Intra-Aneurysmal Hemodynamics—Jet Action

By WILLIAM J. GERMAN, M.D. AND SAMUEL P. W. BLACK, M.D.

Jet action from experimental "berry" aneurysms was evaluated as part of a long-range study of stress-strain-time relations of aneurysmal rupture. It was apparent that free jet action was a potent stress agent upon matter in its path. Calculated velocities of free jets ranged up to 477 cm. per sec. Supplementary observations were made upon jets from glass-model aneurysms, including the jet effects upon gelatin blocks cast about the models. Coefficients of velocity were determined for the various jets studied and the results were correlated with theoretic hydraulics.

A METHOD has been developed for the experimental production of "berry" aneurysms of the common carotid artery in dogs. This consists of grafting a vein-pouch, constructed from an excised segment of the external jugular vein, upon the margins of an opening in the common carotid artery (fig. 1). The hemodynamics of these experimental aneurysms have been the subject of study, toward the ultimate objective of an understanding of the stress-strain-time relations of aneurysmal rupture. Reports have been given upon comparisons of intra-aneurysmal and intra-arterial pressures and turbulence.

The present paper concerns jet action: the energy, force, impulse and reaction of a stream of fluid in motion. This is of special significance immediately following rupture of an intracranial aneurysm.

Jet action is considered primarily at the site of jet emergence from the experimental aneurysms. Measurements of the vertical heights and diameters of the free jets of blood permit calculation of other items, on the basis of theoretical hydraulics. Jet action from experimental aneurysms is also compared with water jets from a glass-model aneurysm, for the purpose of assessing the orifice effects.

A subject of secondary interest in this study is the flow from the parent artery into an aneurysm. Although certain information bearing upon this has been obtained by cinefluoroscopic studies, the use of the method which is later described allows calculation of velocity at a very short interval after zero flow, before vortex motion is well established within the aneurysm.

THEORY

The theory of jets may begin with the discharge of fluid through an ideal orifice, i.e. a small hole in the side of a very thin-walled vessel. The classical formula for such an ideal situation, using c.g.s. terms, is

\[ v = \sqrt{2gh}, \]

where \( v \) is the velocity in cm./sec., \( g \) the acceleration of gravity and \( h \) the head of fluid in cm. Since \( gh \) is equivalent to the pressure \( P \) in dynes/sq. cm. divided by the density of the fluid \( \rho \), this may also be used in the form

\[ v = \sqrt{2P/\rho} \text{ cm./sec.} \]

However, since the discharge varies with the type of orifice, a coefficient of velocity \( C_v \) is usually included: \( v = C_v\sqrt{2gh} \text{ cm./sec.} \) The force in dynes exerted on the orifice, if it were closed and the jet prevented, would be the pressure times the cross-sectional area, \( A \) sq. cm.: \( F_o = PA = \rho ghA \) dynes. However, when the jet strikes an obstruction the velocity may be reversed in direction, producing a total change in momentum twice that of the jet. The dynamic force of the jet on the obstruction is therefore double the above:

\[ F_t = 2PA = 2\rho ghA = \rho Av^2 \text{ dynes} \]

This is the 'impulse' of the jet. There is an equal and opposite 'reaction' on the orifice; the force of each varies as the square of the velocity. Kinetic energy \( K = \frac{1}{2}mv^2 \). Since the mass \( m \) of a jet during 1 sec. consists of the product of its density \( \rho \), its area \( A \), and its length \( v \), its power \( P = \frac{\rho Av^3}{2} \text{ ergs/sec.} \)

The power varies as the cube of the velocity.

METHODS AND RESULTS

Experimental "Berry" Aneurysms. Using the method illustrated in figure 1, "berry" aneurysms were prepared upon four dogs, under Nembutal anesthesia. Guide sutures were applied to either side of the aneurysmal dome and a hollow, beveled...
needle, attached to a blood pressure recording system,* was inserted into the aneurysmal chamber. The intra-aneurysmal pressure was then recorded. Upon withdrawing the needle, the blood jet issued from the hole in the aneurysm. By manipulation of the guide sutures the jet was adjusted to a vertical axis, "against the obstruction of gravity," and its height measured on a centimeter scale. In this manner a total of twenty jet observations was made under various circumstances (Table 1). The diameters of the jet orifices varying from .8 to 1.5 mm. and the arithmetical mean intra-aneurysmal pressure \((\frac{M1 - AP}{h})\) varying from 85 to 165 mm. Hg.

Jets from the experimental "berry" aneurysms spurted to heights \((h_j)\) varying between 42 and 116 cm. Their calculated velocities \((v)\) ranged from 287 to 477 cm. per second, discounting air resistance. The ratio of jet height to the head equivalent of the intra-aneurysmal pressure \((\frac{h_j}{h})\) varied from .33 to .79. The coefficients of velocity \((C_v = \sqrt{\frac{h_j}{h}})\) were spread between .57 and .89 but the lower coefficients were associated with partial jamming of the orifice by clot. The average velocity coefficient for the free orifices was .78, that for the partially occluded ones .63. The theoretic force of these jets varied, depending upon their area and velocity, from 630 to 4300 dynes. The ratio of the dynamic force of the free jets to the calculated hydrostatic force at the orifice \((\frac{F_j}{F_o})\) varied from 1 to 1.6 with an average of 1.2.

**Correlation with Glass-model Aneurysms.** A jet of non-homogeneous, pulsating fluid issuing from a hole in the dome of an expansile "berry" aneurysm presents several factors which are not really two orifices to be considered: the first being between the parent artery and the lumen of the aneurysm, the second being the hole in the arteriogram and the shape of the orifice by clot. The average velocity coefficient for the free orifices was .78, that for the partially occluded ones .63. The theoretic force of these jets varied, depending upon their area and velocity, from 630 to 4300 dynes. The ratio of the dynamic force of the free jets to the calculated hydrostatic force at the orifice \((\frac{F_j}{F_o})\) varied from 1 to 1.6 with an average of 1.2.

**Table 1.—Observations on Blood Jets from Experimental "Berry" Aneurysms**

<table>
<thead>
<tr>
<th>Orifice d cm.</th>
<th>M1-AP</th>
<th>(h_j) cm.</th>
<th>(h_j/h)</th>
<th>(C_v) cm/sec.</th>
<th>(F_j) (dyna) (\times 10^8)</th>
<th>(F_j/F_o)</th>
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\(d\) = diameter. \(M1-AP\) = mean intra-aneurysmal pressure. \(F_o\) = calculated hydrostatic force at orifice. \(h\) = head equivalent of intra-aneurysmal pressure in cm. of blood. \(h_j\) = height of vertical jet in cm. \(C_v\) = coefficient of velocity. \(v\) = velocity of jet, discounting air resistance. \(F_j\) = calculated dynamic force of jet.

* Hathaway type SYB-1; inductance-type of pressure gage, with electronic amplification and photographic recording.
the aneurysmal dome. The two orifices are connected by what may be considered as a diverging-converging tube (the aneurysm). In order to assess the effect of this peculiar type of orifice upon the jet, the factors of non-homogeneous, pulsating fluid and expansion were eliminated in these supplementary studies. Utilizing a water pressure system connected to a glass-model aneurysm similar to the experimental aneurysms, with a hole in its dome 1 mm. in diameter, the heights to which vertical jets arose were correlated with the various hydrostatic heads used, ranging from 13 to 254 cm. H$_2$O. The vertical jet heights in the series of 75 observations varied from 7 to 175 cm. The ratio h$_j$/h and the coefficient of velocity were calculated for each head, the average velocity coefficient being .854. The higher coefficients were found in association with hydrostatic heads of 40 to 120 cm. H$_2$O, the highest coefficient being .89. The data thus obtained afforded a "base-line" for correlation of the velocity coefficients of the free blood jets from the experimental "berry" aneurysms (fig. 2). Since the orifices for the blood jets were produced by needle punctures, variations in their characteristics likely account for the greater variability of their velocity coefficients.

For the purpose of simulating jet action from a ruptured intracranial "berry" aneurysm, the glass-model aneurysm was cast within a mould of gelatin, having a consistency similar to that of brain. The water in the pressure system was cooled with ice and colored with anlin red. Jet action within the gelatin block was released under a hydrostatic head of 165 cm. The jet rapidly traversed the gelatin to a vertical height of about four cm. Its original discrete path was quickly obscured by the appearance of a red stain which expanded into the shape of an inverted pear. The erosion soon extended to the surface of the gelatin, about three cm. above the aneurysmal dome.

Flow at Aneurysmal Neck. The neck of an aneurysm may be considered as a submerged orifice or short tube connecting the lumen of the parent vessel with that of the aneurysm. When a jet is issuing from the aneurysm, the flow through the submerged orifice must be at least equal to that of the external jet. In the intact experimental "berry" aneurysms a "suppressed jet" has been demonstrated by cinefluoroscopic studies. However, the swirling motion of the opacified material within the aneurysm made it impossible to determine the rate of flow through the orifice. In order to eliminate this factor, a glass-model aneurysm was constructed on the side of a glass tube, the ends of which were inserted into the proximal and distal lumina of the transected femoral artery of a dog. The model contained a clear heparin-saline solution, permitting excellent visualization of the initial flow of blood through the submerged orifice as the previously arrested circulation in the artery was released. The initial flow of blood into the model was photographed at the rate of 64 film frames per second. The significant series of film frames, enlarged and printed, is shown in figure 3. The model, having a calculated volume of .32 cc., filled with blood in one-eighth second "from a standing start," giving a flow rate of about 2.5 cc. per second. Although the submerged orifice had an area of .11 cm.$^2$ only about one-third of this would be available to the "suppressed jet," the remainder being occupied by return flow and region of shear. On this basis the velocity of in-flow through the orifice was 68 cm. per sec. The theoretical force of such a "suppressed jet" would be almost 200 dynes. Since the model was rigid, these data cannot be applied directly to the flow through the submerged orifice of an expansile aneurysm. They are offered merely as a first approximation to
Fig. 3. "Suppressed jet" action in a glass-model aneurysm inserted into femoral artery of dog; enlarged motion picture sequence at 64 film frames per second. The action progresses downward in the first column then downward in the second column. The arrow indicates the direction of blood-flow in the artery. The jet of blood makes its appearance in the second frame of the first column. Complete blood-filling of the aneurysm occurs in next to the bottom frame of the second column. The time interval between these two points is one-eighth of a second.

the solution of this problem. The flow is probably determined to a considerable extent by the exact contours of the orifice.

DISCUSSION

Free jet action from an experimental "berry" aneurysm can be correlated with theoretical hydraulics (fig. 4) on the basis of coefficients of velocity. These coefficients form a relatively modern touch to a very old problem. About the year 106 B.C., Sextus Julius Frontinus, inspector of the fountains of Rome, noted that the discharge of water from an orifice was related to the depth below the surface of the reservoir from which the water was supplied. Over 17 centuries later Torricelli, influenced by Galileo's experiments with falling bodies, concluded that the velocity of efflux from an orifice is proportional to the square root of the hydrostatic head. About the middle of the 18th century Bernoulli deduced the relation: \( v = \sqrt{2gh} \). Later experiments indicated that corrections were necessary for various heads and types of orifices. The coefficient of velocity serves this purpose. A mean value for this coefficient for 'standard flat orifices' is .98, that for 'standard short tubes' .82. Since an aneurysm fits neither of these categories, this coefficient was determined for a glass-model aneurysm and found to be about .85. Correlating this with the average velocity coefficient of .78 for free orifices in experimental "berry"
FIG. 4. Correlates of jet action. The height of vertical jets \( h_j \) in cm. is shown on the vertical axis. The bottom horizontal axis scale gives the velocity \( v \) in cm. per sec. The upper horizontal axis scale gives the calculated force \( F \) of the jet in dynes, based upon a jet diameter \( d \) of 1 cm. The formula for calculating the force is shown in the upper left corner; the velocity formula is in the lower right. The latter may be used as shown, without the coefficient of velocity, provided the height of the jet \( h_j \) is substituted for the hydrostatic head \( h \). The "\( g \)" equivalents of velocities are blocked in the lower left corner.

aneurysms, it is apparent that the velocity and therefore the force of the latter is slightly less than for the glass-model. However, the velocities attained by the free jets (287 to 477 cm. per sec.), confirm our previous hypothesis that jet action from a ruptured aneurysm is a highly significant stress factor to anything in its path. In more familiar terms, the jet velocities ranged from about \( \frac{1}{2} \) to \( \frac{3}{2} \) inches per hour, or about \( \frac{1}{2} \) to \( \frac{2}{2} \) miles per hour. The "destructive" effects of such jets are evident from the gelatin-block experiments.

Brief consideration should be given to other characteristics of flow through orifices. The rate of discharge depends to a considerable extent upon the nature of the edge of the orifice. In most instances the stream gradually contracts to form a jet with a cross-sectional area less than that of the orifice; this is the rule with sharp-edged orifices. The coefficients of discharge \( (C_d) \) and of contraction \( (C_c) \) serve to cover these factors. Their relation to the coefficient of velocity \( C_v \) is \( C_v = C_d + C_c \). Since the coefficients of discharge and of contraction could not be accurately determined for the jets from the experimental aneurysms, the calculations of their force should be considered only as reasonable approximations. Furthermore, the data on free jets apply to the problem of a ruptured intracranial aneurysm only during a short interval after rupture. As blood accumulates in the zone of erosion the situation becomes that of flow through a submerged orifice, dependent upon the difference in pressures inside and outside the orifice. Were this not so, it is likely that all ruptured intracranial aneurysms would proceed to a fatal termination.

**SUMMARY**

A method has been developed for producing experimental "berry" aneurysms by grafting a vein-pouch upon an opening in the wall of the common carotid artery of dogs. The present report, one of a series on intra-aneurysmal hemodynamics, concerns jet action. Measurements were made of the vertical height to which jets would spurt from a hole in the dome of such aneurysms. The velocity and force of the jets were calculated and the dynamic force of the jets was compared with the hydrostatic force at the orifice.

Correlative studies upon water jets from a glass-model aneurysm were used to establish a "base-line" coefficient of velocity for the peculiar type of orifice, represented by a hole in the dome of a "berry" aneurysm. The velocity coefficients of the free blood jets were compared with this "base-line." The effects of similar water jets upon an encasing model of firm gelatin were also noted.

Supplementary information was obtained on flow through an aneurysmal neck by inserting a glass-model aneurysm in continuity with the arterial system. Rapid motion pictures were
taken of the "suppressed jet" of blood entering the clear heparin-saline filled chamber as the previously arrested circulation in the artery was released.

The results of the various experiments were considered in their relation to theoretical hydraulics, with special reference to coefficients of velocity.

REFERENCES


Concerning the Adequacy of Electromagnetic Flowmeters for Recording Phasic Changes in Arterial Blood Flow

Investigators of circulation are greatly in need of an instrument which, applied to unopened arteries, will record rapid changes in phasic blood flow. The electromagnetic flowmeter originally described by Katz and Kohn, and subsequently improved considerably by the latter, has been criticized on the ground that experimental tests are lacking which prove that the entire working instrument is able to record rapid fluctuations in flow. Its failure to show evidence of backflow in large peripheral arteries may be due to such lack of responsiveness (Gregg).

Recent physical tests are reported which seem to indicate that an electromagnetic flowmeter can respond faithfully to rapid fluctuations in systolic and diastolic flow rates with a time lag of only \( \frac{30}{60} \) second. A method for in vitro calibration has been suggested which promises to help in eventually making such an instrument serviceable for quantitative measurements in intact blood vessels. Success requires further technical improvements to eliminate completely the instability of the present apparatus.

Used in its present state of development, no evidence of backflow was detectable in the carotid and femoral arteries of rabbits and dogs.

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