AN ANALOG MODEL FOR THE INTERACTION BETWEEN SYSTEMIC AND CORONARY CIRCULATION

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ABSTRACT

An analog electrical model was developed to characterize the hemodynamic relations between the coronary circulation and the systemic circulation. The model for coronary circulation included a nonlinear stenosis resistor, an endocardial channel, and an epicardial channel. The intramyocardial pressure of the left ventricle acted as a back pressure against the coronary flow. The behavior of the complete analog model (both systemic and coronary) was determined by use of a state-space method. As an example, the model was used to simulate and quantify the diastolic augmentation of coronary flow by intracoronary balloon pumping.

INTRODUCTION

The pressure and flow at the aortic root affect the input to the coronary circulation. The intramyocardial pressure also affects blood flow in the coronary vessels which are embedded in the ventricular wall. The purpose of this study is to develop an analog model of the coronary circulation as part of the systemic circulation. The analog model is intended as a framework for studying the interaction between the dynamics of the systemic circulation and that of the coronary circulation on a quantitative basis.

Previously, we developed an analog model and a state-space method to characterize the ventricular and vascular coupling [1]. We also developed a model for the coronary circulation [2] and estimated the intramyocardial distribution of pressure and flow using a swine model with the presence of a severe coronary artery stenosis [3]. This study combines the two analog models and extends the state-space analysis method to the combined model.

METHOD

In Fig. 1 an analog model of the systemic circulation including the coronary circulation is shown. Based on a state-space analysis similar to that described in [4], the circuit behavior as a function of time is determined. The state variables are chosen as follows: left ventricular volume \(V_v\), pressure across the ascending aorta capacitor \(p_{aa}\), aortic flow \(q_{ao}\), volume in the descending aorta/intraaortic balloon section \(V_{da}\), and pressure across the peripheral capacitor \(p_{pe}\). The system dynamics can be completely characterized by use of five state equations. For example, the time-derivative of \(p_{aa}\) is related to other state variables according to

\[
\frac{dp_{aa}}{dt} = \frac{C_{aa}(q_{ao} - q_{aa}) - q_{aa} - q_{pe}}{C_{aa}(1 + \frac{R_{pe}}{R_{aa}})}
\]

The coronary flow \(q_{co}\) is determined from the following two equations.

\[
p_{aa} + R_{aa}C_{aa} \frac{dp_{aa}}{dt} - p_{aa} = R_{aa} + S_{a}q_{co}^2
\]

\[
q_{co} = \text{sgn}(p_{aa} - p_{en})/R_{en} + \text{sgn}(p_{aa} - p_{pe})/R_{pe}
\]

where \(\text{sgn}[x] = x, \text{ if } x > 0; = 0, \text{ otherwise.}\) The back pressures are given by \(p_{en} = 1.1p_a\) and \(p_{pe} = 0.1p_a + 15 \text{ mmHg.}\) The stenosis geometry determines \(R\) and \(S\). Their values along with those for \(R_{en}\) and \(R_{pe}\) are taken from a previous study [3].

Fig. 1 An analog model for the interaction between the systemic and the coronary circulatory system.
**RESULT**

The model-generated waveforms of left ventricular pressure ($p_{lv}$), aortic pressure ($p_{ao}$), and coronary arterial pressure distal to the stenosis ($p_{dc}$) are shown for two consecutive cardiac cycles in Fig. 2 (top). The intraaortic balloon pumping is turned on for the first cardiac cycle and off for the second. The corresponding waveforms of total coronary flow ($q_{co}$), endocardial coronary flow ($q_{en}$), and epicardial coronary flow ($q_{ep}$) are shown in Fig. 2 (bottom). The effect of the intraaortic balloon pumping on systemic and coronary hemodynamics is shown by the change of several parameters in Table 1.

**CONCLUSIONS**

An analog model that characterizes the interaction between the coronary and the systemic circulatory system was developed. The use of the model to quantify the effect of intraaortic balloon pumping on the coronary dynamics was demonstrated. Both magnitude and wave shape of the model-generated coronary pressure and flow were reasonable and representative of those observed in animal models and in human. Future work will include further validation of the model and applying the model-based analysis to circulatory systems of various disease states and under different treatment procedures.

**REFERENCES**


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**Table 1.** Model-predicted changes of hemodynamics by intraaortic balloon pumping.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IABP OFF</th>
<th>IABP ON</th>
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<tbody>
<tr>
<td>Cardiac output (l/min)</td>
<td>2.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Peak LV pressure (mmHg)</td>
<td>115</td>
<td>112</td>
</tr>
<tr>
<td>Tension-time index (mmHg/s)</td>
<td>31</td>
<td>30</td>
</tr>
<tr>
<td>Mean diastolic $p_{ao}$ (mmHg)</td>
<td>81</td>
<td>116</td>
</tr>
<tr>
<td>Endocardial viability ratio</td>
<td>1.46</td>
<td>2.17</td>
</tr>
<tr>
<td>Mean systolic $p_{dc}$ (mmHg)</td>
<td>81</td>
<td>78</td>
</tr>
<tr>
<td>Mean diastolic $p_{dc}$ (mmHg)</td>
<td>35</td>
<td>43</td>
</tr>
<tr>
<td>Mean $q_{co}$ (ml/s)</td>
<td>0.66</td>
<td>0.85</td>
</tr>
<tr>
<td>Mean $q_{en}$ (ml/s)</td>
<td>0.43</td>
<td>0.58</td>
</tr>
<tr>
<td>Mean $q_{ep}$ (ml/s)</td>
<td>0.23</td>
<td>0.27</td>
</tr>
</tbody>
</table>

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