Atherosclerotic plaque formation may lead to stenotic lesions, particularly in coronary arteries. Such plaques are susceptible to rupture or superficial damage of the endothelium, resulting in exposure of thrombogenic materials, especially collagen and tissue factor, to the blood stream. This event may lead to mural thrombus formation and occlusion of the vessel lumen. Clinical conditions associated with such acute thrombotic events are unstable angina, acute myocardial infarction, or sudden death.

Thrombi at stenotic lesions are rich in both platelets and fibrin. The factors promoting their growth are related to the thrombogenic components of the plaque fissure and the local shear rates and/or disturbed blood flow introduced by the geometry of the stenosis. The precipitating event leading to stroke, myocardial infarction, and/or sudden death may be related to the formation of mural thrombus at the site of a ruptured or superficially damaged stenotic plaque. The fluid dynamic properties at atherosclerotic plaques that may be implicated in this thrombus formation have been described in a wide variety of model systems in both the process of plaque rupture and the growth of platelet thrombi. In general, the local fluid dynamic conditions are complex and show major variations from flow in well-defined laminar flow systems. However, no studies have attempted to quantify the effect of stenosis-related disturbances on thrombus formation in native human blood and to compare them with the local fluid dynamics. We developed a parallel-plate perfusion chamber device in which thrombus formation is measured at the "apex" of eccentric stenoses and have correlated such measurements with values of the local fluid dynamics obtained by computer simulation. The extent of stenoses (reduction in the cross-sectional area of the blood flow channel) was 60%, 80%, and 89%, corresponding to "apex" wall shear rates of 2600, 10,500, and 32,000 sec⁻¹, respectively. The wall shear rate in the laminar flow region proximal and distal to the stenoses was 420 sec⁻¹. The surface of the stenosis was purified collagen type III fibrils that were exposed to flowing nonanticoagulated human blood drawn directly from an antecubital vein by a pump placed distally to the perfusion chamber. The resulting blood-collagen interactions were quantified by light microscopy by using a morphometric image analysis technique. Under all conditions studied, platelet thrombus formation at the "apex" was extensive. Thrombi that formed at the two highest shear conditions (10,500 and 32,000 sec⁻¹) showed significant fibrin deposition in lamellae that were surrounded by densely packed platelets. Most of the platelet boundaries were diffuse and difficult to recognize. The direct adhesion of platelets to the collagen surface was greatest at 2600 sec⁻¹ but dropped at the higher shear rates (P<.02). In contrast, the thrombus volume increased steadily with increasing shear but decreased considerably at 32,000 sec⁻¹ (P<.004). The general increase in fibrin formation at shear rates of 10,500 sec⁻¹ and above and the reduction in thrombus volume at 32,000 sec⁻¹ have not been previously reported and are in contrast with their dependence on shear conditions noted at lower shear rates (<10,500 sec⁻¹).

Mechanisms of thrombosis at conditions typical of advanced atherosclerotic lesions may therefore be altered from those observed under physiological flow. (Arterioscler Thromb. 1994;14:1984-1991.)

**Key Words**: perfusion model • stenosis • collagen • thrombus formation • numerical analysis
stenoses. In this model, a parallel-plate stenosis chamber, the upper stenotic surface of which consists of collagen type III fibrils, is exposed to native blood under controlled flow conditions. Chambers with varying levels of stenosis (60%, 80%, and 89%) were designed that corresponded to peak wall shear rates of 2600, 10 500, and 32 000 sec⁻¹, respectively. The blood flow characteristics and shear rate distribution in the vicinity of the stenoses were simulated by means of a numerical analysis program (FIDAP); these values were correlated with the extent of thrombus formation. The introduction of the high-grade (80% and 89%) stenoses to the blood flow channel resulted in a pronounced thrombus formation that was associated with extensive deposition of fibrin. The fibrin component is not generally observed at high shear rates (up to 5200 sec⁻¹) in other models that use laminar flow conditions, although fibrin is often associated with intravascular thrombi associated with stenotic lesions. This finding suggests that the mechanisms of thrombosis at high shear levels, typical of advanced stenoses, may differ from those observed in streamline flow.

Methods
Parallel-Plate Perfusion Chamber With Eccentric Stenosis
Parallel-plate perfusion chambers were constructed with an eccentric stenosis in the blood flow channel based on earlier versions of parallel-plate perfusion chambers with parallel streamlines. The flow characteristics of the original chambers have been well characterized and used in a broad variety of blood-perfusion studies. An 18-mm-long step in the blood flow channel of the perfusion chamber was used to create an eccentric stenosis. The transition from the inlet section of the chamber (a parallel plate with a height of 0.7 mm and a width of 5.0 mm) to the step occurred over a 0.5-mm axial distance and was cosine-shaped to permit a gradual, rather than a step, variation in cross-section. The extent of the stenosis (reduction of cross-sectional area of the flow channel) was varied from 0% to 89% by constriction of different flow chambers. The 0% stenosis corresponds identically to the originally designed parallel-plate chamber (Fig 1). At a blood flow rate of 10 mL/min, the corresponding wall shear rate was 420 sec⁻¹, a value that is characteristic of central epicardial coronary arteries. The depths of protrusion of the three stenoses studied were 0.42 mm, 0.56 mm, and 0.62 mm, which corresponded to reductions of the cross-sectional area of the flow channel of 60%, 80%, and 89%, respectively (Fig 2). These models are intended to simulate flow in coronary arteries with "advanced" single eccentric stenoses with a long axial dimension. Dimensions of the respective blood flow channels at the "apex" and the corresponding fully developed wall shear rates and shear stresses are summarized in the Table.

The cover-slip holder (Figs 1 and 2) has a recess for the positioning of a plastic coverslip. The coverslip can be coated with a variety of materials, eg, collagen, endothelial cells, or extracellular matrix of endothelial cells, depending on the aim of the experiments. All perfusion chambers were made of polymethyl acrylate (Perspex); high precision machining was performed by computer-assisted tooling equipment at Lilas Finmekaniske AS.

Numerical Analysis
The blood flow characteristics and shear rate distribution at the respective stenoses were simulated numerically by using a finite element program developed by Fluid Dynamics International Inc (FIDAP). The computational modeling was performed on a VAX 8800 Computer (Digital Equipment Corp).

![Fig 1. Diagrams showing the parallel-plate perfusion chamber with a single eccentric stenosis. The stenosis is introduced into the flow channel as an 18-mm-long planar surface with a 0.5-mm cosine-shaped step on the cover-slip holder (A), which fits into the recess of the perfusion chamber (B). A coverslip (*) (18×22 mm) is placed into a matching recess of the cover-slip holder. The stenosis is placed 70 mm downstream from the circular flow channel inlet, which is gradually tapered off to rectangular dimensions (C). D. Stenosis with an 80% reduction of the cross-sectional area.](http://atvb.ahajournals.org/)

To perform the simulation, several assumptions were made to simplify the analysis. First, blood was assumed to be a homogeneous, incompressible, and Newtonian fluid; second, the flow was assumed to be steady and laminar; and finally, the flow channel was assumed to be rigid. Finite element solutions to the flow field with 0%, 60%, 80%, and 89% stenosis were obtained at Reynolds (Re) numbers of 10, 20, 40, and 80. These Re numbers were calculated for the flow rates of 5, 10, 20, and 40 mL/min, respectively. Due to the nature of the parallel-plate system, the reduction in cross-sectional height by the protrusion under constant flow rate conditions results in no change in Re number, although shear rate and stress magnitudes are significantly altered. Thus, results obtained at Re=20 for a flow rate of 10 mL/min correspond to conditions

![Fig 2. Diagrams of longitudinal sections through the perfusion chamber showing magnified images of the inlet region of the various stenoses. The length of the stenotic cosine-shaped entrance region of the stenoses is 0.5 mm. The height of the stenoses and the blood flow rate determine the wall shear rates.](http://atvb.ahajournals.org/)
in the present flow chambers. The velocity and shear profiles were obtained by solving the two-dimensional Navier-Stokes equations.

**Blood Donors and Blood Sampling**

Nonanticoagulated blood from six healthy volunteers was drawn through each perfusion chamber for 5 minutes at a blood flow rate of 10 mL/min. Each of the blood donors gave their informed consent to donate 55 mL blood per perfusion experiment. None of the individuals had taken aspirin or other drugs for at least 14 days prior to the perfusion experiments. Immediately before each perfusion experiment, 4 mL blood was collected into EDTA-containing tubes for determination of hemoglobin, hematocrit, and white cell and platelet counts by a Cell Dyn 900 Hematology Analyzer (Sequoia-Turner Corp). Individual hemoglobin, hematocrit, platelet, and leucocyte values were within the normal range for all subjects studied.

**Preparation of the Collagen Surface**

Type III collagen was purified from human placentas by means of a pepsin digest and selective salt precipitation.\(^{(47)}\) A sample of the collagen preparation was hydrolyzed for 24 hours in 6 mol/L HCl under vacuum. The hydrolyzed material was analyzed by a Biotronik LC 5000 amino acid analyzer (Biotronik), and the collagen concentration was estimated from the amino acid composition. Collagen fibrils were formed by dialysis at 4°C against 20 mmol/L Na₂HPO₄, pH 7.5, for 48 hours.\(^{(48)}\)

Thermanox plastic coverslips (Miles Laboratories) were spray coated with human type III collagen fibrils by using a nitrogen operated air-brush (Model 100 GxF, Badge Airbrush) at a pressure of 1 atm (final density, \(\approx 20 \mu g/cm²\). The collagen-coated coverslips were left for 12 to 14 hours at 22°C before they were used in the perfusion experiments.\(^{(49)}\)

The collagen fibrils do not activate the coagulation mechanism,\(^{(28)}\) and the coating gives a maximal thrombogenic stimulus at densities of 10 \(\mu g/cm²\) and greater.

**Human Ex-Vivo Perusions, Fixation, and Embedding**

Ex-vivo perfusion experiments\(^{(49)}\) were performed with the parallel-plate stenosis chambers at 37°C with collagen-coated coverslips forming the “apex” of the stenosis. Venipuncture was performed with a No. 19 butterfly infusion set (Abbott Laboratories). Human blood was drawn from an antecubital vein directly into the chamber; the nonanticoagulated blood flowed over the collagen fibrils at a constant flow rate of 10 mL/min by a peristaltic roller pump (LKB 2115 Multiperfus pump, LKB Products AB) placed distally to the perfusion chamber. Each perfusion experiment lasted for 5 minutes and was terminated by a subsequent 20-second perfusion with buffer C (in mmol/L: NaCl 130, KCl 2, NaHCO₃ 12, CaCl₂ 2.5, and MgCl₂ 0.9, pH 7.4, 37°C) followed by a 40-second perfusion with fixation solution (2.5% glutaraldehyde in 0.1 mol/L cacodylate buffer, pH 7.4, 22°C) at the same flow rate; the pump was not stopped throughout the experiment. Postfixation of the surface was performed in freshly prepared fixation solution at 4°C for 1 hour. The specimens were stored at 4°C in 7% sucrose/0.1 mol/L cacodylate and finally embedded in Epon.\(^{(50)}\)

**Morphometry**

Semithin (\(=1 \mu m\)) sections were prepared from Epon-blocks at locations corresponding to 1 mm from the upstream edge of the coverslip perpendicular to the direction of the blood flow. Semithin sections were also prepared of the fibrin tail that frequently developed downstream to the collagen-attached thrombus material at the two high-grade stenoses. These sections were made 1.5 mm downstream from the outflow region of the stenosis. The sections were stained with toluidin blue and basic fuchsin.\(^{(50,51)}\)

Standardized morphometrical technique\(^{(51)}\) was performed by light microscopy at 1000× magnification (Nikon Labphot-2 light microscope, Type 104) to assess the percentage of the surface covered with platelets (percent platelet adhesion) and with fibrin (percent fibrin deposition). Computer-assisted microscopic morphometry (Kontron Vidas image analyzing system, Zeiss, Eching) was used to assess the average thrombus area, which was expressed as micrometers squared per micrometer sectional length. The average thrombus volume per unit area (micrometers cubed per micrometers squared) was determined from the measured thrombus areas.\(^{(52)}\)

Average percent occlusion by thrombus was calculated from the total area of the thrombi, as measured by computer-assisted morphometry, according to the formula:

\[
\text{Thrombus Occlusion (\%)} = \frac{100\% \times \text{Thrombi (\mu m²)}}{\text{Cross-sectional Area of Blood Flow Channel (\mu m²)}}
\]

**Statistical Analysis**

The significance of difference for unpaired data was calculated by using a Student’s two-tailed t test. \(P<.05\) was considered significant.

**Results**

**Numerical Analysis**

Blood flow in the perfusion chambers was simulated at \(Re=10, 20, 40, \) and 80. Results are presented primarily for \(Re=20\) since these values correspond directly to the experimentally investigated perfusion conditions. At all values of \(Re,\) the computations revealed no zones of recirculation in the prestenotic region. A typical velocity vector pattern for the 89% stenosis is shown in Fig 3A. Recirculation regions did develop downstream of the stenosis at the higher \(Re\) numbers of 40 and 80 (not shown), but these were not apparent at \(Re=20\) (Fig 3B).

Shear rates were determined throughout the flow field according to the formula for two dimensional fluid flow

\[
y = \sqrt{2 \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2}^{1/2}
\]

where \(u\) and \(v\) are fluid velocities in the \(x\) (axial) and \(y\) (height) directions, respectively. Values of shear rate at the upper bounding surface (stenotic intrusion) were collected and plotted as a function of axial position, as shown for an 89% stenosis in Fig 4. The computed values of wall shear rate in the upstream position...
remained constant at the value theoretically predicted (420 sec\(^{-1}\)) for such flow between parallel plates until approximately 0.5 mm from the beginning of the stenotic intrusion into the flow (Fig 4A). Wall shear fell approximately an order of magnitude within this 0.5-mm region and then abruptly increased at the beginning of the stenosis (1.5-mm axial distance), reaching an increase of three orders of magnitude to 32 000 sec\(^{-1}\) at 2-mm axial distance. The wall shear rate remained constant at this value throughout the planar section of the stenosis. This value of wall shear rate would be characteristic of the area where thrombotic deposits were evaluated. The downstream section (Fig 4B) was symmetrically similar. Wall shear rates began to decrease from the value of 32 000 sec\(^{-1}\) as the stenosis receded (1.0-mm axial distance), reached a minimum more than three orders of magnitude less at 1.5-mm axial distance, and then increased to the theoretically predicted values of 420 sec\(^{-1}\) over a 0.5-mm distance. The numerical simulations indicate that values of wall shear rate may vary as much as three to four orders of magnitude over a relatively small distance of 0.5 mm. For values of 80% and 60% stenosis the variation in overall shear rate is accordingly reduced in this region; however, increases of one to two orders of magnitude were still observed (Fig 5).

Platelet-Collagen Adhesion

The platelet-collagen adhesion (percent surface coverage with adherent platelets) after 5-minute perfusions was highest at 420 sec\(^{-1}\) (no stenosis) and 2600 sec\(^{-1}\) (60% stenosis) but dropped when the wall shear rate increased to 10 500 sec\(^{-1}\) (80% stenosis) and 32 000 sec\(^{-1}\) (89% stenosis) (P<.001; Fig 6A). There was no significant difference in platelet adhesion at the two highest shear rates.

Thrombus Volume

The thrombus volume increased approximately eightfold when the wall shear rate was increased from 420 sec\(^{-1}\) (no stenosis) to 10 500 sec\(^{-1}\) (80% stenosis) (P<.0001; Fig 6B). However, a further increase of the wall shear rate to 32 000 sec\(^{-1}\) (89% stenosis) resulted in a pronounced drop in thrombus volume (P<.004).

Fibrin Deposition

The fibrin deposition at 420 sec\(^{-1}\) (no stenosis) was not significantly different from that observed at 2600 sec\(^{-1}\) (60% stenosis). The fibrin deposition at 5 minutes of perfusion was substantially increased at 10 500 sec\(^{-1}\) (80% stenosis) and 32 000 sec\(^{-1}\) (89% stenosis) compared with the deposition at 2600 sec\(^{-1}\) (60% stenosis) (P<.03; Fig 6C).

Percent Thrombotic Occlusion

The percent thrombotic occlusion was less than 1% at a wall shear rate of 420 sec\(^{-1}\) (without stenosis) and increased to 13% at 2600 sec\(^{-1}\) (60% stenosis). The thrombotic occlusion was 42% and 33% when the shear rate was further increased to 10 500 sec\(^{-1}\) (80% stenosis) and 32 000 sec\(^{-1}\) (89% stenosis), respectively (Fig 7).

Morphology

Fig 8 shows representative photomicrographs of thrombi formed on collagen without a stenosis (Fig 8A)
and on the stenotic apex at wall shear rates of 2600 (Fig 8B), 10 500 (Fig 8C), and 32 000 (Fig 8D) sec⁻¹. Because the collagen surface is not visible at this level of magnification, it is denoted by the asterisk. Note the pronounced fibrin deposition at the two highest shear conditions (Fig 8C and 8D). The small arrows point at fibrin strands deposited parallel to the direction of the blood flow. Fibrin has also been deposited at the collagen surface, in lamellas in the platelet thrombi, and on top of the thrombi. Trapped erythrocytes and a few leukocytes (big arrow) are seen.

Fig 9 shows a micrograph of a "fibrin tail," with erythrocytes trapped in the fibrin mesh (arrow). The section was made 1.5 mm downstream from the outflow region of an 80% stenosis (10 500 sec⁻¹). Such fibrin tails are frequently formed downstream from the platelet thrombus at wall shear rates of 10 500 and 32 000 sec⁻¹ after 5 minutes of blood perfusion. The fibrin tail is anchored to the platelet-rich thrombi at the apex of the stenoses.

**Discussion**

It has long been recognized that blood flow conditions play a significant role in thrombus formation. By the use of various well-defined perfusion systems, the influence of laminar blood flow at various shear conditions on thrombus formation has been investigated under controlled experimental conditions, and wall shear conditions have been identified as an important parameter governing the growth of platelet thrombi and fibrin deposition. However, arterial thrombus formation is often associated with stenotic lesions of the vessel wall, specifically in cases of rupture or superficial damage of atherosclerotic plaques, such as in unstable angina, myocardial infarction, and sudden death. Geometric changes introduced by such stenoses disturb laminar blood flow; however, little of a quantitative nature is known concerning thrombus formation at such lesions, where blood flow is significantly disturbed. In the present investigation we have constructed a new generation of parallel-plate perfusion systems to study the influence of wall shear conditions on thrombus formation.
Thrombus formation in flowing nonanticoagulated human blood was stimulated by purified type III collagen fibrils positioned at the apex of the different stenoses.

All perfusion experiments were conducted at a blood flow rate of 10 mL/min, which corresponded to a Reynolds number of 20. The numerical analysis at this Reynolds number revealed neither recirculation phenomena proximally or distally to the respective stenoses, although reduction of wall shear rates was noted in the proximal and distal regions. In addition, blood flow conditions at the respective stenoses yielded wall shear rates as high as 36,000 sec\(^{-1}\) at the upstream apex of the most severe stenosis (89%). However, the laminar flow pattern was very rapidly reestablished, and the wall shear rate leveled off to 32,000 sec\(^{-1}\) and remained constant throughout the entire length of the stenosis apex. Consistent with these computations, wall shear rates exceeding 40,000 sec\(^{-1}\) (1200 dynes/cm\(^2\)) as well as shear stresses exceeding 3000 dynes/cm\(^2\) have been estimated in mechanically constricted coronary arteries in dogs\(^{2,4}\) corresponding to about 80% and 60% occlusion of the cross-sectional lumen area, respectively. These findings suggest that such high shear rates and shear stresses are present in vivo at the apex of severely stenosed arteries.

Rapid changes in shear distributions, although of a lesser magnitude, were also introduced by the other two stenoses (60% and 80%). In these cases, constant wall shear rates of 2600 and 10,500 sec\(^{-1}\) were present throughout most of the length of the stenotic regions.

Morphometry was performed 1 mm downstream from the upstream edge at a location where the wall shear rate was essentially constant and the flow fully developed.

### Platelet Adhesion to Collagen

The type III collagen fibrils at the stenoses triggered rapid platelet adhesion; the highest levels were observed at a wall shear rate of 2600 sec\(^{-1}\). The platelet-collagen adhesion decreased gradually when the wall shear rate was increased to 10,500 and 32,000 sec\(^{-1}\). The increase of adhesion with wall shear rate in laminar flow has been observed previously on collagen for shear rates up to 1600 sec\(^{-1}\); however, no previous studies with collagen have been reported at shear rates exceeding 5200 sec\(^{-1}\). Interestingly, a decrease in adhesion as shear was increased from 1600 to 5200 sec\(^{-1}\) was observed. Such observations may be related to the enhanced shear stresses imposed by the flow on adherent platelets, the shortened residence time of the platelet at the collagen surface, and the local platelet consumption by growing thrombi, which lessens the availability of platelets in the vicinity of the collagen surfaces. The finding of reduced thrombi at the highest shear levels (32,000 sec\(^{-1}\)) would be more consistent with the former two explanations rather than the latter.

### Thrombus Size and Fibrin Deposition

A prominent feature of the thrombus formation in the stenotic region was the extensive deposit of platelet and fibrin material and its strong dependence on the wall shear rate. The average thrombus volume at 2600 and 10,500 sec\(^{-1}\) was four- and ninefold increased above the corresponding volume observed at 420 sec\(^{-1}\), respectively. However, at 32,000 sec\(^{-1}\), the thrombus...
volume was significantly reduced over that measured at 2600 and 10 500 sec\(^{-1}\). The corresponding average occlusion of the cross-sectional lumen by thrombotic material was from 35% to 40% at the two highest shear conditions. Complete thrombotic occlusion of parts of the cross-sectional area of the flow channel was observed at both shear rates. Morphological evaluation of thrombotic deposits revealed that material deposited at the higher shear rates of 10 500 and 32 000 sec\(^{-1}\) was much more heterogeneous in nature. A greater percentage of blood components, including fibrin, red cells, and white cells, was observed, and numerous flow channels through thrombi could be distinguished at the higher shear rates. In addition, the platelets appeared densely packed, and the borders became difficult to identify at higher shear rates, much like the morphology of platelet plugs from bleeding time wounds of healthy individuals.\(^55\)

A striking feature of the thrombi formed at these high shear rates was the pronounced deposition of fibrin. In general, at low shear rates on procoagulant surfaces, such as subendothelium\(^16\)-\(^18\) or extracellular matrix of stimulated endothelium,\(^56\) fibrin formation decreases with increasing wall shear rate; however, in the present disturbed flow regions an increasing fibrin formation with increasing shear rate was observed. Morphologically, fibrin was noted as a cap on the collagen-anchored platelet masses; occasionally this fibrin cap occluded the flow channel completely. Fibrin was also observed in lamellae surrounded by densely packed platelets. However, the most pronounced fibrin deposition was observed downstream from the apex (thus downstream from the constriction). Similar red fibrin tails have also been observed downstream from occluding arterial platelet-rich thrombi in vivo.\(^55\) The enhanced fibrin deposition with increasing wall shear rate may be inherently related to the heterogeneous nature of the flow produced by stenotic disturbances. As is well known, geometric alterations in the flow path, such as those produced in the present studies, can produce wide variations in local shear levels at the respective stenoses even in the absence of gross recirculation zones. Further complicating the flow situation is the deposition of additional material through the thrombotic process, which enhances the geometric disturbance, especially since initial deposit seems to favor the apex area. Under such conditions an even greater enhancement of shear levels would be expected with thrombus deposit, but as noted morphologically, within the thrombi themselves regions may be produced that are characteristically of low shear (channels). The deposition of red cells and the production of fibrin indirectly suggest such mechanisms. Thrombotic deposit and the subsequent production of local flow heterogeneities have not been considered in the present computational analysis of shear flow over an experimental stenosis.

As significant literature on the mechanisms of platelet deposition and even fibrin formation on surfaces exposed to laminar blood flow exists for the range of physiologically encountered wall shear conditions. However, little is known concerning the influence of shear levels on thrombosis in the pathological range of shear encountered in stenotic lesions. The present findings suggest that a several-order increase in shear levels may be produced in advanced stenoses and that such flow may result in occlusive thrombi that are rich in both platelets and fibrin. The extent to which classic mechanisms of adhesion and coagulation are applicable to such flow situations is the subject of future investigations. We believe that the novel perfusion model developed here, which simulates thrombogenesis at ruptured stenotic plaques, will allow detailed studies of human thrombus formation at pathologically high shear conditions. Further characterization of this novel model is currently being performed by time-course studies with blood from healthy individuals, from patients with bleeding disorders, and from patients on antithrombotic therapy.

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A perfusion chamber developed to investigate thrombus formation and shear profiles in flowing native human blood at the apex of well-defined stenoses.

R M Barstad, H E Roald, Y Cui, V T Turitto and K S Sakariassen

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