CRRT
The Technical Questions.
Access/Membrane/Circuit

Luis A. Juncos
John Bower Chair of Nephrology
Professor of Medicine, Physiology and Biophysics
Department of Medicine/Nephrology/CCM
University of Mississippi Medical Center
Keys to Successful CRRT

Relationship Between Access, Circuit, Filter/Membrane

- Vascular Access
- Circuit Blood Pump
- Filter Membrane
CRRT Prescription vs. Delivery

Filter and Circuit Function

Failure and Clotting

• Not always due to insufficient anticoagulation.

• Blood Flow mechanics

• Circuit Factors

Equal or Greater Importance
VASCULAR ACCESS FOR CRRT
Hemodialysis Catheters

Characteristics of the Ideal HD Catheter:

- Long use-life
- Provide adequate blood flow rates
- Low rate of complications; e.g. infections, thrombosis, etc

- Tunneled Dialysis Catheters → TDCs
  - Sizes: Diam = 13.5 – 16 F  Length = 19 cm – 50 cm
  - usually cuffed

- Temporary Dialysis Catheters → TDCs – STHDCs
  - Sizes: Diam = 11.5 – 14 F  Length = 12.5 cm – 24 cm
  - usually uncuffed
Temp HD Catheters: Shapes

Straight

Curved Extensions

Precurved
Temp HD Catheters: Lumen Characteristics

Double Lumen
Two Separate Lumens
Triple Lumen – A small infusion port

Concentric or Coaxial
Circle C
Double D
Cylindrical or Double Barrel
Temp HD Catheters: Tip Characteristics

Venous End Hole with Arterial Side Holes

Shotgun Tips

Symmetrical Tips
Temp HD Catheters: Materials

Polyurethane – Polyvinyl Chloride - Polyethylene
- Thermoplastic (softens and body temperature)
- High Tensile Strength → “Memory” - Kink
- Thinner walls → larger luminal diameters
- Reduced bacterial colonization

Silicone
- Softer and Flexible → No “Memory”
- Lower risk of vascular damage
- Less thrombogenic
- Resistant to Chemicals
Internal Jugular Approach

**Advantages**
- Decreased PTX
- Low Recirculation
- Low Stenosis Rate
- Longevity

**Right Internal Jugular**
- Straightest approach
- Short distance to RA
- Less vessel wall trauma
- Low complication rate

**Disadvantages**
- Technically more difficult
- Tracheostomy in way
- Oral Secretions
- Beard in males
- Longevity
- Thoracic Duct on Left
- Insertion requires Trendelenburg positioning

**Complications of Canulation**
- Carotid Artery Puncture
- Pneumothorax/Hemothorax
- Rupture of Vena Cava/RA
- Pericardial tamponade
- Arrhythmias
- IJ Thrombosis
- Infection
Temp HD Catheters: Sites of Insertion

Right Internal Jugular
• Straightest approach
• Short
• Less vessel wall trauma
• Low complication rate
**Temp HD Catheters: Tip Location**

**IJs and SCs → SVC at the Caval Atrial Junction**

1. HD Catheter tips > 4 cm from the RA are not acceptable
2. Catheter tips should be ~ 3 cm caudal of the right tracheobronchial angle.
3. Tip must be parallel to vessel lumen

**Femoral → IVC = 24 cm Catheter**
Temp HD Catheters: Tip Location
Size it Correctly: Peres Formulas (& derived)

<table>
<thead>
<tr>
<th>Insertion Site</th>
<th>Formula</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Internal Jugular</td>
<td>Hgt/10</td>
<td>90%</td>
</tr>
<tr>
<td>Left Internal Jugular</td>
<td>Hgt/10 + 4 cm</td>
<td>94%</td>
</tr>
<tr>
<td>Right Subclavian</td>
<td>Hgt/10 - 2 cm</td>
<td>96%</td>
</tr>
<tr>
<td>Left Subclavian</td>
<td>Hgt/10 + 2 cm</td>
<td>97%</td>
</tr>
</tbody>
</table>

**Key Points:**

1. Insertion Sites vary and alter the accuracy of these formulas.
2. TDCs are meant to be “buried” to a specific spot.
3. Insertion point of some of the precurved catheters is not as obvious (butterfly clamp are used to fix the depth).
Femoral Approach

Advantages
- Safest Approach
- Fastest Insertion
- Control of Bleeding
- Can place with patient semi-recumbent

Disadvantages
- Highest Infection rate
  - • CATHEDIA???
- Non-ambulatory
- 72-hour limit
- Recirculation

Positioning
- Knee mildly flexed, leg rotated and abducted

Complications
- Puncture of Femoral Artery
- Wire passing into ileofemoral vein
- Retroperitoneal Hemorrhage
- Infections
- Thrombosis
Subclavian Approach

Advantages
- Slow Recirculation
- Patient Comfort
- Easy Ambulation
- Longevity
- Low Infection Rates

Disadvantages
- Technically more difficult
- Pneumothorax
- Arterial Stick
- Subclavian Stenosis
- Insertion requires Trendelenburg positioning

Complications of Canulation
- Puncture of Subclavian Artery
- Pneumothorax/Hemothorax
- Rupture of Vena Cava/RA
- Pericardial tamponade
- Arrythmias
- SC Thrombosis
- Infection
Temp HD Catheters: Primary Complications

**Insertion-Related**
- Arterial Puncture
- Pneumothorax / Hemothorax
- Venous / Atrial Puncture
- Pericardial Tamponade
- Arrhythmias / Cardiac Arrest
- Air Embolism
- “Lost” Wire
- Laryngeal Nerve Palsy

**Reduced BFR or Recirculation**
- Malpositioning
- Kinking
- Improper Catheter Tip Location
Temp HD Catheters: Secondary Complications

Infections
- Extraluminal
- Hematogenous
- Intraluminal

- Risk Factors
  - Non-Nephrology Personnel using it
  - Frequency of Manipulation
  - Indwelling time
  - Severity of Illness
  - Immunosuppression
  - Presence of other CVC
  - Colonization of Hubs

Thrombosis (33-67%)
- Adherent to the vessel
- Fibrin Sleeve
- Nonmobile in the RA
- Mobile → ↑ PEs

- Risk Factors
  - Non-Nephrology Personnel using it
  - Frequency of Manipulation
  - Indwelling time
  - Severity of Illness
## Risk Factors for Secondary Complications

### Risk Factors for Infections
- Catheter material
- Urgent insertion
- Frequency of manipulation
- Number of infusion ports
- Operator experience
- Insertion site
- Indwelling time
- Severity of illness

### Risk Factors for Thrombosis

#### Patient-related factors
- Hypercoagulable states
- Thrombophilic states
- Age > 64
- Underlying malignancy
- Dehydration
- Impaired tissue perfusion
- Absent prophylaxis/treatment

#### Catheter-related factors
- Polyurethane/polyvinyl catheters
- Additional central lines
- Traumatic insertions

#### Site-related factors
- Femoral > IJ > Subclavian

---

TDCs should only be used for RRT!
Primary Factors Affected by Access

- Blood Flow Rate ($Q_b$)
- Treatment Time (Failure and Clotting)
- Blood Recirculation
Blood Flow Rate (Qb) in D

• The machine doesn't check or display the real Qb. Qb is calculated.

• Qb → Calculated based on:
  – Pump RPM
  – Diameter of the tube

• Real Qb may differ from the display because of:
  – Internal reverse leak: the rollers never squeeze the tube completely so not all the blood is pushed forward, a little goes backward.
  – High arterial and/or venous pressure reduces the ability of the pump to suck or to deliver.
Access Blood Flow Rates (BFR)

- Usually underestimate TRUE BFRs.
  - Magnitude depends on access characteristics.

**Poiseuille’s Law**: \( Q = \pi \Delta P D^4/128 \mu L \)

- \( Q \) = Flow (Blood Flow Rate = \( Q_b \))
- \( \Delta P \) = Pressure drop along length (L) of the tube
- \( D \) = Diameter of lumen
- \( \mu \) = dynamic viscosity

**Applies to developed laminar flow in a rigid straight tube**

**Shorter, Wider, Straight Catheters are Best**
HD Catheters Affect Qb and Recirculation

- Poiseuille’s Law: assumes a straight rigid tube.
  - Curves reduce blood flow
    - $Q$ in LIJ can be $>30\%$ less than $Q$ in RIJ
  - HD Catheters are not rigid.

![Diagram](Diagram.png)

- Negative Pressure < 100 mmHg
- Negative Pressure ~ 400 mmHg
Why Roller Pumps May Not Deliver Desired Qb
Qb in Diverse Access Sites
In Vitro Pressure/Flow Profiles

>19cm vascular access catheters access lumen flow/pressure profile

Blood temp. 37°C
Hct 32

- Medcomp 11.5F 20cm
- Quinton-Mahurkar 11.5F 19cm
- Gamm cath 11F 20cm
- Medcomp 11.5F XTP 20 cm
- Vascath Niagara 13.5F 20cm
- 10 F single lumen 40 cm
- Circuit only (Prisma M6)
### Recirculation

- Increases with Blood Flow
- Varies with Catheter Location
- Varies with Catheter Type

### Consequences of Recirculation

- Decreases clearance
- Increases clotting of CRRT
Summary of Access Recommendations

• Larger is better

• Right IJ → Left IJ → Femorals → Subclavian

• Use appropriate sized catheters and place tips in appropriate locations.

• Only Nephrology (or specially trained personnel should use.

• Minimize manipulations

• Do not reduce lumen with smaller gauge connectors/3-ways

• Assess reasons for clotting; it will commonly be due to suboptimal access.
THE
MEMBRANE / FILTER
**The Filter Membrane:** → The most important part of the circuit

- It is the part that has the largest degree of exposure to blood

- Cylindrical case → contains ~8000 Semipermeable hollow fibers

- They are the functional units of the CRRT circuit
  - It determines the hydraulic permeability
  - It determines the selectivity of solute removal
Anatomy of a Hemofilter

CRRT: The Filter / Membrane

Blood in

Dialysate in

Dialysate out

Blood out

Cross Section

Hollow fiber membrane

Inside the Fiber (blood)

Outside the Fiber (dialysis or effluent)
Anatomy of a Hemofilter

- Potting Agent
- Blood Space
- Membrane Fibers
- Membrane Pores
- Dialysate Out
- Dialysate In
- Blood In
- Blood Out
CRRT: The Filter / Membrane

**Materials:** → Synthetics (Thermoplastics)

- AN69
- Polymethylmethacrylate (PMMA)
- Polysulfone
- Polyamide
- Polyethersulfone
- Polyamide / Polyethersulfone

**Symmetric**

- AN69
- Polymethylmethacrylate (PMMA)

**Asymmetric**

- Polysulfone
- Polyamide
- Polyethersulfone
Relationship Between Pore Size and Sieving Coefficient
Mechanisms of Clearance during CRRT

- Ultrafiltration → Fluid Transport
- Convection
- Diffusion
- Adsorption

Solute Transport
Ultrafiltration

Blood In (from patient)

Blood Out (to patient)

Fluid Volume Reduction

LOW PRESS  →  HIGH PRESS

to waste

Ultrafiltrate

• Composition of plasma.
• It is not replaced.
• Solute clearance = small
Hemofiltration: Convection or Solute Drag

Blood In  
(from patient)

Blood Out  
(to patient)

LOW PRESS  ←  HIGH PRESS

to waste

Replacement Solution
**Hemodialysis: Diffusion**

**Mechanisms of Clearance**
- **Solute**
  - Diffusion
  - Adsorption
- **Fluid** → Ultrafiltration

**Diagram**
- **Dialysate Out**
- **Dialysate In**
- **Blood In** (from patient)
- **Blood Out** (to patient)
- **Blood Out** (to waste)
- **LOW CONC** → **HIGH CONC**
**Diffusion vs. Convection**

Solute transport across a semi-permeable membrane

**Diffusion** → Solutes move across following a concentration gradient.

Best for small molecule clearance

**Convection** → Solutes pass across along with the solvent ("solvent drag") following a pressure gradient

Effectiveness less dependent on molecular size
Convection Via Backflux in High-Flux HD

- Blood Out
- Blood In
- Dialysate In
- Dialysate Out
- Reinfusion
- Diffusion
- Ultrafiltration
Adsorption: Molecular adherence to the membrane.

Certain membranes display adsorptive characteristics

- Surface adsorption onto the membrane surface.
- Adsorption within the membrane when the molecules can permeate it.
Clearance Profiles by Modality

Indexed Toxin Clearance

Hemodialysis

Hemofiltration

Natural Kidney

Urea (Small Molecule)

B2-m (Middle Molecule)

Albumin (Large Molecule)

Molecular Size
Clearance Characteristics during CRRT

- **Kidney**
- **CVVH**
- **Dialysis**

**Clearance in %**
- Urea (60)
- Creatinine (113)
- Myoglobin (17,000)
- Albumin (66,000)
Solute Clearance in Diffusion vs. Convection
### Solute Clearances in High-Volume Isovolemic CVVH\#,\*  
**Li et al, ASN 2001**

<table>
<thead>
<tr>
<th>Solute (MW)</th>
<th>Pre-Dilution Mode</th>
<th>Post-Dilution Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urea (60)</td>
<td>53.6 ± 5.3</td>
<td>66.1 ± 2.4*</td>
</tr>
<tr>
<td>Creatinine (113)</td>
<td>54.5 ± 2.1</td>
<td>69.9 ± 3.5*</td>
</tr>
<tr>
<td>Vancomycin (1448)</td>
<td>36.2 ± 3.7</td>
<td>39.3 ± 11.2</td>
</tr>
<tr>
<td>Inulin (5200)</td>
<td>29.3 ± 3.0</td>
<td>27.7 ± 4.7</td>
</tr>
<tr>
<td>Myoglobin (17,800)</td>
<td>20.7 ± 5.6</td>
<td>13.2 ± 3.0</td>
</tr>
</tbody>
</table>

\#: $Q_p = 200 \text{ mL/min}; Q_F = 67 \text{ mL/min}$  
\*: POST FF = 0.33; PRE Dilution factor = 0.25  
\*: $P<0.05$ vs PRE
Consequences of Protein Adsorption

Formation of a Secondary Membrane:

- Albumin
- Fibrinogen
- Immunoglobulins
- LMW proteins

% Rejection vs. Log [Molecular Weight]

Plasma and Saline plots showing rejection percentage for different molecular weights.
THE CRRT CIRCUIT
CRRT: The Circuit

Pre-Filter Replacement

Blood Pump

Dialysate

Post-filter Replacement

Effluent
CRRT: The PreFilter Circuit

Pre-Filter Replacement

A = Access Pressure Pod
F = Filter Pressure

Blood Pump

Pre-Pump Infusion

Syringe Pump
CRRT: The Post-Filter Circuit

$R = \text{Return Pressure}$
CVVHDF: Continuous Venovenous Hemodiafiltration

Pre-Filter Replacement

Dialysate

Effluent

Access

Return
CVVHDF: Continuous Venovenous Hemodiafiltration
CRRT Circuit Pressures: What do they Mean?

**Measured Pressures:**

- **Access Pressure** → Located Pre-Blood Pump
  - Determined resistance of the arterial access and BFR

- **Filter Pressure** → Located Post Blood Pump – Pre-filter
  - Determined by influx (BFR+ prefilter infusions) x Post-pod resistance

- **Return Pressure** → Located Post Filter
  - Determined by influx x venous return resistance

- **Effluent Pressure** → Located Pre Effluent Pump
  - Determined by total effluent volume x membrane permeability

**Calculated Pressures:**

- **Transmembrane Pressure** = Mean Filter Pressure – Effluent Pressure
- **Pressure Fall Across the Filter** = Pre-Filter Pressure – Return Pressure
CVVH vs CVVHD vs CVVHDF

- **Clearances**
  - Small Solutes $\rightarrow$ CVVH = CVVHD = CVVHDF
  - Middle Molecules $\rightarrow$ CVVH > CVVHDF > CVVHD

  **Assumptions:**
  - Same total Clearance
  - Optimal Function of Circuit

- Local Expertise/Preference
- Availability of Equipment
- Availability of Fluids
Keys to Successful CRRT

Relationship Between Access, Circuit, Filter/Membrane
A balance between flow and resistance.