

# COMPUTERIZED STUDY OF THE BLOOD FLOW IN ARTERIAL STENOSIS

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## REZUMAT

Curgerea sângelui prin artere este caracterizată printr-o curgere netaționară. În anumite circumstanțe, condiții hemodinamice neobișnuite induc un răspuns biologic anormal. Apariția stenozei poate duce la formarea unui curgeri turbulente, fenomen asociat cu pierderi prin frecare și disturbarea regimului de curgere. Detectarea și analiza calitativă și cantitativă a stenozelor stă la baza intervenției chirurgicale. Elementele din mecanica fluidelor joacă un rol determinant în generarea, detectarea și tratarea bolilor arteriale. Multe dintre bolile arteriale sunt focale și sunt determinate de factori locali care acționează pe o porțiune specifică din aparatul circulator. Așadar, înțelegerea și interpretarea corectă a relației dintre presiune, curgere și simptomele apărute în stenoza cardiovasculară rămâne o problemă critică.

**Cuvinte cheie:** hemodinamică, flux sanguin, stenoză vasculară, simulare numerică

## ABSTRACT

Blood flow in arteries is dominated by unsteady flow phenomena. In certain circumstances, unusual hemodynamic conditions induce an abnormal biological response. The stenosis can cause turbulence and reduce flow by means of viscous head losses and flow choking. Detection and quantification of stenosis contribute as the basis for surgical intervention. Each fluid mechanics aspect plays a role in the generation, detection, and treatment of arterial diseases. Most of arterial diseases are highly focal and must be caused by local factor acting at a specific site. Hence, complete understanding of the relationship between pressure, flow, and symptoms for cardiovascular stenosis remains a critical problem.

**Key Words:** hemodynamics, blood flow, vascular stenosis, numerical simulation

## INTRODUCTION

Several studies suggested that is mainly the shear stress that is most important as far as atherosclerosis is concerned. High and low wall shear stress regions have been proposed as dangerous.

Laminar flow is the normal condition throughout most of the circulatory system and is characterized by concentric layers of blood moving in parallel down the length of a blood vessel.

Turbulence occurs when smoothly flowing, laminar flow is disrupted, distal to stenotic (narrowed) heart valves or arterial vessels, at vessel branch points,

and in the ascending aorta at high cardiac ejection velocities (e.g., during exercise). Turbulence results in characteristic sounds (e.g., ejection murmurs, carotid bruits) that can be heard with a stethoscope. Because higher velocities enhance turbulence, audible sounds resulting from turbulence will become louder whenever blood flow is increased across the valve or through the vessel where the turbulence is found. Elevated cardiac outputs even across anatomically normal aortic valves can cause physiological murmurs because of turbulence. This sometimes occurs in pregnant women who have elevated cardiac output and who may also have anemia which decreases blood viscosity. Turbulence also causes increased energy loss and a higher axial pressure drop.<sup>1</sup>

More recent work indicates that even more important than the magnitude of the wall shear stress (WSS) is how rapidly it varies in space or time. To help resolve such issues, analytical, numerical, and experimental studies have been carried out on blood flow in normal, unstenosed arteries. The wall shear stresses in such stenotic regions may be highly elevated or reduced, the flow downstream and upstream highly disturbed, etc.<sup>2-4</sup>

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## HEMODYNAMICS IN BLOOD VESSELS

### Motivation for studying the blood flow in stenotic vessels

Hemodynamics is concerned with the physical factors governing blood flow within the circulatory system. Blood flow through an organ or any vascular network is driven by a pressure gradient or perfusion pressure that is normally represented by the difference between the arterial and venous pressures across the organ. The actual blood flow at any given pressure gradient is determined by the resistance to blood flow.

The most accepted clinical predictors of impending heart attack, stroke, and lower-limb ischemia are based on the presence of hemodynamically significant stenosis. The art of cardiology and vascular surgery changes constantly, but current treatments for cardiovascular disease are based on the severity and location of stenosis. Currently, the best indicator for surgical treatment of arteriosclerosis is the degree of stenosis.

Atherosclerosis is a type of arteriosclerosis caused by a build-up of plaque in the inner lining of an artery (arteriosclerosis is a general term for thickening or hardening of the arteries). It is a slow, progressive disease that may start as early as childhood. The disease has the potential to progress rapidly, or may not become threatening for several decades.

### Hemodynamics of stenosis

In vascular stenosis the velocity of blood flow through a narrowed portion of a vessel will increase if the volume of flow per unit time in the segment is constant. The volume flow rate  $Q$  is equal to

$$Q = v_1 A_1 = v_2 A_2 \text{ (Fig. 1)}$$

Where:  $A$  - vessel cross-sectional area, and  $v$  - average flow velocity; therefore,

$$\frac{v_2}{v_1} = \frac{A_1}{A_2}$$

and as  $A$  decreases,  $v$  increases.

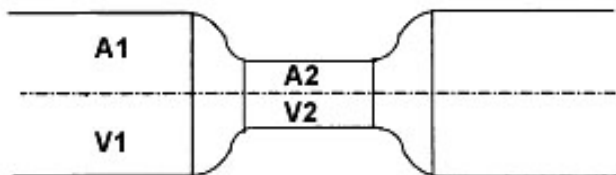


Figure 1. Sketch of the arterial stenosis

As the residual diameter of a stenosis decreases, there is an increase in resistance.

From a clinical perspective, a lesion is hemodynamically significant if it causes a perfusion deficit during rest or exercise. The greater the degree of

stenosis and the larger its length, the greater the associated pressure decrement. The degree of stenosis beyond which a small increase in severity results in a significant reduction of flow is referred to as a critical or hemodynamically significant narrowing. (Fig. 2, 3)

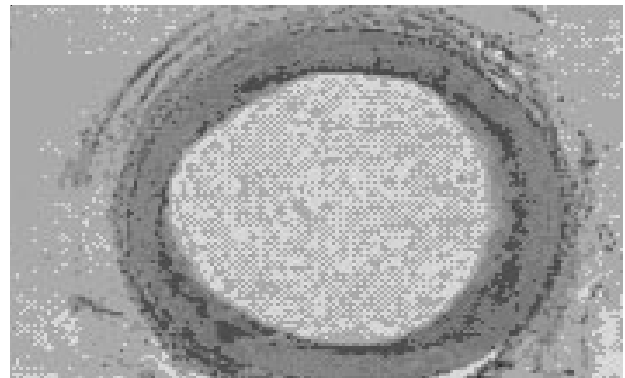


Figure 2. Normal artery

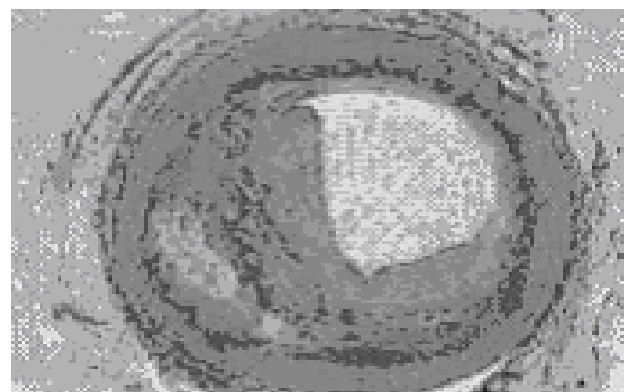


Figure 3. Vascular stenosis

This value is generally acknowledged to be 50% of the luminal diameter in the peripheral arterial system, which corresponds to a 75% decrease in the cross-sectional area. This number is somewhat arbitrary in that it is strongly affected by peripheral vascular resistance and the status of the pre-and poststenotic vasculature.

The problem of simulation of blood flow in arteries has several levels of complexity. For the blood flow in large arteries the system of incompressible, unsteady momentum equations for viscous fluid together with the equation of mass conservation (continuity equation) are considered.<sup>5</sup> The system of the above equations can be coupled with the system of the motion equations for the deformable walls for the case of the largest arteries.

For moderate size arteries the unsteady flow equations are taken into account while the deformation motion equations of the arterial walls are neglected, because the artery wall can be considered as solid.

For small size arteries (arterioles and capillaries), the flow can be described as steady because the flow pulse is damped.

## MATERIAL AND METHODS

The study was performed at the National Center for Engineering with Complex Fluids, from the Politehnica University, Timisoara, by a multidisciplinary research team of fluid mechanics engineers and cardiology researchers. The problem of the blood flow in the vessels was simulated using the professional commercial software FLUENT 6.0.<sup>6</sup> The blood flow was mathematically modeled using the Navier-Stokes equations for an incompressible fluid.<sup>7</sup> A Newtonian fluid was used to approximate the rheological behavior of blood, which is a reasonable assumption for blood flow in large arteries.

In clinical medicine, stenosis is commonly defined as percent occlusion by diameter:

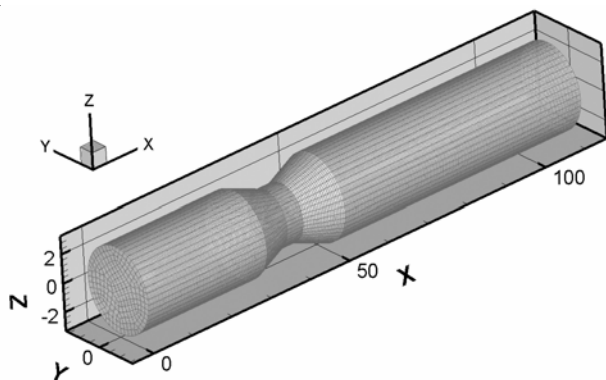
$$\text{percent stenosis} = \frac{D_1 - D_2}{D_1} \times 100 \%$$

The present test case is selected as representative for the study of stenosed arteries in the arterial system.

## RESULTS

The stenotic area is 50% of the inlet area. The geometry of the vessel and the used numerical grid are depicted in Figure 4.

The fluid domain was partitioned into discrete control volume using a structured tetrahedral computational grid.



**Figure 4.** Geometry and numerical grid for the solution of blood flow inside the 3D stenosed artery

Stenotic flows is characterized by: flow separation in the expansion region; between the central jet and the recirculation region a strong shear layer develop. (Figs 5, 6)

The flow separation at the step edge results in a recirculation zone downstream of the stenosis. The length of this zone (distance between the step and the reattachment of the separation streamline) increases as the Reynolds number increases.

Turbulence downstream of the stenosis is very large and creates significant resistance. Separation of flow can also contribute to pressure loss and is a major factor at lower percent stenosis. Separation region will occur in most arterial stenosis. For high-grade stenosis, turbulence is the major loss mechanism.<sup>8</sup>

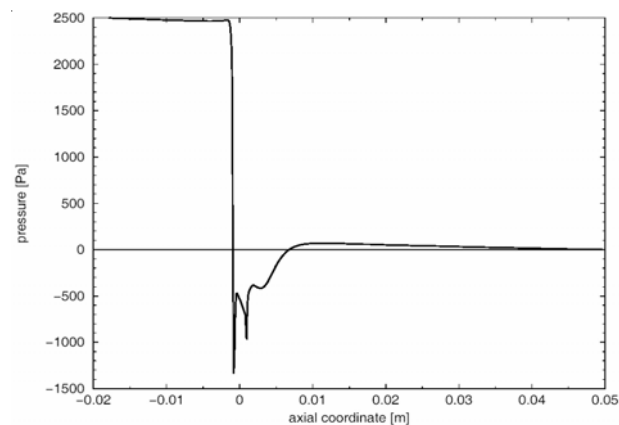


**Figure 5.** Streamlines pattern and recirculation zones of the flow in asymmetric stenosis



**Figure 6.** Velocity profiles for the flow over stenosis

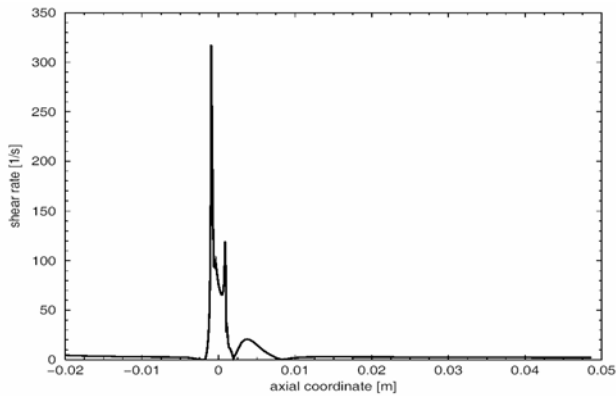
Figure 7 shows the pressure distribution over the stenosis. In this figure one can observe a larger pressure drop upstream the stenosis. Analyzing Figures 5 and 7 it becomes evident that the re-circulation zones grow quickly in size after the stenosis.



**Figure 7.** Pressure distribution over stenosis

Wall shear stress is the product of wall shear rate, i.e. the radial derivative of the velocity near the wall, and local blood viscosity. In large arteries the velocity profile, i.e. the velocity distribution over the cross sectional area, is a flattened parabola; shear in this case is low in the center of vessel and high near the vessel wall.

Figure 8 presents the local wall shear rate estimation along the stenosed vessel. One can observe that near the stenosis the shear rate is high, corresponding to the high value of the velocity gradient and shear rate is low after the stenosed vessel region. (Fig. 6) Shear rate evolution in stenotic vessels is correlated with the complex rheology of the blood, explaining the decrease in time of the vessel circular area.



**Figure 8.** Shear rate distribution for stenosed vessel

## **CONCLUSIONS**

The severity of the stenosis may be indirectly obtained from the fluid mechanics of stenosis. Stenotic arterial lesions may or may not alter resting blood flow. Atherosclerosis is a disease process that occurs over years. The circulation distal to a stenotic lesion will often undergo collateralization which reduces resistance and thereby maintains normal resting blood flow despite a reduced perfusion pressure. Furthermore, even acute reductions in perfusion pressure lead to a fall in distal vascular resistance and normalization of blood flow by the mechanism of autoregulation.

The FLUENT code used in this study validated correctly the hydrodynamic flow field. However, computed results indicate that the recirculation zones

are strongly influenced by the geometry of the square step (stenosis) and the flow regime. Appearance of large recirculation zones and the strong increase of the pressure drop depending on the severity of the stenosis.

The hemodynamic effect on arterial walls represents the primary clinical interest in stenosis surgery.

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