Pressure drop, mass transfer, haemolysis: a difficult relationship

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Oxygenator pressure drop

- Diameter 3/8 inch (9.65 cm)
- L = 38.7 m
- Diameter 2 mm
- L = 7.5 cm

\[ \text{P} = 300 \text{ mmHg} \]
\[ \text{Q}_b = 5000 \text{ mL/min} \]

\[ \text{\(\frac{\text{erg/cm}^3\text{/min}}{7.2 \times 10^5} \approx 1.6 \times 10^7\)} \text{ erg/cm}^3\text{/min} \]
RBC hemolysis

<table>
<thead>
<tr>
<th>Pressure (mmHg)</th>
<th>Test sample Paired control</th>
<th>Test sample Paired control</th>
</tr>
</thead>
<tbody>
<tr>
<td>-710</td>
<td>3.6</td>
<td>2.3</td>
</tr>
<tr>
<td>-680</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>-650</td>
<td>4</td>
<td>2.6</td>
</tr>
<tr>
<td>-600</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>-100</td>
<td>8</td>
<td>7.3</td>
</tr>
<tr>
<td>350</td>
<td>3.7</td>
<td>2.8</td>
</tr>
<tr>
<td>1000</td>
<td>4.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Absolute plasma free Hb values (mg/dL)

Blood-air interface

Blood-mineral oil interface

Shear stress

1. Laminar Flow Model

2. Force Balance

\[
(\Delta P) \pi r^2 = (\tau_w)(2 \pi r)(L)
\]

\[
\tau_w = \frac{(\Delta P)(r)}{2(L)}
\]

Shear example
Shear stress and platelets
Serotonin release

- 141 cm$^{-1}$
- 81 cm$^{-1}$
- 57 cm$^{-1}$
- T: 5 min

Shear stress (dynes/cm$^2$)

Serotonin Release (%)

Shear related cellular activation

- $\tau > 75$ dyne/cm$^2$
  - Leukocyte activation
- $\tau > 100$ dyne/cm$^2$
  - Platelet activation
- $\tau > 2000$ dyne/cm$^2$
  - Rupture of the erythrocyte membrane

Shear stress oxygenator

- Complex geometry
- Open area for flow: hydraulic radius
  \[ R_h = \frac{V}{A} \]
- Pressure drop = $\Delta P$ membrane + $\Delta P$ HE
Current Technology: Cross Flow Fiber Bundles

Frontal area, \( A_f \)

Hollow fibers of diameter \( d \)

Blood Flow

Fiber bundle with void fraction \( V_f \)

Blood flow path length, \( L \)

Aspect Ratio, \( A_R = \frac{A_f}{L} \)

Cobe Optima XP

Medtronic Affinity

Heat exchanger offers excellent performance with easy prime.
Threshold for shear-induced hemolysis

Threshold for shear-induced platelet release of 5-HT, ADP, ATP, and β-TG

Threshold for shear-induced trauma
Relationship shear stress - time

![Graph showing relationship between shear stress and time]

- Threshold for shear induced trauma
- Minimum recommended for material-induced trauma
- "Safe" zone

Oxygenator pressure drop

![Graph showing oxygenator pressure drop]

- Segers 2001

Funakubo 2003

- Maxima PRF
- Forte
- Affinity
- Quantum
- Optima
- Capiox 1.8
- Quadrox
- Hilite
“The high pressure gradients in some of the devices did not result in more haemolysis.”

<table>
<thead>
<tr>
<th>Device</th>
<th>Plasma free Hb [mg/dL]</th>
<th>CPB time [minutes]</th>
<th>Ao clamp [minutes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hilite</td>
<td>1.6 ± 1.88</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Capiox 1.8</td>
<td>1.3 ± 1.37</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Quadrox</td>
<td>3.5 ± 1.86</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Optima</td>
<td>8.4 ± 3.366</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Capiox 1.8</td>
<td>4.0 ± 2.567</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Quantum</td>
<td>1.3 ± 0.775</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Affinity</td>
<td>5.3 ± 4.562</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Affinity NT</td>
<td>4.6 ± 3.565</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Forté</td>
<td>3.0 ± 1.684</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Maxima</td>
<td>8.4 ± 3.366</td>
<td>15 ± 13</td>
<td>5 ± 2</td>
</tr>
</tbody>
</table>

Pulsatile flow, ΔP, shear stress

- **Quadrox vs Capiox 1.8**
- **Low vs high ΔP**
- **Average pulsatile blood flow 5 L/min**
  - Peak flow: approx. 10 L/min
  - Base flow: 28% (1.4 L/min)
  - Frequency 72 beats/min
### Hemolysis

<table>
<thead>
<tr>
<th></th>
<th>Low ΔP Oxygenator</th>
<th>High ΔP Oxygenator</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIH (g/100 L)</td>
<td>0.088 ± 0.074</td>
<td>0.104 ± 0.089</td>
<td>0.4</td>
</tr>
<tr>
<td>Systolic inlet pressure (mmHg)</td>
<td>619 ± 28</td>
<td>827 ± 53</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Systolic pulse pressure (mmHg)</td>
<td>648 ± 25</td>
<td>838 ± 38</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>
Cannula

- DLP ref 71424
  - Length: 25 cm (tapered)
  - Diameter: 24 Fr, 7.9 mm
  - ΔP 4 L/min: 46 mmHg
  - ΔP 6 L/min: 105 mmHg
  - Shear stress 4 L/min: 485 dyne/cm²
  - Shear stress 6 L/min: 1109 dyne/cm²
Window of a given oxygenator

Flow vs Tau & Reynolds

Blood flow [LPF]

Reynolds number

Reed-Thurston presented in Dubai 2011

Mechanical Problems with Oxygenators - Neonates and Pediatric Patients

<table>
<thead>
<tr>
<th>Oxygenator</th>
<th>Pressure</th>
<th>Flow</th>
<th>Oxygen saturation</th>
<th>Shear stress</th>
<th>Shear stress [dyne/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avant</td>
<td>Low</td>
<td>10</td>
<td>98%</td>
<td>Low</td>
<td>5 dyne/cm²</td>
</tr>
<tr>
<td>Monolyth</td>
<td>Medium</td>
<td>20</td>
<td>95%</td>
<td>High</td>
<td>10 dyne/cm²</td>
</tr>
<tr>
<td>Nre Avant</td>
<td>Medium</td>
<td>25</td>
<td>96%</td>
<td>Medium</td>
<td>8 dyne/cm²</td>
</tr>
<tr>
<td>Nre Monolyth</td>
<td>Medium</td>
<td>30</td>
<td>92%</td>
<td>Medium</td>
<td>6 dyne/cm²</td>
</tr>
<tr>
<td>Total [LPF]</td>
<td>Medium</td>
<td>35</td>
<td>94%</td>
<td>Medium</td>
<td>7 dyne/cm²</td>
</tr>
</tbody>
</table>

O₂ transfer and shear stress

R = 0.61

Segers 2001
O₂ transfer and shear stress

- Avant
- Apex
- Eos
- Primo2x
- Monolyth
- Optima XP

R = 0.88

O₂ transfer and shear stress

R = 0.95

DARCY’S LAW

\[ \frac{\Delta p}{L} = k \frac{U}{\mu} \]

Superficial Velocity \( U_s \) = \( \frac{Q}{A_i} \) [m/s]

Porosity \( \epsilon = \frac{V_{void}}{V_{total}} \) [ ]

Frontal Area \( A_i = L \times (D_o - D_i) \) [m²]

Flow Rate \( Q \) [m³/s]
Stroomverdeling experimenteel

vector plot of velocity current 5.0d

Re

N
Sh

·N
Sc

-1/3

M

·N
Re

m'

N
Sh

·N
Sc

-1/3

= M

·N
Re

Sarns Turbo 440
Cobe Optima
Dideco Compactflo

"Ideal" oxygenator

Mass transfer O₂, CO₂, heat
Surface area Blood interaction
Shear stress Hemolytica (RBC, WBC, PLTs)
Conclusions

DP is not an independent variable of hemolysis

Shear causes hemolysis
- Time
- Absolute value
- CAVE: local shear