Infusing Liquids Into Veins And Other Tissues
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Infusing Liquids in Veins and Other Tissues

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History

Clinical IV Systems
  Conduits - tubing and catheters
Veins
  Collapsible tubes of latex
History of Clinical IV Systems


1966  La Cour & Ferechak - Drops are an inaccurate volume measure. Size = F{Temp, Composition, Orifice diameter, Orifice shape}

1974  Flack & Whyte - Tubing creeps (cold-flow of plastic), varies flow, usually decreases flow

1984  Philip & Philip - Constant high pressure provides high flow
Studies of Fluid Flow in Veins

1912  Starling -
Used tubing collapse to produce constant pressure
Used for afterload on the heart
Incorrectly claimed "resistance"
Produced constant pressure - "Starling Resistor"

1941-1963 Numerous Authors -
Physical model for vein collapse
Penrose Drain
Studies of Fluid Flow in Veins

1963 Permutt and Riley -
Defined “Critical Closing Pressure”
Showed Flow is independent of pressure drop
Coined the name “Vascular Waterfall”

1977 Shapiro (at MIT) -
Developed “One dimensional theory of steady flow in thin-walled tubes partly collapsed by negative intramural pressure.
Explained the collapse of rubber tubes
Irony

Researchers studied latex tubes

Latex tubes (Penrose Drains) don’t collapse

That’s why they’re “surgical drains”

Veins do collapse completely

In vivo and in vitro
Compress a Vein

Pressure

Veins

Collapse

Completely
Compress Tubing

Pressure → Tubes

Collapse

Incompletely
Compress Tubing

Pressure

→

Tubes

Collapse

Incompletely

Two Tubes Remain
Make Tubing Collapse

Two Small Tubes
Filled with Silicone Close Completely

Big Tube Collapses Completely
Latex Tubes vs. Veins

Latex Tubes (Penrose Drains)
- Complex Behavior
- Collapse Incompletely
  - 1 big tube becomes two small small tubes

Veins
- Simple Behavior
- Collapse Completely
Veins

Can be collapsed
Can be compressed

Cartoon depiction
Vein

Can collapse completely
Would require pressure

Can open partly

Can open widely

If compressed, require opening pressure
$P_{vein} = P_0 = \text{Tourniquet Pressure}$

Require additional pressure for flow
$P_{vein} = P_0 + R F$
Vein

\[ P_{\text{vein}} = R \ F \]
Vein

\[ P_{\text{vein}} = R F \]

If compressed, require opening pressure
\[ P_{\text{vein}} = P_0 = \text{Tourniquet Pressure} \]

Require additional pressure for flow
\[ P_{\text{vein}} = P_0 + R F \]
Pressure-Flow Relationship (PFR) and appearance of a Vein

\[ \text{Flow} \]

\[ G = \frac{\Delta \text{Flow}}{\Delta \text{Pressure}} = \text{Conductance} = \frac{1}{\text{Resistance}} \]

- \( F = 0 \) if \( P < P_o \)

- Pressure (transmural = \( P_{in} - P_{out} \))
- Appearance
- Description

- collapsed
- no flow
- opening
- fluttering
- Fully open
- flowing fast
Non- Linearity

Another one Grand Rounds 2 weeks ago
Vaporizer with a liquid that almost boils
Phase transition or a State Transition Liquid to Gas
Flow - Pressure Relationship (FPR) and appearance of a Vein

\[ R = \frac{\Delta \text{Pressure}}{\Delta \text{Flow}} = \text{Resistance} = \frac{1}{\text{Conductance}} \]

- **Opening fluttering**
- **Fully open**
- **Flowing fast**
- **No flow collapsed**

\[ F = 0 \text{ if } P < P_o \]
The Pressure-Flow Relationship and Clinical Systems

Science

Easy read: ftp://jphilip.bwh.harvard.edu/technology/ fluids/
Model Elements

Pressure Source - Elevated Bag (P=ht)
Flow Source - Pump

Resistors - tubing, catheter, vein, roller clamp, tissue

Obstructers - Starling Resistors, Tourniquet, BP Cuff, Compressed Veins, water falls
Graphs of relationships between P and F

Elevated bag and Flow Measure (drop rate)

Pressure-driven PFR

Pressure

Flow
Graphs of relationships between $P$ and $F$

- **Flow-driven**
- **Pressure**
- **Flow**

**FPR**

Infusion Pump and Pressure Transducer

Flow-driven

Flow
Pressure Source - Elevated Bag

Pressure = free-air surface height above reference level minus (-) height of air gaps.

\[ P = P_0 = (\text{at any flow, + or -}) = \text{Bag Height} \]
Flow Source - Infusion Pump

\[ F = F_{\text{set}} \]

\( P \ (\text{mmHg}) \)

\( F \ (\text{L/hr}) \)
Flow Source - Infusion Pump

Infuse at set rate (e.g., 0.1 - 999 mL/hr)

Despite impediments
tubing, catheter, patient
R = 2, 6-17, 5-100 mmHg/L/hr

May require or provide high pressure
5 psi = 250 mmHg, 10 psi = 500 mmHg

1 psi = 50 mmHg - remember

May convert infiltration to injury
Linear peristaltic mechanism
flow comprised of one microliter volumes

Pressure Transducer
Just distal to pumping mechanism
presses against in-line pressure-sensing disk
Disk is in IV tubing

\[ P \pm 2 \text{ mm Hg accuracy (mmHg) with or without flow} \]
\[ \text{R units are } P / F = \text{mmHg/L/hr} = \text{mmHg} \cdot \text{hr} / \text{L} \]

\[ \text{IVAC Alaris Model 560 and later} \]
Resistors and Resistance

\[ R = \text{Resistance [mmHg/L/hr]} \]

\[ R = \frac{\Delta P}{\Delta F} \]
Resistors and Resistance

\[ R = \text{Resistance [mmHg/L/hr]} \]

\[ R = \frac{\Delta P}{\Delta F} \]
Resistance = Slope of PFR

\[ R = \frac{\Delta P}{\Delta F} = \text{Slope} \]

\[ R = \text{Resistance [mmHg/L/hr]} \]
Resistors resist flow

R = Resistance [mmHg/L/hr]

\[
R = \frac{\Delta P}{\Delta F} = \text{Slope} = \frac{4 \text{ mmHg}}{0.1 \text{ L/hr}} = 40 \frac{\text{mmHg}}{\text{L/hr}}
\]

\[
\Delta F = 0.1 \text{ L/hr}
\]

\[
\Delta P = 4 \text{ mmHg}
\]
Catheters are Resistors

$R = \text{Resistance [mmHg/L/hr]}$

Pressure (mmHg) vs. $F$ (mL/hr)

- #24 (66)
- #22 (34)
- #20 (17)
- #18 (6)
- #16 (6)
- tubing (3)
Tubings are Resistors

R = Resistance [mmHg/L/hr]
Roller Clamps are Resistors

R = Resistance [mmHg/L/hr]

Roller clamp (800) (300)

#Ga(R mmHg L/hr)

#24(66)
#22(34)
#20(17)
#18 (6)
#16 (6)
tubing(3)
Veins are Resistors

Pressure (mmHg) vs. Flow (mL/hr)

Veins (5-100 mmHg/L/hr)

Vein (22): 100 mmHg/L/hr

Roller clamp: 800, 300 mmHg

#Ga(R mmHg/L/hr)

#24 (66), #22 (34), #20 (17), #19 (6), #16 (6), tubing (3)

R = Resistance [mmHg/L/hr]
Total Resistance
  = Sum of Individual Resistances
Tubing
Catheter
Roller Clamp
Other Devices
Patient Vein
Resistances in Series Add

Total Resistance = Sum of Individual Resistances
(Units = mmHg/L/hr)

Tubing = 3
Catheter = 6 - 16
Roller Clamp = 0 or 800
Other Devices are small
Patient Vein = 0 - 100, Average = 22
Total Resistance

Dominated by patient vein
Affected by tubing and catheter
Veins are predominantly Resistors

Normal Vein

R = 22 mmHg/L/hr

Low resistance
Veins have low Opening Pressure

Po

Low opening pressure

Po = CVP

Normal Vein

F (mL/hr)

R = 22 mmHg/L/hr

Pressure (mmHg)
Veins alter fluid flow two ways

Resistance to fluid flow 0 - 200 mmHg/L/hr

Opening pressure at zero flow

Opening pressure = Po

Obstructs vein

Depends on tissue forces outside the vein

Starling Resistor
With Tourniquet

Normal Vein

Po = Tourniquet pressure

Elevated opening pressure

Po

Pressure (mmHg)

CVP

R = 22 mmHg/mL/hr

With Tourniquet

Normal Vein

R = 22 mmHg/mL/hr

F (mL/hr)
Fat compresses and obstructs veins

\[ R = 22 \text{ mmHg/mL/hr} \]

Elevated opening pressure

\[ P_F = \text{Fat pressure} \]

Obese Arm

With Tourniquet

Normal Vein
BP Cuffs obstruct veins

Opening pressure = Cuff Pressure, almost

Po = Pext
Catheter malposition can obstruct veins

\[ P_o = 80 \text{ mmHg} \]
Tissue Resistance is large

\[ R_{\text{tissue}} \gg R_{\text{vein}} \]

\[ R_{\text{tissue}} = 1125 \pm 1376 \text{ (SD) RU} \]

\[ R_{\text{vein}} = 22 \pm 20 \text{ (SD) RU} \]

Distribution of vein resistance for 46 surgical patients
Distributions of Vein and Tissue Resistances

Distribution of Vein Resistance

Distribution of Tissue Resistance

Veins

Tissues

RESISTANCE (mmHg/l/hr)

COUNT

More R
Normal Vein, Obstructed Vein, Infiltrated Tissue

Infiltrated Tissue $R = 500, P_o = ?$

Obstructed vein $R = 22, P_o = 80$

Normal vein $R = 22, P_o = 10$

Pressure (mmHg) vs. $F$ (m L / hr) graph
Obstructed Vein and Infiltrated Tissue can appear similar

Infiltrated Tissue $R = 500$

At $F = 200$ here, Infiltrated Tissue and obstructed vein cannot be distinguished

Obstructed vein $R = 22$, $P_o = 80$

Normal vein $R = 22$, $P_o = 10$
Requirements to Monitor an IV infusion

FLOW - controlled
PRESSURE - measured
or the reverse
P - F RELATIONSHIP - analyzed
RESISTANCE - computed as $R = \frac{\Delta P}{\Delta F}$
OBSTRUCTING PRESSURE - measured as $P_o$
RESULTS - trended and analyzed
Requirements to Monitor an IV infusion

FLOW - controlled
PRESSURE - measured
or the reverse
P - F RELATIONSHIP - analyzed
RESISTANCE - computed as $R = \frac{\Delta P}{\Delta F}$
OBSTRUCTING PRESSURE - measured as Po
RESULTS - trended and analyzed
PATENT - J Philip. BWH Licensed to IVAC, 1985
PRODUCT - IVAC/Alaris Signature Edition
Monitors Resistance
Alaris (IVAC) Signature Pump monitors Hydraulic Resistance
Alaris (IVAC) Signature Pump monitors Hydraulic Resistance
Present
Clinical Applications
of Resistance

Device evaluation (catheters, tubing,..)
Site Assessment
Catheter Size Selection
Fluid Resuscitation Optimization
Space Identification (epidural, axillary,..)
R measured by eye - Bag Elevation

Site Assessment

R measured by Bag Elevation even in the presence of a venous tourniquet

Choice of Catheter Size

20 ga catheter allows a steady IV flow stream. If flow is lower, vein is impeded or system is malfunctioning.

When a 20 ga IV catheter produces low flow, the major flow impediment is probably the patient’s vein, not the IV catheter.

Starting a second IV in a different vein increases flow more than placing a larger cannula because venous resistance dominates.
Choice of Catheter Size
Which usually provides greater flow, One 14 g catheter or Two 20 g catheters in different veins?

Two 20 gauge catheters!

One 14 g catheter
\[ R = R(14g) + R(\text{vein}) = 5 + 22 = 28 \]

Two 20 g catheters:
Each \[ R = R(20g) + R(\text{vein}) = 17 + 22 = 39 \]
2 in parallel, \[ R = \frac{39}{2} = 19.5 \]
R is 1.4 times lower,
Flow is 1.4 times as high = 40% higher

“The only thing wrong with a 20 g catheter is that it’s probably in a 20 g vein”

High Flow Resuscitation

Pressure and resistance limit flow. Both should be optimized

Resistance Lowering Sequence
- Open Roller Clamps
- Remove interposing devices contributing to total resistance.

Removal Order (considering non-linearity)
- Remove coil liquid warmer
- Change catheter from 16 to 14 gauge
- Remove check valve
- Change catheter from 14 to 12 gauge
- Replace regular tubing with wide bore tubing
- Change catheter from 12 to 10 gauge
- Remove stopcocks
- Remove 10 gauge catheter and insert sterile tubing in vein

Catheters usually cannot be changed
Stopcocks need not be removed!

Viscosity Effects

Apparent Resistance is proportional to Viscosity

Goodie DB, Philip JH. Viscosities of commonly infused substances. BJA 1995; 74:491-492
Viscosity = \nu = 5

Apparent Resistance is proportional to Viscosity

R = \frac{P}{1000}$
## Viscosities of Dextrose Solutions

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Viscosity</th>
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<tbody>
<tr>
<td>Water</td>
<td>1.0</td>
</tr>
<tr>
<td>Saline</td>
<td>1.0</td>
</tr>
<tr>
<td>D_5 W</td>
<td>1.03</td>
</tr>
<tr>
<td>D_10 W</td>
<td>1.1</td>
</tr>
<tr>
<td>D_20 W</td>
<td>1.4</td>
</tr>
<tr>
<td>D_30 W</td>
<td>1.9</td>
</tr>
<tr>
<td>D_40 W</td>
<td>2.6</td>
</tr>
<tr>
<td>D_50 W</td>
<td>3.5</td>
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</table>

\[
R_{D_CW} = R_{water} (1 + C^2 /1000).
\]
Viscosities of Dextrose Solutions

\[ R_{DCW} = R_{water} \left(1 + \frac{C^2}{1000}\right). \]

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<td>3.00</td>
</tr>
<tr>
<td>D₅₂W</td>
<td>4.00</td>
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It is easy to make liquids of varied viscosity

Viscosity $= \nu = 5$

$R = P_{1000}$
Viscosity of Various Clinical Infusates

## Viscosities of other infusates

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<td>5% Albumin</td>
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<td>Dextran 40 in saline</td>
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</tr>
<tr>
<td>Intralipid</td>
<td>1.36</td>
</tr>
<tr>
<td>D$_{17}$ W</td>
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Clinical viscosities of other infusates

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High Flow is Nonlinear

F < 3 L/hr PFR is linear
F >> 3 L/hr, PFR is non-linear
Nonlinearity limits flow during fluid resuscitation

PFR for IV tubing systems and other fluid conduits is distinctly non-linear

Not Laminar flow (Reynolds Number > 5,000)

\[ P = R_L F + R_T F^2 \]

PFR for Standard Tubing Set

\[ P = R_T F + R_L F^2 \]

or

\[ P = A F^n \]

\[ P = R F \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \]

\[ F \text{ ml/s} \]
Plot of Residuals shows Quadratic is Correct

Analysis of residuals, Comparing 3 flow models

\[ P = R F \]

\[ P = R_T F + R_L F^2 \]

\[ P = A F^n \]
Analyzing Tissue Spaces

Femoral Head

Avascular Necrosis - Is it produced by Vascular Outflow Obstruction?

No!

Warner, Philip, Brodsky, Thornhill

Clin Ortho & Relat Res. 1987; 225: 128-140

1987 Stinchfield Award Orthopedic Research
Epidural Space

We can learn a great deal by carefully creating fluid flow and measuring pressure.

Epidural Space

Experiment

Find Space

P - V relationship, through a 17 G Needle

$P_{\text{initial}} =$ negative, - 15 to - 5 mmHg

Add 0.1 mL  $P =$  0 mmHg
Add 0.1 mL  $P =$  10 mmHg
Add 0.1 mL  $P =$  10 mmHg
Add 1.0 mL  $P =$  10 mmHg
Add 3.0 mL  $P =$  13 mmHg
Add 3.0 mL  $P =$  16 mmHg
Epidural Space

Annotated Automated Epidural Graphic Report

P (mmHg)

Flow

Volume = 6 mL

Time (seconds)

0 50 100 150 200 250 300

0 10 20 30 40

0.1 mL

3 mL

3 mL

0.1 mL

6 mL
Epidural Space

Plateau after 0.1 - 0.3 mL

Flow = 360 mL/hr = 0.36 L/hr = 6 mL/min = 1 mL/10 sec = 3 mL/30 sec = 0.1 mL/sec

Plateau = 10 mmHg

Volume = 6 mL
Epidural Space

Inflow Resistance = \( \frac{\Delta P}{\Delta F} \) during infusion

Flow = 0.36 L/hr

\[ R_{in} = \frac{\Delta P}{\Delta F} = \frac{25 \text{ mmHg}}{0.36 \text{ L/hr}} = 70 \text{ RU} \]
Epidural Space

Compliance = \( \frac{\Delta V}{\Delta P} \)

Flow = 360 mL / hr = 0.36 L / hr = 6 mL / min = 1 mL / 10 sec = 0.1 mL / sec

\[ R_{in} = \frac{\Delta P}{\Delta F} = \frac{25 \text{ mmHg}}{0.36 \text{ L / hr}} = 70 \text{ RU} \]

\[ C = \frac{\Delta V}{\Delta P} = \frac{6 \text{ mL}}{6 \text{ mmHg}} = 1 \text{ mL/mmHg} \]

Plateau = 10 mmHg

Volume = 6 mL
Epidural Space

Measure Several Parameters
Inflow Resistance = $R_{in}$
Compliance = $C$
Outflow Resistance = $R_{out}$

$R_{in}$ differentiates different Clinical Conditions
$R_{in}$ is elevated in Spinal Stenosis and other inflammation
$R_{in}$ is normal with herniated disc
$C$ is normal in Spinal Stenosis and Disc Disease
$R_{out}$ is normal in Spinal Stenosis and Disc Disease

Impact of treatment on $R_{in}$ - Not studied yet
Epidural Pumps and Dangers of Free Flow

If an epidural pump were capable of free flow from an elevated bag, would it be dangerous?

Yes

> 500 mL / hour free flow into epidural space
Epidural drug absorbed

Epidural drug volume stays at approximately 18 mL
Anesthetic could be replaced at 500 mL / hr
Overdose of effect, overdose of systemic drug
There is a lot more to learn from the physics of fluid flow.
Thank you
Further Reading on Infusion

Science

Summary

Thank you