Hydrodynamic Forces in Dissecting Aneurysms

IN-VITRO STUDIES IN A TYGON MODEL AND IN DOG AORTAS

By Edward K. Prokop, M.S., Roger F. Palmer, M.D., and Myron W. Wheat, Jr., M.D.

ABSTRACT

It has been argued that pulse wave characteristics are important factors in extension and rupture of acute dissecting aneurysms. To test this, a standard model of an aorta was constructed, consisting of an outer layer of Tygon tubing and an inner layer of rubber cement. An "intimal tear" was produced and the "aorta" was subjected to nonpulsatile and pulsatile flow with increasing increments of pressure.

With nonpulsatile flow alone (97 experiments) no dissection occurred at pressures up to 400 mm Hg. Pulsatile flow produced rapid and usually complete dissection with a maximum systolic pressure of 120 mm Hg.

The extent of dissection per pulse was related to dp/dt\text{max} in the fluid. No dissection occurred until a critical value of dp/dt\text{max} (790 mm Hg/sec) was reached. Dog aortas were then used in place of the Tygon tube "aorta" with similar results; i.e., dissection did not occur with nonpulsatile flow, but did occur with pulsatile flow (3800 mm Hg/sec). The dissecting dog aorta ruptured to the outside or reentered the vessel lumen.

It was concluded that pulse wave characteristics, particularly dp/dt\text{max}, are important in the propagation of dissection.

ADDITIONAL KEY WORDS

pulsatile flow

nonpulsatile flow

pulse wave

pressure gradient

initiation and propagation of dissection

It has been suggested that the shape of the pulse wave is the most important initiator of the force which acts on the aortic wall to cause extension and rupture of acute dissecting aneurysms (1). It also has been argued that drugs which affect the rate of ventricular fiber shortening should change the shape of the pulse wave and thus decrease the major force tending to further the dissection (2). These drugs are well known (e.g., reserpine and trimethaphan) and have proved beneficial in preventing further extension and rupture of acute dissecting aneurysms (3). However, little information on the effect of the pulse wave at the level of the aorta has been advanced. Therefore, it was the purpose of this study to construct an aortic model in which the effect of the pulse wave on the propagation of dissection could be examined.

Materials and Methods

Construction of a Standard Model of an Aorta.—The following model is a modification of one previously described (1). Tygon tubing (9.5 mm i.d., formulation B44-3) was coated on the inside with Carter's rubber cement dissolved in toluene (two parts rubber cement to one part toluene). Ink was added to the solution to differentiate the two layers more easily. This two-layered system (Tygon tubing and rubber cement) resembled an aorta in which the adventitia and media were represented by Tygon tubing and the intima by the rubber cement lining. When the rubber cement hardened (6 to 24 hours), an "intimal tear" was created as shown in Figure 1.

Standard Model of an Aorta Subjected to Nonpulsatile and Pulsatile Flows.—The Tygon tubing with the intimal tear was then connected into the system shown in Figure 2, 40 cm from the
A: Sketch of a section of the standard model of an aorta showing Tygon tubing and rubber cement lining.  
B: A cut is made (approximately 1 cm circumferentially) in the rubber cement lining with an ophthalmic scalpel.  
C: An "intimal tear" is produced by separating the rubber cement lining from the Tygon tube approximately 0.5 cm proximal and distal to the cut.

Y junction. Ten tubes were first subjected to a steady flow of water (produced by Sarns portable pump model 3500) at rates varying from 500 ml/min to 2000 ml/min (Reynolds number \( \text{Re} \) 1120-4470) in increments of 500 ml/min. The flow was then increased in increments of 1000 ml/min to a final value of 6000 ml/min (Re 13,420).

Next, the flow was held constant at 2500 ml/min. The initial pressure was approximately 50 mm Hg. Pressure was then increased by changing the resistance in the distal tube in increments of 50 mm Hg at intervals of 15 minutes until a final pressure of 250 mm Hg was reached.

The tube was then subjected to pulsatile flow generated by a Harvard pulsatile blood pump (model 1403). The stroke volume was set at 60 ml/min with a mean pumping rate of 70 strokes/min with systole being 60% and diastole 40% of the entire cycle. The peak systolic pressure at this time was approximately 60 mm Hg. The tube usually dissected its entire length within 15 minutes.

Pressure waveforms were measured through a rubber catheter 6 inches long and 3/16 inch in diameter connected to a Statham (model P23AC) physiological pressure transducer. The pressure recording system had an amplitude response uniform with frequency over the range 0 to 9 cps (4, 5). The pressure was measured at the distal part of the tube by attaching a no. 17, blunt-nosed, thin-walled needle to the catheter and inserting the needle directly through the Tygon tubing with the tip of the needle positioned as close to the wall as possible. The values obtained by this pressure recording system were compared with the values obtained by a system consisting of a 15-gauge, thin-walled needle connected directly to a pressure transducer (Statham model P23Db: frequency response uniform from 0 to 20 cps) for low and high values of \( \frac{dp}{dt_{\text{max}}} \). At values of \( \frac{dp}{dt_{\text{max}}} \) of 800 and 4000 mm Hg/sec the values recorded through the rubber tubing were respectively 82 and 70% of the values obtained by the system consisting of the needle connected directly to the pressure transducer. The pressure was recorded on a Grass polygraph (model 7).

The rate of dissection was calculated by recording the time necessary to dissect the intimal lining from the Tygon tubing. The rate of
dissection was measured in the same direction as flow. The value was expressed as cm/min.

**Step Increase of Pressure.**—The Tygon tubing with an intimal tear was subjected to a step increase of $dp/dt_{max}$. This was accomplished by changing the systole-diastole time ratio of the Harvard pulsatile blood pump. $dp/dt_{max}$ was determined by measuring the slope at the steepest point on the pulse wave. The paper speed used for recording the pulse wave was 100 mm/sec. The final value for $dp/dt_{max}$ was the average of five consecutive measurements (maximum range that any one measurement varied from the mean was 80 mm Hg/sec or 3.2%). However, by changing the systole-diastole time ratio of the pulsatile pump, the number of pulses per minute also changed. Therefore, to take this into account, the dissection of the rubber cement lining from the Tygon tubing was expressed as dissection/pulse. Typical pulse tracings are shown in Figure 3.

**Dog Aortas.**—The descending branch of the aorta from approximately the left subclavian artery to the diaphragm was removed from 15 killed dogs. The posterior lumbar arteries were tied off. Next, the needle of a syringe containing saline solution was directed from the inside of the vessel through the intima into the media. Approximately 0.3 ml of the saline solution was then injected to form a bleb, which was cut with a knife, forming a flap similar to that in the rubber-lined Tygon tube. The length of the cut circumferentially was essentially the same each time (0.8 cm ± 0.2 cm) and approximately 1 to 1.25 cm from the end. The depth of the cut was not controlled. The largest diameter of the dog aortas varied from 0.75 to 1.25 times the diameter of the tube (0.95 mm i.d.). The aorta was fastened to the tube at its in-vivo length.

The aorta then was subjected to nonpulsatile flow at a rate of 2500 ml/min. The peak systolic pressure was increased in increments of 25 mm Hg at intervals of 3 minutes until a final pressure of 175 mm Hg was reached. After each 3-minute interval, the aorta was disconnected from the system and checked to see if any dissection occurred. It was then subjected to pulsatile flow at a stroke volume of 60 ml/min with a mean pumping rate of 60 strokes/min and the presence of dissection noted every 3 minutes or until the vessel ruptured. The aortas without intimal tears were subjected to pulsatile flow.

Next, five aortas with intimal tears were subjected to a step increase of $dp/dt_{max}$ similar to the Tygon experiments; $dp/dt_{max}$ was recorded by inserting a 15-gauge, blunt-nosed, thin-walled needle connected directly to a Statham P23AC pressure transducer into one of the posterior lumbar arteries. The pressure recording system had a frequency response of 0 to 20 cps. Similarly the presence of dissection was noted every 3 minutes or until the vessel ruptured. The peak pressure at this time averaged 230 to 250/70 to 90 mm Hg.

**Results**

**Nonpulsatile and Pulsatile Flow.**—With nonpulsatile flow, only two tubes out of 97 dissected completely. This dissection occurred in less than 1 minute and can be attributed to improper preparation of the tubes by not allowing the rubber cement to harden. In 30% of the other tubes, there was a slight initial dissection (approximately 0.5 to 1 cm), which was probably due to transient disturbances in the system when the pump was first turned on. However, once the flow reached a steady state (in approximately 0.5 to 1 second), no further dissection occurred. There was also no further dissection in the system when the static pressure was increased in by steps to 250 mm Hg. In 10 of the initial experiments, the static pressure was increased to 400 mm Hg without dissection.

When the tubes were subjected to pulsatile flow, dissection occurred in both directions. However, dissection was completed in the forward direction for a distance of approximately 13 cm before it was completed in a

---

**Figure 3**

Typical tracings of two pulse waves—the lower tracing represents the shape of the pulse wave after the rubber cement lining began to dissect. The upper tracing represents the shape of the pulse wave after the rate of dissection reached a plateau.
Variation of Dissection with dp/dt max—A step increase in dp/dt max was followed by a proportionate increase in the rate of dissection. This is shown in Figure 4. As can be seen, dissection did not occur below a certain threshold dp/dt max (790 mm Hg/sec). Above the threshold value, the rate of dissection is related to dp/dt max, and at higher values for dp/dt max, the rate of dissection reaches a plateau and shows little additional change for additional large increases in dp/dt max.

Dog Aortas.—No dissection was seen when the 15 dog aortas with intimal tears were subjected to nonpulsatile flow. Also, the three aortas without intimal tears showed no dissection when exposed to pulsatile flow. When subjected to pulsatile flow, 12 of the 15 dog aortas with intimal tears dissected within approximately 3 minutes. Because of the difficulty of observing the rate of dissection, no measurements were made of this variable. Instead, the vessel was observed to see if dissection occurred. In 9 of the 12 aortas, the vessel dissected and ruptured to the outside. In the remaining three aortas, the vessels dissected, but instead of rupturing, there was a recanalization of the dissected channel back into the main vessel channel. Photographs of two typical vessels are shown in Figure 5.

One of the five dog aortas subjected to a step increase of dp/dt max did not dissect when exposed to the maximum dp/dt max (4500 mm Hg/sec) produced by the pump. The other four aortas did not dissect until a certain value of dp/dt max (average 3800 mm Hg/sec; range 3100 to 4300 mm Hg/sec) was reached. The mean pressure was 170 to 200 mm Hg at this time.

Discussion

An acute dissecting aneurysm is the result of two processes acting on the aorta. The first
HYDRODYNAMIC FORCES IN DISSECTING ANEURYSMS

FIGURE 5
Top: Dog aorta subjected to pulsatile flow in which there was dissection and rupture to the outside. A = the cut in the vessel wall; B = the rupture; C = the dissection. Bottom: Dog aorta subjected to pulsatile flow in which there was dissection and instead of rupture to the outside, there was recanalization back into the main vessel channel. A = the cut; B = the recanalization opening; C = the dissection.

process consists of those factors which are responsible for the initiation of dissection, e.g., disruption of media and intimal lining by trauma or disease (6-8). The second process is concerned with factors that are important for the propagation of dissection once the vessel has started to dissect.

As stated previously, it has been suggested that the shape of the pulse wave is the important factor in the propagation of dissection in the acute dissecting aneurysm. It has been shown also that drugs which reduce the rate of pressure change (dp/dt$_{max}$) are effective in arresting further dissection and rupture of an acute dissecting aneurysm in humans (9) and turkeys (10). The results of the present study support the premise that the shape of the pulse wave is an important factor in the propagation of dissection. In this study it was shown also that there is a critical dp/dt$_{max}$ (average 790 mm Hg/sec) for the "standard model of the aorta" above which dissection will occur and that the rate of dissection is related to dp/dt$_{max}$ (Fig. 4).

The importance of the shape of the pulse wave was also illustrated in the dog aorta. In this case, although the wall of the aorta was rendered susceptible to dissection by a prior intimal tear in the vessel wall, no dissection occurred with nonpulsatile flow even though the flow was turbulent (at Re > 1300, entrance conditions are not met in this system).
Ascending portions, A and B, of two idealized waves in the coated Tygon tubing. The shaded area represents the part of the intimal lining exposed to the action of the pulse waves A and B. The forces tending to separate these two layers are related to the pressure differences $\Delta P$. Thus, for pulse A the pressure difference that the shaded area is exposed to is $\Delta P_A$. Likewise, for pulse B, the pressure difference is $\Delta P_B$. Since the magnitude of the forces tending to separate the layers is related to the pressure difference ($\Delta P$) across the vulnerable area, there is a larger force associated with pulse A than with pulse B.

It is important to note that the mean pressures which produced dissection were in the range 170 to 200 mm Hg. Static mean pressures producing dissection when $dp/dt_{\text{max}}$ was suprathreshold were significantly lower than the 500 mm Hg static pressures needed to rupture the aorta (11).

To relate $dp/dt_{\text{max}}$ to dissection, consider the model of the two-layered system with the defect in the inner lining represented diagrammatically in Figure 6. The pulse wave is traveling from left to right. The area surrounding the point where the inner lining is disrupted can be considered the “susceptible area to dissection,” i.e., the region where separation of the layers can take place. It can then be seen that the magnitude of the force tending to push apart the material at this point is related to the pressure difference ($dp/dt_{\text{max}}$) of the pulse wave. Thus, for pulse A, in which the pressure gradient is larger than for pulse B, the magnitude of the force tending to separate the layers will be greater for pulse A than for pulse B.

The theoretical model considered above does not take into account the properties of the aortic wall. Another approach that can be taken to describe the generation of forces in the media would be to consider the elastic properties of the aortic wall. When the pulse wave causes the vessel to expand in the area of the defect, that part of the media which surrounds the defect will not necessarily expand at the same rate or to the same extent as the intact portion of the vessel wall. Thus, a pressure gradient necessary for generation of the forces causing dissection can be formed in this manner.

An experiment designed to see what effect distention of the vessel played in continuing dissection consisted of replacing the elastic tube with a rigid glass tube. This tube was coated on the inside with rubber cement as previously described for the Tygon tubing. When glass was substituted for the Tygon, dissection still occurred. Thus, it seems that distention of the vessel in the area of the defect is not principally responsible for the development of forces causing dissection.

Considering the threshold for dissection, the layers of the vessel wall are held together with a certain binding force. To separate these layers, the forces produced by the pulse wave must be greater than the binding forces of the tissue. Where the force is equal to or less than the tissue-binding force, dissection will not occur. However, when the force is greater than the tissue-binding force, the tissue is separated in the region of the pressure wave. As discussed previously, the magnitude of the force tending to separate the layers is related to $dp/dt_{\text{max}}$. Thus, if the slope of the pulse wave is decreased below a certain value, no dissection will occur.

Another force related to $dp/dt_{\text{max}}$ is the shearing force which acts in the direction of the fluid flow, i.e., parallel to the vessel wall. There are many mathematical expressions for this force, but the expression most representative of the system in question is that expressed by Fry (12) where he showed that the shearing force may be approximated by:

$$ T \approx \frac{R}{2} \cdot \frac{dp}{dZ} \left( \text{or} \frac{dp}{dt} \right)^2 $$

where $C$ is the velocity of the pulse wave traveling through a tube.

Circulation Research, Vol. XXVII, July 1970
where \( R \) is the channel radius, \( Z \) is the distance along a coordinate placed on the center line of the tube, and \( dp/dZ \) is the pressure gradient parallel to the axis of the tube. Thus, the shearing force or, more precisely, the rate of change of shear is directly related to \( dp/dZ_{\text{max}} \) (or \( dp/dt_{\text{max}} \)).

Just what part the rate of change of shear plays in the dissection of the vessel is difficult to assess in this study. However, two points can be made which tend to support the minor role the shearing force plays in the early propagation of dissection. First, dissection in the direction opposite to fluid flow cannot be explained by a force which acts only in the direction of fluid flow \((9)\). Another argument supporting the minor role of shear forces is that no dissection occurs when there is nonpulsatile flow, even at high flow rates \((> 6,000 \text{ ml/min}; \text{Re} > 14,000).\)

In summary this study does establish the following points: (1) with nonpulsatile flow in the model aortas and dog aortas no dissection occurred, but with pulsatile flow it did occur; (2) when pulsatile flow was employed, there was a critical value for \( dp/dt_{\text{max}} \) below which there was no dissection. Above this value the extent of dissection was related to \( dp/dt_{\text{max}} \); (3) dissection in this model did not occur at high Reynolds numbers, suggesting that shear forces play little or no role in the early propagation of dissection.

The rationale for decreasing \( dp/dt_{\text{max}} \) as a worthwhile method of therapy in acute dissective aneurysms of the aorta is supported by these studies.

**Acknowledgment**

We would like to thank Dr. L. J. Krovetz and Dr. Bent A. Christensen for their technical assistance and critical review.

**References**


Hydrodynamic Forces in Dissecting Aneurysms: In-Vitro Studies in a Tygon Model and in Dog Aortas

EDWARD K. PROKOP, ROGER F. PALMER and MYRON W. WHEAT, Jr.

doi: 10.1161/01.RES.27.1.121

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1970 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/27/1/121