Artificial Heart Valves

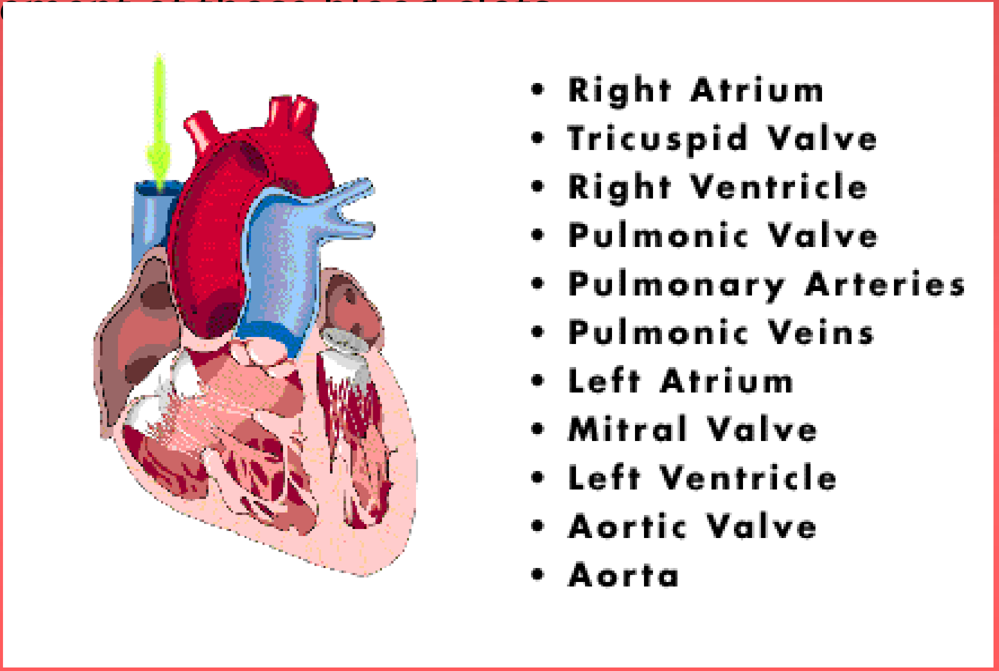
Aiyush Bansal
Sandra Escandor

Outline

- Basic Anatomy of heart valves
- Fluid dynamics of how a normal valve works
- Diseases concerning heart valves
- History of artificial heart valves
- The different types of artificial heart valves today
  - Fluid dynamics of those valves
- Heart valves of the future

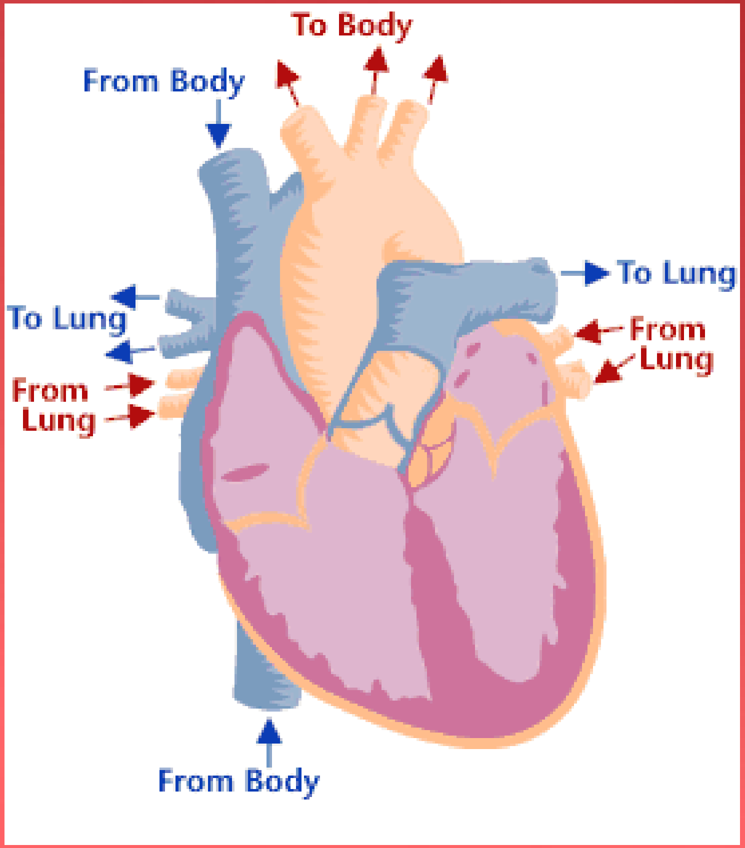
The flow of blood

- Right Side
  - Right atrium -> tricuspid-> right ventricle -> pulmonic valve ->pulmonary arteries
- Left Side
  - Lung -> left atrium -> mitral valve -> left ventricle -> aortic valve -> aorta
- **Thrombogenesis** – the creation of blood clots
- **Embolism** – movement of these blood clots



Workings of the valves

- Systole (contraction)
  - Tricuspid & mitral are closed
  - Aortic & pulmonic open
  - Left ventricle -> aorta
  - Right ventricle -> lung
- Diastole (relaxation)
  - Tricuspid & mitral are open
  - Aortic & pulmonic closed
  - Atria -> respective ventricles

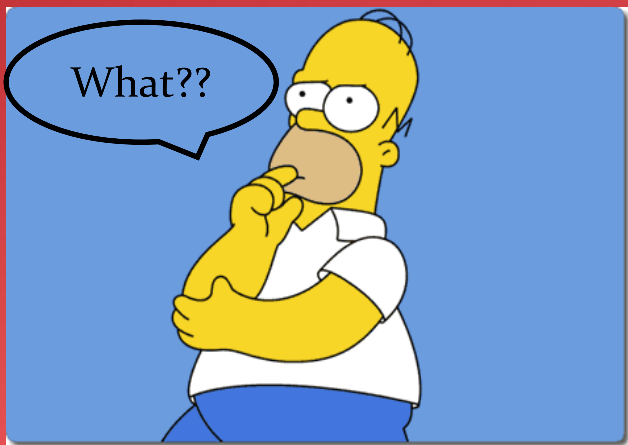


Source: Tortora & Derrickson

Fluid Dynamics "Basics"

- Fluid flows from areas of high pressure to areas of low pressure
- Heart valves open and close in response to pressure gradients
  - valves open when pressure in the preceding chamber is higher and close when the gradient reverses
  - These one-way valves are important in ensuring that the blood flows in the proper direction
- Central flow – blood moves through the center of the valve
- Turbulence – fluid flowing randomly
- Shear stress – force exerted by the movement of blood on walls (stress exerted parallel)

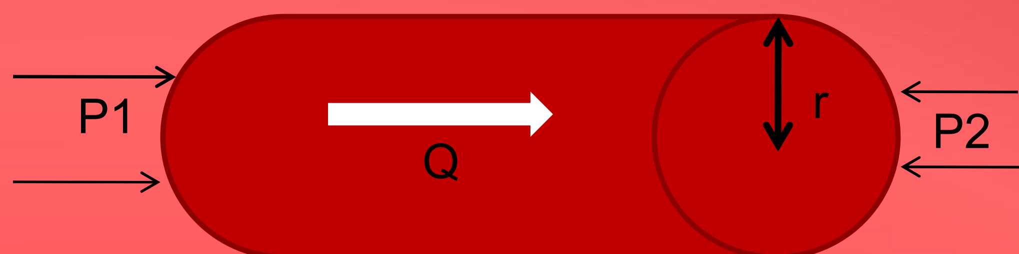
Fluid mechanics cont'd



- Goal:
  - minimal pressure drops=>minimize Q
  - Lower R=>higher Q=>more turbulence=>more clots

Q= Δp /R
R~1/r^4

Q – flow rate
R – resistance to flow of blood
Δp - pressure difference



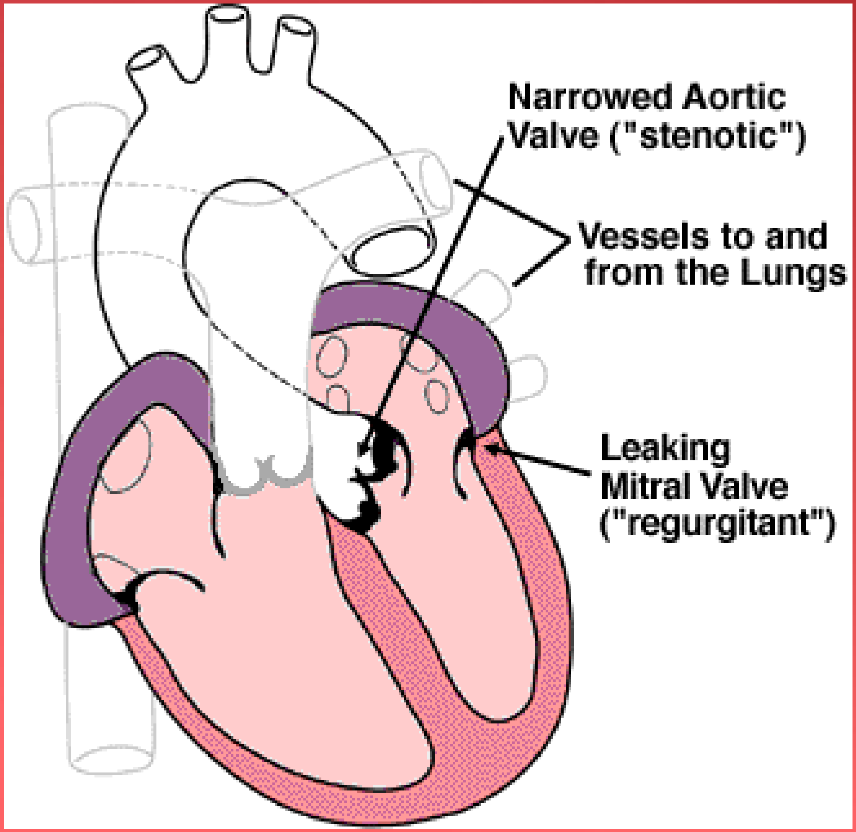
Δp=P1 - P2 > 0

Did you know?

Valvular heart disease is a life-threatening disease that afflicts millions of people worldwide and leads to approximately 250,000 valve repairs and replacements each year.

Heart Valve Diseases

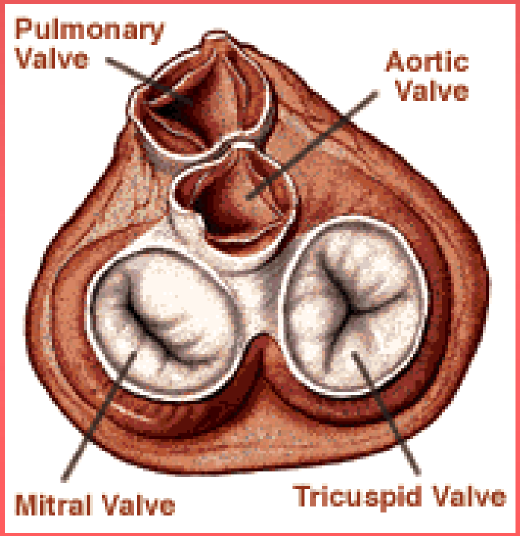
- Stenosis – does not fully open
  - If affecting mitral valve, left ventricle will not receive as much blood =>less oxygenated blood is supplied by heart
  - If affecting tricuspid valve, right atrium will not receive as much blood =>less blood becomes oxygenated
- Incompetence – does not fully close
  - If affecting mitral valve, left ventricle will back up blood to left atrium
  - If affecting tricuspid valve, right ventricle will back up blood to right atrium



Source: http://www.sjm.com/conditions/condition.aspx?name=Heart+Valve+Disease

Heart Valve Diseases

Name	Description
Endocarditis	Occurs when germs (i.e. from another part of your body) enter blood stream and infect damaged areas of heart. If untreated, may destroy heart valves – life threatening
Calcific degeneration	Buildup of calcium in mitral or aortic valves => causes valves to thicken
Regurgitation	Blood is leaking backwards because the valve does not close properly



Heart valve repair

- Video break!! Video about mitral clip.
- http://youtube.com/watch?v=Foaj6TkQbxc

Source:
http://www.sjm.com/procedures/procedure.
aspx?name=Heart+Valve+Replacement

History

1952 – The first valve, the Hufnagel valve was developed and was made out of plexiglass and silcone-coated nylon. Later, it was implanted; patient lived for 14 hours.

Problem:

•High rate of blood clot formation

•Sounded like a ticking time bomb

•Lack of central flow => causes turbulence => creates blood clots

1961 – Starr-Edwards Ball and Cage is developed. Only 6/8 patients lived.

Problem:

•Initial design was susceptible to creating blood clots!

•Cloth covered version induces blood clots since cloth tears

Upside: Overall reduction in rate of embolization, but permanent blood thinner therapy was needed.

History cont'd (Allografts/Xenografts)

A porcine valve (Source: Penn State Bioengineering. DESIGN OF A MOCK CIRCULATORY FLOW LOOP . Senior Design 2007)

1962 – Allografts/Xenografts are developed

Big Idea: Improved on mechanical valves by ultimate reduction in blood clot formation

Upside :
Patients do not need blood thinners

Downside:
Limited supply
Durability is poor since collagen material denatures

History cont’d

Late 1960s –Bioprosthetic valves (hybrids) also developed

Big Idea: Improved on the cage and ball design by removing the restriction of central flow of blood

•Reduced turbulence
•Reduced resistance (in forward flow direction)
•Reduced shear stress

History cont'd (The Bioprosthesis)

Carpentier did this:

1.Washed porcine (pig) aortic valve with Hank's solution and an oxidizing agent =>hides valve's antigenic components
2.Treated porcine aortic valve with glutaraldehyde => prevents collagen denaturing by stabilizing cross-links
3.Combined the treated valve with a fabric covered metal frame => keeps the three dimensional shape of the valve; easy to implant

Upside:
•No Need for blood thinners!
•Central flow achieved

Downside:
•Valves have a harder time opening due to stiffness
•Calcium deposits easily on valves due to preservative used => strokes are more prevalent since calcium deposits chip off

History cont'd (Tilting disc)

Late 1960s – Tilting disc is discovered. Also pyrolytic carbon is discovered by the space program

Big Idea: Improved on the cage and ball design by removing the restriction of central flow of blood

Reduced turbulence

Reduced resistance (in forward flow direction)

Reduced shear stress

Upside:

Need for blood thinners was greatly reduced

Downside:

blood clots formation was not totally eliminated

History cont'd (Bileaflet)

1976 - St. Jude's introduces the bileaflet valve. Today, this design is more than 25 years old

Big Idea: Improved on the tilting disk design by removing the restriction of central flow of blood even more than the tilting disk!

Upside:

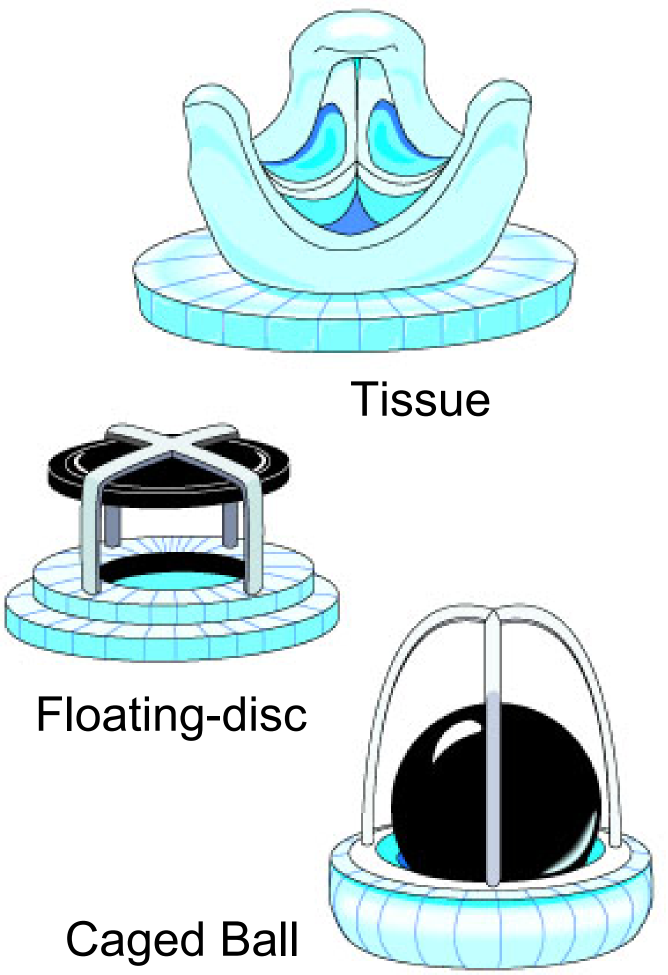
•Central flow achieved!

Downside:

•Still need blood thinners for life

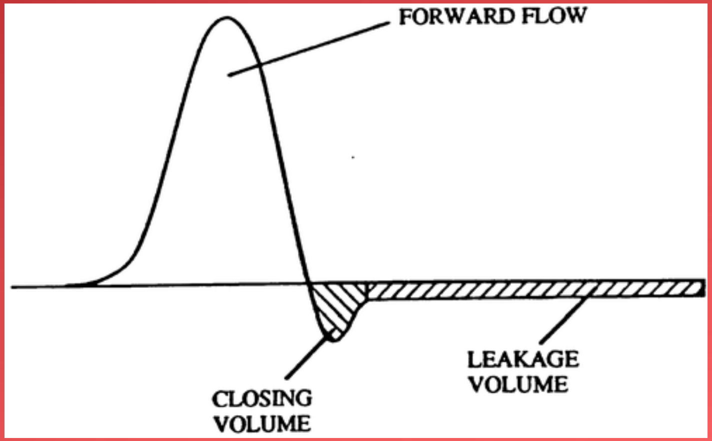
•More regurgitation than tilting disk

Current Technology: Mechanical and Biological Valves



- Mechanical valves
  - Caged-ball
  - Tilting-disc (single leaflet)
  - Bileaflet
- Bioprosthetic valves
  - Xenograft (made from animal tissue)
  - Allograft (made from human tissue)

Fluid Mechanics of heart valves

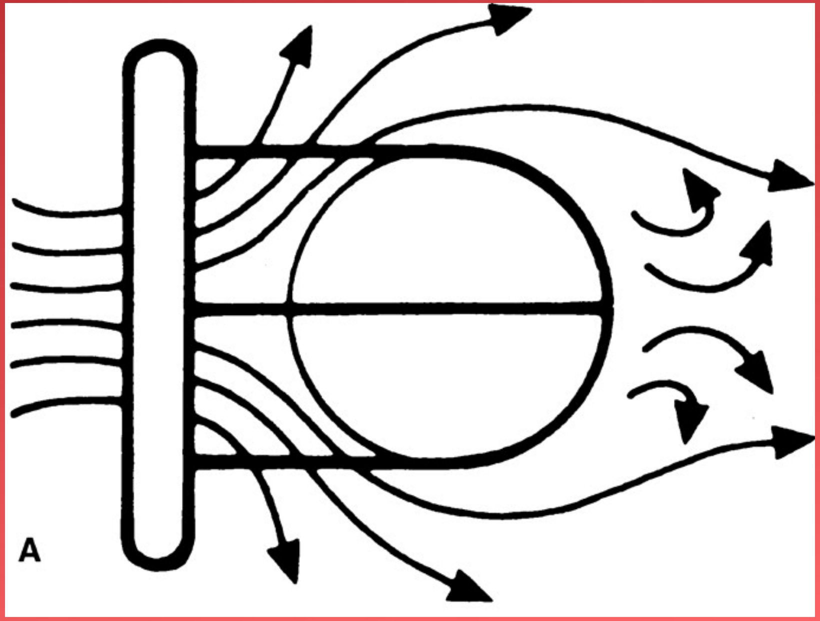


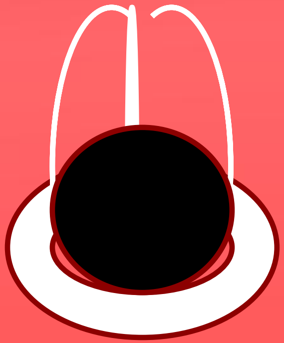
Flow cycle divided into forward flow, closing volume, and leakage volume

Ideal heart valve requirements:

- Produce minimal pressure drops
  - A larger pressure drop on a prosthetic valve means a even larger pressure from the ventricle to drive the flow of blood through.
- Small regurgitation volumes (reverse flow)
  - Equal to the sum of the closing volume and leakage volume.
  - The closing volume is the volume of retrograde flow through the valve during valve closure.
  - Leakage volume is any fluid volume accumulation after valve closure.
- Minimize turbulence and high shear stresses
  - Not create stagnation or flow separation regions in the flow fields.

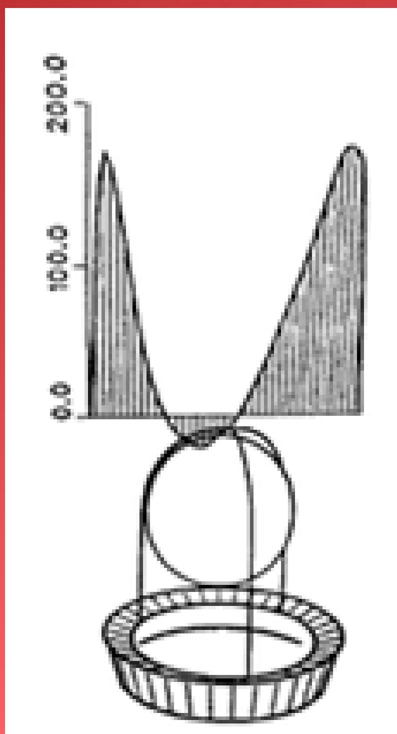
Caged-ball valve



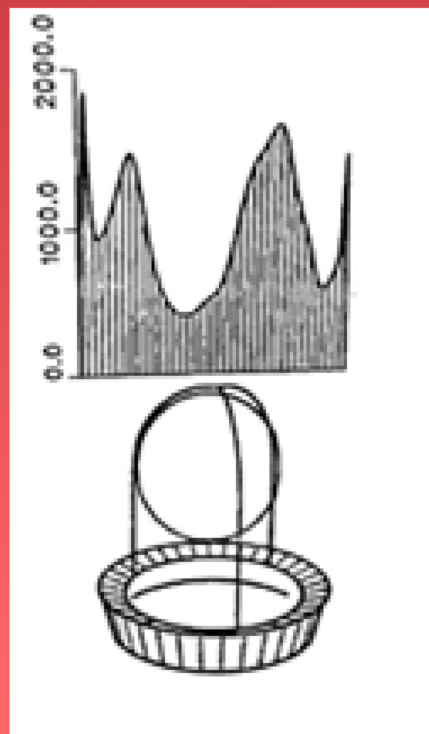


- Pros
  - Very little regurgitation
- Cons
  - Ball blocks central flow i.e. blood has to move around the ball.
  - Increases collisions of blood cells => blood clots
  - The weight and wear resistance of the occluder affect the opening and closing of the valve

Fluid Mechanics of Caged-Ball



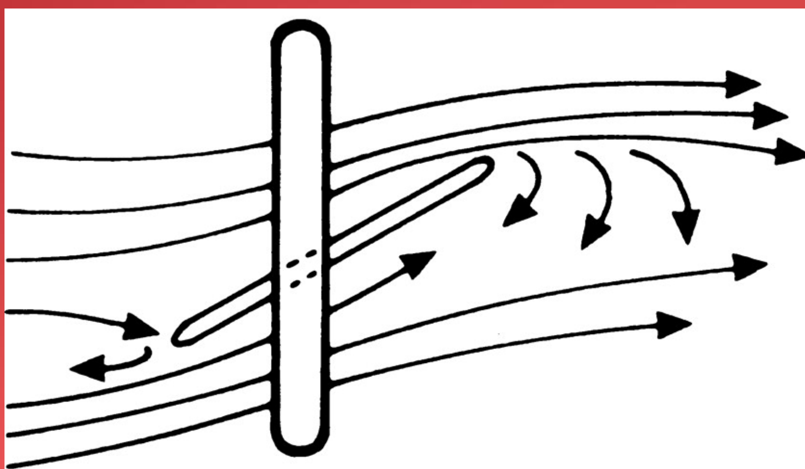
Velocity during systole (cm/s)



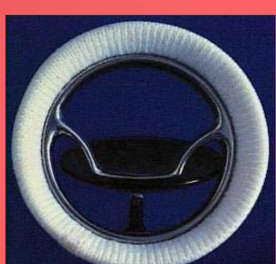
Turbulent shear stresses (dynes/cm^2)

- Maximum velocity of 2.2 m/s at peak systole
- Peak reverse velocities in the wake region can be as high as 0.25 m/s
- Regurgitation volumes are around 5ml/beat
- Turbulent shear stresses are around 1850 – 3500 dynes/cm^2

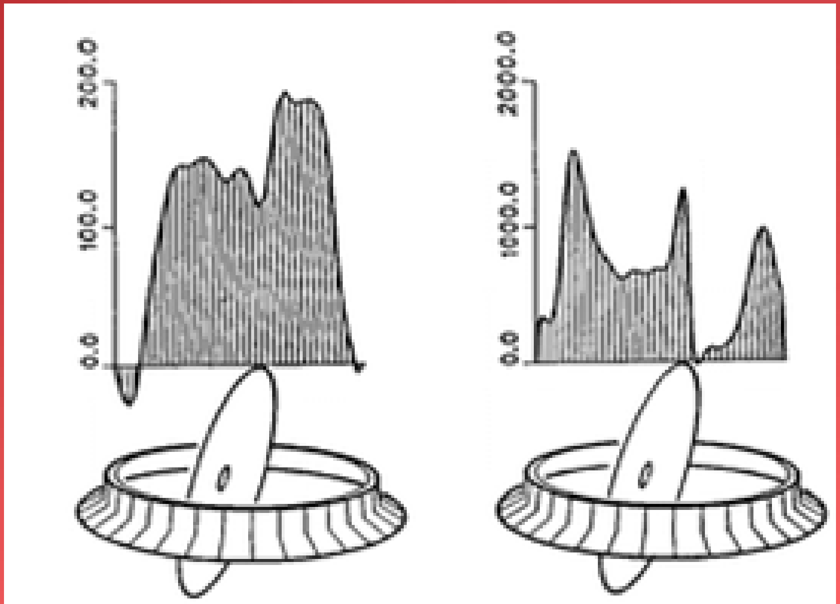
Tilting-disc (single leaflet)



- Pros
  - Uses a tilting occluder disk to better mimic natural flow patterns through the heart
  - Tilting pattern allows more central flow while still preventing backflow
- Cons
  - Some damage still occurs to blood cells
  - Reduces thrombosis and infection, but does not eliminate either problem



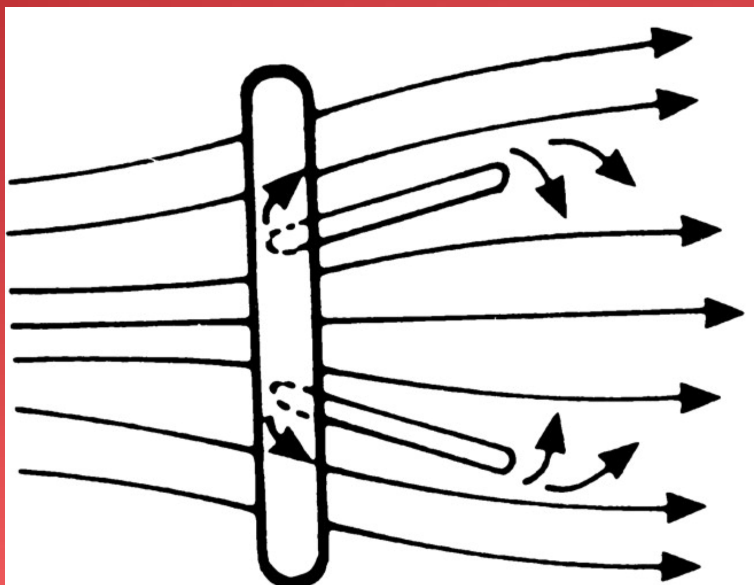
Fluid Mechanics of Tilting disc



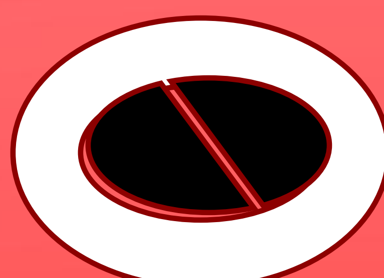
Velocity during systole (cm/s) | Turbulent shear stresses (dynes/cm²)

- Has major and minor orifices divided by a tilting disc.
- The peak velocities are 2.1 m/s and 2 m/s in the major and minor orifice regions, respectively
- Maximum reverse velocity of 0.25 m/s in the minor orifice.
- Regurgitation volumes are around 9 ml/beat
- Turbulent shear stresses are 1200-1500 dynes/cm²

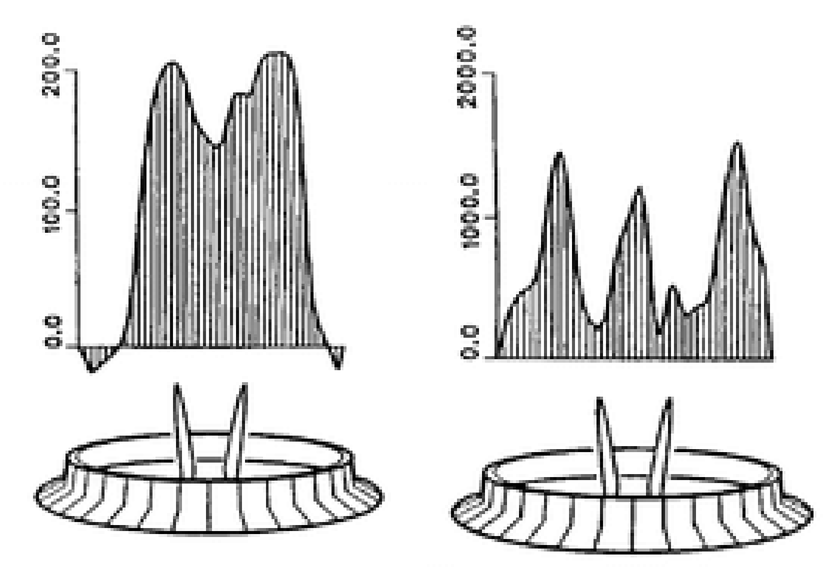
Bileaflet valve



- Pros
  - Most common
  - Record spanning 3 decades of excellent results
  - Lowest complications=>lower cost
  - Carbon leaflets exhibit high strength and excellent biocompatibility
  - Closest approximation to central flow
- Cons
  - Allows some backflow since leaflets cannot close completely



Fluid mechanics of bileaflet



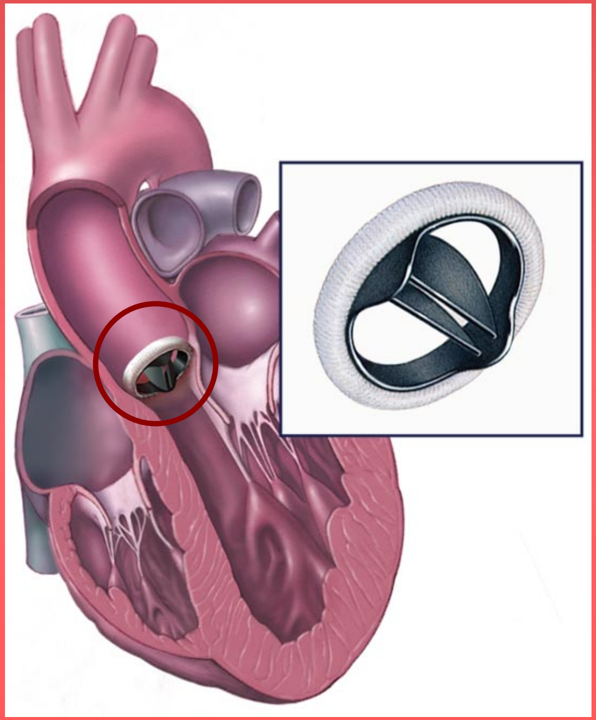
Velocity during systole (cm/s)

Turbulent shear stresses (dynes/cm^2)

- Two semicircular leaflets divide into three regions: two lateral orifices and a central orifice
- Turbulent shear stress levels exceeding 1150-1700 dynes/cm^2.
- The lateral and central orifice jets reach maximum velocities of 2.2 m/s and 2 m/s, respectively
- Regurgitation volume >9 ml/beat

Summary of Mechanical Valves

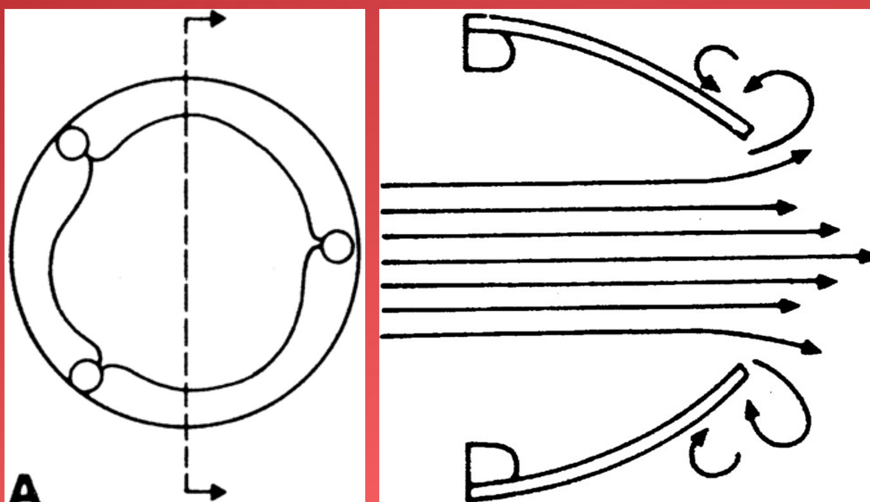
- Least Turbulence
  - Bileaflet>>Tilting disc>>Caged ball
- Least Regurgitation
  - Caged ball>>Tilting disc>>Bileaflet



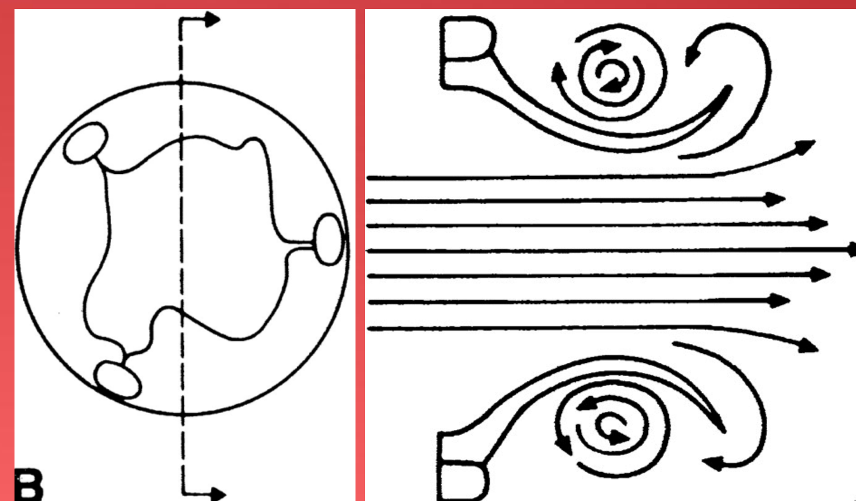
Animal tissue valves

- Heterograft/Xenograft – animal to human
- Porcine valves – from pig
  - Has good durability and and good hemodynamics
  - Materials: Porcine valve tissue, Elgiloy(cobalt-nickel alloy), sewing ring-knitted Teflon
- Bovine pericardial valves – from cow
  - Lasts as long as standard porcine valves at 10 years
  - The pericardial valve has excellent hemodynamics, and has gained a large market share (about 40% of US tissue valves) in this group of patients
- Biggest problem is biocompatibility between animal and human tissue i.e. the immune response of the human system

Fluid mechanics of tissue valves



Bovine pericardial valves



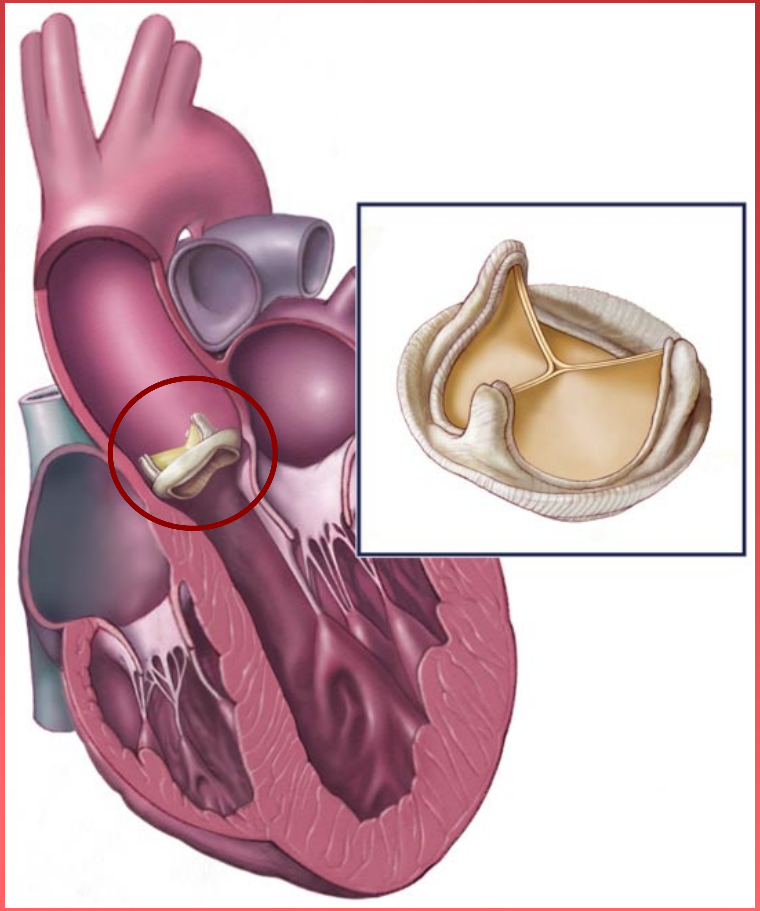
Porcine valves

Bovine valves are better hemodynamically because there's less resistance to flow

Human tissue valves

- Homograft – human to another human
  - After donation, valves are preserved in liquid nitrogen (cyropreserved) until needed
  - Since the valve must be thawed overnight, the patient’s size must be known beforehand
  - Limited supply because donors are limited
- Autograft – human to same human
  - Usually replaces diseased aortic valves with pulmonic valves.
  - Patient receives a living valve in the aortic position
  - Better durability and hemodynamics
  - The procedure called “Ross Procedure” is very complicated and requires much skill and time

Animal VS Human Tissue Valves

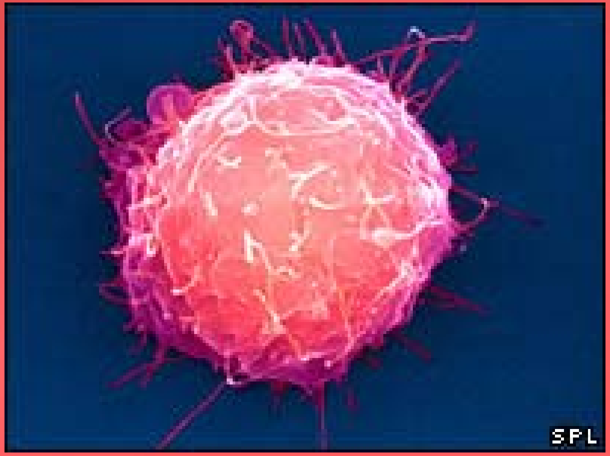


- Animal valves
  - Less biocompatible
  - More supply
- Human valves
  - More biocompatible
  - Less supply
  - More complicated procedure (autograft)

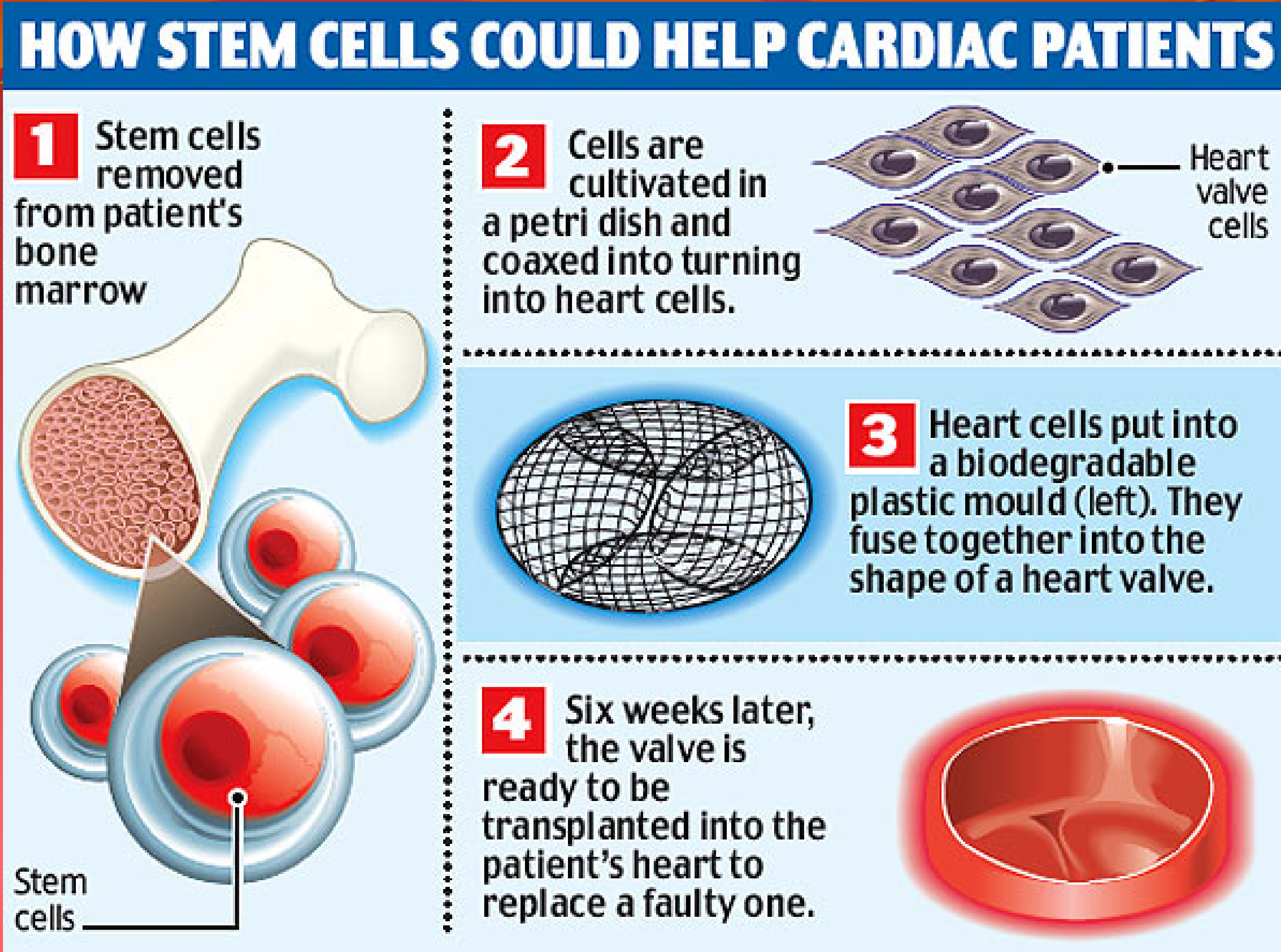
Mechanical Vs Tissue Valves

- Mechanical valves
  - Pros
    - Extremely durable. The struts and occluders are made out of either pyrolytic carbon or titanium coated with pyrolytic carbon, and the sewing ring cuff is Teflon, polyester or dacron
    - Typically last about 20 - 30 years
    - Preferred choice for children, teens, and adults age 60 and younger
  - Cons
    - The hard mechanical tissue of the valve causes blood cells to tear as they pass through, causing clots to form.
    - People must constantly take anticoagulants
- Biological valves
  - Pros
    - Typically last about 10 - 15 years
    - Virtually no regurgitation volume
    - Much lower risk of blood clotting than mechanical valves
    - Better for people who are older than 60 and cannot take anticoagulants
  - Cons
    - Can also tear or become infected
    - May fail for the same reason the original one did

Heart valves of the future!!!



- Engineers are still trying to make better artificial heart valves using better materials and designs.
- Stem cells may provide the answer!
  - Scientists for the first time have now grown human heart valves using stem cells from the amniotic fluid that cushions babies in the womb.
  - The world's leading surgeon, Sir Magdi found a way to turn adult stem cells from bone marrow into


HOW STEM CELLS COULD HELP CARDIAC PATIENTS
1 Stem cells removed from patient's bone marrow
Stem cells
2 Cells are cultivated in a petri dish and coaxed into turning into heart cells.
Heart valve cells
3 Heart cells put into a biodegradable plastic mould (left). They fuse together into the shape of a heart valve.
4 Six weeks later, the valve is ready to be transplanted into the patient's heart to replace a faulty one.

That's all folks!!

Any questions??

Sources

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