Artificial Kidney and Hemodialysis

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February 6, 2020
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
Inner diameter: ~ 200 µm
Membrane thickness: ~ 20 µm
Material: Cellulose Triacetate, Polysulfone, Polyamide, Polyethersulfone

Membrane cross-section

Pore size: ~ 5 nm
Performance Evaluation

\[ J = k_o A (C_B - C_D) \]

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

\[ \frac{1}{k_o} = \frac{1}{k_B} + \frac{1}{k_M} + \frac{1}{k_D} \]

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

\[
SC = \frac{2C_{uf}}{C_{Bi} + C_{Bo}}
\]
Revaclear Max

Blood side

Dialysate side

Revaclear Max
Evaluation of Local Clearance for Dialyzers

Inner Ring (Dialyzer 1)  
Middle Ring (Dialyzer 2)  
Outer Ring (Dialyzer 3)
Experiment Setup

Reservoir (patient pool) → Qb → Blood pump → Blood flow → Qb → Water bath

Blood flow → Qb → Dialysis machine → Qd → Dialysate flow → Dialyzer → Qd
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

\[ 4\text{Al} + 3\text{O}_2 \Leftrightarrow 2\text{Al}_2\text{O}_3 \quad \text{(Anode)} \]

\[ 2\text{H}^+ + 2\text{e} \Leftrightarrow \text{H}_2 \quad \text{(Cathode)} \]
Comparison of Ceramic Membrane and Synthetic Membrane

Surface

Ceramic Membrane

Polysulfone Membrane

Cross section
Pore Size Distribution and Hydraulic Permeability (Ceramic Membrane)

- $39.1 \times 10^{-15} \text{ m}^2 \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$
  (ceramic membrane at 3% sulfuric acid)

- $15.1 \times 10^{-15} \text{ m}^2 \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$
  (Syntra 160 membrane)
Mini Module Dialyzer

Nano-porous alumina tube
### Table 1: Solute clearance for the alumina membrane

<table>
<thead>
<tr>
<th>Solute</th>
<th>Clearance mL/min</th>
<th>Reduction ratio/hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urea</td>
<td>9.03 ± 0.15</td>
<td>0.36 ± 0.01</td>
</tr>
<tr>
<td>Creatinine</td>
<td>8.96 ± 0.15</td>
<td>0.36 ± 0.01</td>
</tr>
<tr>
<td>Vancomycin</td>
<td>7.81 ± 0.18</td>
<td>0.31 ± 0.01</td>
</tr>
<tr>
<td>Inulin</td>
<td>6.88 ± 0.31</td>
<td>0.28 ± 0.01</td>
</tr>
</tbody>
</table>

*Normal Urea Reduction Ratio is 0.22/hour

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

<table>
<thead>
<tr>
<th>Solute</th>
<th>( R_{\text{obs}} )</th>
<th>Sc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urea</td>
<td>0.014</td>
<td>0.98</td>
</tr>
<tr>
<td>Creatinine</td>
<td>0.002</td>
<td>0.99</td>
</tr>
<tr>
<td>Vancomycin</td>
<td>0.044</td>
<td>0.95</td>
</tr>
<tr>
<td>Inulin</td>
<td>0.047</td>
<td>0.95</td>
</tr>
<tr>
<td>Albumin</td>
<td>-</td>
<td>&lt; 0.003</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th>Urea</th>
<th>Creatinine</th>
<th>Vancomycin</th>
<th>Inulin</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 % PRE</td>
<td>35.1 ± 0.7</td>
<td>35.5 ± 0.3</td>
<td>36.7 ± 3.8</td>
<td>33.6 ± 3.1</td>
</tr>
<tr>
<td>75 % PRE</td>
<td>41.1 ± 0.4</td>
<td>40.9 ± 0.6</td>
<td>32.1 ± 0.8</td>
<td>32.1 ± 1.7</td>
</tr>
<tr>
<td>50 % PRE</td>
<td>45.0 ± 0.7</td>
<td>45.3 ± 0.4</td>
<td>32.7 ± 2.3</td>
<td>33.8 ± 0.9</td>
</tr>
<tr>
<td>25 % PRE</td>
<td>51.5 ± 1.3</td>
<td>50.6 ± 0.9</td>
<td>35.2 ± 1.5</td>
<td>35.5 ± 1.1</td>
</tr>
<tr>
<td>100 % POST</td>
<td>54.0 ± 1.2</td>
<td>54.0 ± 1.2</td>
<td>31.9 ± 0.6</td>
<td>34.7 ± 5.6</td>
</tr>
<tr>
<td>P-Value</td>
<td>1.596E-08 *</td>
<td>3.693E-09 *</td>
<td>0.0738366</td>
<td>0.704991</td>
</tr>
</tbody>
</table>
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
Blood flow is governed by Navier-Stokes equations

**Continuity equation:**
\[ \nabla \cdot \mathbf{u} = 0 \]

**Momentum equations:**
\[ \mathbf{u} \cdot \nabla u_r = -\frac{1}{\rho} \frac{\partial p}{\partial r} + \frac{\mu}{\rho} \nabla^2 u_r \]
\[ \mathbf{u} \cdot \nabla u_z = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{\mu}{\rho} \nabla^2 u_z \]

**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:**
\[
\nabla \cdot \mathbf{u} = \frac{1}{r} \frac{\partial}{\partial r} \left( = \frac{\partial u_r}{\partial r} + \frac{\partial u_z}{\partial z} = S_m
\]
\[
S_m = \frac{J_v \cdot A_m}{\Delta V}
\]

**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:

\[ J_v = L_p (P_b - P_d) - \sigma L_p RT (C_{bs} - C_{ds}) \]

\[ J_s = C_s^* (1 - \sigma) J_v + P_s (C_{bs} - C_{ds}) \]
Results…
Distribution of pressure in dialysate side
(CT190G, $Q_b = 360\text{ml/min}$, $Q_d = 500\text{ml/min}$, $P_{dout}=P_{bout}=0$)
Distribution of urea concentration in dialysate side

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

Diagram:
- Hemofilter
- FILTRATE
- membrane
- kidney cell layer
- RAD (Renal Assist Device)
- Post Hemofilter blood
- Post RAD blood
- Venous blood
- urine

Bio-artificial Kidney
Wearable Artificial Kidney

Schematic sketch of wearable renal support device
Thanks for Attention