficult to analyze. For this reason, the simulation results are usually represented as surface plots, contour plots, diagrams and other graphics. To create them, "FIDAP" provides the user with an exceptional post-processor program module.

3.5 Geometry and Dimensions; Generation of the Mesh

A special pre-processor program module of "FIDAP" allows us

(a) to create a computer representation of the geometry and the dimensions of the flow domain of a stenosed epicardial artery with an arbitrary shape, and then

(b) to generate the mesh automatically, using the so-called PAVEMENT algorithm as described by Blacker and Stephenson [1991].

We will now describe these procedures for the case of a severe eccentric stenosis in the circumflex artery. The real geometry and dimensions of this stenosis have fully been considered; no simplifications or approximations had to be made.

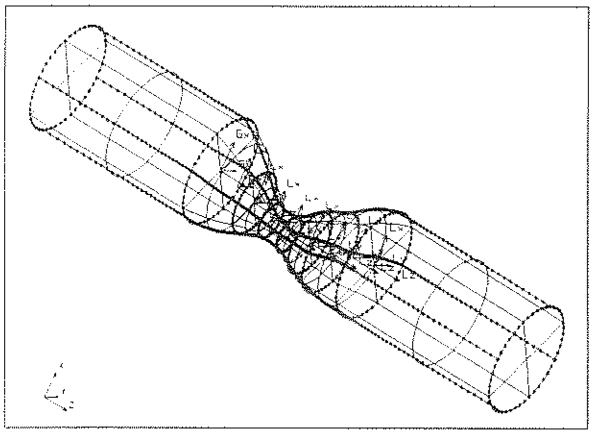

Fig. 2. Geometry and dimensions of the flow domain around the chosen eccentric stenosis in the circumflex artery, subdivided into sections.

Fig. 2 depicts the geometry of the flow domain around the stenosis. In this figure, all the specifications necessary for the generation of the mesh (nodes, mesh edges, mesh faces, and mesh solids) are already contained. The flow domain is subdivided into several sections.

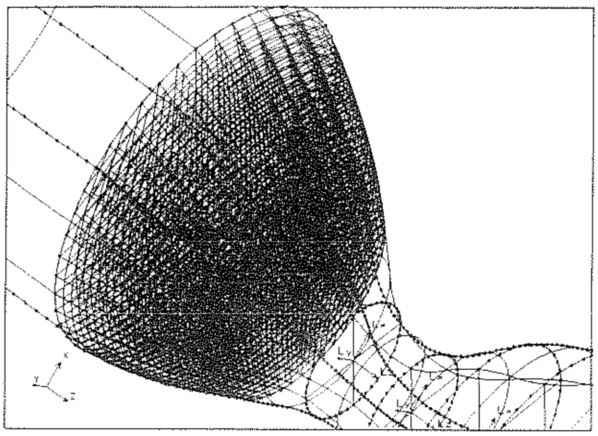

Fig. 3. Geometry and dimensions of the flow domain around the chosen eccentric stenosis in the circumflex artery, subdivided into sections, with a mesh in one section.

Each section (c.f. Fig. 2) is divided into the so-called finite elements, which form a mesh. Fig. 3 is an enlargement of the left half of Fig. 2 and shows a mesh generated in one of these sections. The meshes of the individual sections are generated one after the other. The mesh of each section abuts on the meshes of adjacent sections. In this way, the mesh of the whole flow domain around the stenosis is generated (c.f. Fig. 4).

3.6 Boundary Conditions

In order to perform computer simulations of a steady flow problem, it is necessary to specify boundary conditions.

It is obvious to assume

(a) "no slip" conditions at the wall of the stenosed artery and

(b) "natural" boundary conditions at the outlet. This term means that the normal stress is equal to zero. As the contribution of viscosity to the normal stress is relatively small, "natural" boundary conditions force the pressure to be close to zero at the outlet.

It also obvious to assume a paraboloid velocity profile at the inlet, but we have to bear in mind that this is only a qualitative characteristic. However, an appropriate quantitative specification of the boundary conditions at the inlet is also necessary. In general, it is difficult to arrive at such quantitative specification, since the model describes the flow in a particular stenosed artery that is only one of many sections of the coronary system. In previous models of three-dimensional coronary flow in the domain of a stenosis, the authors made plausible assumptions but could not prove whether or not these assumptions were really meaningful for an individual patient. In contrast to all contemporary modeling concepts, we are able to solve this problem rather easily by using our lumped parameter model to calculate the required boundary conditions.

4. SIMULATION RESULTS AND DISCUSSION

In the following, we first present the mesh and then the simulation results for a stenosed artery (circumflex artery). The stenosis is severe (90% stenosis). The assumed geometry and the dimensions of the stenosis are completely realistic; the stenosis is markedly eccentric.

In all the graphical representations of the mesh (Fig. 4) and the simulation results (Fig. 5 to 8), we used a three-dimensional Cartesian coordinate system (XYZ coordinates).

The Z axis is the longitudinal axis of the stenosed artery; the X axis lies in the longitudinal cross-section that has the greatest eccentricity. The plots in the Figures 4 to 7 depict the mesh and simulation results on this longitudinal cross-sectional plane (X-Z plane).

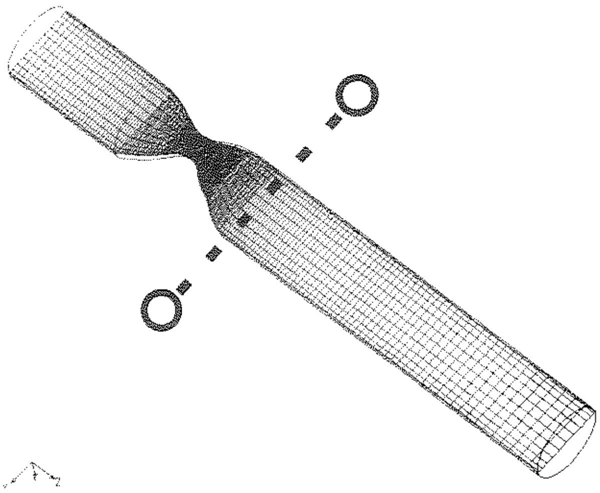

Fig. 4. Finite element mesh discretization on the longitudinal cross-sectional plane (X-Z plane).

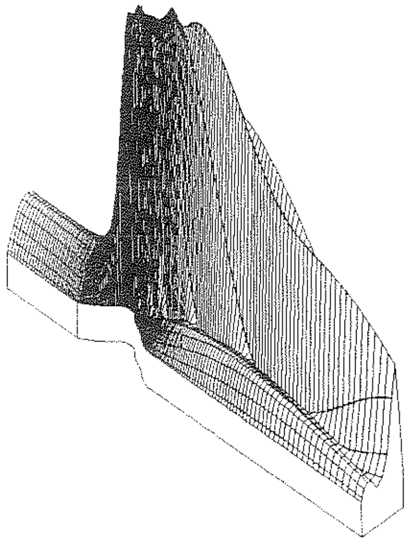

Fig. 5. Surface plot of the variation of the absolute value of velocity on longitudinal cross-sectional plane (X-Z plane); maximum: 691.7 mm/s; minimum: 0.0 mm/s.

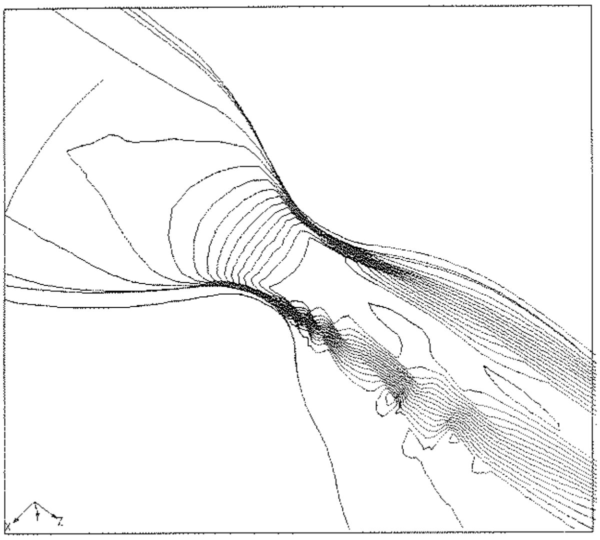

Fig. 6. Surface plot of the variation of the Z component of velocity on longitudinal cross-sectional plane (X-Z plane); maximum: 686.1 mm/s; minimum: -249.5 mm/s.

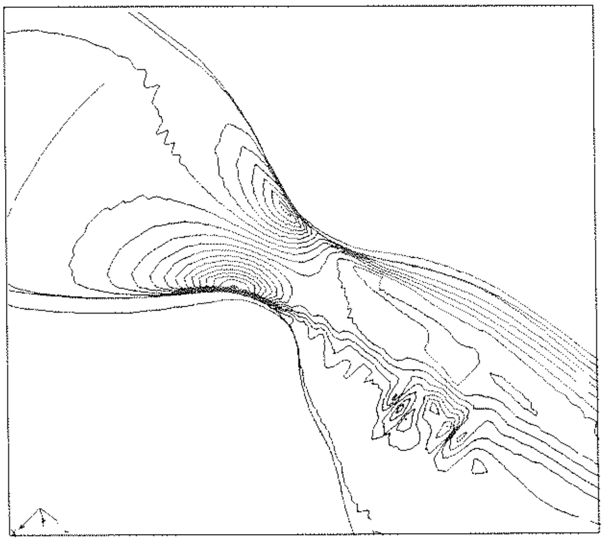

Fig. 7. Surface plot of the variation of the X component of velocity on longitudinal cross-sectional plane (X-Z plane); maximum: -188.0 mm/s; minimum: 88.8 mm/s.

Fig. 5 presents a so-called surface plot (three-dimensional "fishnet" plot) of the variation of the absolute value of velocity (speed) on the above-mentioned longitudinal cross-sectional plane (X-Z plane).

Fig. 6 and 7 represent contour plots of the variation of the Z component and X component of velocity on the above-mentioned longitudinal cross-sectional plane (X-Z plane) in the central region of the stenosis.

Fig. 8 depicts the variation of the Z component of the velocity along the line O-O of Fig. 4. This line lies in the X-Z plane, is parallel to the X axis and is positioned downstream from the stenosis (c.f. Fig. 4). As can be seen in Fig. 8, the flow downstream from the stenosis is partially retrograde.

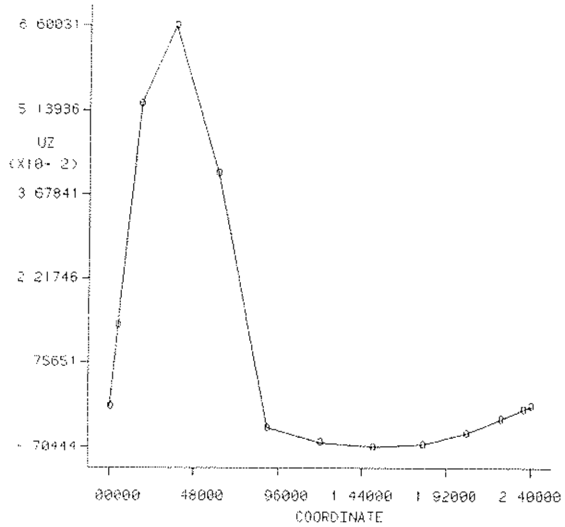

Fig. 8. Variation of the Z component of velocity along the line O-O of Fig. 4;
maximum: 660.0 mm/s; minimum: -70.4 mm/s.

5. CONCLUSIONS

In this paper, we have dealt with important clinical problems caused by stenoses and thrombus formation in stenosed coronary arteries (epicardial arteries). These problems can only be solved with a fair quantitative knowledge of the three-dimensional blood flow in the stenosed artery, which can only be attained by simulation. Since the performance capacity of previous simulation methods in this area is rather limited, we developed a simulation method that allows us to simulate the three-dimensional flow in a stenosed epicardial artery, especially in the domain of the stenosis which may have an arbitrary shape or, more specifically, arbitrary geometry and dimensions. It is also possible to adapt the simulation system to the geometry of the stenosis of an individual patient by using clinical data obtained from a three-dimensional reconstruction of the stenosed vessel based on high-quality coronary arteriograms taken in two views, preferably angled at 90°. In the future, we will continue to refine our simulation method and plan to consider the fluid/structure interaction (blood/vessel interaction). Thus, the simplification of rigid walls will no longer exist. We also plan other improvements.

6. REFERENCES

Ang, K.C., and J.N. Mazumdar, Mathematical Modelling of Three-Dimensional Flow through an Asymmetric Arterial Stenosis, *Mathl. Comput. Modelling 25*(1), 19-29, 1997.

Blacker, T.D., and M.B. Stephenson, PAVING: A New Approach to Automated Quadrilateral Mesh Generation, *Int. J. Num. Meth. Eng. 32*, 811-847, 1991.

Dankelman, J. *On the dynamics of the Coronary Circulation,* Ph.D. Thesis, University of Technology Delft, The Netherlands, 1989.

Gertz, S.D.; A. Kurgan, and S. Banai, Pathogenesis of Coronary Atherosclerosis, in *Physiology and Pathophysiology of the Heart. Third Edition. Developments in Cardiovascular Medicine (Vol. 151),* N. Sperelakis, ed., 1173 pp., Kluwer Academic Publishers, Boston, Dordrecht, 1995.

Gould, K.L., *Coronary Artery Stenosis,* Elsevier, 396 pp., New York, Amsterdam, 1991.

Fung, Y.C., *Biomechanics: Circulation, Second Edition,* Springer, 571 pp., New York, 1997.

Fuster, V. and M. Verstraete, eds., *Thrombosis in Cardiovascular Disorders.,* 565 pp., W.B. Saunders, Philadelphia, 1992.

Lüscher, T.F., M. Turina, and E. Braunwald, ed., *Coronary Artery Graft Disease: Mechanisms and Prevention,* Springer, 396 pp., Berlin, 1994.

Milnor, W.R., *Hemodynamics, Second Edition,* William & Wilkins, 419 pp., Baltimore, 1989.

Quatember, B., and F. Veit. Simulation model of the coronary artery flow dynamics and its applicability in the area of coronary surgery, paper presented at EUROSIM Conference EUROSIM '95, Vienna, Austria, September 11-15, 1995.

Seely, B.D. and D.F. Young, Effect of Geometry on Pressure Losses Across Models of Arterial Stenoses, *Journal of Biomechanics 9*(7), 439-448, 1976.

Spaan, J.A.E., Coronary Diastolic Pressure-Flow Relation and Zero Flow Pressure Explained on the Basis of Intramyocardial Compliance, *Circulation Research 56*(3), 293-309, 1985.

Spaan, J.A.E., ed., *Coronary Blood Flow: Mechanics, Distribution, and Control. Developments in Cardiovascular Medicine (Vol. 124),* 389 pp., Kluwer Academic Publishers, Dordrecht, Boston, 1991.

Wang, J.-Z.; B. Tie; W. Welkowitz; J. Kostis, and J. Semmlow, Incremental network analogue model of the coronary artery, *Med. & Biol. Eng. & Comput. 27*(4), 416-422, 1989.