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THE AORTIC VALVE

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Chapter 3

DYNAMICS OF THE AORTIC VALVE

I. INTRODUCTION

The geometry of the static aortic valve was described in Chapter 1. However, the aortic valve in its natural state is always in motion; it is not a static structure. In this chapter we will examine the dynamic behavior of the aortic valve in its natural functional state. The dynamic behavior will be considered in four steps: (1) opening and closing of the valve, (2) motion of various parts of the valve, (3) design of the valve *in vivo*, and (4) high-speed studies of leaflet motion.

II. OPENING AND CLOSING OF THE VALVE

The most prominent feature of the functioning aortic valve is the movement of the leaflets causing the valve to open and close. This movement occurs so rapidly that special techniques are necessary to view it. In humans, the technique of aortic root cineangiography is used to determine the opening and closing behavior of the valve. In this technique, radiopaque dye is injected into the aortic root and the movement of the contrast medium is visualized under X-ray and recorded on cine films or videotape. Although this technique is used commonly, it does not provide a precise definition of the valve orifice. Two-dimensional echocardiography has been used to examine a cross-section of the valve orifice, but the orientation of the cross-section is difficult to ascertain (Chapter 6). The understanding of precise movements of the leaflets is gained from studies using a marker-fluoroscopy technique in dogs. In this technique, small radiopaque markers are placed at known positions on the valve and movement of the markers is studied. Other techniques used to study valve motion include injecting a clear liquid into the left atrium and then visualizing the valve. Valve motion has also been studied *in vitro* by use of a pulse duplicator system in which a clear liquid is pumped through the valve. Some of these studies are considered below.

A. THE VALVE ORIFICE

Stein et al. studied the human aortic valve using aortic root angiography in which an X-ray tube was positioned at a predetermined angle in order to obtain an almost direct view of the valve orifice.[1] The angle of the X-ray tube was determined in patients with prosthetic aortic valves. In these studies the angle of the X-ray tube deviated from the valve axis by an average of 12°, thereby resulting in an oblique projection. The normal open aortic valve was observed to have both a circular as well as a triangular orifice. As a matter of fact, in angiograms, depending upon the angle between the X-ray beam and the valve axis, different shapes of the orifice can be seen. Figure 1 shows a nearly circular and a nearly triangular orifice of a human aortic valve. Figures 2 and 3 show other configurations of so-called valve orifice, where the central region of low contrast can be considered to represent the orifice. However, as we will see, this central region is not the true orifice of the open valve.

Thubrikar et al. studied angiograms of human and canine aortic valves, and the projections of the aortic valve models to understand the angiograms.[2] They made one model of the valve that showed a circular opening and another that showed a triangular opening. Using the appropriate orientation of the model with a circular opening, they established that almost all of the angiograms could be interpreted correctly. For example, Figures 2 and 3 show human angiograms and projections of the aortic valve model with a circular opening. The central openings in the angiograms are identical to those of the model (C, E, and G in Figures 2 and 3). It is important to note that the margins of the central openings do not consist of just the leaflet-

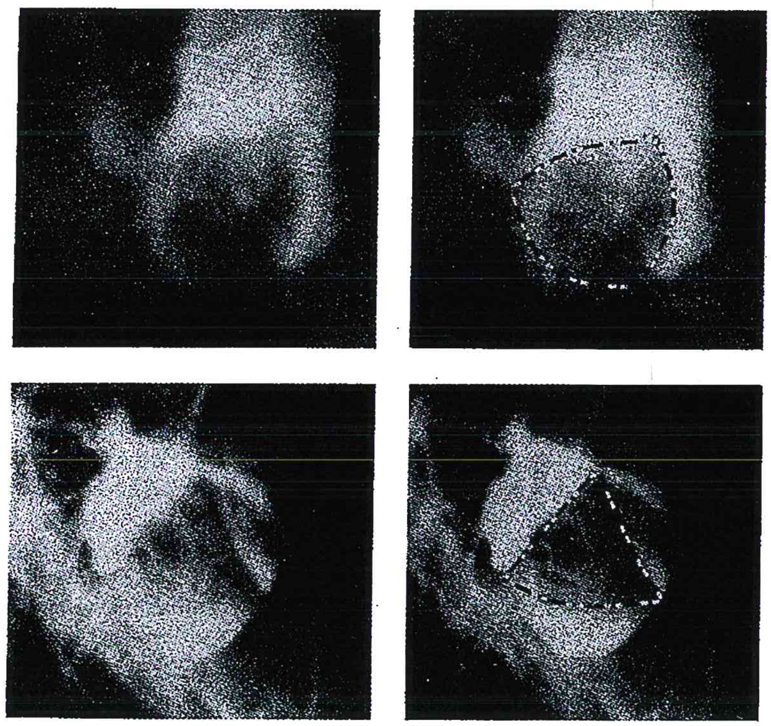

FIGURE 1. Aortograms of patients with normal aortic valve (top) and with mild aortic regurgitation due to Marfan's syndrome (bottom). Top — Orifice appears nearly circular as also outlined with dotted lines. Bottom — Orifice appears triangular and aortic sinuses appear aneurysmal. (From Stein, P. D., *Am. Heart J.*, 81(5), 622, 1971. With permission.)

free margins, but rather of both the free margins and the lines of leaflet attachment. In Figures 2G and 3G, for example, the margin of the central opening marked by the dotted line represents the line of leaflet attachment and that marked by the solid line represents the leaflet free edge. This means that in an oblique projection of the valve, the central opening does not represent the orifice of the valve. This is also true for angiograms obtained from dogs. Figures 4 and 5 show angiograms from dogs with appropriate projections of the aortic valve model with a circular opening. Once again the central opening in the angiograms is identical to that in the model (B, F, E, and H in Figure 4 and A and B in Figure 5). Thubrikar et al. found that the projections of the aortic valve model with a triangular opening did not match with any of the angiograms. Therefore, they concluded that in humans and in dogs the aortic valve orifice is circular, particularly in early systole.

In summary, since angiographic projections most often show an oblique view, i.e., the X-ray beam is not exactly along the axis of the aorta, the margins of the valve orifice may appear straight or curved. This is because oblique projection of a curved line can be a straight line. In other words, a circular orifice can project itself as partly triangular. However, it is clear that the normal valve orifice is not triangular since a triangle will not project with curved borders. Also, the orifice decreases continuously during systole causing its shape to change. The shape of the aortic orifice, determined with two-dimensional echocardiography, is discussed in Chapter 6.

III. THE LEAFLET MOTION

A detailed analysis of leaflet motion in a functioning valve *in vivo* was carried out by

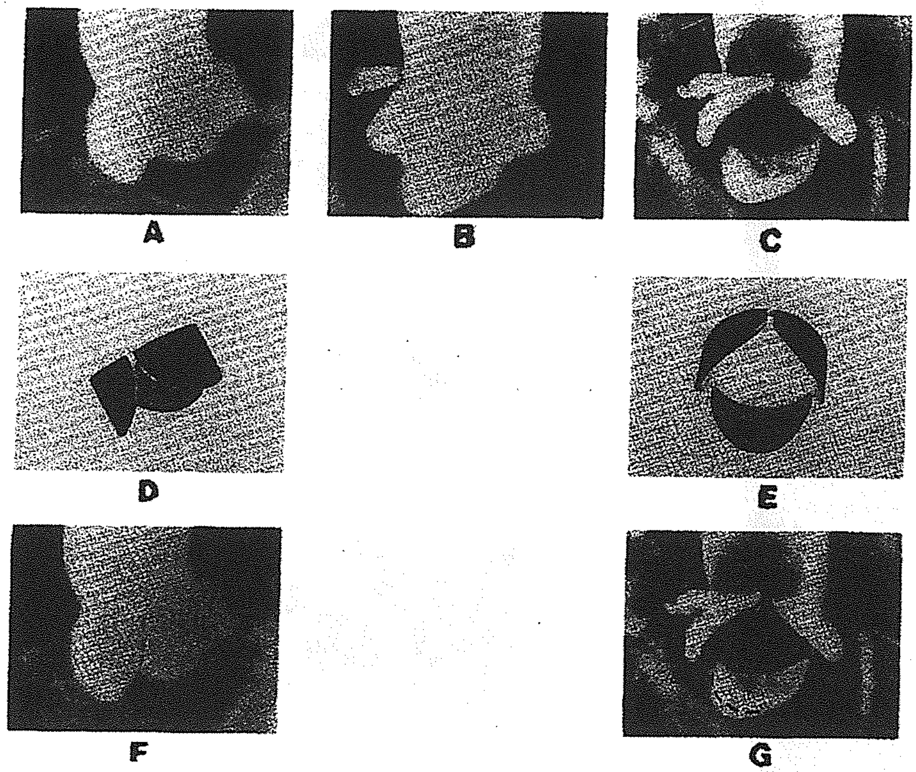

FIGURE 2. Biplane aortogram of an infant (2 months) with a normal aortic valve. (A) Side view of a closed valve. (B and C) Oblique views of the valve in diastole and in systole, respectively. (D and E) Views of the cylindrical model matching those in A or F and C or G. (G) The valve orifice is composed of the line of attachment (dotted line) and the free edge (solid line) of the leaflets. (From Thubrikar, M. et al., *Cardiovasc. Res.*, 16, 16, 1982. With permission.)

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Thubrikar et al. using the marker fluoroscopy technique.[3] Small radiopaque markers were placed at various locations in the aortic valves of dogs and the movement of the markers was observed under X-ray. Figure 6 shows the position of the markers on the leaflets and in the commissures. The markers in the commissures were used for obtaining appropriate projections of the valve and for determining the outline of the valve orifice. The movement of the markers was recorded as described below. Figure 7 shows the orientation of the X-ray beam used for obtaining the projections. In the closed valve, when the X-ray beam is along the valve axis, the commissure markers project at the apices of the triangle and the leaflet markers project at the center. When the X-ray beam is perpendicular to the valve axis, the commissure markers project in a straight line and the leaflet markers project below or above the straight line. Figure 8 shows the actual radiograms in which the markers can be seen in both the triangular and the straight line projections. The movement of the markers was recorded at a rate of 60 fields/s which provided 60 data points/s.

Figure 9 shows a plot of distance between the two leaflet markers and the aortic pressure vs. time. The aortic valve opens rapidly at the beginning of systole and closes rapidly at the end of systole. During a cardiac cycle, one may picture the valve in action as follows: a sudden opening of the valve, then only a little movement while the valve remains open, a sudden closure of the valve, and then almost no movement while the valve remains closed. Little time is spent in the opening and closing process. During a cardiac cycle, most of the time is spent in filling the heart

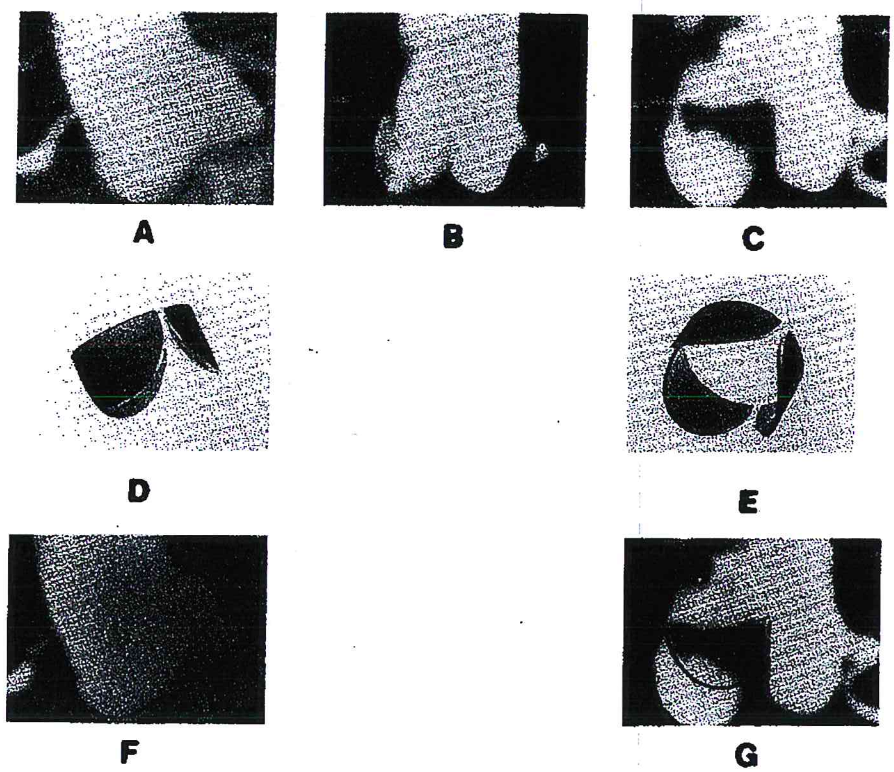

FIGURE 3. Biplane aortogram of another infant (8 months) with a normal aortic valve. (A) Side view of the valve in diastole. (B and C) Oblique views of the valve in diastole and in systole, respectively. (D and E) Views of the cylindrical model matching those in A or F and C or G. (G) The valve orifice is composed of the line of attachment (dotted line) and the free edge (solid line) of the leaflets. (From Thubrikar, M. et al., *Cardiovasc. Res.*, 16, 16, 1982. With permission.)

when the valve is closed and ejecting the blood when the valve is open. This magnet-like to-and-fro motion of the leaflet is the most prominent feature of the aortic valve in action.

It would be incorrect to say that no motion is taking place while the valve is open or closed. For example, while the valve is open, the leaflets are gradually moving towards the center of the valve. This is indicated in Figure 9 by a gradual decrease in the distance between the two leaflets. Hence, the valve is maximally open in early systole, gradually closes during systole, and rapidly closes at the end of systole. The time required for the rapid opening or the rapid closure of the valve is 17 to 20 ms. To analyze the leaflet motion in these two rapid phases, one needs a technique of high-speed recording, which is described later in this chapter.

The orifice of the aortic valve appears circular or nearly circular (Figure 8). The orifice is gradually changing during systole as the leaflets are moving towards the center of the valve. Therefore, the valve orifice may appear circular, bulged triangular, or triangular depending upon whether it was observed in early, mid, or late systole. The shape of the orifice may also depend upon cardiac output, condition of the myocardium, and dynamics of the aortic root.

The valve orifice has also been studied by direct visualization. Injection of a clear solution through the valve makes it visible in a beating heart. This technique makes it possible to see the entire free edge of the leaflet, unlike the marker technique which allows identification of only one point on the free edge. On the other hand, injection of a clear liquid creates artificial circumstances by changing the fluid environment (e.g., viscosity, density) and it might also change the cardiac function.

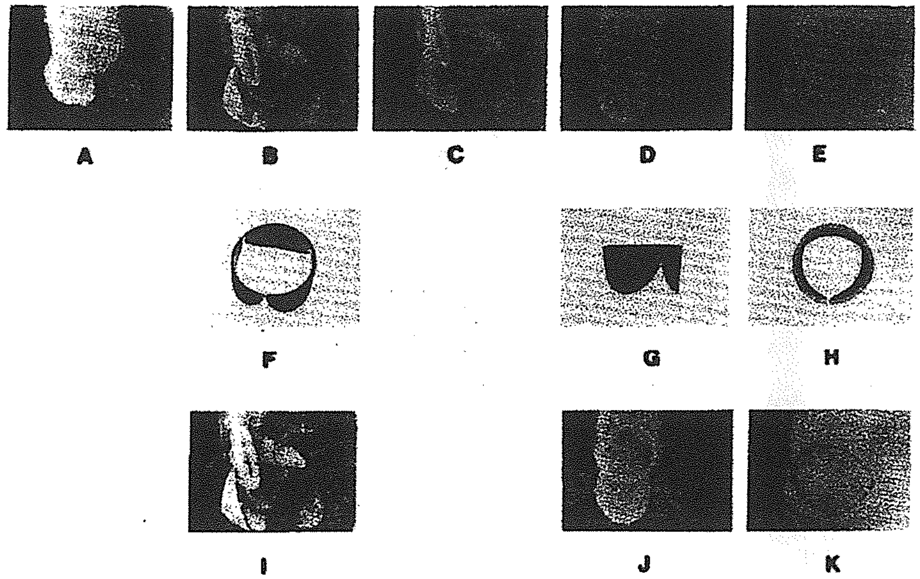

FIGURE 4. Cineangiograms of a canine aortic valve. A, B, and C are oblique views of the valve. (A) Valve in diastole; (B and C) valve in systole; (D) a side view of the valve in diastole; and (E) the best obtainable top view of the valve in systole. Configurations of the valve orifice appear different (B, C, and E) when viewed from different angles. (F) An oblique view of the cylindrical model. (G and H) Side and top view, respectively, of the conical model of the aortic valve in systole. The views F, G, and H of the models match those in B, D, and E or I, J, and K. I and K show that the orifice is composed of the line of attachment (dotted line) and the free edge (solid line) of the leaflets. (From Thubrikar, M. et al., *Cardiovasc. Res.*, 16, 16, 1982. With permission.)

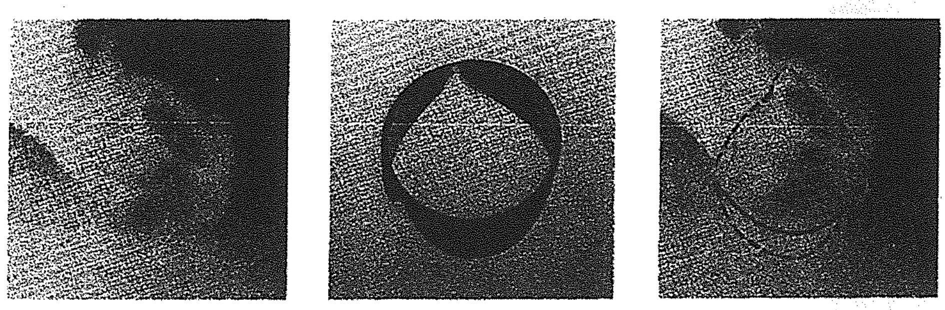

FIGURE 5. (A) Cineangiogram of another canine aortic valve. (B) An oblique view of the cylindrical model that matches with the view in A or C. (C) The orifice in A is composed of the line of attachment (dotted line) and the free edge (solid line) of the leaflets. (From Thubrikar, M. et al., *Cardiovasc. Res.*, 16, 16, 1982. With permission.)

Steenhoven et al., using the technique of injection of a clear liquid in dogs, observed that while the valve orifice is nearly circular in early systole it changes to bulged triangular and then to triangular towards the end of systole.[4] The configurations of the valve orifice during complete systole are shown in Figure 13, Chapter 4. Hider[5] found, using a similar technique, that the valve

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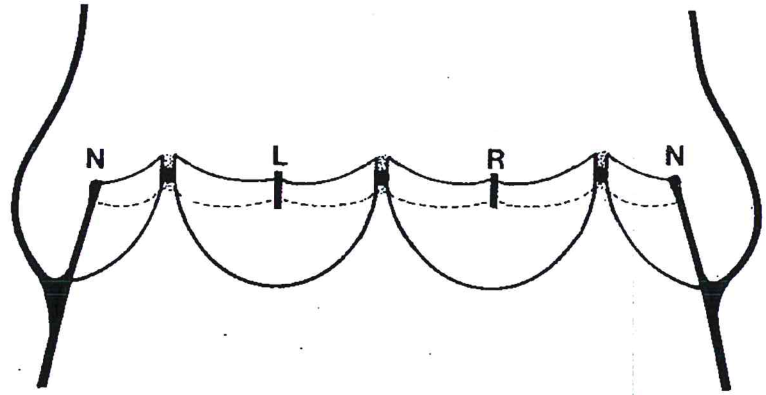

FIGURE 6. Schematic presentation of an aortic valve opened by a vertical incision through the noncoronary sinus. L, R, and N are the left, right, and noncoronary leaflets, respectively. The dotted line is the line of leaflet coaptation. Three radiopaque markers in the commissures (closed circles) and two markers at the center of the free edge of the leaflets (vertical bars) are shown. (From Thubrikar, M. et al., *J. Thorac. Cardiovasc. Surg.*, 77, 863, 1979. With permission.)

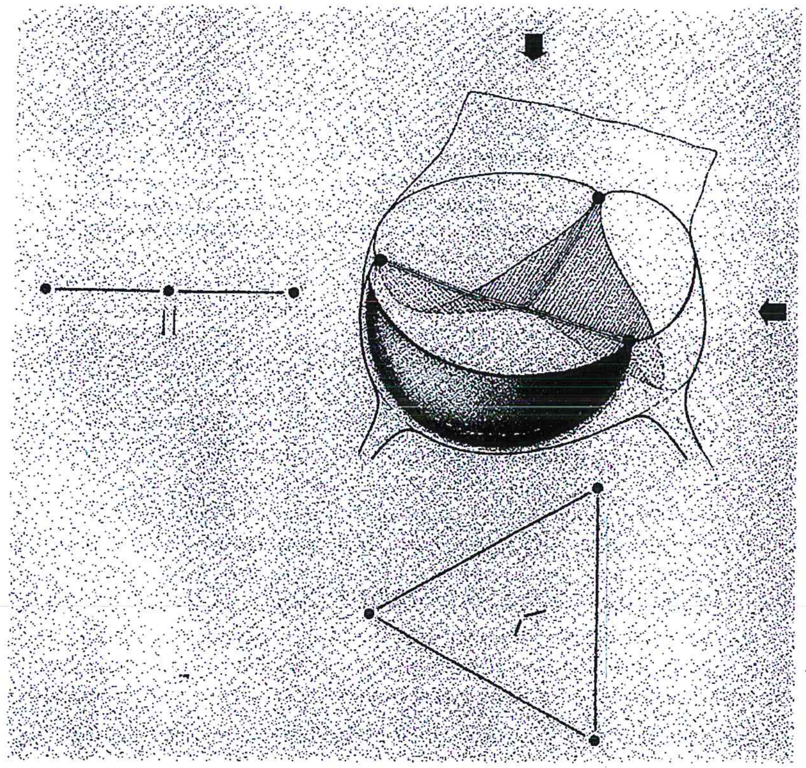

FIGURE 7. Aortic valve in the closed position. The portion of the leaflets shown is between the base and the level of coaptation; for clarity, the redundant portion has been omitted. One of the sinuses is shaded to give perspective to the sinus bulge. An X-ray beam along the axis of the aorta (arrow pointing downward) projects the commissural markers in a triangle and the leaflet markers at the center as shown below the valve. An X-ray beam perpendicular to the axis of the aorta (arrow pointing leftward) projects the commissural markers in a straight line and the leaflet markers below the straight line as shown to the left of the valve. (From Thubrikar, M. et al., *Am. J. Cardiol.*, 40, 563, 1977. With permission.)

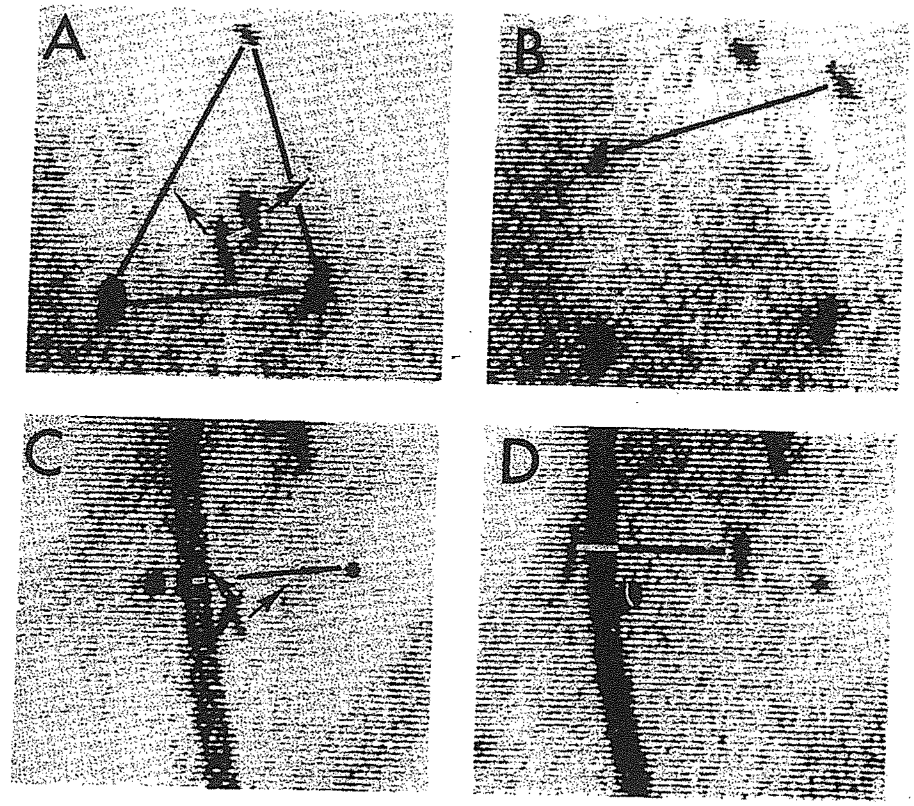

FIGURE 8. Actual frames of a cineradiograph of the aortic valve. Panels A and B were obtained with the X-ray beam along the axis of the aorta. A — in diastole, the three commissural markers form a triangle and the two leaflet markers appear in the center. Arrows indicate the direction in which the leaflet markers move when the valve opens. B — in systole, the two leaflet markers indicate that the orifice of the opened valve is circular. C and D were obtained with the X-ray beam perpendicular to the axis of the aorta. C — in diastole, the three commissural markers form a straight line and the two leaflet markers appear below the plane of the commissures. Arrows indicate the direction in which the leaflet markers move when the valve opens. One catheter in the left ventricle and another just above the valve are also visible. D — in systole, the three commissural markers are still in a straight line but the relative distance between the markers has changed because of the rotation of the heart (two markers on the left appear to touch each other). The two leaflet markers above the plane of the commissures indicate once more that the orifice of the opened valve is circular. (From Thubrikar, M. et al., *Am. J. Cardiol.*, 40, 563, 1977. With permission.)

orifice is circular at normal viscosity and triangular at low viscosity. The fluid viscosities used were 3.4 cSt and 0.7 cSt where the former is similar to the blood viscosity. Padula,[6] using similar techniques in dogs, observed that in a functioning heart, the valve orifice is circular in early systole and gradually changes to triangular in late systole. In the nonfunctioning heart, however, the orifice is triangular when a clear fluid is pumped through the valve by a mechanical pump. These observations suggest that fluid viscosity and myocardial function are important in producing a circular orifice.

IV. MOTION OF VARIOUS PARTS OF THE VALVE

Although the leaflets are the most dynamic parts of the aortic valve, the motions of other parts of the valve are also important because they play a role in the opening and closing of the valve.

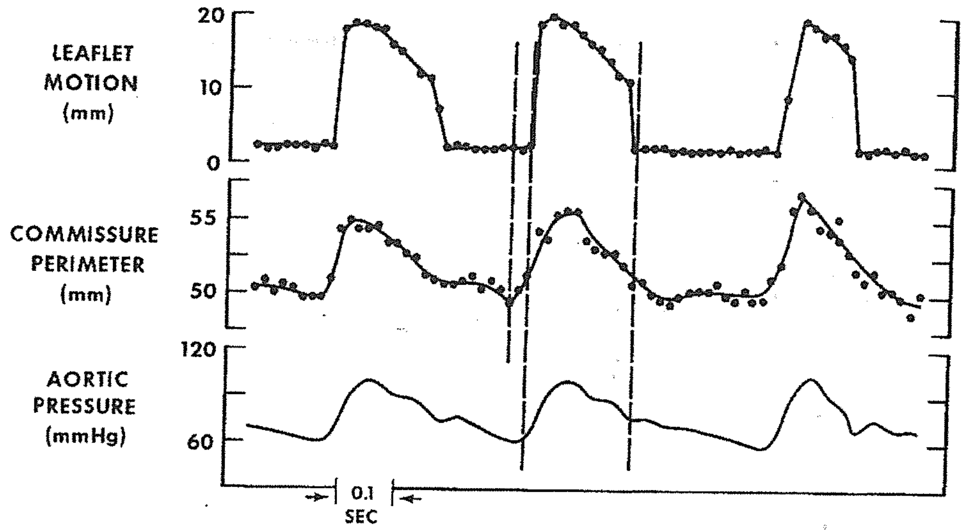

FIGURE 9. Plot of leaflet motion (the distance between two leaflet markers), commissural perimeter (perimeter of a triangle formed by commissure markers) and pressure in the ascending aorta. The graph shows rapid opening of the leaflets, maximal opening in early systole, gradual decrease in the opening during systole and a rapid closure of the leaflets. The commissures expand during systole and the expansion begins 20 to 40 ms before the valve opens. (From Thubrikar, M. et al., *Am. J. Cardiol.*, 40, 563, 1977. With permission.)

A. MOTION OF THE COMMISSURES

Thubrikar et al. studied the motion of the commissures of the aortic valve in dogs by placing radiopaque markers at the commissures and observing their movement under X-ray.[3] The scheme of the marker placement is shown in Figure 6. Figures 7 and 8 show the triangular and the straight line projections of the markers in which the marker movement was determined. Commissure perimeter was measured as the perimeter of a triangle formed by the commissure markers, and commissure radius as the radius of a hypothetical circle that passes through the three commissure markers. The commissure radius was obtained from the straight line projection. The motion of the commissures was quantified in terms of the commissure perimeter or the commissure radius.

Figure 9 shows a plot of commissure perimeter, leaflet motion, and aortic pressure during three cardiac cycles. The commissures move outward during systole and inward during diastole. Their motion follows the aortic pressure curve closely, suggesting that the motion is a function of the aortic pressure. The average increase in the perimeter of the commissures from diastole to systole is 12% for a control blood pressure in the range of 102/60 to 140/97 mmHg (Table 1). The outward motion of the commissures begins 20 to 40 ms prior to the opening of the valve (Figure 9).

The commissural motion was also studied as a function of systemic pressure. The pressure was increased by using angiotensin, which produces vasoconstriction, or decreased by using nitroprusside, which produces vasodilatation. Figure 10 shows a plot of leaflet motion, commissure perimeter, and aortic pressure vs. time over a wide range of systemic pressures. In general, the commissure perimeter decreases as the systemic pressure decreases. When the commissure perimeter is plotted versus aortic pressure, two separate curves, one for diastole and one for systole, are obtained (Figure 11). The curve for diastole lies below the curve for systole, indicating that for a given aortic pressure commissure perimeter is greater in an open valve than in a closed valve. This important observation suggests an interplay between the commissures

TABLE 1
Change in the Commissure Perimeter (ΔP_c) During a Cardiac Cycle

Dog no.	Blood pressure (mmHg)	$\Delta P_c \pm$ SD (%)
1	Unanesthetized	11.3 ± 0.7
	CA 110/65	11.8 ± 1.0
	FA 120/78	11.7 ± 1.1
	FA 126/85	10.7 ± 0.8
	Asc Ao 102/60	12.0 ± 1.0
2	Unanesthetized	11.4 ± 1.9
3	FA 135/100	11.7 ± 2.0
	FA 145/66	12.9 ± 1.5
	Asc Ao 102/70	12.6 ± 0.8
4	Asc Ao 140/97	12.3 ± 0.5
5	FA 180/100	14.0 ± 2.0
Mean		12.0
SEM		0.4

Note: CA — carotid artery, FA — femoral artery, Asc Ao — ascending aorta, SEM — standard error of the mean.

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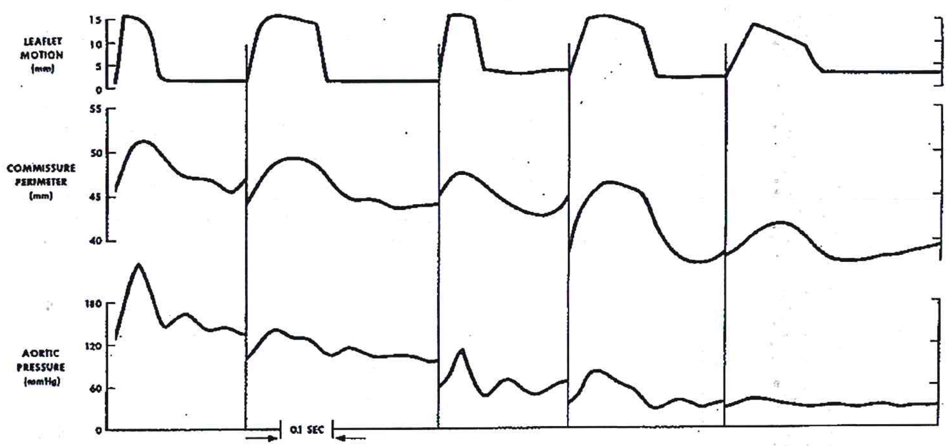

FIGURE 10. Plot of leaflet motion, commissural perimeter and aortic pressure showing the effect of a wide range of systemic pressure on commissural perimeter in one animal. Only one representative heart cycle is shown at each systemic pressure. The commissural perimeter decreases when systemic pressure decreases. (From Thubrikar, M. et al., *Am. J. Cardiol.*, 40, 563, 1977. With permission.)

and the leaflets. For example, when the aortic pressure remains unchanged, the commissural motion is a function of whether the leaflets are in the open position or closed position. This interplay will be studied in detail in the next section. During a single cardiac cycle, the commissural movement occurs as follows: When the pressure increases from 80 mmHg diastolic to 120 mmHg systolic, the commissures move by 12% from point A to point D in Figure

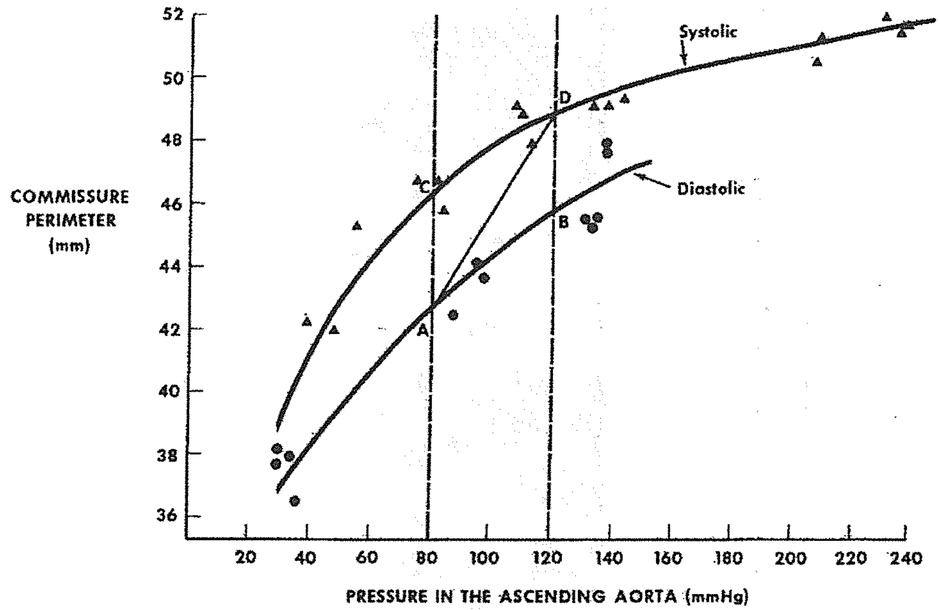

FIGURE 11. Relation between aortic pressure and commissural perimeter in one animal. The commissural perimeter at various systolic aortic pressures is indicated by closed triangles and at diastolic aortic pressures by closed circles. Diastolic and systolic curves indicate the relation with the valve in closed or open position, respectively. For a pressure change from 80 to 120 mmHg the commissural perimeter increases from A to B if the valve remains closed or from C to D if the valve remains open (4 to 5% increase in either case). However, for the same pressure change the commissural perimeter increases from A to D if the valve goes from a closed to an open position (12% increase). (From Thubrikar, M. et al., *Am. J. Cardiol.*, 40, 563, 1977. With permission.)

11. This total movement is composed of two parts, A to C and C to D, where the former occurs in response to the opening of the valve at a pressure of 80 mmHg, and the latter occurs in response to the increase in pressure from 80 to 120 mmHg. A similar phenomenon occurs during the valve closure. About 5 to 6% motion of the commissures appears to occur in response to the aortic pressure and 6 to 7% in response to whether the valve is open or closed.

The commissural movement suggests that the aortic root is elastic, a feature which is helpful in reducing the shock on the leaflet at the time of valve closure. The commissural expansion also plays a role in the mechanism of valve opening and is discussed in the next section. This outward movement of the commissures during systole has also been observed by Brewer et al.[7]

B. THE MECHANISM OF OPENING OF THE AORTIC VALVE

The aortic valve is generally regarded as a passive structure changing mainly in response to hemodynamic forces. For the most part this is true; however, there are active components to the valve behavior. For example, there is interaction between the commissures and the leaflets, as noted in the previous section. Classically, the aortic valve is thought to open when blood ejected from the ventricle pushes the leaflets open. This would be true if the leaflets were attached to a nonexpansile structure. However, the leaflets are attached to an expansile structure and the expansion of that structure alone can open the valve. The leaflets are attached to the aortic wall at the commissures, which move outward during each cardiac cycle.

Thubrikar et al. studied the mechanism of opening of the aortic valve using the marker-fluoroscopy technique.[8] Figure 6 shows the positions of the markers on the leaflets and in the commissures. They studied the marker movement in a triangular projection obtained with an X-

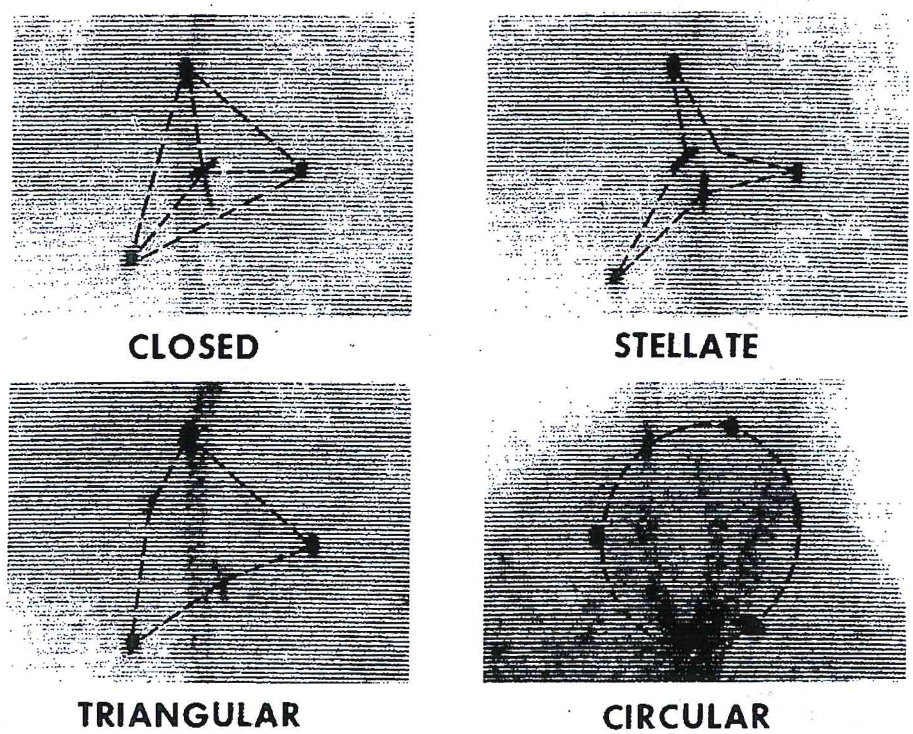

FIGURE 12. Single fields of a cineradiograph of the aortic valve, obtained with the X-ray beam parallel to the axis of the aorta. In a closed valve, the three commissure markers form a triangle and the two leaflet markers appear in the center. The separation of the leaflet markers indicates a stellate orifice, shown by the dotted line. The triangular and circular orifices are also shown by dotted lines. A catheter in the left ventricle, inserted through the aortic valve, is also visible. (From Thubrikar, M. et al., *J. Thorac. Cardiovasc. Surg.*, 77, 863, 1979. With permission.)

ray beam along the valve axis (Figures 7 and 8). In this projection, the two leaflet markers touch each other in a closed valve, as shown in Figure 12, and appear almost at the center of the triangle formed by the three commissure markers. When the valve is open, the leaflet markers and the commissure markers together form the orifice of the open valve (Figure 12). To study the various stages of valve opening, the valve was examined during premature cardiac cycles when the ventricular stroke volume was less than normal. Premature ventricular contractions are not uncommon and occur frequently if a catheter is present in the left ventricle. During their study, aortic flow, aortic pressure, and ventricular pressure were recorded where the ventricular pressure was measured with a pressure catheter placed in the ventricle. The marker positions were recorded at a rate of 60 video fields/s. During premature beats, the open valve could be seen for three or more video fields. Depending upon the type of ventricular contraction, the open valve was observed to show a stellate-shaped orifice, a triangular orifice, or a normal circular orifice (Figure 12). Leaflet displacement, commissure perimeter, aortic blood flow, aortic pressure, ventricular pressure, and electrocardiogram are shown for both normal and premature heart beats in Figure 13. The normal and premature heart beats are identified from the electrocardiogram. During the normal beats, A and C in Figure 13, the normal leaflet displacement, commissural expansion, and aortic flow are evident. During the premature beat, B, the peak ventricular pressure does not equal the aortic pressure and the valve does not open but the commissures expand. In the abnormal beat, D, the peak ventricular pressure barely exceeds the aortic pressure and the valve opens, the commissures expand, and the blood flow occurs through

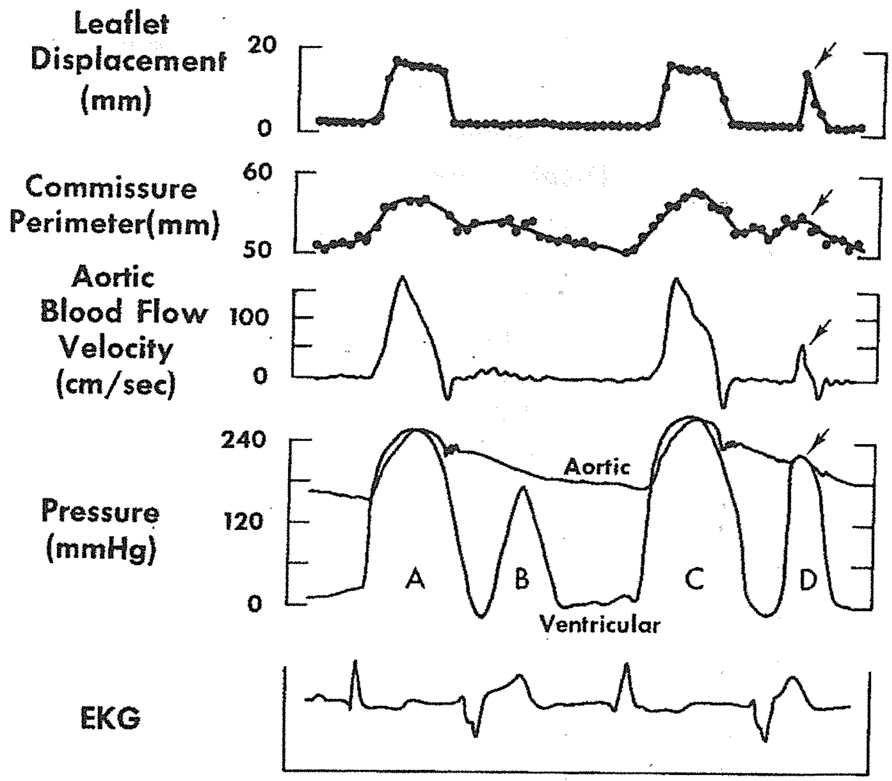

FIGURE 13. A continuous plot of leaflet displacement and commissure perimeter, with corresponding recordings of aortic blood flow velocity, aortic pressure, ventricular pressure, and electrocardiogram (EKG). Each data point on the first and second curves was obtained from a single field of videotape. The normal beats A and C show normal leaflet displacement and a normal increase in the commissure perimeter. For the abnormal beat B the valve does not open but the commissure perimeter increases slightly. For the abnormal beat D (arrows) the valve opens to a normal orifice and the commissure perimeter increases 10%. The beat D is associated with a small volume of forward flow and a narrow aortic pulse pressure. (From Thubrikar, M. et al., *J. Thorac. Cardiovasc. Surg.*, 77, 863, 1979. With permission.)

the valve. It is noteworthy that even for a small forward flow velocity, as in beat D, the valve opening reaches its maximum.

Figure 14 shows the plot of leaflet displacement (i.e., size of the valve orifice), aortic blood flow velocity, and aortic pulse pressure. Leaflet displacement is expressed as a percentage of the maximum distance between the two leaflet markers in a normal cardiac cycle. Three types of orifice configurations were observed at different blood flow velocities. These configurations indicate intermediate stages in a continuing process of valve opening. As the leaflets begin to separate they first produce a stellate shape orifice, which then changes to a triangular shape, and then to a circular shape as the flow velocity increases. For a stellate shape opening there is no forward flow and no aortic pulse pressure (Figure 14D). For a barely perceptible forward flow velocity and a barely perceptible aortic pulse pressure, the valve orifice is variable between a triangular and a circular shape (Figure 14B and C). For the normal forward flow velocity and the normal pulse pressure, the valve orifice is circular (Figure 14A).

Figure 15 relates the leaflet displacement (orifice shape) to forward flow velocity. At zero velocity the valve is either closed or open with a small leaflet separation and a stellate shape orifice. Leaflet displacement increases rapidly as the velocity increases from 0 to 30 cm/s. In this

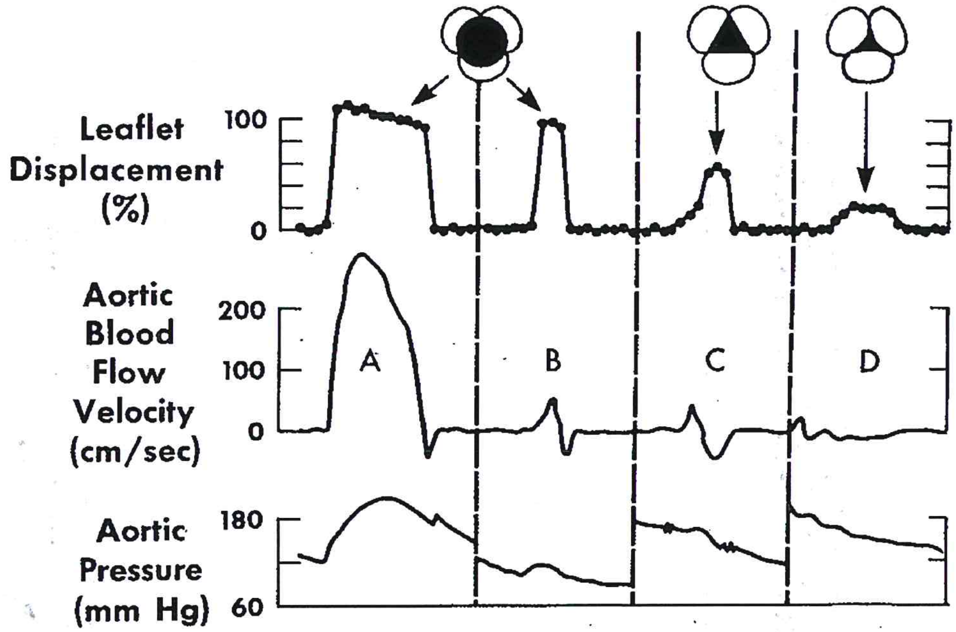

FIGURE 14. Four separate representative cardiac cycles showing leaflet displacement (percentage of full opening) with corresponding recordings of aortic blood flow velocity and aortic pressure. For the normal beat A the valve orifice is circular. For the abnormal beats B and C the valve orifices are circular and triangular, respectively, and are associated with a small blood flow velocity and a narrow pulse pressure. For the abnormal beat D the valve orifice is stellate and is associated with no detectable forward flow and no increase in the aortic pressure. (From Thubrikar, M. et al., *J. Thorac. Cardiovasc. Surg.*, 77, 863, 1979. With permission.)

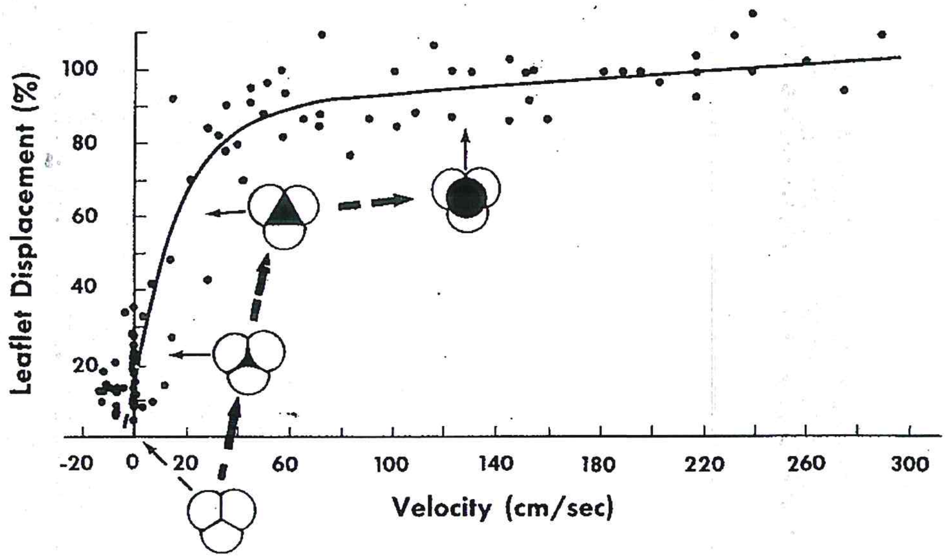

FIGURE 15. Relationship between the maximum aortic blood flow velocity and maximum leaflet displacement (percentage of full opening). The closed valve corresponds to 0% leaflet displacement. The initial valve orifice is stellate, and there is no detectable forward flow. As the blood flow velocity increases to 30 cm/s, the orifice becomes circular. The greatest change in the valve orifice (leaflet displacement) occurs over a narrow range of blood flow velocity. The negative velocity with the stellate orifice indicates regurgitant flow. (From Thubrikar, M. et al., *J. Thorac. Cardiovasc. Surg.*, 77, 863, 1979. With permission.)

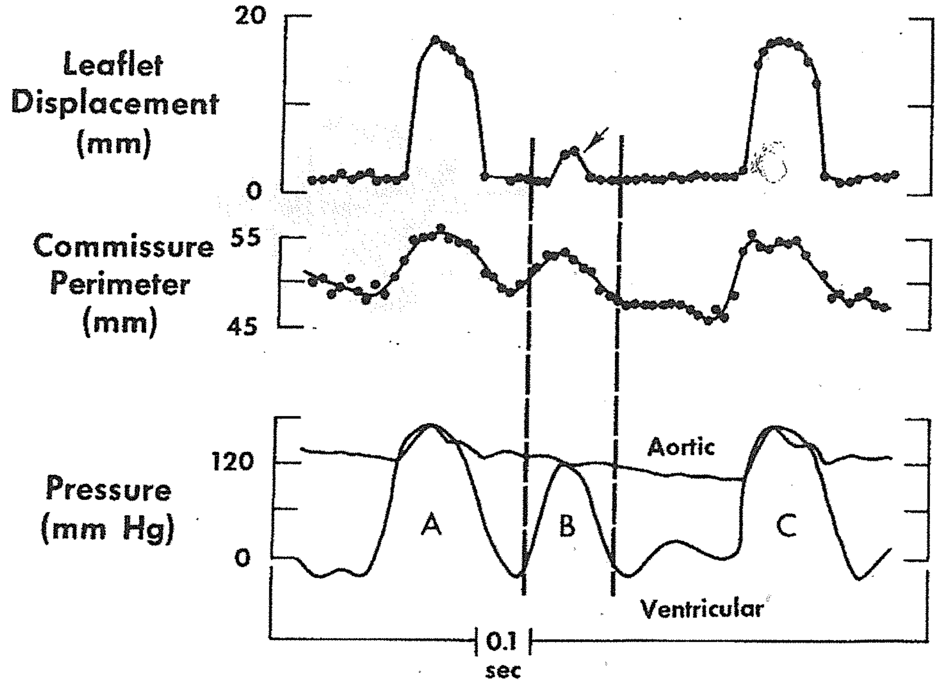

FIGURE 16. A continuous plot of leaflet displacement and commissure perimeter with corresponding aortic and ventricular pressures. The normal beats A and C indicate a circular orifice, a normal increase in the commisure perimeter, and a normal aortic pulse pressure. The abnormal beat B indicates a stellate orifice, 10% increase in the commissure perimeter, and no increase in the aortic pressure. The stellate orifice occurs when the ventricular pressure equals the aortic pressure. (From Thubrikar, M. et al., *J. Thorac. Cardiovasc. Surg.*, 77, 863, 1979. With permission.)

range a triangular orifice can be seen. When the velocity exceeds 40 cm/s, a circular orifice is seen. The leaflet displacement and the orifice change very little for the velocity ranging from 40 to 300 cm/s. The rapid increase in leaflet displacement for the initial increase in velocity is a remarkable feature of the aortic valve. Leaflet displacement which occurs due to a positive blood flow velocity represents passive opening of the valve. The leaflet displacement which occurs at a zero flow velocity and which produces initial stellate shape opening must find its origin in another phenomenon.

Figure 16 shows a stellate type of valve opening in a premature beat (B) where ventricular pressure barely equals aortic pressure. The commissural expansion in this beat is quite significant. The average increase in the commissural perimeter is reported to be $9 \pm 2.5\%$ for the stellate type of valve opening.[8] Hence, the mechanism of initial valve opening, illustrated in Figure 17, may be stated as follows: As the ventricular pressure rises and equals the aortic pressure, the commissures move outward and carry the attached leaflets along with them, thereby causing the leaflets to separate and the valve to open. Blood flow through the valve is not necessary for this initial opening. There are two possible explanations for the outward motion of the commissures:

1. In diastole, the leaflets are under tension from the closing pressure in the aorta. When the ventricular pressure equals the aortic pressure, the pressure gradient across the leaflet vanishes and the leaflets are no longer under tension. This changes the equilibrium of forces in the aortic root and causes the commissures to move outward.

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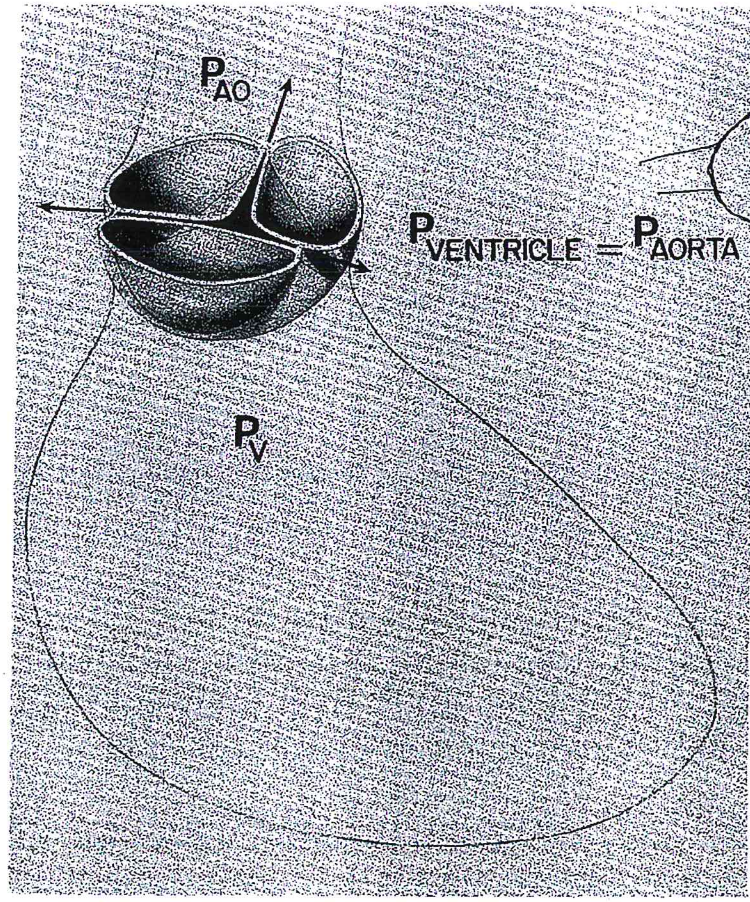

FIGURE 17. The mechanism of opening of the aortic valve. When pressure in the left ventricle equals the pressure in the aorta, the commissures move outward (arrows) and carry the leaflets along with them to produce a stellate orifice. (From Thubrikar, M. et al., *J. Thorac. Cardiovasc. Surg.*, 77, 863, 1979. With permission.)

2. The ventricular side of the aortic root, especially the coronet-shaped region, is at a low ventricular pressure in diastole. When the ventricular pressure equals the aortic pressure, this region must expand and develop greater tension in order to be in equilibrium with the increased pressure. As this region expands it must also cause the commissures to move outward because this region is continuous with the commissural region.

These mechanisms also explain why the commissures begin their outward movement prior to the valve opening (Figure 9), and why the commissural perimeter is larger in an open valve than in a closed valve (Figure 11). Basically, the commissural movement is coincident with the ventricular pressure during isovolumetric contraction of the ventricle.

There is another factor which is important in the initial opening of the valve. The leaflet is longer when it bears the pressure load and shorter when the pressure gradient across it becomes zero. This leaflet shortening must contribute to the initial valve opening. The change in leaflet length is discussed in detail in Chapter 5.

Bernuth et al.[9] studied the abnormal aortic valve opening in dogs using a technique of right atrial pacing to produce extrasystole at a desired time and observed aortic regurgitation using

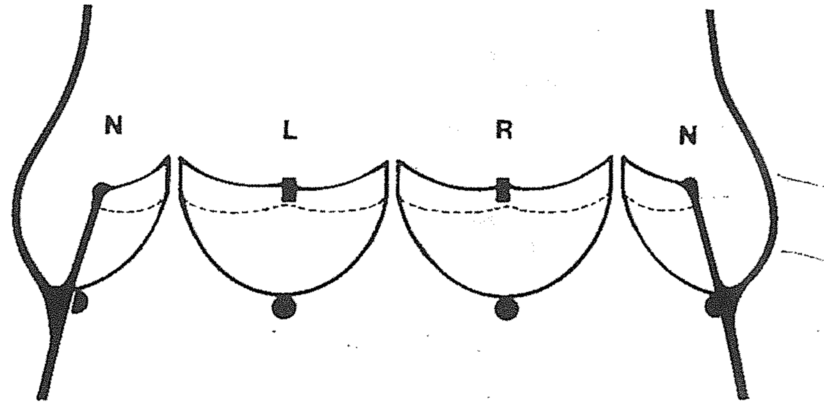

FIGURE 18. Aortic valve exposed by a vertical incision. L, R, and N are the left, right, and noncoronary leaflets, respectively. Three radiopaque markers at the base of the leaflets are represented by closed circles. Two radiopaque markers at the center of the leaflet free edge are represented by vertical bars. (From Thubrikar, M. et al., *Am. Heart J.*, 99, 217, 1980. With permission.)

roentgen videodensitometry. Their observations were similar to those described earlier in that the aortic valve opened and a small amount of reflux aortic regurgitation occurred when the ventricular pressure was barely sufficient to open the valve. During this type of reflux aortic regurgitation, the aortic pulse pressure was close to zero and forward flow was less than 20 ml/s.

C. MOTION OF THE BASE

The base of the aortic valve is a circumferential region at the proximal attachment of the aortic leaflets. It has been described as a fibrous annulus, which suggests a ring-like nonexpansile structure. However, as was seen in Chapter 2, no ring-like structure exists at the base and instead the leaflet attachment forms a coronet-shaped outline. We will now examine whether the base of the leaflet changes dimensions in a cardiac cycle.

The base of the human aortic valve has been studied using echocardiography and has been shown to change diameter during a cardiac cycle. Using angiography, the left ventricular outflow tract in humans was shown to change diameter during a cardiac cycle.[10] Since the base of the aortic valve is continuous with the outflow tract, the base also changes diameter. The detailed study of the motion of the base was carried out by Thubrikar et al. using the marker-fluoroscopy technique in dogs.[11] They placed small radiopaque markers at the three bases of the aortic valve leaflets and observed the movement of the bases during a cardiac cycle.

Figure 18 shows a scheme of marker placement used in their study and Figure 19 shows the motion of the base in a cardiac cycle. Base perimeter in Figure 19 represents the perimeter of a triangle formed by the three base markers. The base moves as follows: (1) the base perimeter is maximum at the end of diastole (point A in Figure 19), (2) the perimeter decreases during systole, (3) the perimeter is minimum at the end of systole (point B in Figure 19), and (4) the perimeter increases during diastole. It is noteworthy that the base is maximally dilated at the time of valve opening and maximally contracted at the time of valve closure. The percentage of change in the base perimeter varies widely from 9 to 22% at control blood pressures (Table 2), and from 5 to 28% over a broad range of systemic pressures. The motion of the base was also studied in abnormal cardiac cycles and the results are shown in Figure 20. In some abnormal cardiac cycles the base contracted (A_1 to A_2 in Figure 20), whereas in others it expanded (B_1 to B_2 in Figure 20).

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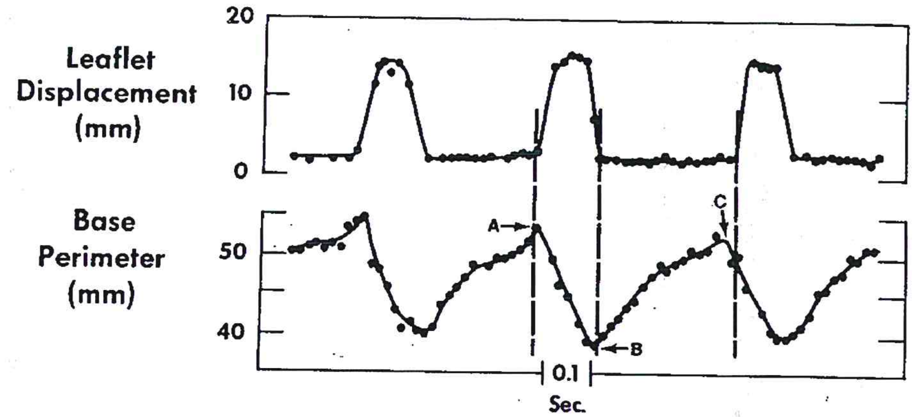

FIGURE 19. Plot of leaflet displacement and base perimeter (perimeter of a triangle formed by the base markers) vs. time. The base perimeter is maximum (point A) in early systole. The perimeter decreases (A to B) in systole and increases (B to C) in diastole. (From Thubrikar, M. et al., *Am. Heart J.*, 99, 217, 1980. With permission.)

TABLE 2
Blood Pressure vs. Base Perimeter

Dog no.	Blood pressure (mmHg)	Base perimeter (% change[a])
1	Aortic 120/60	22 ± 2
2	Aortic 122/90	16 ± 1.5
3	Aortic 113/78	8.8 ± 1.8
4	Femoral 108/85	9.6 ± 2
	Mean 115/78	Range 9 to 22
	Aortic Blood Pressure	
1	70/50—260/160	5—10
2	94/48—255/150	10—16
	90/35—270/187	6.5—12
3	88/50—252/216	10—18
	120/60—240/210	20—28
4	70/42—280/156	15—28
	Range 70/50—280/216	Range 5 to 28

[a] Base perimeter % change = $\frac{\text{P max} - \text{p min}}{\text{P min}} \times 100\%$

(where P = perimeter)

From Thubrikar, M. et al., *Am. Heart J.*, 99, 217, 1980. With permission.

The change in the base perimeter during a cardiac cycle is qualitatively identical to the change in the circumference and volume of the left ventricle. Figure 21 shows a plot of left ventricular pressure, left ventricular circumference, and aorta to apex length vs. time.[12] The change in the left ventricular volume is reflected by the combined change in the left ventricular circumference and aorta to apex length. The base perimeter as well as the left ventricular volume is maximum in early systole. This coincides with the ventricle becoming more globular during isovolumetric contraction (Figures 19 and 21). The base perimeter decreases during systole, and this coincides with the decrease in the ventricular volume during systolic ejection. The base perimeter is