Eddy Formation and Turbulence in Flowing Liquids

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The steady flow of liquids through straight rigid tubes has been extensively analyzed, but these data cannot be applied directly to the pulsatile flow of blood through distensible, tapered and branching vascular channels. Since it is very difficult to follow flow patterns in the living animal, certain types of studies must be performed in models. Laminar flow, eddy formation and turbulence can be identified with streamers of dye. This method is widely used; however, it reveals the flow pattern only where the concentration gradients of the dye are steep. Furthermore, observation can continue only until the dye is mixed and the flow pattern is obscured. The complex hydrodynamics of the cardiovascular system, however, make more complete investigations necessary.

Detailed analysis of the formation of eddies and turbulence requires clear detection of changes in flow pattern at any time and at any place in the flow channel and continuous observation of the flow field over a considerable period of time. These conditions are fulfilled by several colloidal solutions such as vanadium pentoxide, red dye benzopurpurin 4B4 and certain clay suspensions. Most of these substances have been used for some years in engineering and chemistry as means of visualizing flow. The particles in these fluids obey the principles of streaming birefringence, i.e., double refraction in connection with shear forces.

A colloidal solution of white Hector bentonite has been used successfully by Hauser and Dewey,1 Wayland,2- 7 and Lindgren and others in these observations. The technique has been adapted for this study of changes in flow patterns in models designed to simulate flow conditions in cardiovascular channels.

Methods

White Hector bentonite (National Lead Company, Los Angeles, California) was prepared for aqueous suspension by fragmenting the clay into tiny particles of less than 0.5 μ equivalent spherical diameter by means of mesh screens (no. 200) and high-speed agitators. A solution containing about 1% solids was satisfactory for model channels up to 25 mm thick. To stabilize the suspension, 0.01% of tetra sodium pyrophosphate was added. The density of this solution was 1.0847 g/cc at room temperature. Glycerin was added to alter the viscosity at room temperature to 0.036 poise.10 No precipitation occurred when the solution was left undisturbed for weeks; such lack of gravitational effects suggests a colloidal solution rather than suspension. Thus, the bentonite solution acts as a single unit and the particles faithfully represent the motion of the fluid flowing along flat flow channels.

It is usually assumed for ease of explanation that crystals of bentonite are elongated slender particles of colloidal size. They are probably elliptical and have a variable length-to-diameter ratio. At zero flow the particles are randomly oriented, owing to thermal agitation (fig. 1). With the onset of viscous shear flow, different velocity gradients impinge upon the sides of these elongated particles. A particle crosswise to the flow is subjected to different velocities at either end and rotates until its longitudinal axis is aligned parallel to the shear forces, or perpendicular to the velocity gradient. Viscous fluids may induce relaxation effects and impede rotation. Nevertheless, a very small velocity gradient acts on a particle which is oriented parallel to the laminae of flow. Thus, in steady flow, a particle rotates along an axis perpendicular to the direction of streaming, but it does so with an angular velocity which is minimum when the major axis of the particle lies along the stream. At any instant more particles will be in this position than in any other. Also, there will...
FIGURE 1

The left side shows a sketch of the experimental apparatus. The right side is a schematic representation of the orientation of the bentonite crystals as though the observer moved with the flow. When the liquid is stationary, the particles are oriented at random due to thermal forces. During laminar flow, the particles tend to be oriented along a certain mean angle to the streamlines. In turbulent flow, the particles outline small eddies, which again outline smaller eddies.

The optical system used to monitor changes in the orientation of the bentonite crystals consisted of a white light source, two polarizing filters (commercial Polaroid) and a quarter wave plate (fig. 1). Light from the source passing through the first polarizing filter (the polarizer) emerged vibrating in one plane. When the second filter (the analyzer) was placed parallel to the first and turned 90°, the light was maximally attenuated. When a birefringent crystal (e.g., bentonite) was placed between such crossed polarizing filters, light emerged from the analyzer. Rotation of the birefringent substance through 90° resulted in alternate appearance and disappearance of this light. Thus, the observer saw changes in light intensity on a dark background as the crystals rotated according to acting shear forces. Although a light field would have transmitted more light, brilliance of color would have been lost.

For visual observation, the dark field and a 100 watt light source were satisfactory. For motion picture photography, four no. 2 photoflood lamps were used. The video images were converted into plane polarized light by the quarter wave plate, placed between the flow section and the analyzer.
Flow patterns in a flat flow channel downstream from a constriction at different rates of steady flow. The flow increased from numbers 1 to 6 from 3 cc/sec to 36 cc/sec.

Results

At very low velocities the over-all flow near from a constriction in a two-dimensional flow section remained laminar (fig. 2, strip 1). Shear forces acted at the boundary where the entering jet made contact with the stable fluid. Changes in light intensity at this boundary appeared as a bright area. As the rate of flow was increased to 8 cc/sec (fig. 2, strip 2), the central core became disturbed and then small localized eddies appeared (strip 3). The fully developed jet pattern is illustrated in strips 4 and 5. Eddies formed simultaneously along the margins of the issuing jet. The area of localized turbulence consisted of eddies of ever smaller size. With further increase in velocity (fig. 2, strip 6), the size of the flow channel limited further development of the jet pat-
FIGURE 3
Flow patterns in a round transparent Tygon tubing downstream of an orifice at flow rates of 8 cc/sec (3a) and 36 cc/sec (3b).

In the three-dimensional system these vortices were displayed simultaneously in all radial planes of the tube, so that complete turbulence occupied the area beyond the constriction. The jet formed downstream from the circular constriction is shown in figure 3.

At low flow rates changes in light intensity appeared as dark areas some distance downstream from the constriction (fig. 3a). Individual eddies could not be distinguished, although the presence of non-laminar flow was easily detected. Immediately behind the orifice the flow was laminar and no changes in light intensity were present. As the flow rate was increased, the eddies formed closer to the orifice and the turbulent area became more pronounced (fig. 3b). Turbulence occurred over a wide region starting at the orifice; due to viscous damping this turbulent motion disappeared completely just a few diameters downstream from the turbulent area.

Corresponding phenomena were seen in a flat plastic model of the outflow tract of the left heart with the simulated aortic valves fixed in an open position. At low rates (60 cc/sec) of pulsatile flow, a trail formed, starting from the edge of the valve at either side of the orifice and becoming turbulent farther downstream (fig. 4a); only the trail originating on the left is clearly visible in figure 4b because the inner curve of the aorta obscures that on the right. When the flow was steady but doubled to 120 cc/sec the over-all pattern
FIGURE 4
Flow pattern observed in a flat model of the outflow tract of the left ventricle with rigid "open valves." The flow rate in a is 45 cc/sec and 60 cc/sec in b, 120 cc/sec.

was much more disturbed (fig. 4b). The center stream through the open valve was turbulent, as was the flow through the aortic arch and the descending aorta. The disturbances began in the ventricle and were induced by both the high flow velocities and the changes in the caliber of the inlet to the ventricle. The trails seen forming from the edges of the valve in figure 4a developed into a train of eddies at the higher flow rate. The eddies from the right valve edge were visible behind the right aortic valve. The long eddying trail from the left valve extended to the crest of the aortic arch; additional eddies in this trail developed at the origin of the branches.

In another model the point of outflow into the aorta was narrowed to simulate aortic stenosis. A jet formed at the constriction and turbulence developed downstream. At a low flow rate, 20 cc/sec, the pattern in the ventricle was only slightly disturbed (fig. 5a). Downstream from the stenosis a clear jet flow pattern developed with eddies along its margins. A big stable vortex originated where the jet first made contact with the outside walls; this vortex swirled clockwise. This area of turbulence was carried on through the aortic arch and was damped out in the descending aorta after a few diameters. At the origin of the branches the eddy formation was very clear. Figure 5b shows the patterns at a flow rate of 50 cc/sec. The pattern in the ventricle broke down partly because of this high flow rate and partly because of the changes in the caliber at the inlet. The jet pattern downstream from the constriction was greatly extended. The great vortex in the ascending aorta enlarged and swirled counterclockwise.
behind the right valve a clear rotating vortex developed. The center core of the issuing jet seemed to hit the opening of the first branch (innominate artery) and split into two streams: one contributed to the swirling vortex and the other continued downstream along the vessel wall. The eddying motion at the entrance of the branches was obvious. Another stream of vortices seemed to form at the inside of the aortic arch and was carried downstream through the descending aorta. No viscous damping occurred in the descending aorta because the flow velocity there was still high.

Discussion
As this method of streaming birefringence is based upon the physical characteristics of a single solution, it precludes some technical difficulties which arise when two solutions are manipulated simultaneously. In the indicator methods, for instance, it is difficult to introduce the dye in such a way that it outlines the small areas along the side of the tube where disturbed flow appears first. Also, there are no problems of matching velocities and densities, and the effects of varying flow are easily observed. Furthermore, changes at all regions along the flow section can be observed simultaneously rather than successively, and the duration of an experiment is not limited by mixing of indicator and substrate. Lindgren9 has mentioned possible distortions of flow patterns, even with a solution of less than the 1% bentonite used in this study; however, these distortions are more serious in quantitative than in qualitative observations.

The major disadvantage of this method in biological research is the lack of means for making comparable observations in the living subject.
animal. Consequently, extrapolation is necessary, but must always be undertaken cautiously. The desirability of flat flow sections may also be considered a disadvantage since anatomical structures usually have other configurations. Observation of laminar and turbulent flow in a cylindrical tube is possible, although the flow pattern is not clear and single eddies cannot be distinguished (fig. 3). This problem undoubtedly arises because eddies are simultaneously shed in all directions along the axis of the space. What appears on the analyzer is an over-all picture of the integral motion of particles in space. The flat flow section does provide the possibility of observing two-dimensional flow. Actually, the flow in such models is not ideally two-dimensional because the bottom and top of the section establish boundary layers that induce shear forces in a third dimension.

The criteria of the change from laminar to turbulent flow still constitute a moot point in hydraulics. In most physiological studies, the distinction between laminar and turbulent flow has been established by the familiar curves of sudden change in resistance when driving pressure is plotted against rate of flow. This curve is combined with the ratio of inertial to viscous forces and the result is expressed as Reynolds number. For water in uniform pipes the critical value for transition from steady laminar to turbulent flow is given as 2000. The critical Reynolds number for circulating blood is variously given. Indeed, the validity of any Reynolds number for the cardiovascular system is very doubtful. The effect on the flow profile of sudden acceleration and deceleration is not yet clearly understood, but the results of calculating a Reynolds number for pulsatile flow in channels of non-uniform caliber like the blood vessels are undoubtedly distorted. Figure 3 shows turbulence occurring downstream from a constriction at very low flow rates. The velocity of the fluid through the constriction applied to Reynolds formula yielded a value of 800, which would indicate that the jet in the constriction was not turbulent. It can be seen, however, that the interaction between the entering jet of relatively high velocity and the almost stationary fluid in the channel produced instability in the core of the jet and created localized disturbances downstream from the constriction. At a slightly higher velocity these areas of eddy formation expanded across the whole flow channel, producing a condition fulfilling the definition of turbulence: "... an irregular condition of flow in which the various quantities show a random variation with time and space coordinates." Holms and McDonald observed vortices in blood flowing slowly through veins and suggested the term "disturbed flow" for this phenomenon to characterize it as neither laminar nor turbulent.

In the model of the aorta depicted in figure 4 disturbances of this type were observed with pulsatile flow at rates within the physiological range. At low flow rates (fig. 4a) the production of turbulence was localized and the disturbance was carried only a short distance before it was eliminated by viscous effects. (Although the disturbances in the ventricle were artifacts, they can be considered somewhat comparable to the turbulent mixing of blood within a functional ventricle.) As seen in figure 4b the flow pattern became generally disturbed at higher flow rates and at a critical velocity the disturbance reached all points in the flow channel.

The eddies originating from the edges of the semilunar valves have two functional effects: to make the valves close more quickly by keeping their cusps from opening completely and touching the side walls, and to keep the orifices of the coronary vessels open. At a low flow rate, the vortex trail in the model became turbulent only downstream, but at the high rates, the vortices formed at the edges of the cusps. These events are typical of eddy formation when an obstacle projects into a stream of flowing fluid.

As can be seen in figure 4, the system is extremely complex. The trail originating from the right valve cusp collides with the inner wall of the aortic arch. Here the trail is
partly deflected, so that it has some effect on the center stream, and its progression is generally interrupted. If the channel continued as a straight pipe, these vortices would not be deviated and would not affect the center stream at all. In vivo, the three flaps of the aortic valve would generate simultaneously eddying trails. These trails would not continue undisturbed, but would be deflected by the aortic sinus and by the steep curvature of the aortic arch. The aortic sinus would thus act as another impediment and contribute to the formation of eddies that traveled on downstream.

A relatively short distance farther along the flow is subjected to centrifugal forces within the aortic arch. In photographs of flow in a model arch, Timm1 observed helical flow generated by the centrifugal forces associated with the motion in a curve. Since the axial stream moves fastest, the greatest force acts on it; the least force is exerted on and near the walls where the liquid moves slowest. Hence, the fluid in the center of the stream forms a secondary flow towards the outer boundary and forces the fluid near that wall to flow towards the inner wall of the curvature.1, 3 As suggested by Timm, the presence of the branches has effects which contribute to turbulent flow at low Reynolds numbers. In figure 4a, vortices appear at the entrances to the branches, and in figure 4b the transverse motion is very clearly developed and appeared to affect the flow in the main channel.

Clearly, projection of eddies from the edges of the valves, the induction of secondary flows in the aortic arch and at the origin of the main branches, and the rapid changes in velocity from zero to very high to zero, as well as the ensuing brief period of backflow, all contribute to turbulence in the outflow from the left ventricle. These observations also show how easily the flow pattern is disrupted at any surface of discontinuity.

**Summary**

The birefringent properties of a colloidal solution of white Hector bentonite were used as a means of studying the development of flow patterns in transparent models. The liquid had approximately the same viscosity as blood; flow rates were within the physiological range; and some of the flow channels were shaped to resemble portions of the cardiovascular system. The light patterns produced by laminar flow were distinct from those of eddy formation and turbulence. Turbulent flow developed downstream from a constriction, where the velocities of the entering jet were much below the so-called critical Reynolds number. The same flow pattern was observed in a model of aortic stenosis. Also displayed was the flow pattern as it might develop in vivo during midsystole when the semilunar valves are widely opened. Eddies originating from the edges of the valves, the flow around the aortic arch and the effects of the openings of the branches all contributed to a complex turbulent pattern. Eddy formation and turbulence can be produced at low velocities when unsteady flow and sudden changes in diameter occur. This technique is useful in the study of changes in flow pattern under different physiological or pathological conditions. Observations from these models indicate that a more detailed analysis of flow conditions is both possible and worthwhile.

**References**

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