Prosthetic Heart Valves

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Presentation Outline

- Introduction
- History of the Prosthetic Heart Valve
- Diseases Affecting the Heart Valves
- Prosthetic Heart Valves
  - Mechanical Heart Valves (MHV)
  - Bioprosthetic Heart Valves (BHV)
Heart Valve Anatomy

There are four different valves in the heart:

- **Semilunar:**
  - Pulmonary Valve
  - Aortic Valve

- **Atrio–Ventricular:**
  - Mitral Valve (left)
  - Tricuspid Valve (right)

- Semilunar valves are open during ventricular systole while atrio–ventricular valves open during ventricular diastole
Introduction (cont’d)

Figure 1  Typical pressure and flow curves for the aortic and mitral valves (15).
Introduction (cont’d)

- Video on normal heart valve function
History of the Prosthetic Heart Valve

- Founded on a number of developments in cardiac therapy arising in the first half of the 20th century:
  - Cardiac catheterization by Andre Cournand & Dickinson Richards
  - Innovation of methods of cardiac surgery by pioneers like Alfred Blalock (Pictured)
  - Heart–lung machine by John Gibbon
  - Blood thinners like Heparin by Jay McLean and Dicumarol by Karl Paul Link
Corrective surgery for valvular heart disease was being established in the early 20th century, but wasn’t very promising.

- Methods such as valvuloplasty were used to relieve stenosis but were not effective.

The first attempt at HV replacement was done by Dr. Charles Hufnagel in the early 50’s.

- A ball valve was used but there were large amounts of regurgitation and thrombosis and therefore was not a success.
History of the Prosthetic Heart Valve (cont’d)

- September 1960: Dr. Albert Starr (right) performs the first successful HV replacement using a Starr–Edwards Ball Valve in the mitral position.
  - Mr. Lowell Edwards (left) was a hydraulics engineer (retired) with an interest in medicine and together with Dr. Starr developed this MHV.

- Mr. Lowell formed the first company to manufacture prosthetic heart valves.

- In the past five decades, over 250,000 Starr–Edwards ball valves have been implanted and are considered the performance standard for new designs today.

- Dr. Dwight Harken implanted the first MHV in the aortic position.
History of the Prosthetic Heart Valve (cont’d)

- Although these implants were a great success, the ball valve design was not perfect.
- Thrombosis occurring at the site of implantation required the use of blood thinners
- The ball design provided a large central obstruction to flow

- These issues have led to the design of new, more effective MHV’s and also to the use of BHV’s which we will be discussing...
Diseases

There are two types of valvular heart disease:

- **Congenital Heart Valve Disease**: Caused by an abnormality of the heart valve before birth.

- **Acquired Heart Valve Disease**:
  - It affects heart valves that were once normal.
  - Valvular Degeneration
  - Rhumatic Fever
  - Bacterial Endocarditis
  - Calcific Aortic Valve Disease
  - Atherosclerosis/Thrombosis

- About 300,000 Heart valve replacements are performed each year.
Effects of Valvular Heart Diseases

- **Stentosis**
  - The valve becoming narrow, which limits the amount of blood pumped to the rest of the body

- **Regurgitation (Valve insufficiency)**

  - Leakage that causes blood to flow backwards. It reduces heart’s ability to pump blood and causes a buildup of back pressure on the heart and lungs
There are two common diseases that cause valvular degeneration:

- **Fibroelastic deficiency**
  - It is connective tissue deficiency, that results in the thinning of leafets. There is also prolapsing segments, that are filled in with myxoid (mucus-like protein) and causes thickening in those areas. Usually happens to patients over the age of 60

- **Barlow’s Disease**
  - It is like the opposite of fibroelastic deficiency. It is caused by myxoid infiltration causing the leaflets to be thick and billowy. Usually occurs to patients under the age of 60

- Both diseases lead to the valves to thin out or rupture and the leaflets to become useless. They also cause regurgitation.
Rheumatic Fever and Bacterial Endocarditis

**Rheumatic Fever:**
- It is caused by an untreated streptococcal infection. The actual infection does not attack the heart valve but the antibodies come in contact with the valves and inflames them. It causes the leaflets to be misshaped. It causes either or both stenosis and regurgitation.

**Bacterial Endocarditis:**
- It is a bacterial infection of the endocardium of the heart. The bacteria attaches to the heart valves and basically attacks them. It causes either or both stenosis and regurgitation.
Calcific Aortic Valve Disease

- About 1% of calcium the body uses dissolves in the blood vessels
- Calcification is the process of slow calcium build up that eventually hardens body tissue
- This commonly happens in the aortic valve
- It is linked to aging and obesity
- As a result, the calcium deposits harden the aortic valve and causes stenosis
Atherosclerosis / Thrombosis

- **Atherosclerosis:**
  - The slow accumulation of plaque along the arteries and heart valves

- **Thrombosis:**
  - The slow build-up of platelets and fibrin along blood vessels and heart valves

- They both cause stenosis.
Prosthetic Heart Valves

- Mechanical Heart Valves (MHVs)
- Bioprosthetic Heart Valves (BHVs)

The Ideal Prosthetic Heart Valve should:
1. Produce minimal pressure drops
2. Yield low regurgitation volume
3. Minimize turbulence and shear stresses
Types of MHVs

Ball and Cage Valve

Bileaflet Valve

Tilting Disk Valve

Fig. 3. Tilting disc valves in 1970s, (a) Bjork–Shiley valves, (b) Medtronic–Hall valves [10].

Fig. 4. St. Jude MHV [10].
MHV Comparison – Pressure & Regurgitation

- The pressure drop across the valve is a direct indication of valve performance. Larger pressure drops across the valve require a larger systolic pressure to drive the flow.

\[ EOA(\text{cm}^2) = \frac{Q_{rms}}{51.6 \sqrt{\Delta p}}, \]

- \( Q_{rms} \) – root mean square systolic/diastolic flow rate (cm\(^3\)/s)
- \( \Delta p \) – mean systolic/diastolic pressure drop (mm Hg)

- Regurgitation Volume is the amount of blood that flows against circulation while the valve is in the closed position. Larger RVs reduce the effective use of the heart’s power output, since,

\[ P_w = Q \Delta P \]

- \( Q \) – volumetric flow rate (cm\(^3\)/s)
- \( \Delta p \) – mean systolic/diastolic pressure drop (mm Hg)
MHV Comparison – Pressure & Regurgitation

**Table 3** In vitro hemodynamic data for common aortic valve prostheses (61)

<table>
<thead>
<tr>
<th>Valve type</th>
<th>Valve</th>
<th>Size</th>
<th>Regurgitant volume (ml/beat)</th>
<th>EOAb (cm²)</th>
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</table>

**Figure 2** Flow cycle divided into forward flow, closing volume, and leakage volume (38).
MHV Comparison – Flow Characteristics

- Velocity and Turbulent shear stresses induced by the valve will affect longevity and thrombogenicity.
- Stagnation/Separation regions of flow lead to thrombosis and therefore, any patient using current MHVs must be treated with blood thinners.

- High levels of shear stress can lead to hemolysis (the threshold Reynolds shear stress is estimated at 8000 dynes/cm²).

- Turbulent shear stresses are higher in the aortic position than in the mitral position.

[ NOTE: 1 dyne = 10⁻⁵ N ]
The resulting shear stresses induced by these valves (at peak systole < 2000 dynes/cm²) will not cause hemolysis (8000 dynes/cm²).

However, due to regurgitation, lots of cells will pass through the valve several times and so the damage caused to them by these shear stresses can accumulate over multiple cycles and lead to thrombosis.
Ball and Cage Design

- The centrally obstructive ball causes blood to flow in jet-like streams around the circumference creating vortices downstream of the valve.

*Figure 3* (a) Velocity profile 30 mm downstream on the centerline for the Starr-Edwards ball valve at peak systole; (b) turbulent shear stress profile 30 mm downstream on the centerline for the Starr-Edwards ball valve at peak systole (38).
Tilting Disk Design

- Largest separation of flow caused by the hinge in the minor orifice
- A stagnation region forms immediately downstream of the minor orifice (adjacent to the wall)

Figure 4 (a) Velocity profile 15 mm downstream on the centerline across the major and minor orifices of the Medtronic-Hall tilting disc valve (major orifice to the right) at peak systole; (b) velocity profiles 13 mm downstream in the major and minor orifices of the Medtronic-Hall tilting disc valve at peak systole; (c) turbulent shear stress profile 15 mm downstream on the centerline across the major and minor orifices of the Medtronic-Hall tilting disc valve (major orifice to the right) at peak systole; (d) turbulent shear stress profiles 13 mm downstream in the major and minor orifices of the Medtronic-Hall tilting disc valve at peak systole (38).
MHV Comparison – Flow Characteristics

Bileaflet Design

- Flow separation regions occur downstream of the walls (a) and around the hinges (b).

**Figure 5**  
(a) Velocity profile 13 mm downstream on the centerline for the St. Jude Medical bileaflet valve at peak systole; (b) velocity profile 13 mm downstream across the central orifice for the St. Jude Medical bileaflet valve at peak systole; (c) turbulent shear stress profile 13 mm downstream of the centerline orifice for the St. Jude Medical bileaflet valve at peak systole; (d) turbulent shear stress profile 13 mm downstream across the central orifice for the St. Jude Medical bileaflet valve at peak systole (38).
MHV Flow Characteristics (Leakage)

- Leakage between the leaflets/disc and valve housing flows at very high velocities and can produce shear stresses much higher than those seen in forward flow.

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>Model</th>
<th>Size (mm)</th>
<th>Peak leakage velocity (m/s)</th>
<th>Peak turbulent shear stress (dyne/cm²)</th>
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</thead>
<tbody>
<tr>
<td>St. Jude Medical</td>
<td>Standard</td>
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<td>St. Jude Medical</td>
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<tr>
<td>St. Jude Medical</td>
<td>Regent</td>
<td>17</td>
<td>0.75</td>
<td>2000</td>
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</table>

- The jets formed from this leakage tend to wash away gap regions but the local shear stresses lead to a phenomenon called cavitation...
MHV Flow Characteristics (Cavitation)

- The leakage jets formed during valve closure create surrounding vortices so intense that the pressure at their centre drops enough to produce air bubbles.

- These bubbles only last for a few hundred microseconds after which time they collapse, producing a shockwave that can damage nearby material.

- Combined with fatigue caused by impact of the leaflet with the housing, this has led to mechanical failure and patient death.
Polymeric MHVs

- Polymeric valves are currently being investigated.

- Because of polymers ability to mimic the natural tissues of normal heart valves, they show a lot of promise.

- They have been used in some cases as short-term solutions, but there has yet to be any designed with the right combination of material and structural properties to warrant them as a competitor with the other MHVs.
Bioprosthetic Heart Valves (BHV’s)

- Types of BHV’s
  - Stented
  - Non-Stented
**BHV Comparison – Pressure & Regurgitation**

- **Stented**
  - Higher pressure drop because of stent

- **Non-Stented**
  - Lower pressure drop because it has a larger orifice area
BHV Comparison–Flow Characteristics

- Stented Valves

![Graphs and figures showing flow characteristics and valve profiles.]

**Figure 7**  
(a) Velocity profile 15 mm downstream on the centerline for the Carpentier-Edwards 2625 porcine valve at peak systole; (b) turbulent shear stress profile 15 mm downstream on the centerline for the Carpentier-Edwards 2625 porcine valve at peak systole (38).

**Figure 8**  
(a) Velocity profile 17 mm downstream on the centerline for the Carpentier-Edwards pericardial valve at peak systole; (b) turbulent shear stress profile 17 mm downstream on the centerline for the Carpentier-Edwards pericardial valve at peak systole (38).
Although the shear stresses are elevated by the BHVs, their low regurgitation volume limits the amount of cells that are recycled through the valve.

Reduced flow separation also eliminates any accumulation downstream of the BHV.

This means that patients with BHVs do not require the use of Blood thinners.
BHVs and Calcification

- Since BHVs are made from natural tissues, they will undergo calcification after a really long time.

- After 10+ years, the patient will require replacement surgery

- This is a disadvantage and this is why BHVs are rarely used in adults

- However, they are ideal for children because their hearts are growing, so they will need undergo replacement surgery to accommodate for the growth
**Fig. 6.** Increase in use of BHVs for aortic valve replacement, reaching ~80% in recent years. Data from a total of 6648 patients treated at the Providence St. Vincent Hospital, Portland, Oregon, USA [37].
Conclusion (cont’d)

- Video on prosthetic heart valves
References


References (cont’d)


References (cont’d)


