Modelling of the Nonlinear End-Systolic Pressure-Volume Relation and Volume-at-Zero-Pressure in Porcine Experiments

Shaun M. Davidson¹, D. Oliver Kannangara¹, Chris G. Pretty¹, Shun Kamoi¹, Antoine Pironet², Thomas Desaive², J. Geoffrey Chase¹

¹ University of Canterbury, Department of Mechanical Engineering, New Zealand
² University of Liège, GIGA-Cardiovascular Sciences, Belgium

Objective
- The End-Systolic Pressure-Volume Relationship (ESPVR) can be used to evaluate the contractile state of the heart, and is typically modelled as a linear relationship.
- Extrapolation of the ESPVR can be used to determine $V_0$, which is important in normalising cardiac behaviour models, however this extrapolation can yield negative, non-physical values.
- The focus of this research was to evaluate and compare models for the ESPVR on experimental data across a range of cardiac states without suppression of cardiac reflexes.

Experimental Data
- Left ventricular volume and pressure data was gathered from a cohort of 6 pure pietrain pigs, using a micromanometer-tipped admittance catheter sampling at 1000 Hz.
- The pigs underwent preload reduction via vena cava occlusion to provide a range of ventricular volumes and pressures for ESPVR curve construction, across a variety of PEEPs.
- Ethics approval was granted by the Ethics Committee of the University of Liège Medical Faculty.

Methods
- Two models were fitted to end-systolic pressure and volume to determine ESPVR and $V_0$. The first was the standard linear model:
  $$P_{es} = E_{es}(V_{es} - V_0)$$
- The second was an exponential model:
  $$P_{es} = P_0(1 - e^{-m(V_{es} - V_0)})$$
- Models were compared based off Pearson’s Correlation Coefficients and Akaike Information Criterion (AIC) score:
  $$AIC = n \log \left(\frac{RSS}{n}\right) + 2K$$

Results
- Combined end-systolic pressures and volumes for each pig, with linear and exponential fits, are shown below.

<table>
<thead>
<tr>
<th>Pig</th>
<th>Correlation Coefficient, R, Exp. Model</th>
<th>Correlation Coefficient, R, Linear Model</th>
<th>$V_{es}$ Exp. Model (mL)</th>
<th>$V_{es}$ Linear Model (mL)</th>
<th>Akaikes Information Criterion, AIC, Exp. Model</th>
<th>Akaikes Information Criterion, AIC, Linear Model</th>
<th>Number of Heartbeats</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.943</td>
<td>0.929</td>
<td>11.67</td>
<td>14.3</td>
<td>614.4</td>
<td>703.3</td>
<td>126</td>
</tr>
<tr>
<td>2</td>
<td>0.951</td>
<td>0.939</td>
<td>8.56</td>
<td>-3.29</td>
<td>560.9</td>
<td>595.2</td>
<td>134</td>
</tr>
<tr>
<td>3</td>
<td>0.929</td>
<td>0.923</td>
<td>9.38</td>
<td>3.78</td>
<td>981.3</td>
<td>1020.1</td>
<td>266</td>
</tr>
<tr>
<td>4</td>
<td>0.926</td>
<td>0.900</td>
<td>7.47</td>
<td>-5.87</td>
<td>428.5</td>
<td>467.1</td>
<td>111</td>
</tr>
<tr>
<td>5</td>
<td>0.978</td>
<td>0.947</td>
<td>11.1</td>
<td>4.73</td>
<td>146.8</td>
<td>216</td>
<td>93</td>
</tr>
<tr>
<td>6</td>
<td>0.717</td>
<td>0.708</td>
<td>3.31</td>
<td>-6.33</td>
<td>571.9</td>
<td>624.7</td>
<td>153</td>
</tr>
</tbody>
</table>

Conclusion
- Both exponential and linear models showed strong correlations, with modestly higher exponential correlation coefficients in 6 out of 7 cases.
- The exponential model produced reasonable, positive values for $V_0$ in 6 out of 7 cases while the linear model produced positive $V_0$ values in 3 out of 7 cases.
- The exponential model had significantly lower AIC values for pigs 1 and 4, and modestly lower values for the remaining pigs.
- These combined results suggest that an exponential model of ESPVR may perform better than a linear one for patients where cardiac reflexes are not suppressed.
- While the difference between the two models over the physiologically observed range is relatively small, this has interesting implications when extrapolating ESPVR to determine $V_0$. 
