The flow through prosthetic heart valves

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OUTLINE

1. General Introduction: Heart valve research
2. Fluid Mechanics of Heart Valves
3. Our Experimental Investigation
   – Visualization of flow structures and interpretation
   – Some Ideas for Blood Trauma
4. Foundations for valve design
5. Conclusions
**BIOLOGICAL FLOWS**

Flow through heart valves
- Flow structure and damage

Fish swimming
Shell selection by crabs

**HEAT TRANSFER**

Vortex HT enhancement
- Ring-wall collisions

**TWO-PHASE FLOWS**

**Granular flows**
- Dry stuff
  - Flow around objects
  - Avalanches
- Wet stuff
  - liq. fluidized beds
  - collisions
  - shear flow

**Bubbly flows**
- Newtonian stuff
  - Single bubbles
  - Pseudo turbulence
- Non newtonian stuff
  - Single bubbles

**Emulsions**
- Formation
  - Turbulent-capillary break-up of threads
Heart Research

- 1 million heart surgeries per year worldwide
- 25% are related to failure of valves
- Valve replacements are readily available
- Many unresolved problems…
- Instituto Nacional de Cardiología
  Large scale collaboration project
Heart Valves

Four valves:
Mitral and Tricuspid (inside)
Aortic and Lung (outside)

Two or four leaflets
Prosthetic heart valves

- **Mechanical**
  - caged-ball
    (Starr-Edwards)
  - tilting-disc
    (Medtronic Hall)
  - bileaflet mechanical
    (Saint Jude)

- **Biological**
  - Porcine
  - Bovine

Flexible or rigid

Rigid
Mechanical prosthetic valve

- ✓ Overcome mechanical fatigue
- ✓ Minimize regurgitant volume
- ✓ Bio-compatibility
- ✓ Well studied designs

- ✗ Stagnation & thrombus formation at hinges & pivots
- ✗ Cavitation
- ✗ Unnatural flow → several jets, high shear stress

Biological prosthetic valve

- ✓ Reduce thrombogenic complications
- ✓ Minimize transvalvular pressure drop
- ✓ Mimic native flow → central jet

- ✗ Stenosis → flow occlusion
- ✗ Tissue overgrowth → calcification
- ✗ Mechanical fatigue
- ✗ Manufacture defects
- ✗ Infections
Prosthetic heart valves

• After 40 years ‘these devices are less than ideal and lead to many complications.’
• ‘Many of these complications/problems are directly related to the fluid mechanics associated with the various mechanical and bioprosthetic valve designs.’

Yoganathan et al. (2004)
Fluid mechanics issues for heart valve replacements

- **HEMOLYSIS** (Destruction of Blood Cells)
  - Cells ‘break’ as a result of the applied shear and turbulence
  - Stress level and time dependence
  - Not well understood

- **THROMBOSIS** (Formation of blood clots)
  - (Low) wall shear rate
  - Residence time
  - Chemical reaction (properties of contacting surfaces, coagulability and other factors)
  - Less well understood

- **CAVITATION** (Formation and collapse of vapor bubbles)
  - Low pressure zone appear during valve closing (only for mechanical valves)
  - Implosion of bubbles causes cell damage
  - Well understood but poorly studied
Coagulation and Thrombosis

• Complex physico-chemical process
• Hemostasis
• Main elements:
  – Platelets
  – Tissular factor (F III)
  – Coagulation factors (FI –FXII,12 proteins)
Shear induced platelet activation

• Cell lysis is not necessary for platelet activation

• Dependence of strength of ‘shear’ but ALSO on exposure time

![Image of platelet activation under shear stress](image-url)
‘Activation’ of von Willebrand factor (vWF)

Schneider et al. (2007)
‘Local’ effort

• Design and production of bio-mechanical valves

• Bovine pericardium (cheap, good properties)
• Good performance
• But… Mechanical Properties? Durability? Good Performance?
Associated Research Projects in our ‘local’ effort

- Mechanical properties
- Stenosis (rigidization)
- New materials (for leaflets and structure)
- Mechanical Design and Testing
- FLUID MECHANICS
Part 1.
Study of the flow through replacement heart valves

• Quantify the performance of bio-mechanical heart valves.

• Study the complex flow fields that result from the flow-valve interaction.

• Explain why bio- valves are ‘better’ than mechanical valves.

• Contribute to the understanding of blood trauma mechanisms
Experimental setup

Windkessel model
- Pulsatile Pump
- Compliance chamber
- Resistance valve
Several planes (spatial resolution) and phase locking (temporal resolution)
Pressure traces and phase locking times
‘First’ set of 3D results

• Test valves
  – Mechanical bileaflet and monoleaflet
  – Biological tricuspid-type

• Set of conditions
  – Working fluid water
  – Frequency = 24 cycles/min = 0.4 cycles/s
  – Volume displaced = 45 cm$^3$ / cycle
  – 35% systole, 65% diastole

• Phase Locking
  – Five measuring planes downstream from the valve
  – 30 measurements /cycle
  – average over 200 cycles for each field
  – 5x30x200 = 30,000 images per each set of conditions

• Visualization
  – Velocity fields
  – $Q$-criteria for vortex identification
    (positive second invariant of velocity gradient tensor)
MECHANICAL VALVE

$t/T = 0$

Pressure signal

- Red: downstream pressure
- Blue: upstream pressure
- Green: PIV measurement
Some thoughts about the flow field

- Unsteady, fully three-dimensional, inertial (Re~2500) → visualization and interpretation: not easy

- Measurements → access to all flow quantities

- Phase locking → not ‘proper’ measure of turbulence (approximation)

- Blood cells, nearly neutrally bouyant and small → fluid tracers (very small Stokes number)
Results

Shear Rate

\[ \dot{\gamma} = \frac{\dot{\gamma} \cdot \dot{\gamma}}{\gamma} \]

\[ \tau = \frac{D}{v_{\text{max}}} \]

\[ \dot{\gamma}_{\text{mec}} \approx 200 \text{ s}^{-1} \]

\[ \dot{\gamma}_{\text{bio}} \approx 100 \text{ s}^{-1} \]

\[ T = \text{time} \quad t = \text{period} \]
Q Criteria

\[ Q_{\text{max}} = \left( \| \omega \|^2 - \| \dot{\gamma} \|^2 \right) \]

\[ Q = \left( \frac{D}{v_{\text{max}}} \right)^2 \]
Viscous Stresses

Biological

Mechanical

\[ \tau = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]

\[ \tau_a = \rho u_{\text{max}}^2 \]
Turbulent Stresses

Biological

Mechanical

\[ TT = \rho \bar{v}_i \bar{v}_j \]

\[ \tau_a = \rho \bar{v}_{\text{max}}^2 \]
Interpretation

- Magnitude of \textit{viscous and turbulent stresses}, much \textit{lower} than platelet activation threshold
- Magnitude \textit{shear rate} is close to unfolding threshold of the \textit{von Willebrand factor}.
- It is expected that the shear threshold be smaller for a non-simple shear flow
Part 2.  
A new generation of heart valves

• synthetic materials?
• physiological-like flow
• long-life good performance
• limited understanding: physical mechanisms which lead to a ‘proper performance’
  – Material properties
  – Leaflet dimensions
  – Fluid-structure interaction

• Research in Progress
Simpler geometry

What is the optimal performance?
  • minimize fluid stresses
  • unidirectional flow

What are the optimal geometric dimensions L, d, h?
What is the optimal material?
Flow parameters

Fixed
0.35 - systolic fraction
C - compliance
R - flow resistance

Dynamic
T - cycle duration
V - stroke volume

\[ \rho_f = 1 \times 10^3 \text{ kg/m}^3 \]
\[ \mu_f = 1 \times 10^{-3} \text{ Pa \cdot s} \]

\[ 240 < Re < 960 \]
\[ 90 < Kc < 250 \]
\[ Wi^* \approx 10^{-9} \]
Test different valves: geometries and materials

<table>
<thead>
<tr>
<th>Leaflet</th>
<th>Material</th>
<th>Thickness, ( d/h )</th>
<th>Density, ( \rho_s ) kg/m(^3)</th>
<th>Secant Modulus of Elasticity, ( E_s + 1 \times 10^6 ) kg/m ( \cdot ) s(^2)</th>
<th>Length, ( l/h )</th>
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<tr>
<td>La</td>
<td>Latex</td>
<td>0.027</td>
<td>960</td>
<td>0.83</td>
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<td>Ne</td>
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<td>Silicone rubber</td>
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<td>Si2</td>
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<tr>
<td>Si</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.75</td>
</tr>
</tbody>
</table>

Test different flow conditions: frequency and disp. volume

\[ 20 \text{ pulses/min} < f < 110 \text{ pulses/min} \]
\[ 20 \text{ cm}^3 < V < 100 \text{ cm}^3 \]
Velocimetry

Ordinary 2D PIV, with phase locking
Velocity measurements
Valve performance

GOOD

- Uni-directional flow
- ‘Check’ valve

NOT SO GOOD

- Buckling of leaflets
- Flow reversal
Normalization

Characteristic elastic time scale:

\[ f_E = \frac{\sqrt{dl}}{\sqrt{E/\rho}} \]

Characteristic volume:

\[ V_c = hw l \left( \frac{d}{w} \right) \]
\[ f^* = f \left( \frac{d_c}{U_c} \right) \]

\[ d_c = \sqrt{dl} \]

\[ U_c = \sqrt{\frac{E_s}{\rho_s}} \]

\[ V^* = \frac{V}{2hlw} \left( \frac{h}{d} \right) \]
\[ f = 20 \text{ pulses/min} \quad V = 45 \text{cm}^3 \]

\[ \left| S \right| = \sqrt{S : S^T} \]

\[ S = \frac{1}{2} \left[ \nabla u + \left( \nabla u \right)^T \right] \]

\[ x/h \]

Leaflet
- La
- Ne
- Si
- Si1
- Si2
- Si3
- Si4
- Si5
Normalized strain rate

Scaling?
\[ S_p^* = \left| \frac{S}{U_{max}} \right| \frac{d_c}{\overline{d}} \left( \frac{h}{d} \right)^{1/2} \left( \frac{K_c \cdot Wi^*}{Re} \right)^{1/4} \]
Conclusions

• Simple experimental setup
• Found a relation for proper valve performance

\[ f^* = f \sqrt{wl} \sqrt{\frac{\rho_s}{E_s}} \quad V^* = \frac{V}{ws/l} \quad f^* \propto \frac{1}{V^*} \]

• Strain rate : flow conditions
• Basis for valve design!
General Conclusions

• Experimental investigation
• Complex flow field past replacement heart valves
• Can determine ‘all’ fluid mechanics characteristics of flow
• Mechanisms for blood trauma
• Propose new set of design parameters
Gracias
Coagulation cascade:

1) Damaged blood vessel wall
2) Exposed subendothelium proteins (collagen)
3) Platelets bind collagen with surface collagen coagulation factors I and II (glycoprotein)
4) Adhesion strengthened further by von Willebrand factor (vWF),
5) Links formed, platelets glycoprotein (Ib/IX/V) and the collagen fibrils. Platelet activation.
• Biol
  • Da=0.018m
  • Umax=1.2512 m/s

• Mec
  • Da=0.017m
  • Umax=0.3262 m/s
Some ideas for hemolysis

Velocity gradients, turbulence

Deformation and eventual breakup

Red Blood Cell
Turbulence or shear?

• Viscous shear stresses

\[ \tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]

• Turbulent shear stresses

\[ \tau_{ij} = \rho \langle u_i' u_j' \rangle \]
Mechanical valve
Ideas for hemolysis

*(borrowed from two-phase flows)*

- Forces keeping the cell together:
  \[ F_E \sim \kappa d \]

- Viscous forces:
  \[ F_\mu \sim \mu | S_{ij} | d^2 \]
  where
  \[ S_{ij} = \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]

- Turbulent forces:
  \[ F_t \sim \rho | \langle u'_i u'_j \rangle | d^2 \]

  cell diameter
  \[ d = 10 \mu m. \]
Dimensionless numbers

\[ Ca^* = \frac{F_\mu}{F_E} = \frac{\mu | S_{ij} | d}{\kappa} \]

\[ We^* = \frac{F_t}{F_E} = \frac{\rho | \langle u'_i u'_j \rangle | d}{\kappa} \]
Bubbles break beyond a certain critical turbulent Weber number.
Droplets in extensional/shear flows

Extensional flow

Simple shear flow

Ha and Leal (2001)

Droplets break beyond a certain critical Capillary number.

Marks (1998)
Elastic forces: measurement of $\kappa$

Dao et.al (2003)
Dao et.al (2003)

Shear modulus = 13.3 µN/m
Preliminary results

\[ Ca^* = \frac{\mu}{\kappa} \left| \frac{S_{ij}}{d} \right| = 10^{-2} \]

\[ We^* = \frac{\rho}{\kappa} \left| \frac{\langle u'_i u'_j \rangle}{d} \right| = 10^1 \]
Some ideas for thrombosis

Velocity gradients, turbulence

Deformation, estimulation and activation

Platelet
Falla por fatiga

Carga cíclica

Probeta (pericardio)

$F = F_0 \sin (\omega t)$

Falla
Numero de ciclos

No

Determinar $E_0$ para inferir $N_0$

Esfuerzo
Celda de carga

Mordazas

Probeta de PB
Ensayo de Fatiga
MECHANICAL VALVE

t/T = 0.2

SPEED
MECHANICAL VALVE
$t/T = 0.3$

SPEED
Streamwise vorticity
Streamwise vorticity

MECHANICAL VALVE

$z = 0 \text{ mm}$

$z = 7.2 \text{ mm}$

$z = 15.6 \text{ mm}$

$z = 24 \text{ mm}$

$z = 32.4 \text{ mm}$

$z = 40.8 \text{ mm}$

$t/T = 0.3$
MECHANICAL VALVE

$\frac{t}{T} = 0.4$

Streamwise vorticity
‘Turbulent’ intensity

• Variance of velocity in each direction
MECHANICAL VALVE
\( t/T = 0.2 \)

\[ \text{\textit{Turbulence}} \]
\[ u'^2 + v'^2 + w'^2 \]
MECHANICAL VALVE
\[ t/T = 0.3 \]

\[ u'^2 + v'^2 + w'^2 \]
MECHANICAL VALVE

$\frac{t}{T} = 0.4$

$z = 0 \text{ mm}$

$z = 7.2 \text{ mm}$

$z = 15.6 \text{ mm}$

$z = 24 \text{ mm}$

$z = 32.4 \text{ mm}$

$z = 40.8 \text{ mm}$

'Turbulence'

$u'^2 + v'^2 + w'^2$
Biological valve (Shear Rate)

\[ \gamma \tau = 0.6 \]

[1]
Mechanical valve (Shear Rate)

Diferencia de presiones

\[ \gamma \tau = 0.6 \]

[1]
Hemodynamics