Heart Valves

The human heart includes four "one-way" valves as shown in figures 1 and 2, the tricuspid, pulmonary, mitral and aortic valves. As the heart muscle or *myocardium* expands (relaxes) and contracts the volume

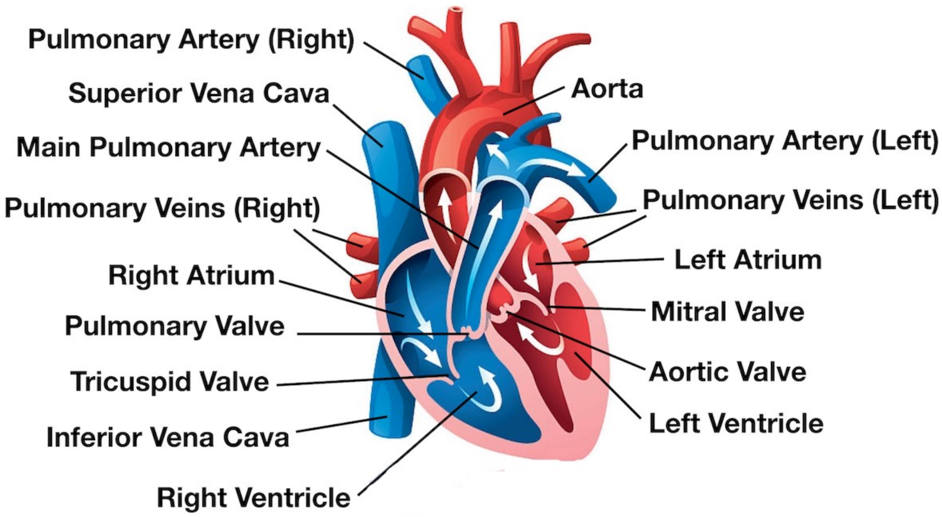

Figure 1: Diagram of the human heart.

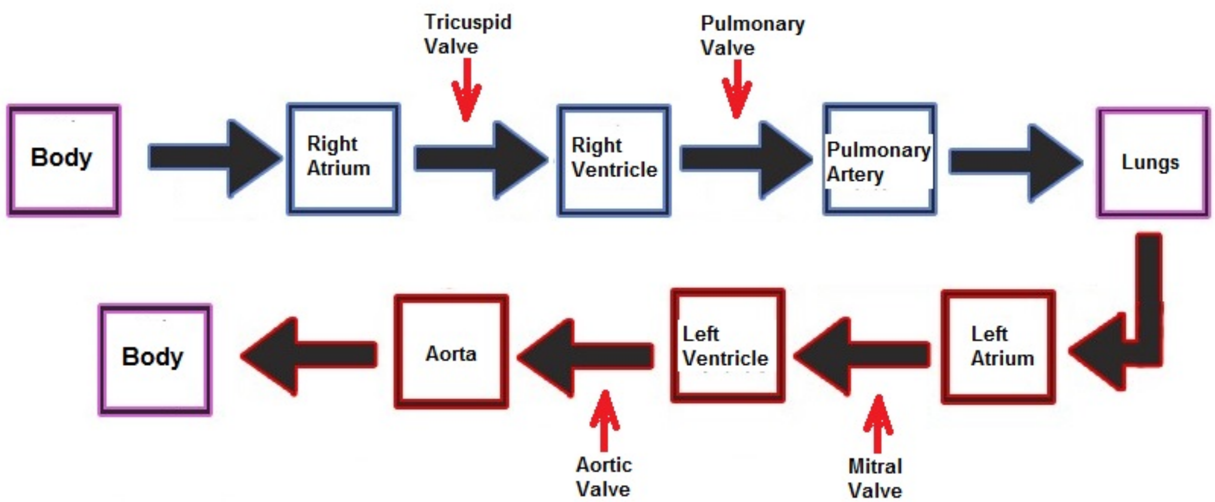

Figure 2: Schematic of the human heart.

of the heart, blood fills the chambers of the heart and then is extruded from the heart. When a chamber contracts, a valve opens to allow blood to flow through it. When the chamber relaxes, the valve closes to prevent blood from leaking back into the chamber and to allow the chamber to fill with blood again. Consequently defective or damaged valves limit the ability of the heart to pump blood. Sometimes it become necessary to replace one or more of these valves with an artifical heart valve and this has now become a common procedure.

An artificial heart valve is a one-way valve implanted into a human heart to replace a natural valve that is not functioning properly; consequently the fluid mechanics of artificial heart valves is crucially important for the effectiveness and durability of those devices. Artificial heart valves come in a range of different designs in two main categories, mechanical valves and biological valves (often transplanted pig heart valves). We concentrate here on mechanical heart valves that are mostly of three main types, caged ball valves, tilting-disc valves and bileaflet valves, each of which are illustrated in figure 3.

Figure 3: Three types of artificial heart valve, cage ball valve, tilting-disc valve and bileaflet valve.

While the rigidity of present mechanical valve designs is major advantage making then last as long as 20 to 30 years, that rigidity also gives rise to their drawback. The rigidity causes high fluid stresses as the valve is closing and these stresses can have several deleterious effects such as clotting or red cell and platelet damage. Thus patients with mechanical heart valves need to take anticoagulants for the rest of their lives. Cavitation is also a serious problem caused by the unsteady fluid pressures generated as the mechanical valve closes. One suspects that designs using softer materials (such as pig valves) would be superior in that they would lead to smaller amplitude pressure pulses but our ability to design and manufacture devices of softer materials is not very advanced.

Though cavitation damage to the valve itself is an issue, the rupture of red bloods cells (*hemolysis*) by the cavitation is the primary concern. We choose to illustrate the phenomenon using the bileaflet type shown in figure 4. The flows associated with this valve prior to and during closure are sketched in figure 5. The two leaflets hinge at roughly the end-on locations shown in figure 5. When first subjected to backflow (stage B, figure 5) these leaflets move in such a way that, just prior to closure (stage C, figure 5), there are narrow passages both along the central diameter and at the circular tips of the leaflets. For a time interval just before and after closure the deceleration of the flow downstream of the valve generates low pressures within the jets and vortices emanating from these temporary narrow passages, thus causing cavitation (Maines and Brennen (2002)).

The extensive and careful research of the Penn State group (Stinebring *et al.* (1991, 1995), Lamson *et al.* (1993), Garrison *et al.* (1994), Zapanta *et al.* (1996, 98)) has done much to elucidate our understanding of this problem. Their observations have shown that both bubble and/or vortex cavitation may occur and that blood is similar to the transparent saline surrogates in so far as its cavitation susceptibility is concerned. Clearly future improvements in these prostheses will depend on improvements in our understanding of the features that promote or inhibit cavitation as well as an understanding of why they are currently inferior to natural valves. Zapanta *et al.* (1996,98) provide some useful insights in this regard. They found that both the valve geometry and material have significant effects on the cavitation though the leakage clearance did not. It appears that softer materials provide compliance that reduces the magnitude of the low pressures

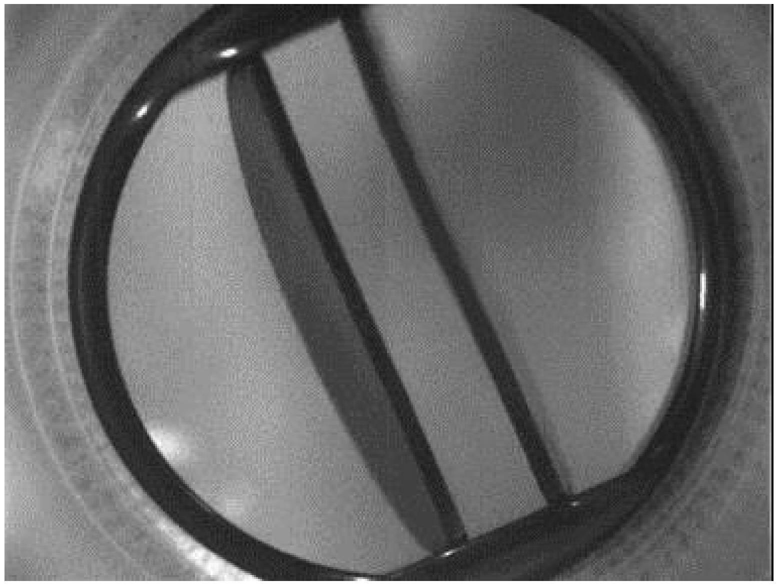

Figure 4: Bileaflet artifical heart valve in the open position viewed from downstream (from Rambod *et al.* (1999)).

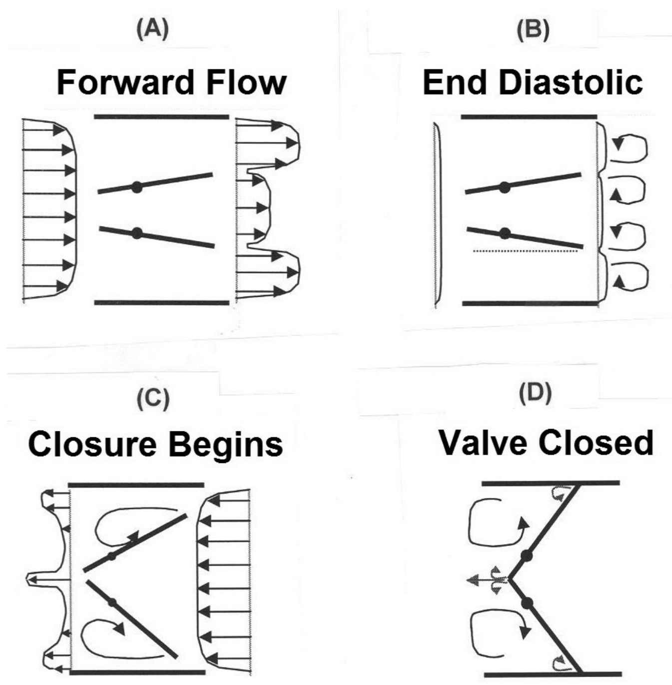

Figure 5: Schematic of the flows associated with the closing of a bileaflet prosthetic heart valve (from Maines and Brennen (2002)).

and reduces the cavitation. This may be the reason that natural valves are superior. Clearly there is a need for better understanding of cavitation in the presence of flexible surfaces.

Prosthetic heart valve cavitation is illustrated herein by the photographs of Rambod *et al.* (1999) one of which is reproduced in figure 6 where the cavitation both along the central diameter and at the tips can be clearly seen. It may be that the fluid used by Rambod *et al.* (1999) contained more cavitation nuclei than some other experiments and hence the prevalence of clouds of cavitation bubbles. The photographs of Stinebring *et al.* (1995) show smaller clouds as well as individual bubbles. Thus it appears that this transient form of cavitation and its consequences may depend not only on the design of the valve and

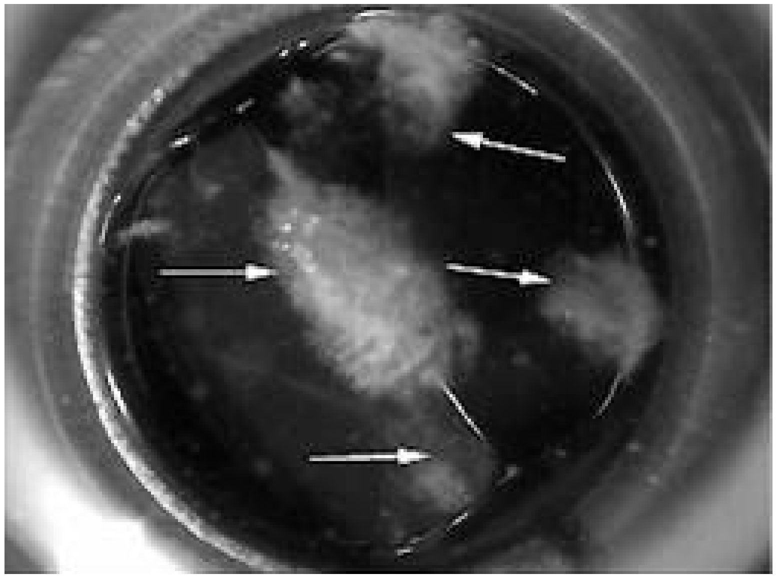

Figure 6: Photograph of cavitation downstream of a closing artificial heart valve (from Rambod *et al.* (1999)).

the flow conditions but also on the number of cavitation nuclei present in the fluid and the statistical coincidence of a nucleus with the transient low pressure region.