Venous Flow – Its Networks, Reservoirs, Dams, Waterfalls, Compression Chambers and Canals.”

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Disclosures

• Stock in Veniti inc.
• US Patent: IVUS diagnostics in CVD
• Stent usage in iliac-femoral veins is currently off label.

ASYNCHRONOUS VOLUME PRESSURE RELATIONSHIP

We are fitted with shocks in our legs!

Penrose are similar to veins: laminar flow (Poiseuille) occurs when they are full. When collapsed, a different type of flow called waterfall may occur.

Venous obstruction = Overflow dam
Wave Speed

- Downstream pressure information travels upstream in Poiseuille Flow (from $p_2$ to $p_1$). This is called wave speed.
- In certain types of venous flow, wave speed may be slower than actual flow. This type of non-Poiseuille flow is called supercritical flow or waterfall flow.

Starling Resistor (Abdomen)

As little as 10% stenosis will increase upstream venous pressure if abdominal pressure is ≤ 5 mm Hg. At 10 mm abd. Pressure, 50% stenosis is required. At higher abd. Pressures, abd pr itself dominates regardless of stenosis.

Microcirculation Network

'Stream' Diagram of the Human Circulation. Venous circulation is like a sponge and flow can take many paths. When the main channel is blocked, higher resistance collaterals open up. There is higher peripheral venous pressure but total flow remains the same.
Collateral Efficiency = Conductance
Conductance = 4th Power of Radius (Poiseuelle)

Number of collaterals needed to keep peripheral venous pressure normal. Less number will elevate peripheral venous pressure. Total flow remains the same.

Saphenous Reflux: Size matters!

Maximum Reflux Potential and Duplex Measured Reflux vs. GSV Diameter (n= 119)
Empiric clinical experience suggests that a GSV Diameter of 5-6 mm is significant.
All limbs except 1 with Measured Reflux > 30cc had a diameter ≥ 5.5 mm
At least 30cc reflux probably required to effect calf pump

Conductance is related to the fourth power of radius (Poiseuelle)
Duplex Reflux Volume vs. VFT (AMVP) (n=66)
Concordant VFT in only 62%. Discordant VFT in 38%.

Asynchronous volume/pressure relationship in the calf

Laminar Flow

Parabolic Flow Profile

Doppler Velocity

Victoria Falls
Poiseuille Law For Laminar Flow

- \( F = \frac{\Delta P}{R} \)
- \( \text{Flow} = \frac{\Delta P}{(8\pi n r^4)} \)
- **NOTE 4th POWER OF RADIUS**
- 4th power of radius because viscosity exponentially increases or decreases related to small or large size of the vessel.
- Flow resistance (eg peripheral resistance) is all due to viscosity changes not vessel size directly per se.

Arterial stenosis is like a hole in a balloon. Flow will increase or decrease according to the size of the hole. Pressure remains the same due to cardiac action and is unaffected by the size of the hole.

The basis of symptoms in CVD is elevation of peripheral venous pressure (back pressure).

- Therefore, % iliac venous stenosis calculated based on anatomic minimums. Based on the assumption that anatomic norms are required to keep peripheral venous pressure normal.
- CIV: 16 mm Diameter; 200 sq mm Area
- EIV: 14 mm Diameter; 150 sq mm Area
- CFV: 12 mm Diameter; 125 sq mm Area

In experimental systems, peripheral venous pressure begins to rise with as little as 20% stenosis and becomes significant at 50% stenosis.

Contrawise, arterial symptoms are based on downstream flow and stenosis is calculated on % stenosis. Typically, 70% stenosis is required to reduce perfusion.

Poiseuille Flow ≈ \( P_1 - P_2 \) when \( P_2 > CP \); When \( CP > P_2 \) Waterfall flow may occur when \( CP \) collapses the penrose.
Wave speed

\[ P_1 \rightarrow p^2 \]

Interaction with vein wall tension after refill necessary for popliteal valve re-opening

Calf-pump Mechanics, Normal and Abnormal

- ↑VV with ↑EV can buffer reflux
- ↓Compliance, ↓VV, ↓EV or ↑Art. Inflow can decrease VFT and magnify reflux even <30cc.

Reflux in motion will not transmit column pressure!

Figure 5

Figure 10
Figure 1

A. Static Model
Pressure measured at the bottom
Pressure Transducer

B. Partially Open Model
Pressure measured at the bottom
Pressure measured at the bottom
Pressure Transducer

Pressure Transducer

Table I: Internal and Transmural Pressures with Positive and Negative Starling Pressures

<table>
<thead>
<tr>
<th>Starling Pressure</th>
<th>Internal Pressure (mmHg)</th>
<th>Transmural Pressure (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+30mmHg</td>
<td>Collapsed</td>
<td>Collapsed</td>
</tr>
<tr>
<td>+20mmHg</td>
<td>Collapsed</td>
<td>Collapsed</td>
</tr>
<tr>
<td>+15mmHg</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>+10mmHg</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>+5mmHg</td>
<td>21</td>
<td>26</td>
</tr>
<tr>
<td>0mmHg</td>
<td>21</td>
<td>31</td>
</tr>
<tr>
<td>-5mmHg</td>
<td>21</td>
<td>36</td>
</tr>
<tr>
<td>-10mmHg</td>
<td>21</td>
<td>41</td>
</tr>
</tbody>
</table>

Table II: Penrose Volume and Flow Changes with Positive and Negative Starling Pressures. With increasing positive Starling Pressures, penrose volume progressively decreases roughly paralleling the decrease in flow. Negative Starling pressures result in only a small increase in penrose volume (maximum 8%); there is no change in flow.

<table>
<thead>
<tr>
<th>Starling Pressure</th>
<th>Penrose Volume (cc)</th>
<th>Flow (mL/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+30mmHg</td>
<td>2 (5%)</td>
<td>2 (3%)</td>
</tr>
<tr>
<td>+20mmHg</td>
<td>6 (15%)</td>
<td>115 (17%)</td>
</tr>
<tr>
<td>+15mmHg</td>
<td>18 (46%)</td>
<td>245 (36%)</td>
</tr>
<tr>
<td>+10mmHg</td>
<td>26 (67%)</td>
<td>411 (60%)</td>
</tr>
<tr>
<td>+5mmHg</td>
<td>30 (77%)</td>
<td>685 (100%)</td>
</tr>
<tr>
<td>0mmHg</td>
<td>39 (100%)</td>
<td>685 (100%)</td>
</tr>
<tr>
<td>-5mmHg</td>
<td>41 (105%)</td>
<td>672 (98%)</td>
</tr>
<tr>
<td>-10mmHg</td>
<td>42 (108%)</td>
<td>666 (97%)</td>
</tr>
<tr>
<td>-15mmHg</td>
<td>43 (108%)</td>
<td>665 (97%)</td>
</tr>
<tr>
<td>-20mmHg</td>
<td>44 (108%)</td>
<td>680 (99%)</td>
</tr>
</tbody>
</table>
Table III: Respiratory variation in cross-sectional area of iliac-caval veins

<table>
<thead>
<tr>
<th></th>
<th>Expiration Area (mm²±SD)</th>
<th>Inspiration Area (mm²±SD)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVC (n=37)</td>
<td>168 ± 83</td>
<td>222 ± 87</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>CIV (n=35)</td>
<td>151 ± 54</td>
<td>158 ± 54</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>EIV (n=35)</td>
<td>135 ± 50</td>
<td>140 ± 51</td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

Vertical Calf Experiment

Hemodynamics of venous obstruction

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Vascular Waterfall

Tandem Stenoses

Evils of Under-stenting

- Normal CIV: diameter 16 mm = area 200 sq mm ($\pi r^2$).
- A 14 mm stent represents 24% stenosis
- A 12 mm stent represents 34% stenosis
- A 10 mm stent represents 60% stenosis
- These will be much worse if the stent develops some degree of ISR- up to 25% is common.
- **USE 18 mm stents, balloon to 16. you have room to dilate later to 18 if ISR develops.**
Negative pressure in the chest does not transmit inside. It makes the vein into a stiff tube, and the internal pressure will stay positive. Negative CVP pressures are not recorded except in shock.

- GSV Reflux: Diameter: 0.62cm; Area: 0.30cm²; Velocity: 3cm/sec.; Duration: 4.9sec; Reflux Volume: 4.5ml
  Velocity and Duration important as well

‘Big saphenous, Small Reflux’