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 fold back against each other 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 outpouching of the proximal aorta. This dilated segment is called the sinus of valsalva, and it is this anatomic relationship that assist the valve to open and close repetitively while minimizing the stress upon any point within this valvular apparatus. Further, the proximal porion of the aortic valve is highly elastic and with this elasticity it can dilate during the contracion phase of the left ventricle. Historically, it has been theorized that this reduces the amount of work that the left ventricle performs. As with anything in nature it is much more complex. The valvular structures are integrally related to the coronary arteries. The function of the coronary arteries are 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 blood 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 particlular 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 for there not to be 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 sinus's 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 suggest 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. (According to the Law of Laplace) The dilatation of this structure by the law of laplace 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 Reynold's 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 seperation 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 which 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 apparatur 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 relationships not only pertain to the gross anatomy of the valvular apparatus, but also to 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 surrounding structures. ~~sinuses of valsalva~~. One of the most comprehensive studies 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 detriminal 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 which would logically lengthen the lifespan of any such device.

To expand these concepts, the theory of laminar flow and how the native aortic valve accomplishes this must be developed. A laminar flow is predicted by a Reynold's number which incorporates the laws as described by Pouiselle and Bernoulli. In general, the lower the