Artificial Kidney and Hemodialysis

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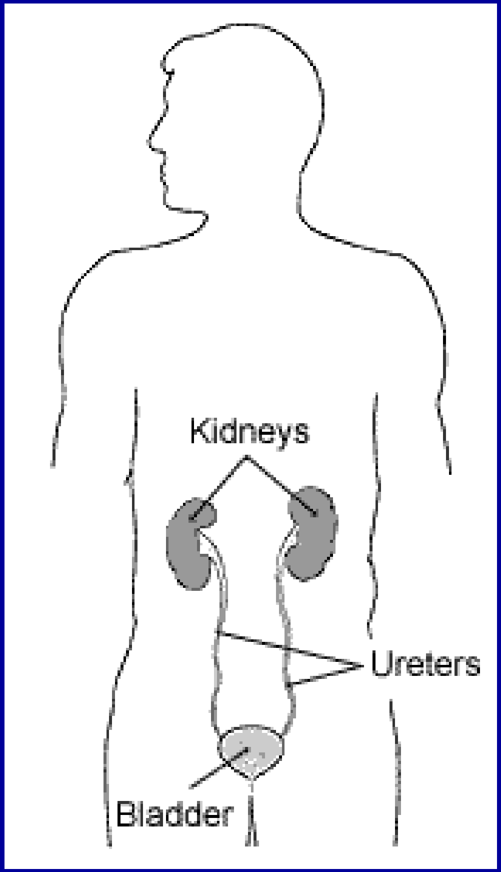
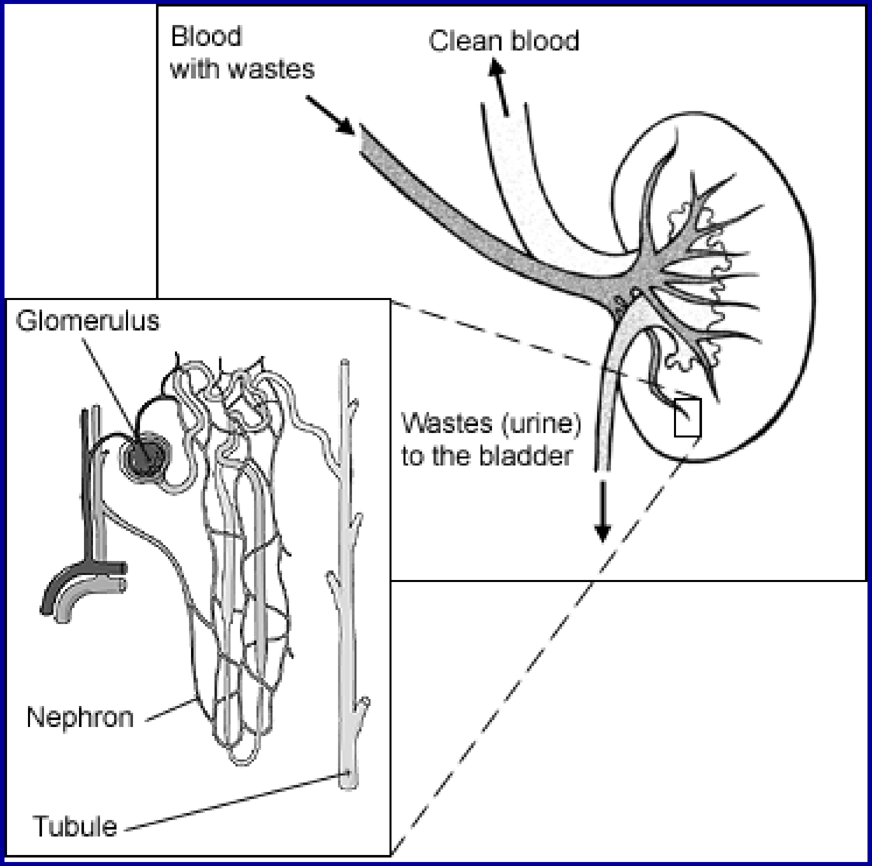
Outline

- Introduction
- Experimental Approach
- Theoretical Approach
- Future Research and Collaborations

Introduction

- Kidney disease is a major problem, affecting about 5% of the population in the United States
- Accounts for about 60,000 deaths per year
- ~ 500,000 Americans are sustained on artificial kidney
- Cost: $23 billion per year





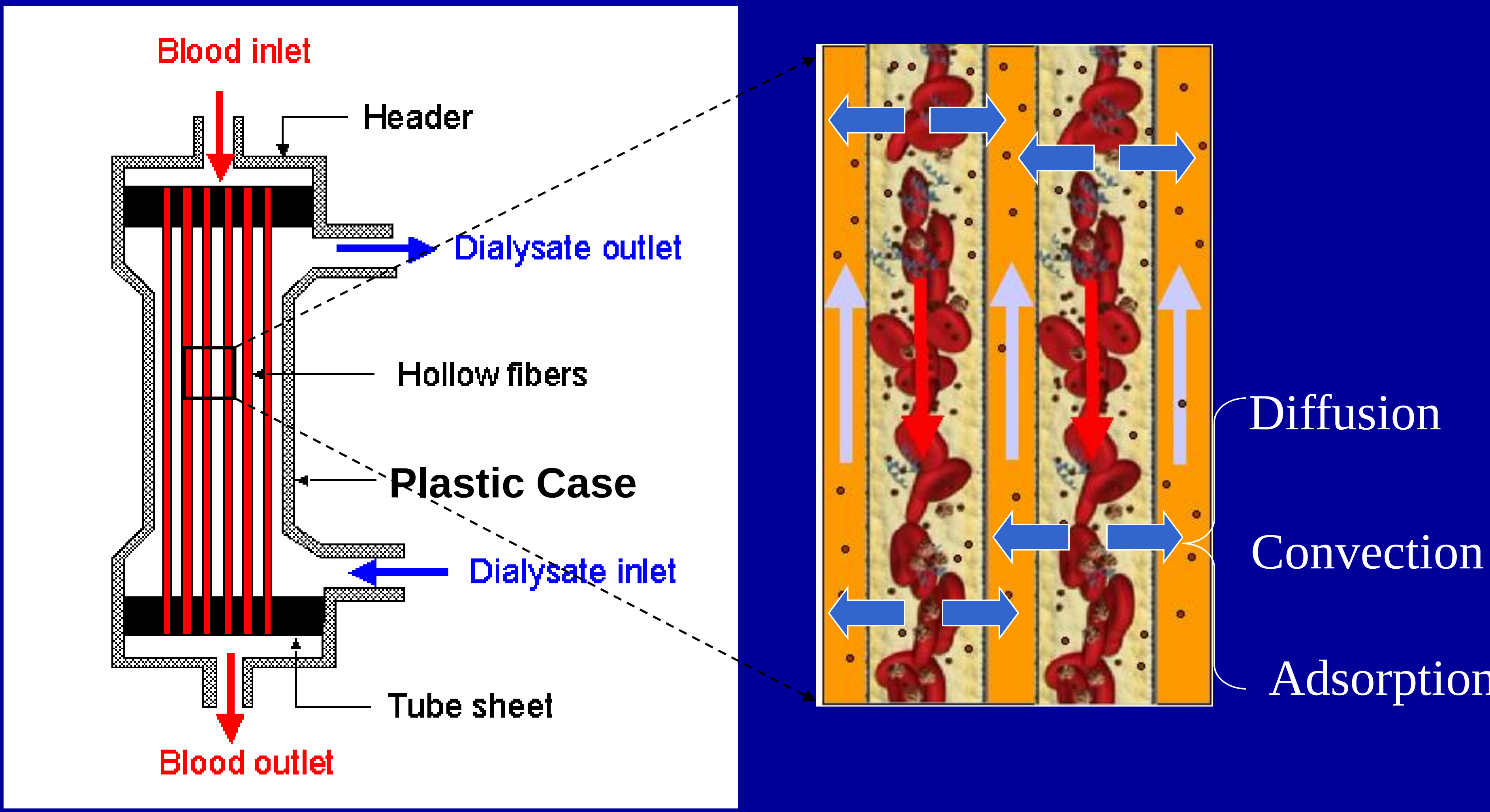
Human Kidneys

Function:

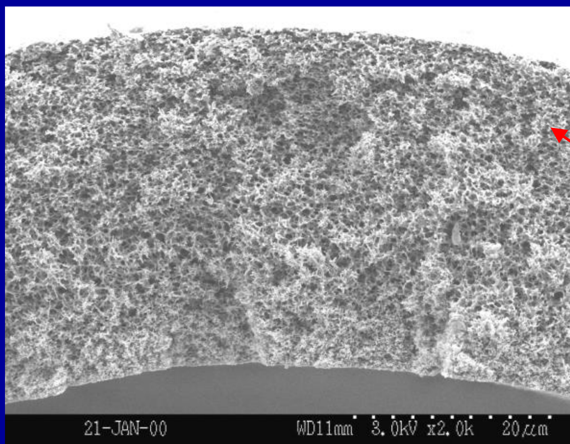
- Remove waste products
- Secrete hormone
- re-absorb useful solutes

Hemodialysis Process

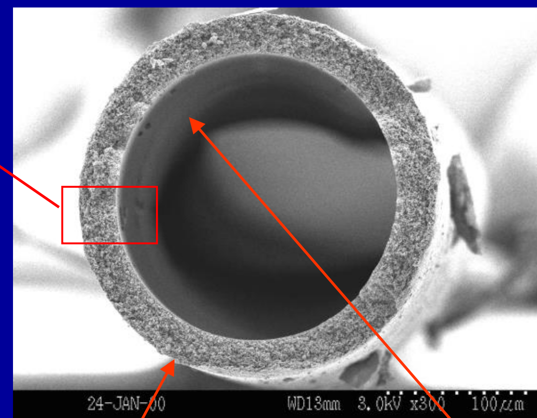
Artificial Kidney

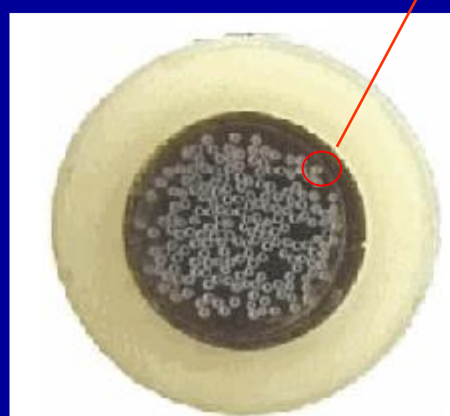


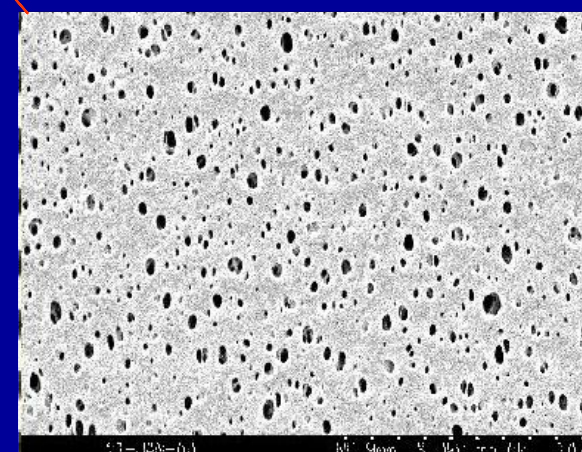
Inner diameter: ~ 200 µm
Membrane thickness: ~ 20 µm
Material: Cellulose Triacetate, Polysulfone, Polyamide, Polyethersulfone



Membrane cross-section







Membrane surface
Pore size: ~ 5 nm

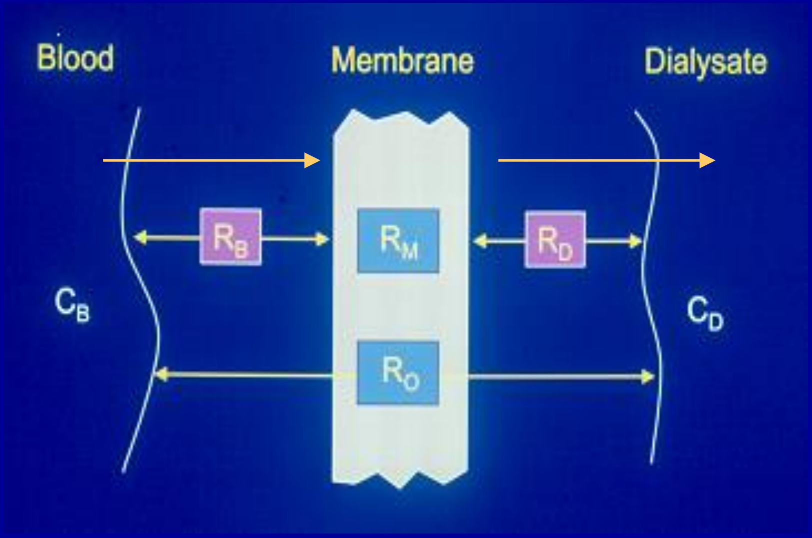
Performance Evaluation

$$J = k_o A \, (C_B - C_D)$$

[moles/min = cm/min * cm^2 * moles/cm^3]

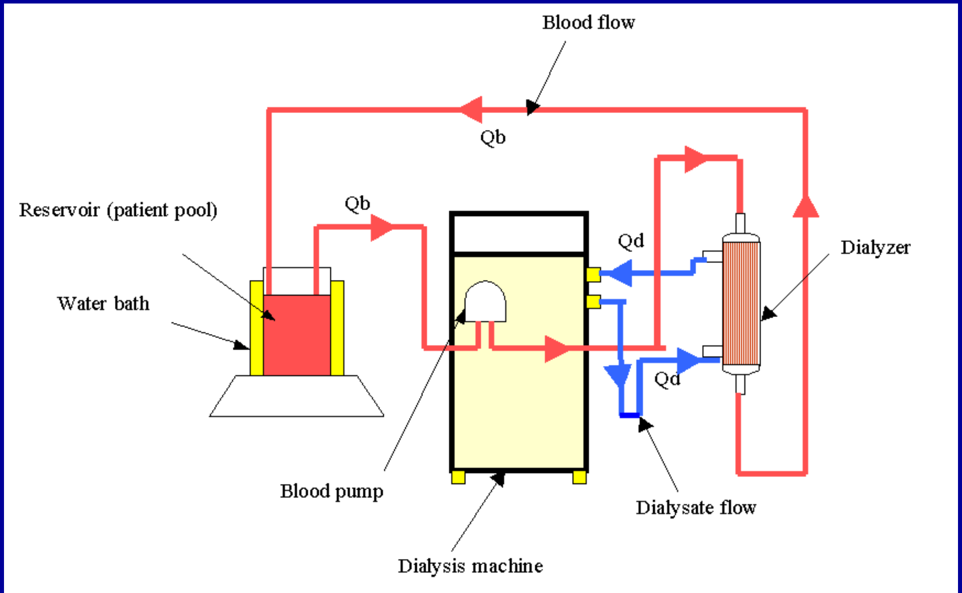
$$1/k_o = 1/k_B + 1/k_M + 1/k_D$$

or $$R_o = R_B + R_M + R_D$$



- Experimental Approach

In Vitro Dialysis Experiment Setup



1. Solute clearance:

The volume of solution cleared of a particular solute in a given time

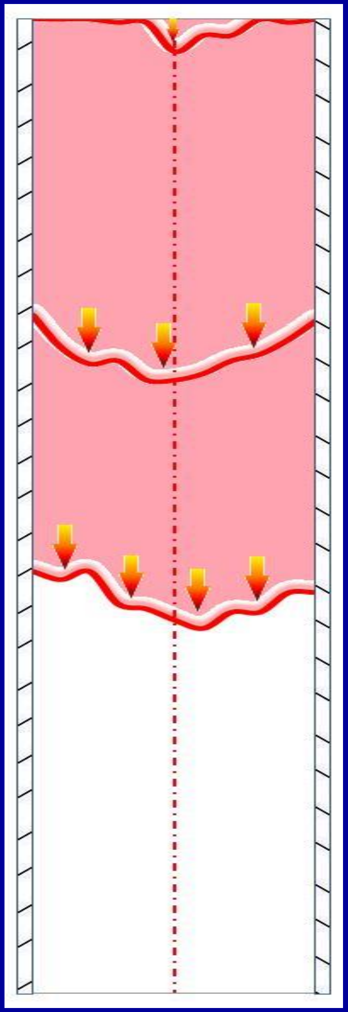
$$Cl = \frac{(Q_{bi}C_{bi} - Q_{bo}C_{bo})}{C_{bi}}$$

2. Sieving coefficient:

How easily the solute can pass through the membrane by solvent drag

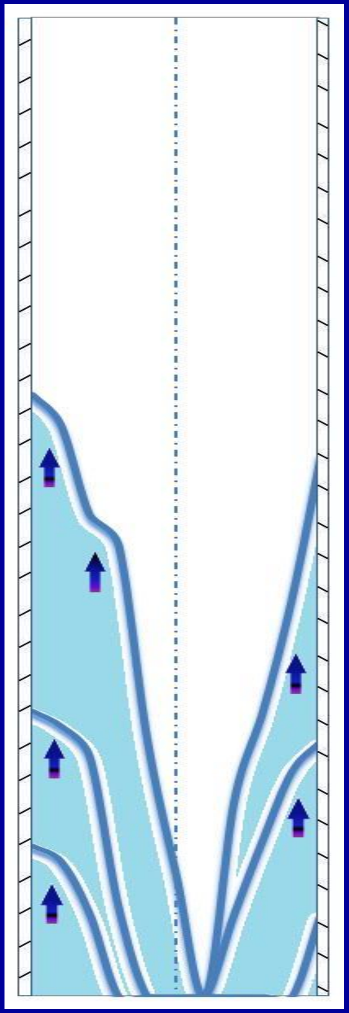
$$SC = \frac{2C_{uf}}{C_{Bi} + C_{Bo}}$$

Blood side



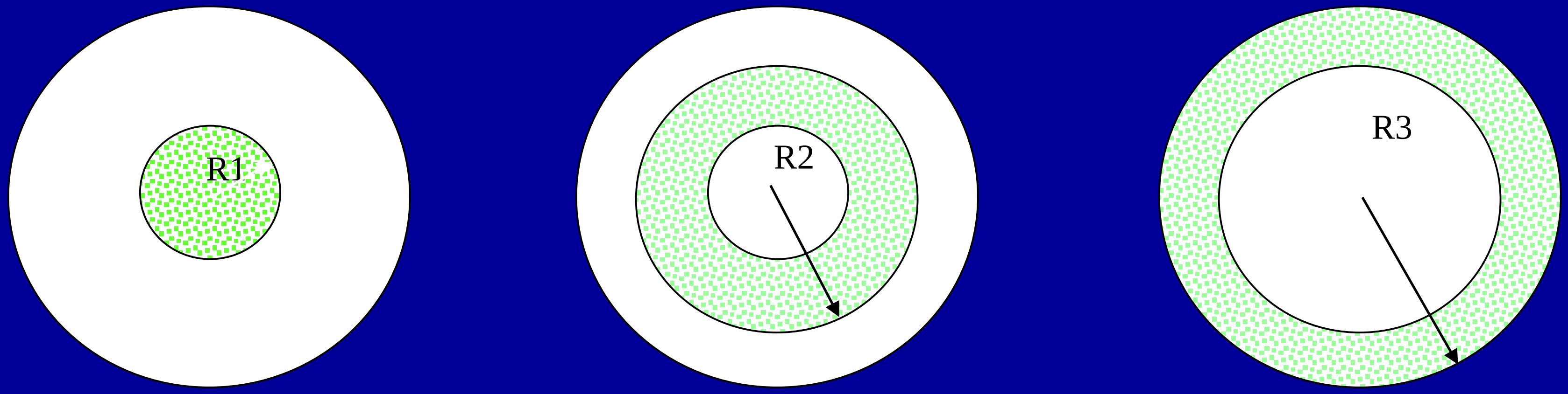
Revaclear Max

Dialysate side



Revaclear Max

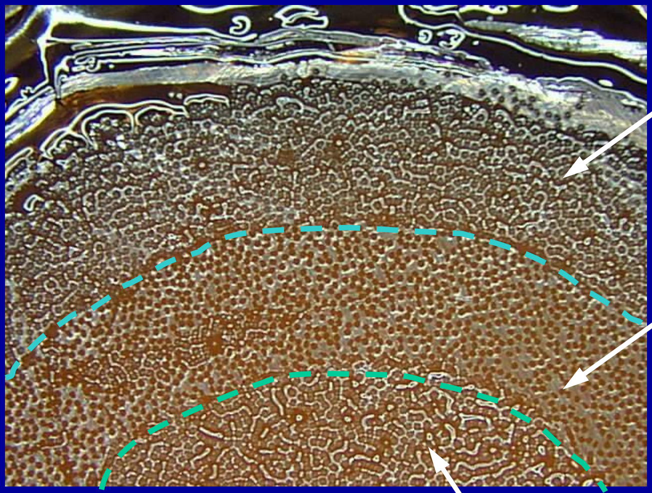
Evaluation of Local Clearance for Dialyzers



Inner Ring
(Dialyzer 1)

Middle Ring
(Dialyzer 2)

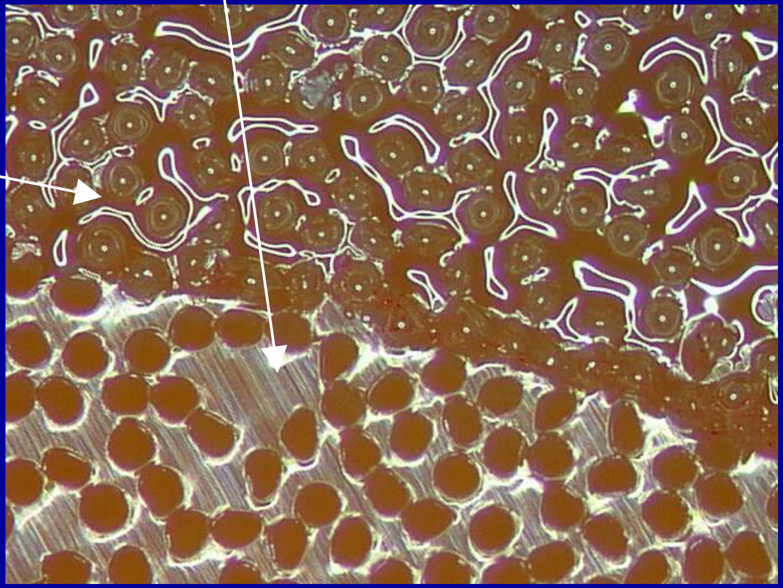
Outer Ring
(Dialyzer 3)



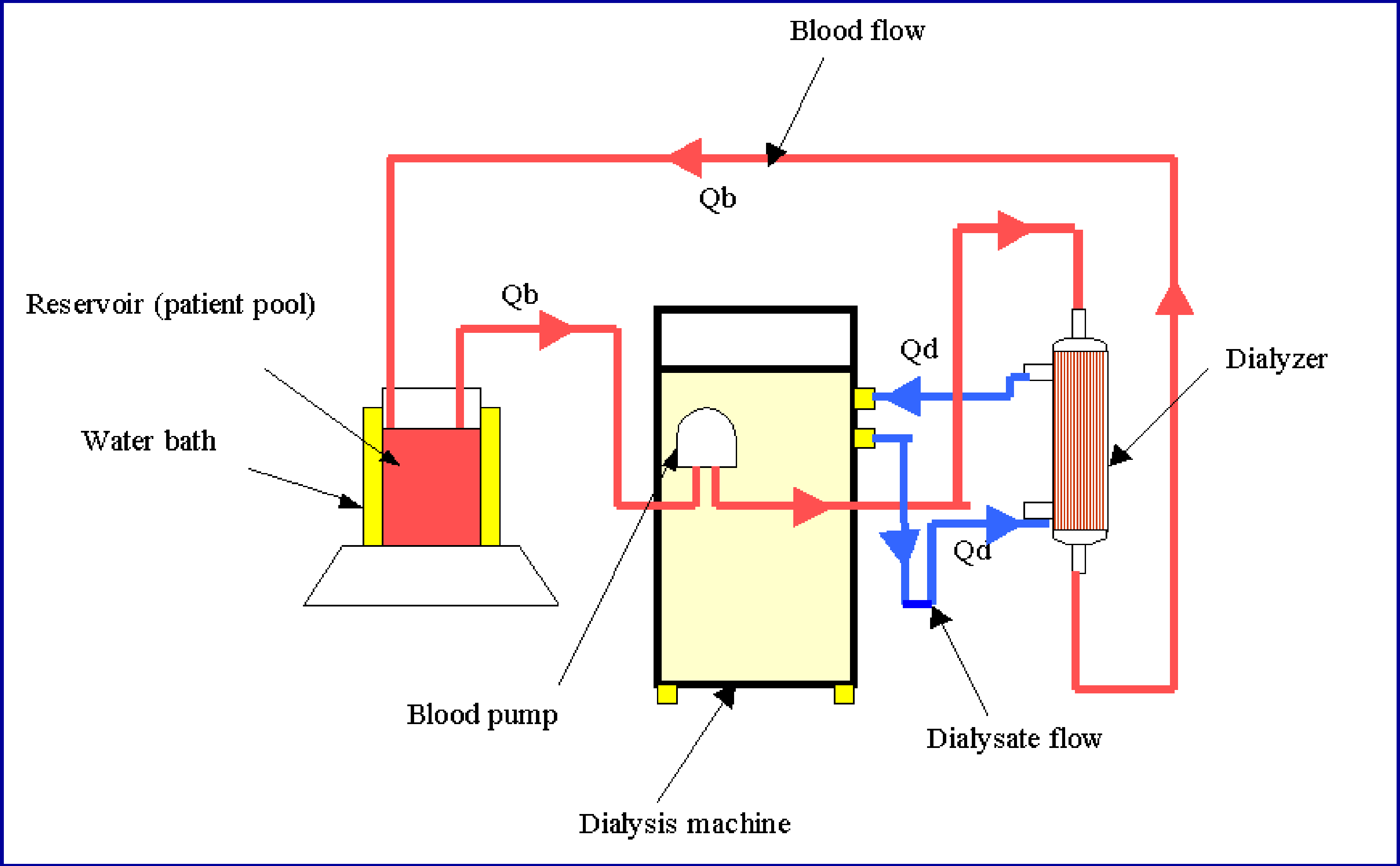
Blocked Ring Region

Unblocked Ring Region

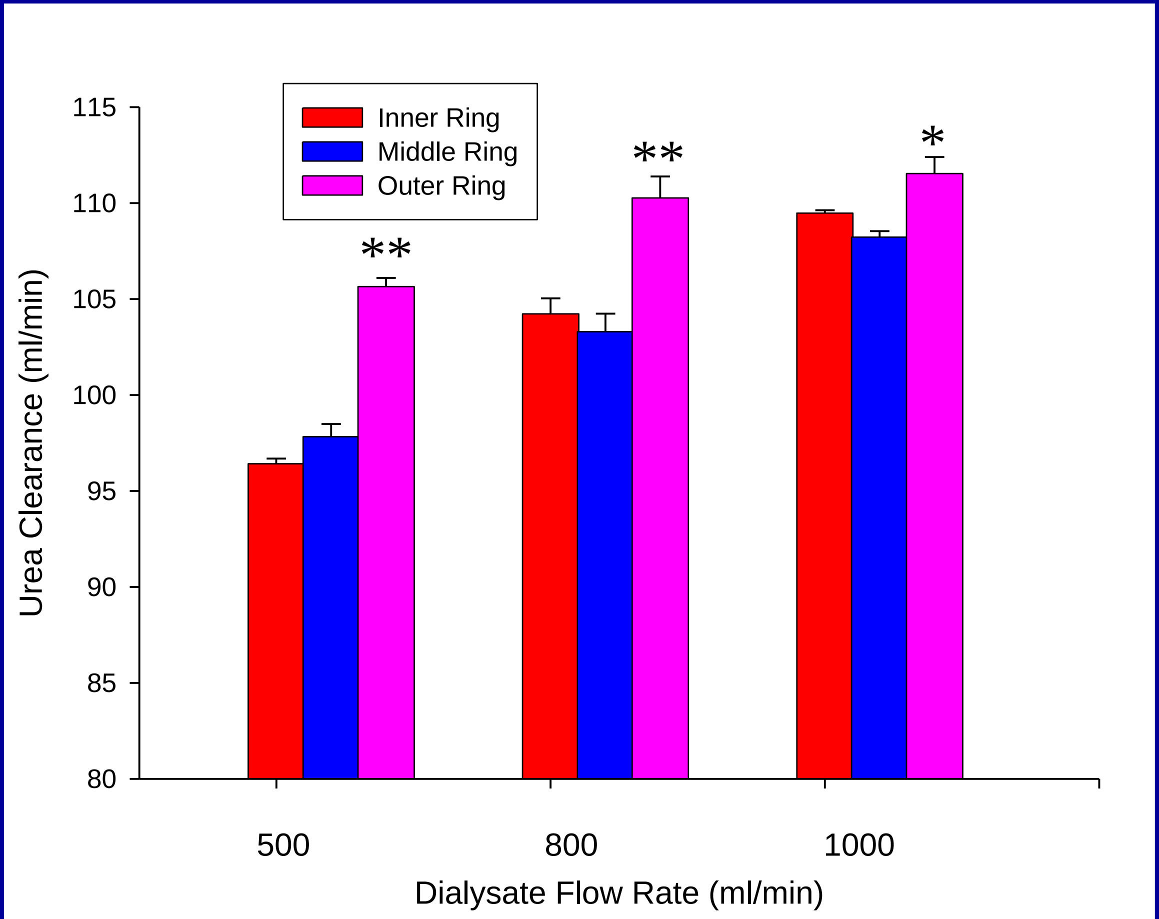
Blocked Ring Region



Experiment Setup



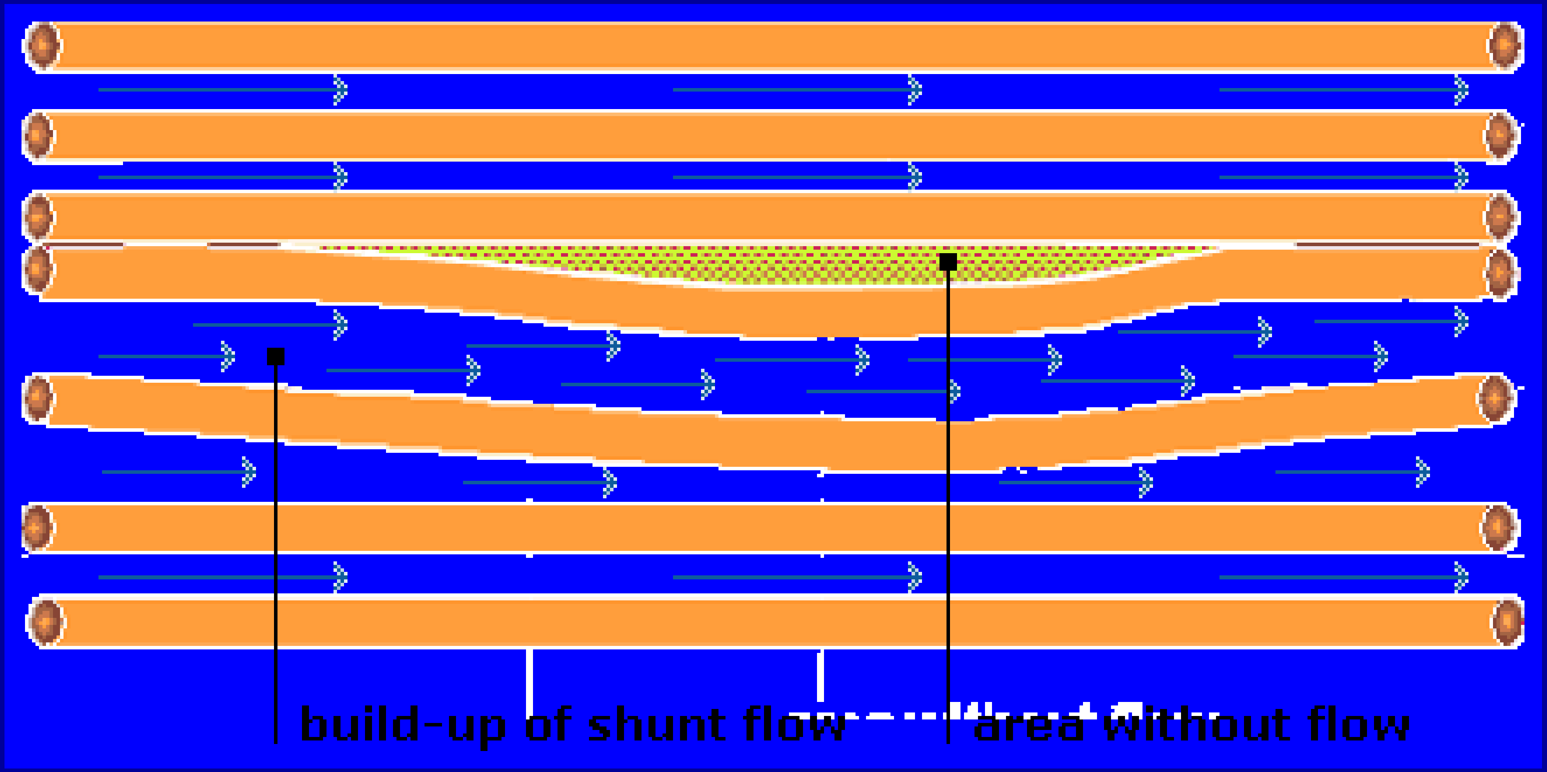
Urea Clearance at Different Annular Ring in CT 190 G



*: P< 0.05 vs. inner ring * *: P< 0.01 vs. inner ring

DISCUSSION

Possible cause of spike-like velocity distribution across the whole cross section, and flow redistribution along the length of the dialyzer in the dialysate compartment …



DISCUSSION

Spacer yarns improved dialysate-side flow distribution …

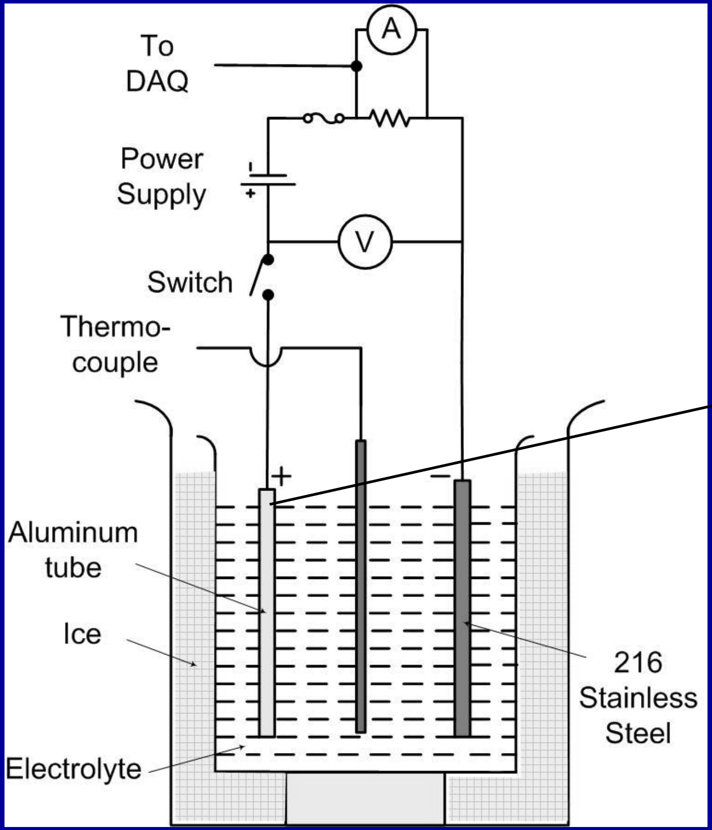
- Keep individual hollow fibers apart
- Stabilize the entire hollow-fiber bundle within the dialyzer housing

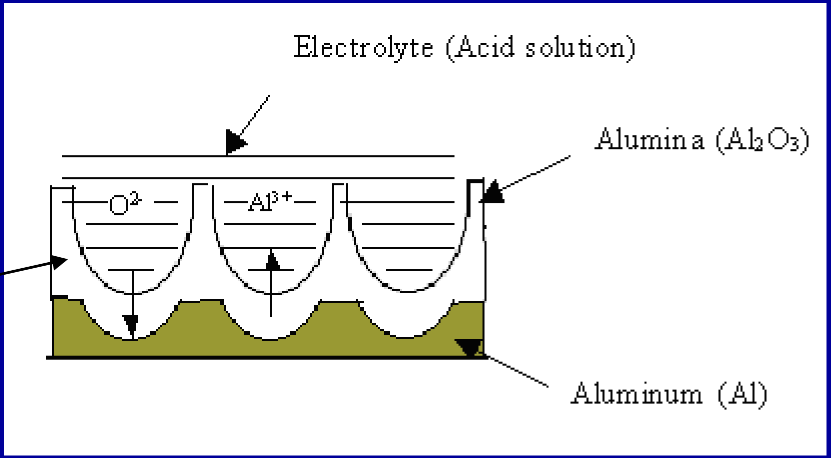
- New membranes development

Current Problems in HD

- Low performance (low middle molecular solutes clearance)
- Albumin loss (cellulose, polymer membrane)
- Potential pyrogen back transfer into blood side
- Low reusability

Aluminum Anodization



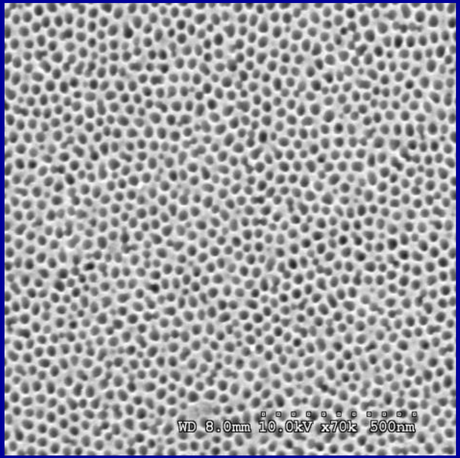


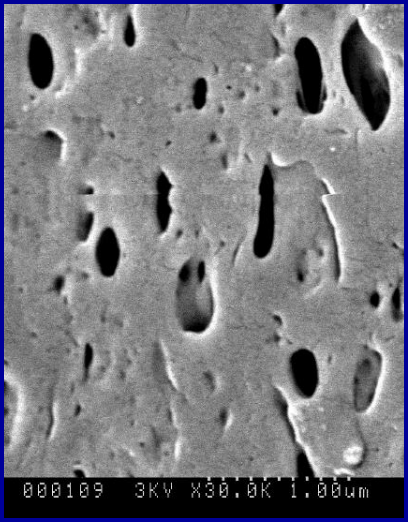
$$4Al + 3O_2 \Leftrightarrow 2Al_2O_3 \quad \text{(Anode)}$$

$$2H^+ + 2e \Leftrightarrow H_2 \quad \text{(Cathode)}$$

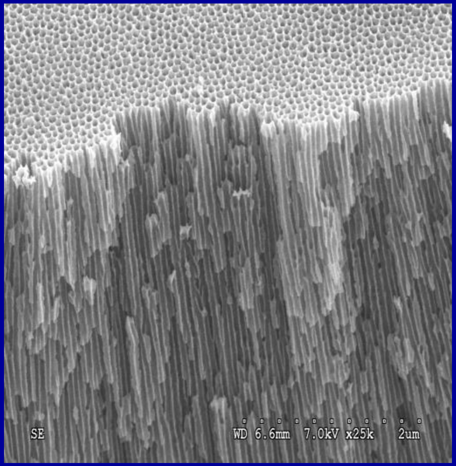
Comparison of Ceramic Membrane and Synthetic Membrane

Surface





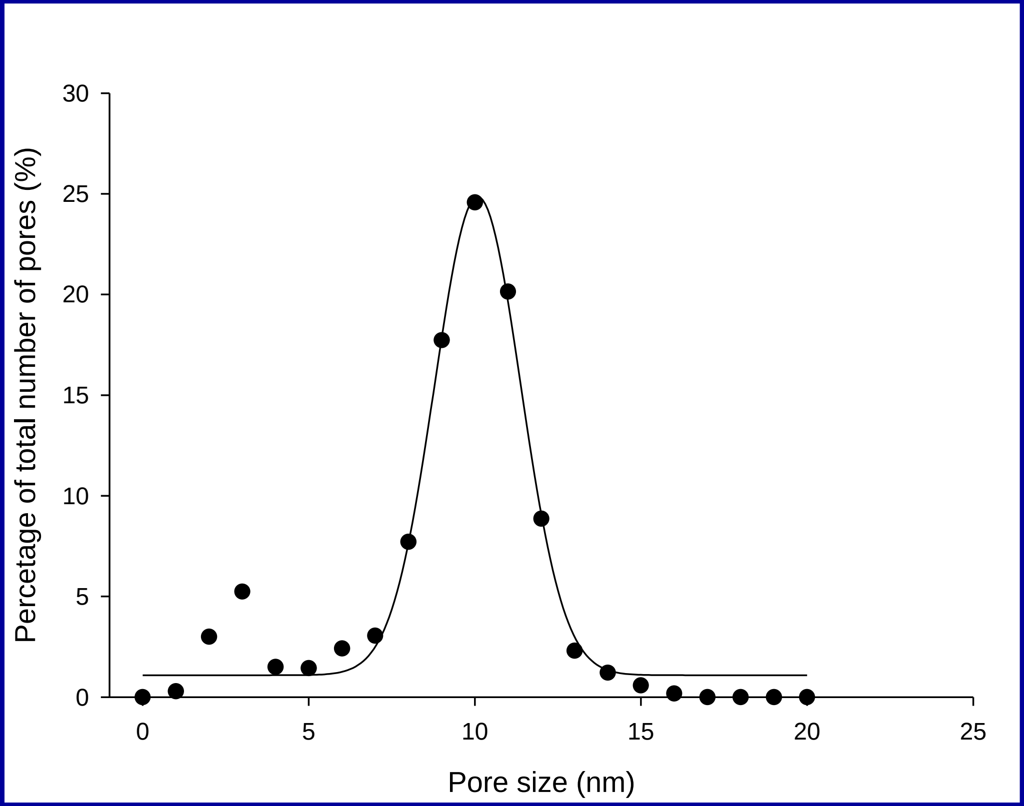
Cross section



Ceramic Membrane

Polysulfone Membrane

Pore Size Distribution and Hydraulic Permeability (Ceramic Membrane)



- **39.1x10^{-15}** $m^2 \cdot s^{-1} \cdot Pa^{-1}$

(ceramic membrane at 3% sulfuric acid)

- **15.1×10^{-15}** $m^2 \cdot s^{-1} \cdot Pa^{-1}$

(Syntra 160 membrane)

Mini Module Dialyzer

Nano-porous alumina tube

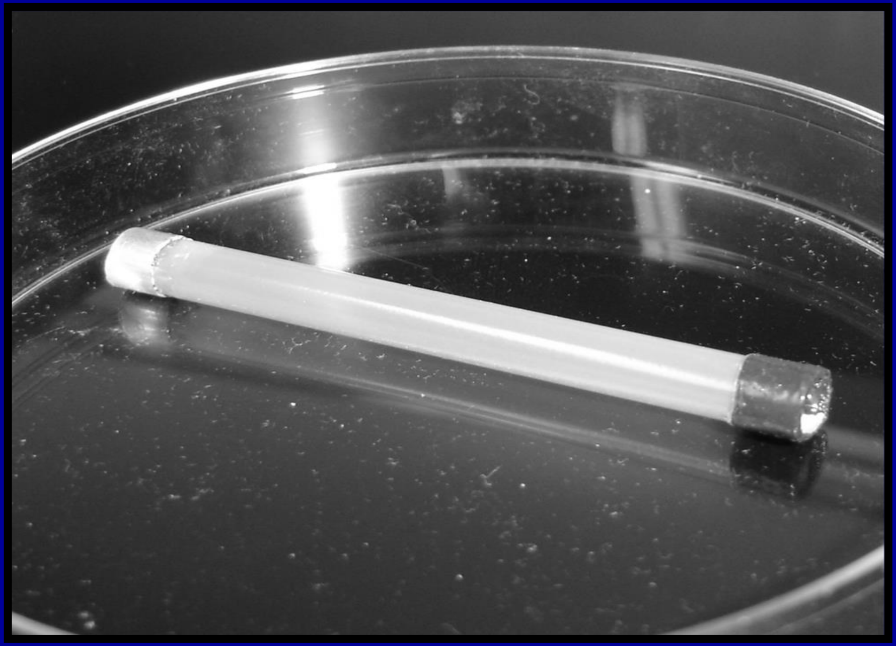


Table 1: Solute clearance for the alumina membrane

Solute	Clearance mL/min	Reduction ratio/hour
Urea	9.03 ± 0.15	0.36 ± 0.01
Creatinine	8.96 ± 0.15	0.36 ± 0.01
Vancomycin	7.81 ± 0.18	0.31 ± 0.01
Inulin	6.88 ± 0.31	0.28 ± 0.01

* Normal Urea Reduction Ratio is 0.22/hour

Table 2: Solute sieving coefficient (Sc) for the alumina membrane

Solute	R_{obs}	Sc
Urea	0.014	0.98
Creatinine	0.002	0.99
Vancomycin	0.044	0.95
Inulin	0.047	0.95
Albumin	-	< 0.003

- Continuous renal replacement therapy (CRRT)

Pre and Post Dilution High Volume Continuous Hemofiltration

filtration fraction

$$FF = \frac{Q_{uf}}{Q_b(1-HCT)}$$

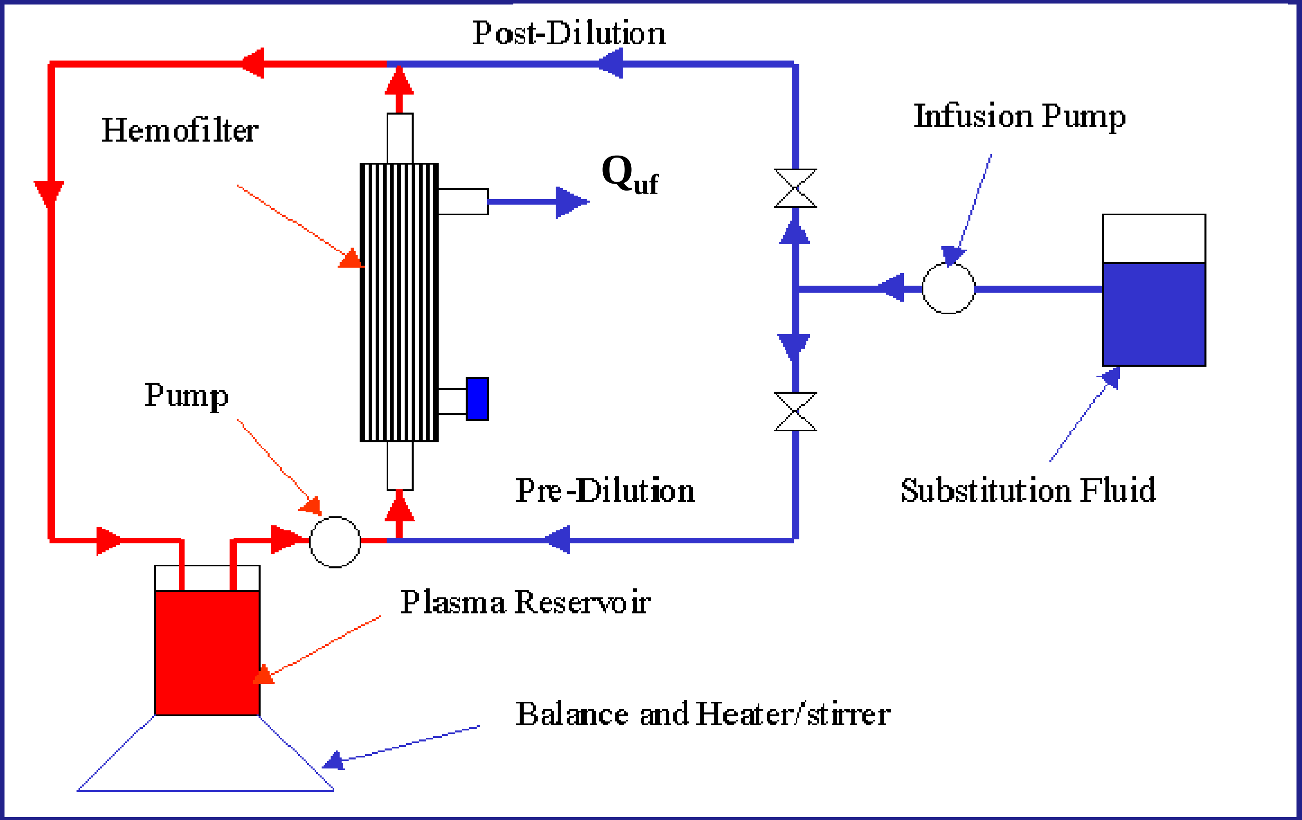


Table 1 Effect of Dilution on Solutes Clearance

	Urea	Creatinine	Vancomycin	Inulin
100 % PRE	35.1 ± 0.7	35.5 ± 0.3	36.7 ± 3.8	33.6 ± 3.1
75 % PRE	41.1 ± 0.4	40.9 ± 0.6	32.1 ± 0.8	32.1 ± 1.7
50 % PRE	45.0 ± 0.7	45.3 ± 0.4	32.7 ± 2.3	33.8 ± 0.9
25 % PRE	51.5 ± 1.3	50.6 ± 0.9	35.2 ± 1.5	35.5 ± 1.1
100 % POST	54.0 ± 1.2	54.0 ± 1.2	31.9 ± 0.6	34.7 ± 5.6
P-Value	1.596E-08 *	3.693E-09 *	0.0738366	0.704991

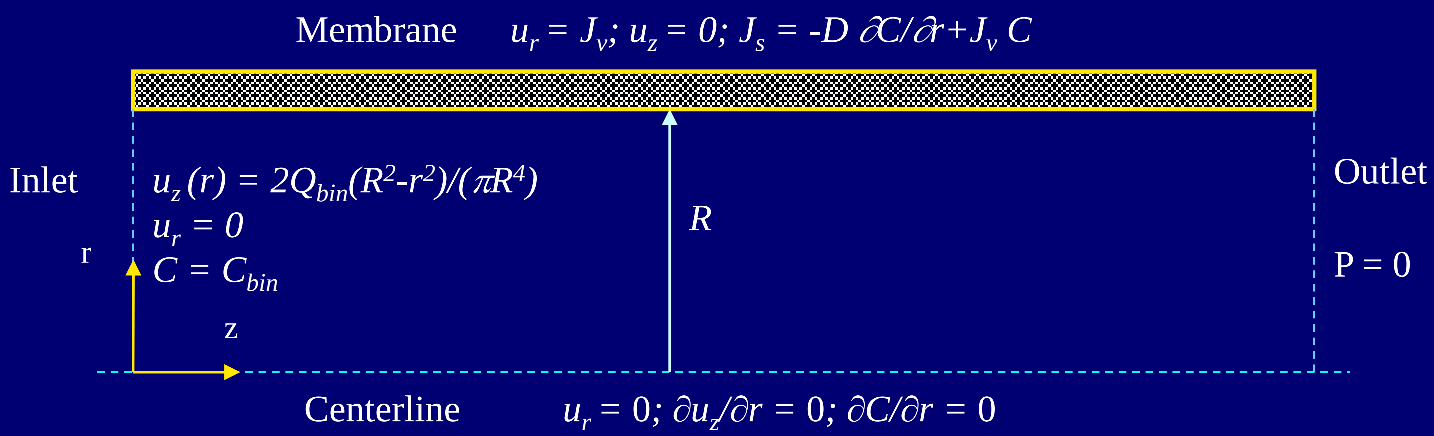
DISCUSSION

- For a given set of flow parameters, the balance between pre-dilution and post-dilution had a significant impact on urea and creatinine clearances.
- The transition from pure post-dilution to pure pre-dilution resulted in an average decrease in small solute clearance of 35%.
- Middle molecule clearances were relatively insensitive to the effects of pre-dilution versus post-dilution,
- Dilution mode had no significant impact on clearance of either vancomycin or inulin.

- Theoretical Approach

Computer Simulation of Mass Transfer in Artificial Kidney

Computational domain of blood flow



Blood flow is governed by Navier-Stokes equations

Continuity equation:

$$\nabla \cdot \mathbf{u} = 0$$

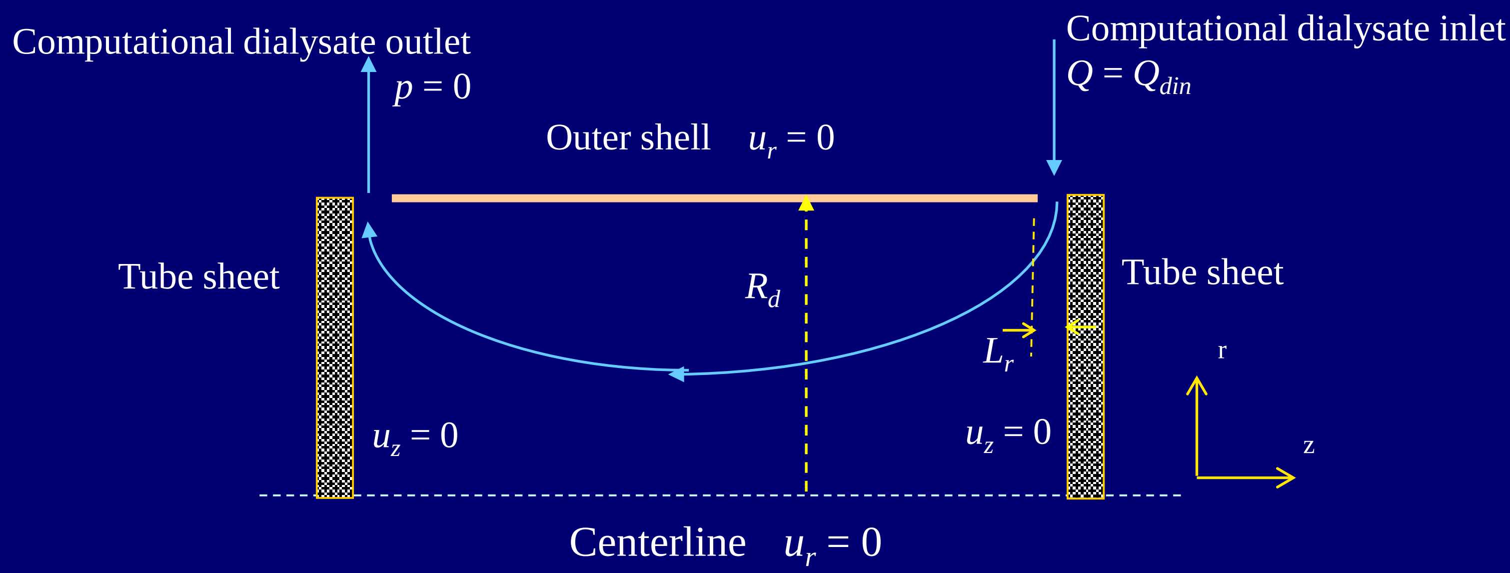
Momentum equations:

$$\mathbf{u} \cdot \nabla u_r = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{\mu}{\rho}\nabla^2 u_r \qquad \mathbf{u} \cdot \nabla u_z = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\mu}{\rho}\nabla^2 u_z$$

Concentration equation:

$$\mathbf{u} \cdot \nabla C = D\,\nabla^2 C$$

Computational domain of dialysate flow



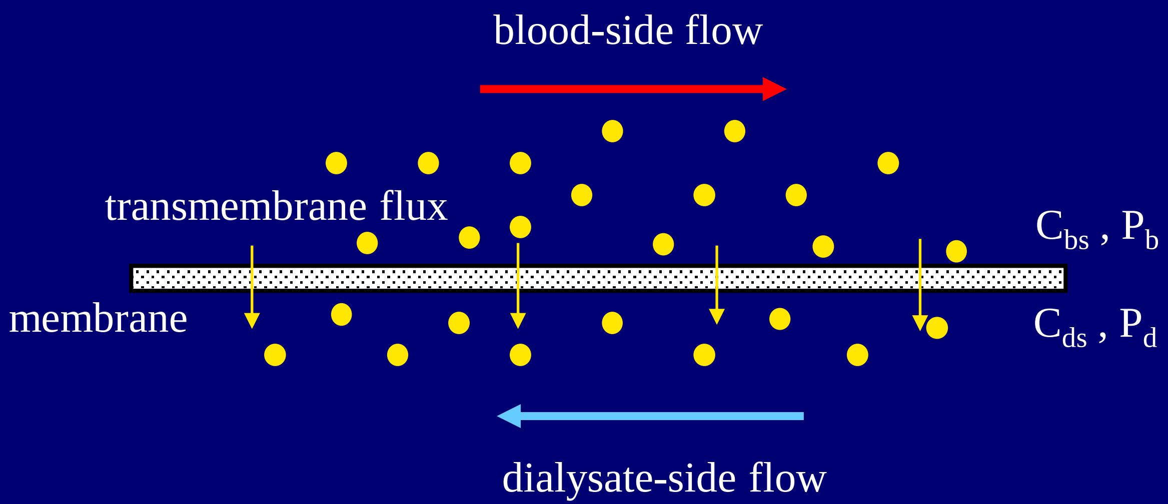
Dialysate flow is governed by Darcy equations:

Continuity equation: $$\nabla \cdot \mathbf{u} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right) + \frac{\partial u_z}{\partial z} = S_m$$ $$S_m = \frac{J_v \cdot A_m}{\Delta V}$$

Momentum equations: $$u_r = -\frac{1}{\mu} k_{rr} \frac{\partial p}{\partial r}$$ $$u_z = -\frac{1}{\mu} k_{zz} \frac{\partial p}{\partial z}$$

Concentration equation: $$\mathbf{u} \cdot \nabla C_s = D\nabla^2 C + S_s$$ $$S_s = \frac{J_s \cdot A_m}{\Delta V}$$

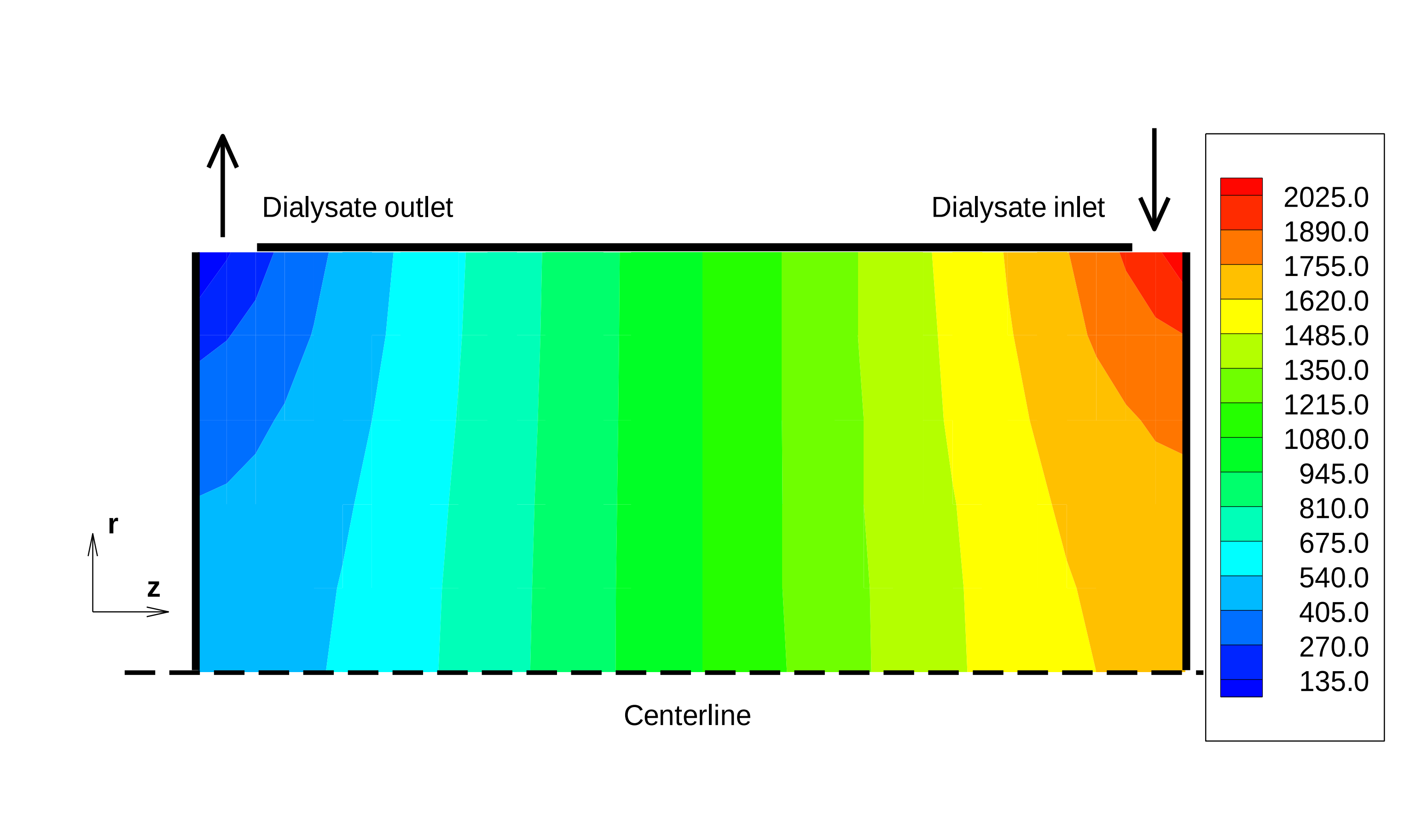
Kedem-Katchalsky (K-K) equations:



$$J_v = L_p\left(P_b - P_d\right) - \sigma L_p RT\left(C_{bs} - C_{ds}\right)$$

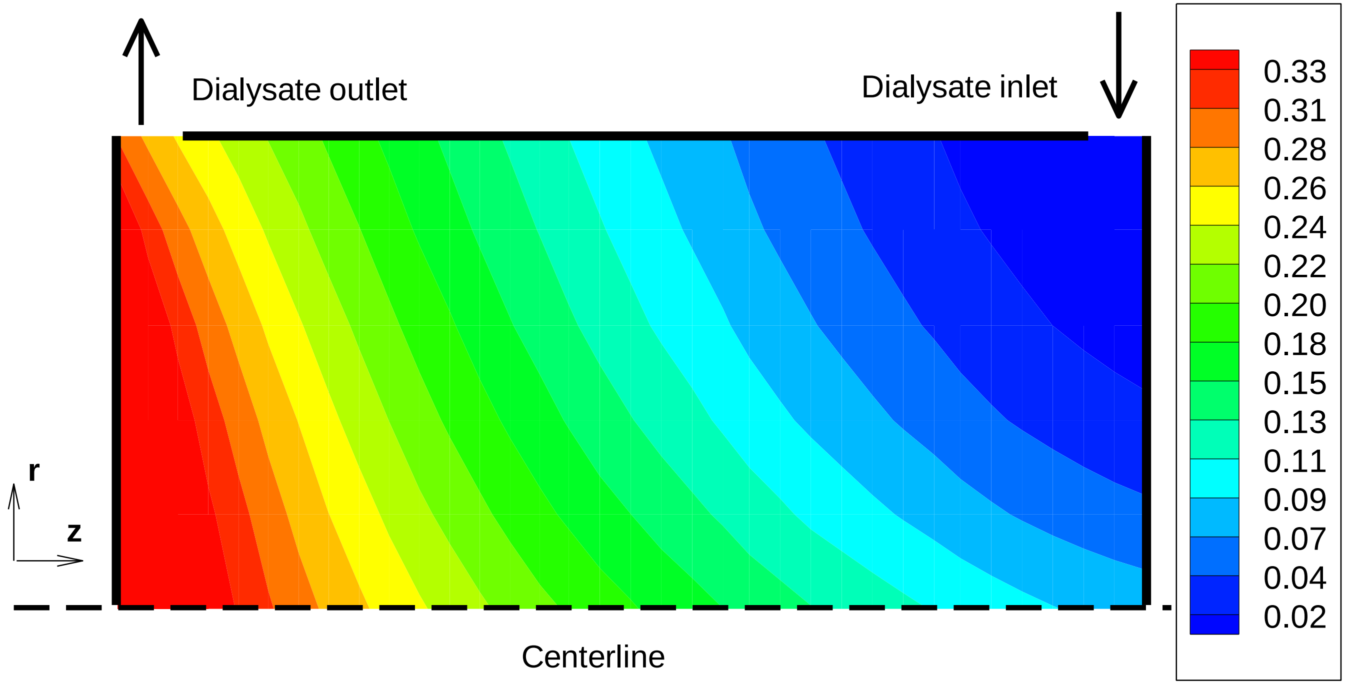
$$J_s = C_s^*\left(1-\sigma\right)J_v + P_s\left(C_{bs} - C_{ds}\right)$$

Results…



Distribution of pressure in dialysate side

(CT190G, Q_b = 360ml/min, Q_d = 500ml/min, P_{dout}=P_{bout}=0)

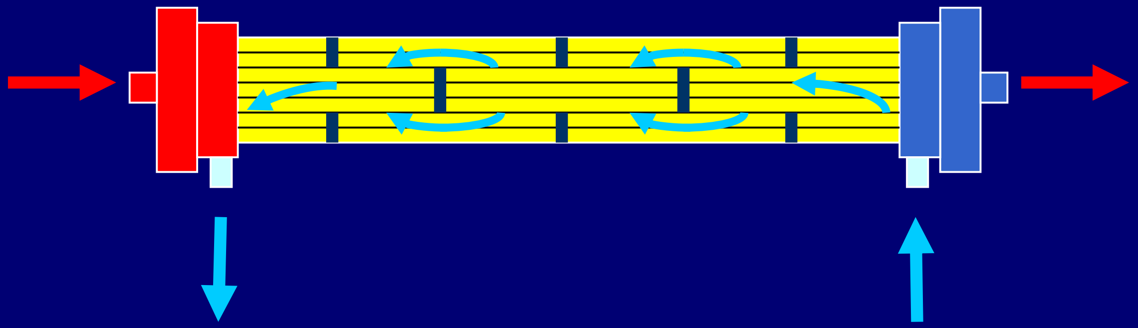


Distribution of urea concentration in dialysate side

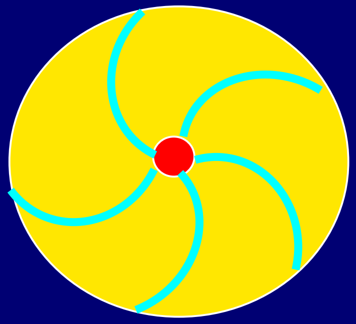
(CT190G, Q_b = 360ml/min, Q_d = 500ml/min, C_{bin} = 0.48 g/l)

- Future Research and Collaborations

- **Design optimal artificial kidney**



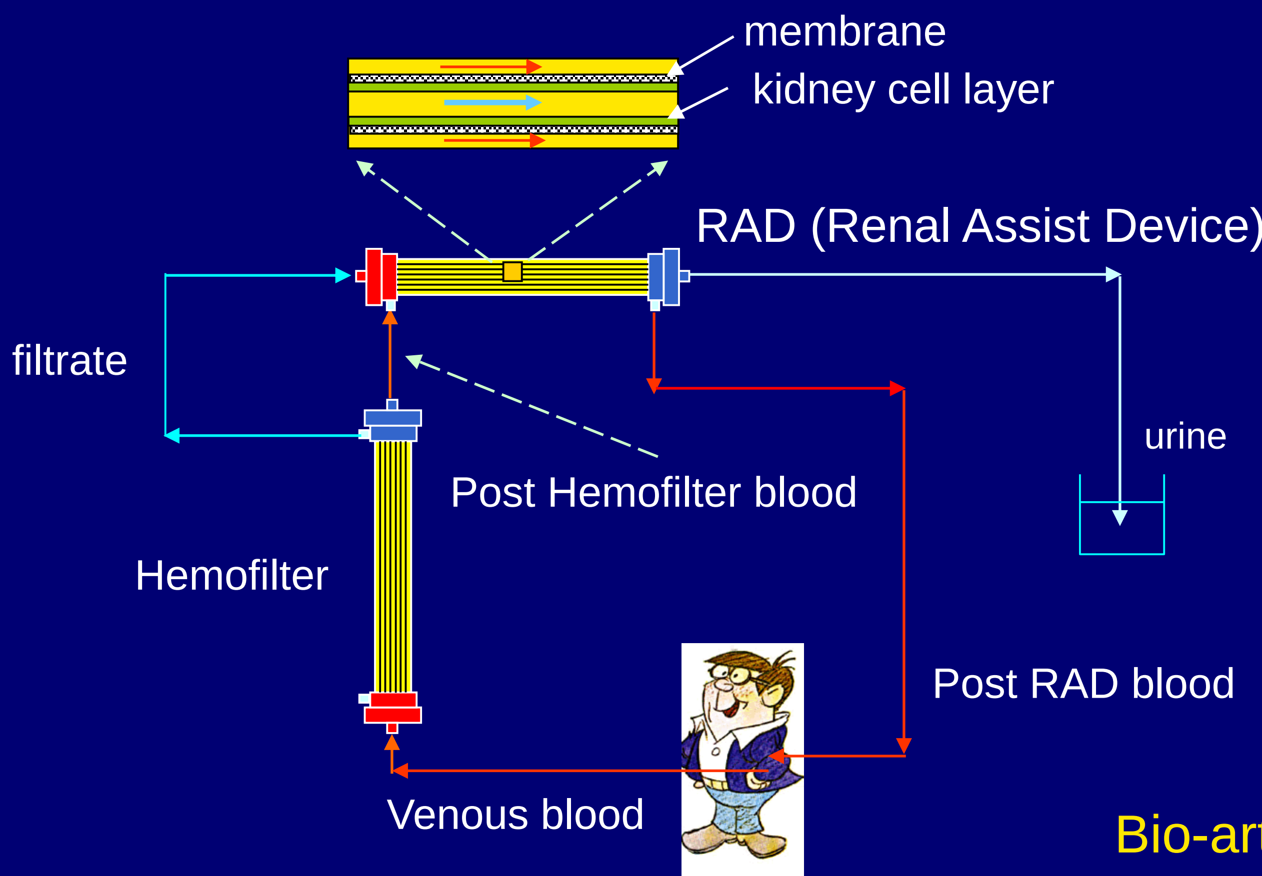
Baffled module



Flower-like blood inlet header design

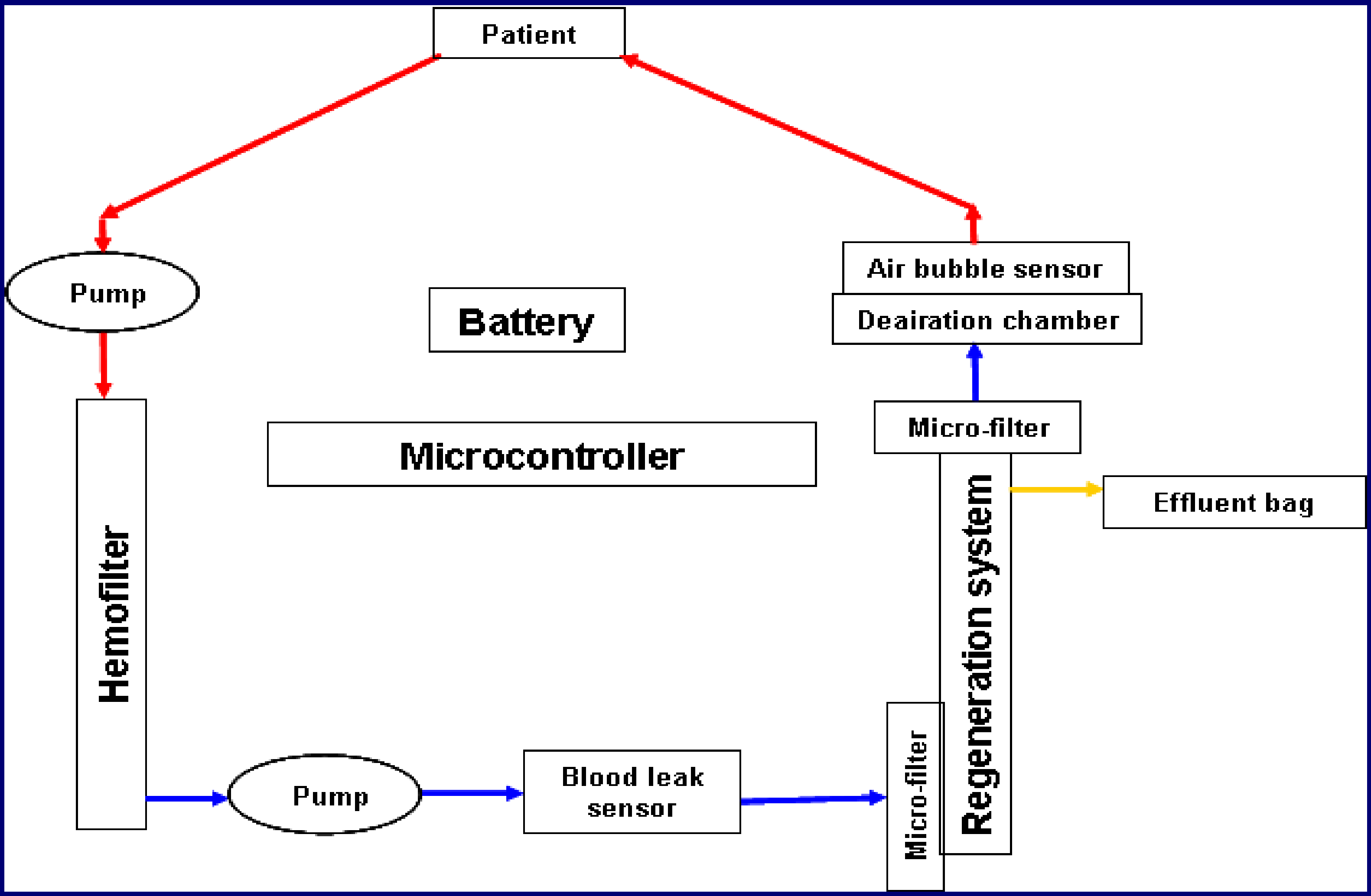
▪ Bio-Artificial Kidney / Cell Cryopreservation

- culture kidney cells in the hollow fiber to secrete hormone and re-absorb useful solutes
- cryopreserve kidney cells



Bio-artificial Kidney

▪ Wearable Artificial Kidney



Schematic sketch of wearable renal support device

Thanks for Attention