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PERCUTANEOUS AORTIC VALVE REPLACEMENT

I. Anatomy

The aortic valve ~~is a structure whose function is to~~ direct the flow of blood from the left ventricle into the systemic circulation through the aortic artery. It accomplishes this function by opening during the contraction of the left ventricle and closing when the left ventricle relaxes. The aortic valve is a tricuspid structure and each cusp folds up toward the aorta during the contraction phase and then folds back against ~~each other~~ the others in the relaxation phase. **(Figure 1 show a picture)** However, the aortic valve is a complex structure with integral relationships beyond merely a three-leaflet valve. For instance, each leaflet sits directly opposite an out pouching of the proximal aorta. This dilated segment is called the sinus of valsalva, and it is this anatomic relationship that assists the valve to open and close repetitively while minimizing the stress upon any point within this valvular apparatus. Further, the proximal portion of the aortic valve is highly elastic and with this elasticity it can dilate during the contraction phase of the left ventricle. Historically, it has been theorized that this reduces the amount of work that the left ventricle performs. However, this simplicity should not mask the complex nature of the valve. The valvular structures are integrally related to the coronary arteries. The function of the coronary arteries is to supply blood supply to the heart. These, as represented **in figure 2,** are located within 2 of the sinuses. In a normally functioning valve, the cusps open widely to allow the unimpeded transference of blood, and then close tightly not allowing any to regurgitate back into the left ventricle. When there is significant restriction to blood flow, this is called stenosis and when it allows blood back into the left ventricle it is regurgitation. Thus, each component plays a vital role in the function and durability of the valve.

The first components of the valve I would like to discuss are the leaflets. Interestingly, the number of the leaflets within a normal aortic valve does not vary to a significant degree. When there are less than three valves, the valve undergoes rapid stenosis and restriction. Among congenital alterations upon the valve number the most frequently encountered is a bicuspid aortic valve. This condition is the most common defect that is survived into adult hood. However, this valve predictably becomes more and more stenotic and regurgitant by the 4th and 5th decade. Unfortunately, this usually results in the need for surgical replacement. A unicusped valve rarely survives beyond the first year of life. **(Figures 3 and 4)**. Rarely a quadricusped valve will be shown to survive into adulthood. This design also results in marked stenosis. Further, the cusps are shaped in a defined convexity. This design permits the dispersion of pressure over a larger surface area. This dispersion resists the exhaustion of the valve in any one particular place. Moreover, this curvature allows the leaflet to reverse curvature. An ability needed in order to fold and allow the maximum opening diameter during contraction. Finally, a curved design allows a redundancy in the coaptation site of the leaflets. The area of coaptation is the edge of the valves that must meet and close in order to prevent regurgitation. Hence, both the number of leaflets and their overall shape is important in the function and durability of the valve.

As mentioned earlier, the valve leaflets have a direct relationship to the sinuses of valsalva. The sinus diameter is almost twice that of the aorta. This cavity plays an important role in the mechanism of valve closure (referenced Mano Thubrikar). An oblique section through the leaflet-sinus assembly shows this remarkable relationship. (**Figure4**). This section reveals that the sinus and leaflet form a circle when the valve is in a closed position. Furthermore, it is angulated to a degree as to allow pressure transduction along the entire surface of this unit. This suggests that the shape of the leaflet-sinus assembly is important I determining how stresses are developed within the valve. It is also this relationship that allows the valves to close without pulling upon the aortic valve as has been suggested. Finally, this relationship of the sinuses and valve allow for the efficient flow of blood in the coronary ostia.

The aortic root has been described to expand during ventricular contraction. The dilatation of this structure by the Poisselles' law reduces tension, which in turn reduces resistance to flow. It is this phenomenon that also allows for complete opening of the aortic valve. Interestingly when the cusps open there is maintained a circular dimension that is at least the same as before contraction. Moreover, it is has been studied to be even larger than the original orifice. (Medical Engineering & Physics 19(8): 696-710,1997). In more detail, this behavior allows the valve to have reduced circumferential stress and a reduced Reynolds shear stress number. This is the number used to evaluate the amount of stress in a confined fluid system. In a similar manner, the inner lining of the cusp of the valve, the lamina ventricularis extends into the ventricular myocardium. There is a confluence of fibers at the base called the fibrous coronet, which is a distinct separation between the elastic fibers above, and the myocardium below. However, this structure is not static. In contrast it is a very dynamic structure, which bends and molds to the forces that are exerted from the ventricular myocardium (Cardiovascular Research, 22,7,1988)(Journal of Biomechanics33 (6): 653-658, 2000June). In a similar fashion as the aortic root this structure allow the valvular apparatus to open with the least amount of strain.

The coronary arteries arise within or above the sinus of valsalva. The blood flow of the heart occurs mostly when the ventricle relaxes. At this time the cusps of the aortic valve are closed and as mentioned the diastolic forces of the blood against the valve are dispersed along the valve and adjacent sinus. The opening or ostia of the coronary arteries when located near the apex and middle of the sinuses allows for the most laminar flow characteristics. This in turn promotes the greatest amount of flow with the least amount of resistance. In disease states where these relationships are lost, it has been proposed that this could lead to increase stress at the coronary ostia. (The Aortic Valve CRC press).

These integral relationship not only pertain to the gross anatomy of the valvular apparatus, but also the microanatomy shows the integral nature of these structures. The amount of elastin is in a higher concentration as shown by staining methods (American Journal of Pathology 445 (7): 1931). This allows a greater amount of dilatation of the structures in this area. Further, scanning electron micrographs have shown the unique arrangement of collagen in the valves, which permit the unique reversal of curvature, which is vital in the function of the valve **(figure 6)**(Anatomic Embryology 172(61): 1985). The fibers are unusually small and arranged in sheets with unique distances between each strand. In theory this would give a greater amount of tensile strength while

allowing continued flexibility. As always, nature has selected the most efficient machinery, and we have only to discover the reasons why.

II. Aortic Valve Dynamics and Physics

The aortic valve is better understood in a dynamic state given it is not a static structure. To fully understand this structure it is integral to understand the opening and closing of the valve, the motion of the various parts, the design of the valve in vitro and the hydrodynamics of the valve. The valve's ultimate function is to allow fluid transfer from the ventricle to the systemic circulation. In order to do this efficiently it minimizes shear stress, resistance to flow and tensile forces.

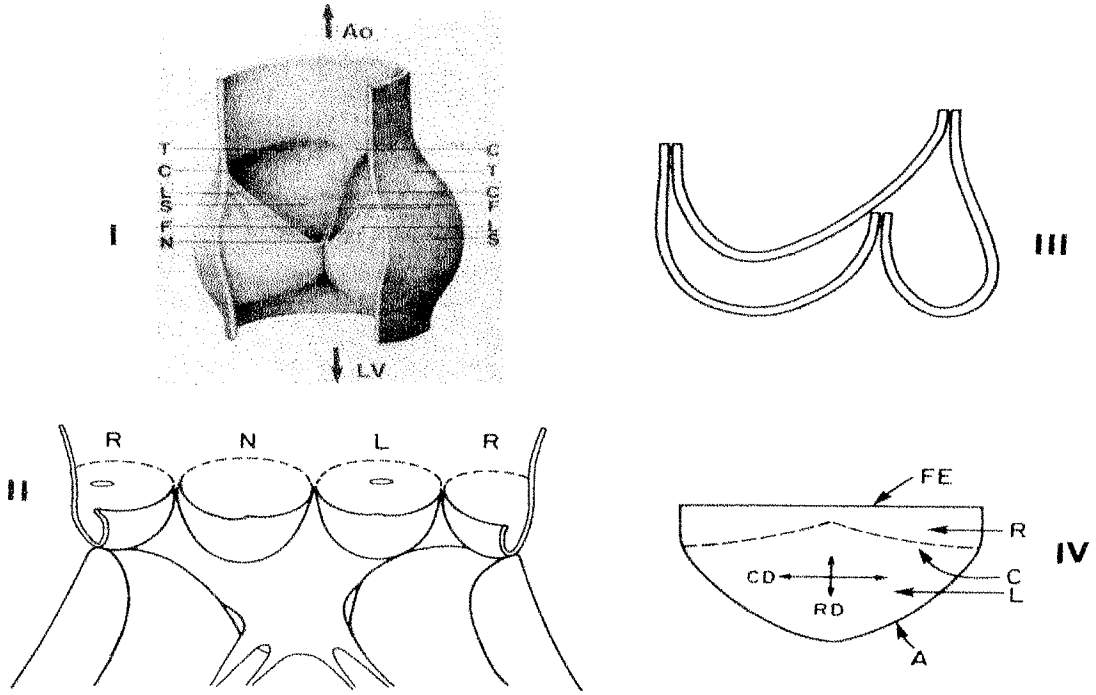
The opening and closing of the aortic valve depends upon differential pressures, flow velocity characteristics and as mentioned earlier the unique anatomic relationship between the valves and the sinuses of valsalva. One of the most comprehensive study encompassed a model developed by Bellhouse et al. In this model, the flow of fluid through the aortic valve was studied by injecting dye within the flow of fluid. Some of the pertinent observations found within this model were as follows: 1) The valve opens rapidly, and as the leaflets move into the sinuses, vortices form between the leaflet and the sinus walls; 2) The flow enters the sinus at the sinus ridge, curls back along the sinus wall and leaflet and then back into the main stream; 3) During the end of systole the vorticeal motion created during contraction forces the valves back toward a closed position. These observations are important to show that absolute pressure differences created between the aorta and ventricle are not the source of initial closure of the aortic valves. In fact, it would be detrimental to valve stress if these forces dictated closure of the aortic valve. For example, if two objects are a greater distance apart and a set amount of force is applied to each, the greater distance would produce greater velocity and the momentum at impact would be greater. Therefore, if the leaflets are closed or near closure as contraction is coming to an end then the force used for coaptation would be less. Less force per cycle equates to greater longevity of the valve. In conclusion, the cusps and the relationship of closure for prosthetic valves must incorporate passive closure during systole that would logically lengthen the lifespan of any such device.

To expand these concepts, we must explore the theory of laminar flow as it relates to aortic valve function. Laminar flow is predicted by Reynolds number, which incorporates the laws as described by Outsell and Bernoulli. In general, the lower the Reynolds number the more likely that flow will be laminar. The equation that describes the Reynolds number in the aorta is as follows:

$$Ua/v = \text{Reynolds number}$$

That is, U which equals the velocity of blood and (a) which represents the radius of the aortic valve is inversely related to the viscosity of blood. As the velocity increases or the viscosity decreases, the tendency towards turbulent flow also increases. Moreover, the behavior of the system is also predicted by the rate of acceleration or deceleration that is described by the Strouhal number. In explanation, in a system where viscosity, velocity and radius vary slightly, the rate of acceleration or deceleration predicts laminar versus non laminar flow. When looked at in perspective, it is easy to see the relevance. Only a small pressure difference is required to open the native aortic valve. Maintaining a small

pressure difference minimizes acceleration to flow. Thus, laminar flow is more likely. The deceleration phase is naturally a gradual process; however, as stated above it is the relationship between the sinuses and the cusps, which allows this deceleration to occur without an abrupt pressure drop. When laminar flow is produced, the resistance to flow, wall stress, shear stress and circumferential stress is reduced. This reduction decreases cardiac work and increases the longevity of the valvular apparatus. Ultimately a design to replace a diseased aortic valve must incorporate many if not all of these relationships.

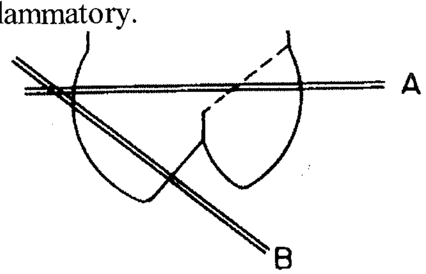


III. Adult Aortic Stenosis

Aortic stenosis is a condition where there is a restriction to the ejection of blood from the left ventricle to the systemic circulation at the aortic valve level. If the aortic valve cusps do not open, or there is failure of the valvular apparatus then a pressure gradient develops. In order to overcome this pressure difference, the left ventricle begins to hypertrophy. Over a period of time this produces pressure overload on the left ventricle. Clinically, this produces dramatic symptoms, and in the most severe form it is fatal unless treated.

The incidence of aortic stenosis varies considerably. In epidemiological studies the incidence is between 2 to 4% of the general population. In the early 20th century the most common etiology of aortic stenosis was rheumatic fever. This streptococcal infection produces inflammatory changes in the aortic valve. Interestingly, these changes affect the coaptation surface to a greater degree than the other structures of the aortic valve. Affecting the coaptation points, results in fusion of cusps. This fusion results in a restriction to the opening of the cusps. A pressure difference develops as well as non-laminar flow. Once this cycle develops, then the valve has increased deterioration and calcification. Unfortunately, post infectious aortic stenosis can result in rapid progression to severe aortic stenosis. Of the total cases of aortic stenosis in the 1940's,

reportedly 52% were the result of rheumatic fever. Currently, less than 9% of the cases of aortic stenosis are post inflammatory.



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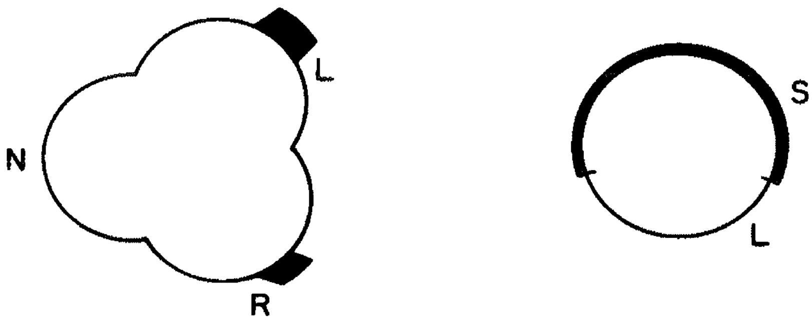

The second most common cause of aortic stenosis is a bicuspid aortic valve. This has remained relatively constant throughout the decades. It accounts for 33 to 40% of the total cases of aortic stenosis. This condition affects most parameters of aortic function. Inherently, it loses the anatomic relationship between the sinuses and the valve cusp. Further, the opening and closing characteristics of the valve are altered which in turn alters the acceleration and deceleration to flow. As a result, non-laminar flow characteristics are developed. Because of the altered anatomy, a bicuspid aortic valve cannot easily reverse curvature. Due to this limitation, the bicuspid aortic valve has increased stress at the base. It is at this point where morphologic changes first appear. However, this valve is usually survived into adulthood.

Currently, the most common cause of aortic stenosis is degenerative aortic stenosis. By the 7th decade, the normal aortic valve can undergo degenerative changes. The characteristics, which define these changes, are increased calcium deposition along the body of the cusps. Predominantly the calcification is located at the bases of the cusp and on the aortic side. When enough calcium is deposited as to restrict flow, then there will be a variable amount of fusion along the coaptation surface. The incidence of aortic

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