Pressure drop, mass transfer, haemolysis: a difficult relationship

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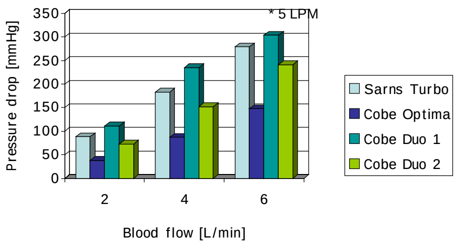
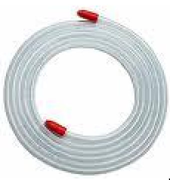
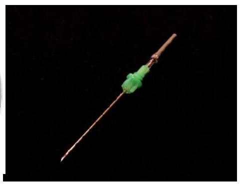
Oxygenator pressure drop







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

$\Rightarrow$ 7.2 10^5 erg/cm^3/min

$\Rightarrow$ 1.6 10^7 erg/cm^3/min

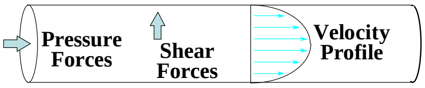
RBC hemolysis

Absolute plasma free Hb values [mg/dL]				
	Blood-mineral oil interface		Blood-air interface	
Pressure [mmHg]	Test sample	Paired control	Test sample	Paired control
-710	3.6	2.3	110	15
-680	10	7	58	21
-550	4	2.6	43	25
-300	12	10	23	11
-100	8	7.3	39	24
350	3.7	2.8	17	11
1000	4.1	2.4	18	16

Chambers 1996

Shear stress

1. **Laminar Flow Model**

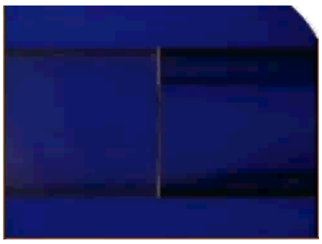


2. **Force Balance**

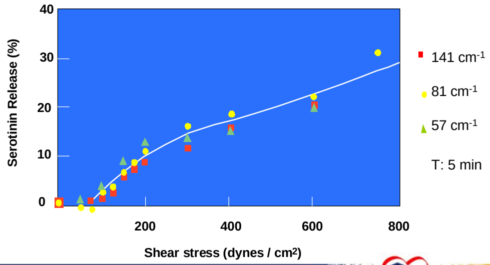
$$(\Delta P)(\pi r^2) = (\tau_w)(2\pi r)(L)$$

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

Shear example



Shear stress and platelets Serotonin release



Hellums 1994

Shear related cellular activation

τ > 75 dyne/cm²

Leukocyte activation

τ > 100 dyne/cm²

Platelet activation

τ > 2000 dyne/cm²

Rupture of the erythrocyte membrane

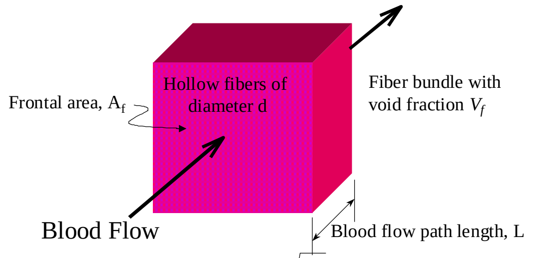
Shear stress oxygenator

- Complex geometry
- Open area for flow: hydraulic radius

$$R_h = \frac{V_e \cdot \varepsilon}{A_s}$$

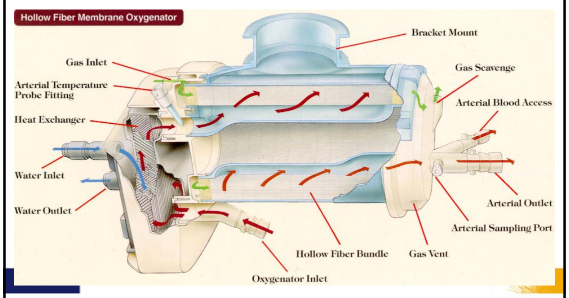
- Pressure drop = ΔP membrane + ΔP HE

Current Technology: Cross Flow Fiber Bundles

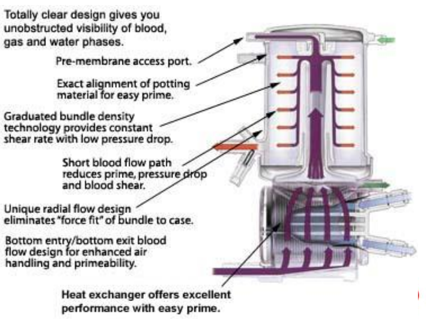


Aspect Ratio, A_R, = $\sqrt{A_f} / L$

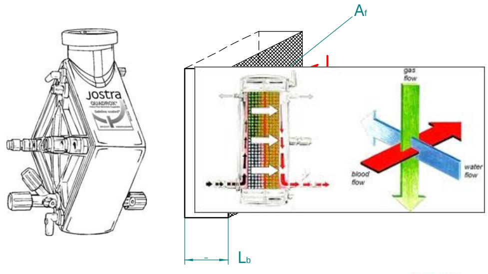
Cobe Optima XP



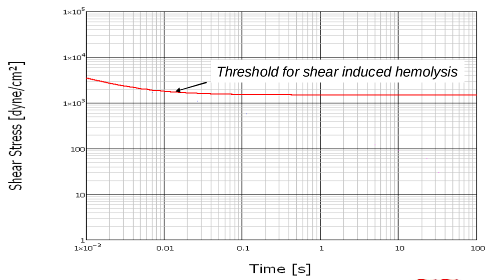
Medtronic Affinity



Quadrox

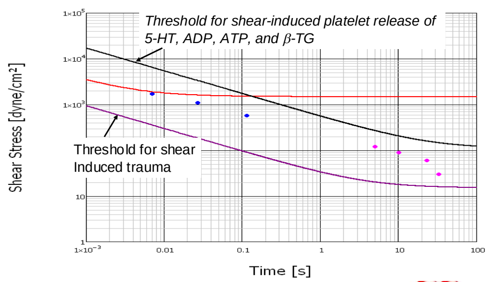


Relationship shear stress - time



Mockros 2001

Relationship shear stress - time



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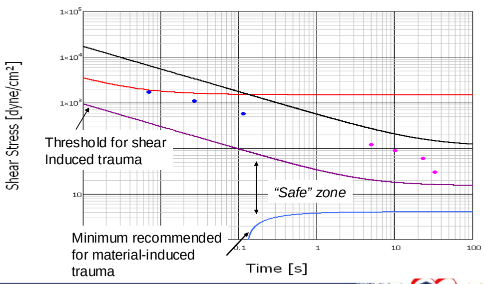
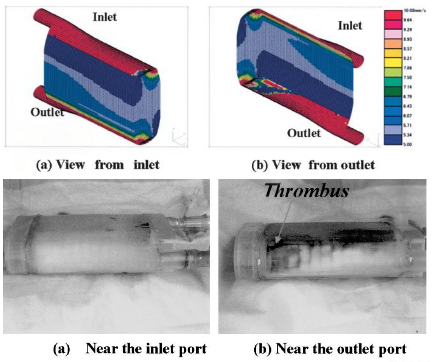
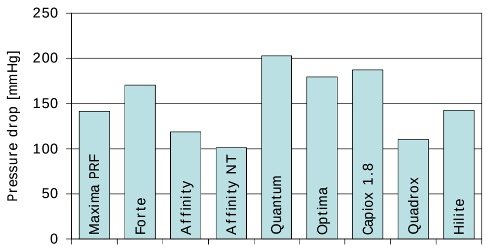




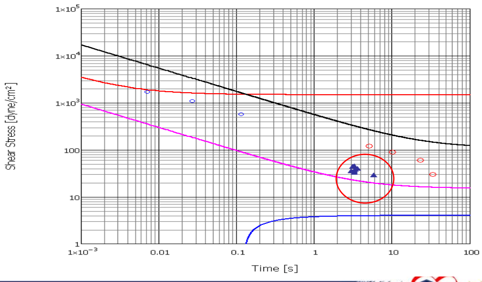
Funakubo 2003

Oxygenator pressure drop



Segers 2001

Relationship shear stress - time



"The high pressure gradients in some of the devices did not result in more haemolysis."

	Ao clamp [minutes]	CPB time [minutes]	Plasma free Hb [mg/dL]
Maxima	50 ± 24	84 ± 37	3.0 ± 1.6
Forté	40 ± 18	65 ± 21	4.6 ± 3.5
Affinity	43 ± 5	62 ± 8	5.3 ± 4.5
Affinity NT	49 ± 14	75 ± 23	1.3 ± 0.7
Quantum	38 ± 11	67 ± 16	4.0 ± 2.5
Capiox 1.8	39 ± 7	66 ± 15	8.4 ± 3.3
Optima	40 ± 9	66 ± 18	3.5 ± 1.8
Quadrox	44 ± 22	79 ± 59	1.3 ± 1.3
Hilite	53 ± 14	82 ± 15	1.6 ± 1.8

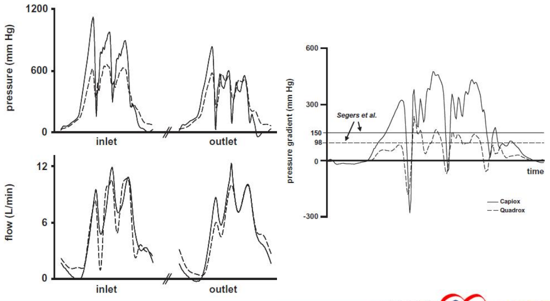
Segers 2001

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

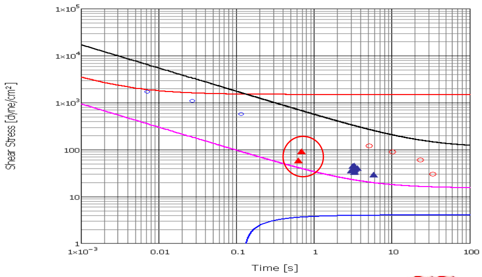
Simons 2010

Relationship shear stress - time



Simons 2010

Relationship shear stress - time

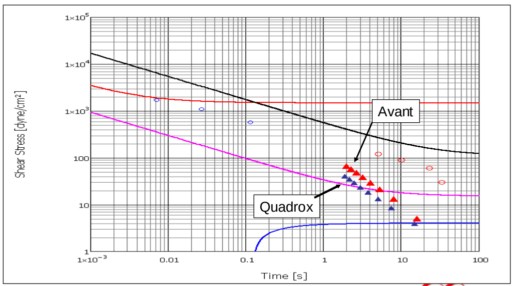


Hemolysis

	Low ΔP oxygenator	High ΔP Oxygenator	P
NIH [g/100 L]	0.088 ± 0.074	0.104 ± 0.088	0.4
Systolic inlet pressure [mmHg]	619 ± 28	827 ± 53	< 0.001
Systolic pulse pressure [mmHg]	648 ± 25	838 ± 38	< 0.001

Simons 2010

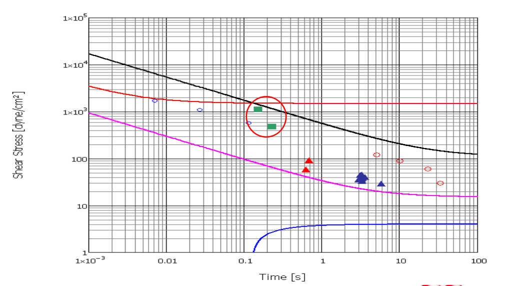
“Optimal window”



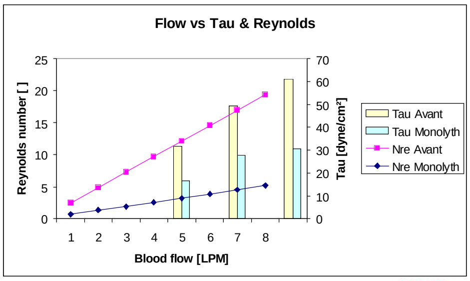
Cannula

- 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

Cannula



Window of a given oxygenator



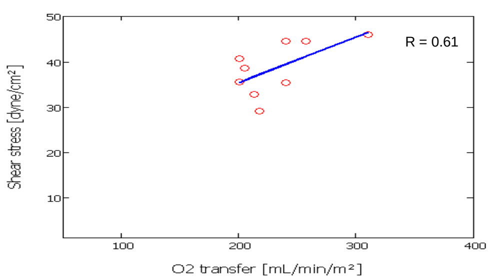
Mechanical Problems with Oxygenators* - Neonates and Pediatric Patients

Oxygenator	Frequent clots	Excess air accumulation	Oxygenator failure in 5 days	Severe coagulopathy	Other	*Total % of all devices*
Neonates						
Medtronic/Sci Med	13	0	6	0	1	*48.8%*
Quadrox iD	3	1	2	0	1	*17.1%*
Quadrox D	6	1	1	1	0	*22 %*
Hilite 800 LT	0	0	0	0	0	*0%*
Minimax	1	0	4	0	0	*12.25*
Baby Rx	0	0	0	0	0	*0%*
Total of complications	*56.1%*	4.9%	31.7%	2.4%	4.9%	
Pediatric pts.						
Medtronic/Sci Med	7	0	3	1	0	*40.7%*
Quadrox iD	2	0	2	0	0	*14.85*
Quadrox D	7	1	1	1	1	*40.7%*
Hilite 800 LT	0	0	0	0	0	*0%*
Minimax	0	0	1	0	0	*3.7%*
Baby Rx	0	0	0	0	0	*0%*
Total of complications	*59.3%*	3.7%	25.9%	7.4%	3.7%	

**Oxygenator type listed in Table 2*

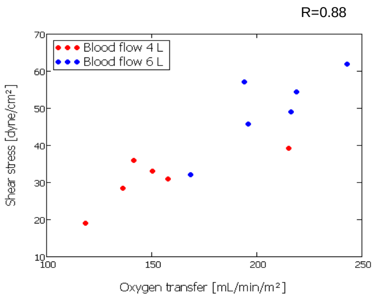
Reed-Thurston presented in Dubai 2011

O_2 transfer and shear stress



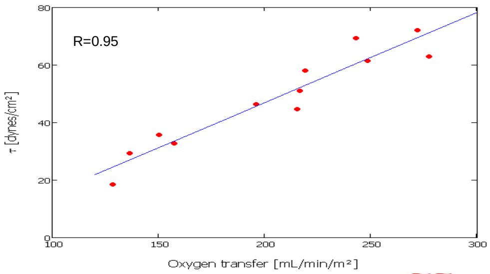
Segers 2001

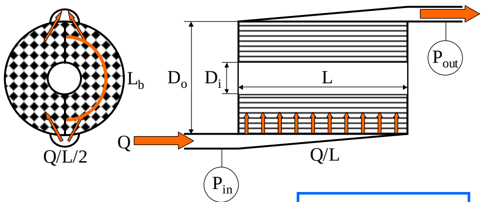
O_2 transfer and shear stress



Avant
Apex
Eos
Primo2x
Monolyth
Optima XP

O_2 transfer and shear stress





POROUS MEDIUM

Porosity $\varepsilon = \frac{V_{voids}}{V_{bed}}\,[\;]$

Frontal Area $A_f = L \cdot (D_o - D_i)\,[m^2]$

Flow Rate $Q\left[\frac{m^3}{s}\right]$

Pressure Drop $\Delta p = p_{in} - p_{out}\,[Pa]$

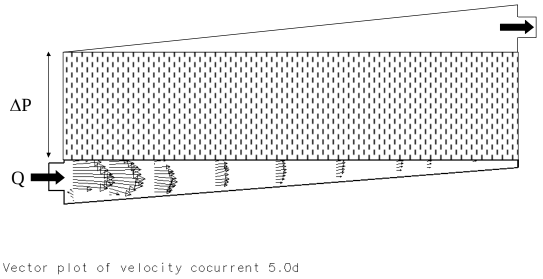
DARCY'S LAW

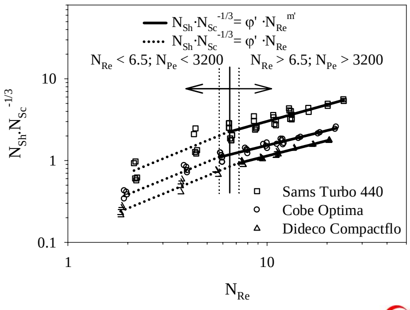
$\bar{u} = -\frac{k}{\mu}\bar{\nabla}p \Rightarrow U_s = \frac{k}{\mu}\cdot\frac{\Delta p}{L}$

Superficial Velocity $U_s = \frac{Q}{A_f}\left[\frac{m}{s}\right]$

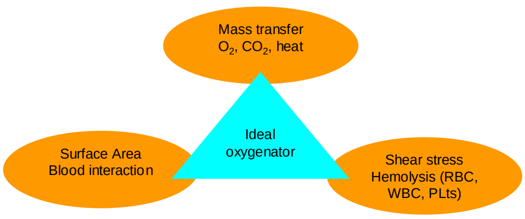
Permeability $k = k(\varepsilon)\,[m^2]$

STROOMVERDELING
experimenteel





“Ideal” oxygenator



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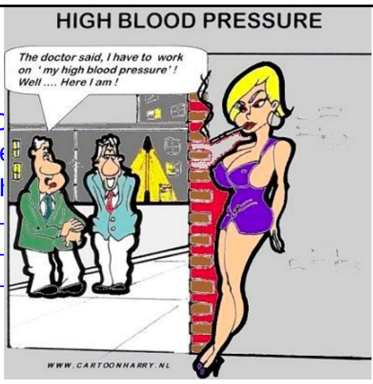
HIGH BLOOD PRESSURE
The doctor said, I have to work on 'my high blood pressure'! Well .... Here I am!
WWW.CARTOONHARRY.NL