Modeling the Arterial System to Improve Ultrasound Measurements of Hemodynamic Parameters

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Flow Phantom

• What is a phantom?
  – Hydraulic fluid system that mimics arterial blood flow and pressure waveform propagation

• Why use build a flow phantom?
  – Enables full control over various parameters
  – Ability to control parameters that we could not on humans
Phantom Introduction

• What makes up a phantom?

<table>
<thead>
<tr>
<th>Arterial System</th>
<th>Phantom</th>
</tr>
</thead>
<tbody>
<tr>
<td>heart</td>
<td>pump</td>
</tr>
<tr>
<td>large arteries</td>
<td>compliant tubing</td>
</tr>
<tr>
<td>arterioles</td>
<td>flow control valve</td>
</tr>
</tbody>
</table>
Phantom Design

Accumulator

Pump

Compliant Tube

Flow Control Valve

Reservoir

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Page 5
Simulation

- Simulated the hydraulic design using MATLAB Simscape Fluids
Simulation Results

Pressure vs. Time

Leading Pressure     Lagging Pressure

Pressure [mmHg]

Time [s]

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Page 7
Simulation Results

Pressure vs. Time

- Pressure vs. Time graph showing leading and lagging pressures.
- The graph illustrates the relationship between pressure and time.

Leading Pressure     Lagging Pressure
Physiological Parameters

• What parameters can we control?
  – **Heartrate**: changing the frequency at which we turn on the pump
  – **Stroke Volume**: changing how long the pump is on for any given heartbeat (duty cycle)
  – **Total Peripheral Resistance**: adjusting the flow control valve
  – **Critical Closing Pressure**: adding or removing water from the reservoir reference point
  – **Arterial Length & Compliance**: changing the compliant tubing within the system
## Physiological Parameters

<table>
<thead>
<tr>
<th>Control Parameters</th>
<th>Measurements</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Peripheral Resistance</td>
<td>Pressure</td>
<td>Pulse Wave Velocity</td>
</tr>
<tr>
<td>Heart Rate</td>
<td>Flow</td>
<td>Pulse Pressure</td>
</tr>
<tr>
<td>Stroke Volume</td>
<td>Diameter / Area</td>
<td>Forward / Backward Flow</td>
</tr>
<tr>
<td>Critical Closing Pressure</td>
<td></td>
<td>Forward / Backward Pressure</td>
</tr>
<tr>
<td>Arterial Length</td>
<td></td>
<td>Change in Diameter / Area</td>
</tr>
<tr>
<td>Arterial Compliance</td>
<td></td>
<td>Characteristic Impedance</td>
</tr>
</tbody>
</table>
Phantom Validation

• How do we know if the phantom is a reasonable model for mimicking arterial blood flow?

• Experiments:
  
  – $\uparrow$ Total Peripheral Resistance = $\uparrow$ Mean Arterial Blood Pressure

$$\text{MAP} = (\text{C. O.})R$$
Low Resistance

High Resistance

Pressure and Flow vs. Time

Lowest Resistance

Highest Resistance

Transient Pressure Increase
Phantom Validation

• How do we know if the phantom is a reasonable model for mimicking arterial blood flow?

• Experiments:
  – ↑ Total Peripheral Resistance = ↑ Mean Arterial Blood Pressure
  – ↑ Stroke Volume = ↑ Cardiac Output = ↑ MAP
Low Stroke Volume  

Motor Voltage vs. Time

High Stroke Volume  

Motor Voltage vs. Time

Pressure and Flow vs. Time

Pressure [mmHg]

Flow Rate [L/min]

Pressure [mmHg]

Flow Rate [L/min]
Phantom Validation

• How do we know if the phantom is a reasonable model for mimicking arterial blood flow?

• Experiments:
  – ↑ Total Peripheral Resistance = ↑ Mean Arterial Blood Pressure
  – ↑ Stroke Volume = ↑ Cardiac Output = ↑ MAP
  – ↑ Heart Rate = ↑ Cardiac Output = ↑ MAP
Heart Rate = 1 Hz

**Motor Voltage vs. Time**

```
Motor Voltage [V]
```

```
Time [s]  6   6.5  7   7.5  8
```

Heart Rate = 2 Hz

**Motor Voltage vs. Time**

```
Motor Voltage [V]
```

```
Time [s]  18  18.5 19  19.5 20
```

**Pressure and Flow vs. Time**

```
Pressure [mm-Hg]
Flow Rate [L/min]
```

```
Time [s]  6   6.5  7   7.5  8
```

```
Time [s]  18  18.5 19  19.5 20
```

Phantom Validation

• How do we know if the phantom is a reasonable model for mimicking arterial blood flow?

• Experiments:
  – $\uparrow$ Total Peripheral Resistance $= \uparrow$ Mean Arterial Blood Pressure ✓
  – $\uparrow$ Stroke Volume $= \uparrow$ Cardiac Output, $\uparrow$ MAP ✓
  – $\uparrow$ Heart Rate $= \uparrow$ Cardiac Output, $\uparrow$ MAP ✓
Arterial System as Transmission Line

• Blood Flow Equations:

\[-\frac{dP}{dx} = \frac{\rho}{A} \left( \frac{dQ}{dt} \right)\]

\[-\frac{dQ}{dx} = \left( \frac{dA}{dP} \right) \left( \frac{dP}{dt} \right)\]
Transmission Line Equations:
\[ - \frac{dV}{dx} = L \left( \frac{dI}{dt} \right) \]
\[ - \frac{dI}{dx} = C \left( \frac{dV}{dt} \right) \]

Arterial System as Transmission Line

Blood Flow Equations:
\[ - \frac{dP}{dx} = \frac{\rho}{A} \left( \frac{dQ}{dt} \right) \]
\[ - \frac{dQ}{dx} = \left( \frac{dA}{dP} \right) \left( \frac{dP}{dt} \right) \]
Arterial System as Transmission Line

• Blood Flow Equations:

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\[- \frac{dQ}{dx} = \left( \frac{dA}{dP} \right) \left( \frac{dP}{dt} \right)\]

<table>
<thead>
<tr>
<th>Artery</th>
<th>Transmission Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure, (P)</td>
<td>Voltage, (V)</td>
</tr>
<tr>
<td>Volumetric Flow Rate, (Q)</td>
<td>Current, (I)</td>
</tr>
<tr>
<td>Inertia, (\frac{\rho}{A})</td>
<td>Inductance per length, (L)</td>
</tr>
<tr>
<td>Compliance, (\frac{\Delta A}{\Delta P})</td>
<td>Capacitance per length, (C)</td>
</tr>
</tbody>
</table>

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Page 21
Physiology to TL Equations

\[ PWV = \sqrt{\frac{A \, dP}{\rho \, dA}} = \sqrt{\frac{1}{LC}} \]

\[ Z_c = \sqrt{\frac{\rho \, dP}{A \, dA}} = \sqrt{\frac{L}{C}} \]

\[ Z_c = \frac{\rho}{A} \, PWV \]
Measurement Site

Leading Flow

Lagging

Leading Flow

Lagging
Effect of Load Resistance

- $R_{\text{Load}} = Z_0, \quad \Gamma = 0$
- $R_{\text{Load}} = 5, \quad \Gamma = .3$
Simulation Results

Voltage and Current vs. Time

Pressure and Flow vs. Time

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Page 26
Reflections

• ABP measurements taken from a dog at different sites along the arterial tree
Reflections in LTspice

Forward and Backward Waves (Leading Point)  Forward and Backward Waves (Lagging Point)

Voltage [V]  Voltage [V]

Forward Wave  Forward Wave
Backward Wave  Backward Wave
Measured Voltage  Measured Voltage

Time [s]  Time [s]

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Page 28
Travel Time for Reflected Waves

Forward and Backward Waves

Voltage [V]

Flow

Leading

Lagging

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Page 29
Reflections in LTspice

Forward and Backward Waves (Leading Point)

- Forward Wave
- Backward Wave
- Measured Pressure

Forward and Backward Waves (Lagging Point)

- Forward Wave
- Backward Wave
- Measured Pressure
Travel Time for Reflected Waves

Forward and Backward Waves

<table>
<thead>
<tr>
<th>Voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>4.5</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>

- Green: Forward V (Leading)
- Green dashed: Backward V (Leading)
- Red: Forward V (Lagging)
- Red dashed: Backward V (Lagging)

Leading → Flow → Lagging

Artery

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Page 31
Conclusion

• A flow phantom can properly mimic the properties of arterial blood flow

• The phantom allows control over all parameters enabling a more defined set of relationships to be studied, some of which cannot be evaluated in the human body

• Both the arteries and the elastic tube in the flow phantom behave like a transmission line

• Transmission line behavior can be simulated in LTspice to explore crucial dynamic behaviors, like reflections
Questions?